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Geotechnical aspects of tunnel lining with segmental joint parameters to improve soil surface settlement prediction

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Abstract. Conventional lining design usually considers tunnel lining as a uniform rigid ring model by implying high partial safety factor on the bending moment which is overestimated, due to inaccurate assumptions. To overcome this problem, investigation on the influence of joints on the behaviour of the global lining is significantly important especially when the interaction between segments is included. This paper presents investigation in tunnel segment joint influence on global tunnel lining behaviour especially when the interaction between segments becomes nonlinear, in different type of soil, so that more realistic soil-tunnel lining response can be obtained. The effect of segment joint parameters (linear or nonlinear) and soil parameters was investigated via numerical modelling. The predicted stress and displacement results from the numerical model were verified with the result obtained from field data collection. FEM model of original soil and settlement monitoring data depicted similar pattern of settlement but the FEM model did not captured the sudden settlement at the distance of 40 m from starting point. This was due to the simplification of FEM model and assumption of greenfield. The sand model gave similar result pattern like original case study soil behaviour. Clay model, in opposite, showed heaving at the beginning of construction that caused by the pressure induced by the weight of concrete and moving the water pressure toward the ground. One could conclude that, the elastic settlement profile occurred due to selected parameters of soil and Mohr Coulomb model.

1. Introduction

This paper is written to explain the behaviour of different type of soil on tunnel construction. A tunnel construction model was constructed in Mohr-Coulomb soil criterion in ABAQUS software [1]. Sequential of soil excavation and lining installation are modelled respectively in finite element method. Each tunnel construction was modelled in three dimensional (3D) with 19 rings of lining installation. The linings are modelled in shell which consists of 5 segments and 1 key segment. Interactions between segments joint were included. The effect of segment joint parameters (linear or nonlinear) and soil parameters were investigated. The results of finite element models (FEM) are then compared with the site condition for validation. However, only soils respond due to tunnel construction was taken into account.

2. Theory of Segmental Tunnel Lining Design

Application of segmental tunnel lining design has been widely used in construction of tunnel. A ring of lining will consist of jointed segmental precast concrete linings which are connected by steel bolts [2]. The stiffness of joints and the concrete segment play important role in stability of tunnel. An equation which was proposed by Muir Wood [3] can be used to calculate the equivalent stiffness of the lining as follows:

$$I_e = I_j + I\,(4/n^2) \quad (1)$$

where,
$I_j << I$ for an expanded and articulating lining
I_j : The moment of inertia at the joint which mainly affected by the contact zone
n : Number of segments in a ring ($n > 4$; 4 is minimum numbers of segment in tunnel) and

I : The moment of inertia of the tunnel lining with complete cross-section

Conventional approach of lining design was based on parameter called flexibility ratio, F. Flexibility ratio is the flexural stiffness ratio between the soil and the lining which can be written as in equation 2 [4]

$$F = \frac{E_s/1+v_s}{6E_L I_L/(1-v_L^2)R^3} \quad (2)$$

where,

E_s : Young's modulus of the soil
v_s : Poisson's ratio of the soil
E_L : Young's modulus of the lining
v_L : Poisson's ratio of the lining
I_L : The effective moment of inertia of the lining
R : Radius of the lining

Further studies of tunnel lining design brought researcher to step up to modelling. Peck *et al*. [5] and Muir Wood [3] tried to model a single rigid lining under a body of soil. However this model will result of high bending moment in concrete lining as well as it does not represent the actual condition of lining installation.

Do *et al*. [6] were succeeded in developing a 3D model of tunnel which introduces segment's joint stiffness, lining joint pattern and the construction tunnel process (*i.e*., jacking forces and grouting pressure). Hence, the only coefficient of joint stiffness was adopted for this purpose.

3. Case Study

Construction of Circle line stage 3 (C852), Serangoon Interchange Station was used as a case study for an original soil condition [6]. A body of soil with dimension of 63 m x 50 m x 46 m which consists of layers of soil as it was found on site will be used in modelling. In the meantime, Tunnel will be constructed 23 m from the surface. A progressive step of excavation of soil and installation of lining will be done along 22.4 m in longitudinal direction (Y-axis).

Three models which contain different condition of soil will be modelled, namely (a) original soil condition, (b) clayey soil, and (c) sandy soil. These variations were made to assess tunnel behaviour and to investigate fundamental of soil response due to tunnel excavation. However, this paper was limited only on investigating response of each soil due to tunnel excavation. Several results of site monitoring were used as comparison and validation of FEM model.

3.1 Tunnel lining properties and interaction

Tunnel lining of 6.35 m diameter with 1.4 m width and 0.275 m thickness were modelled. Ring joints and segment joints interaction were assigned in segment and lining interaction respectively. Figure 1 shows model of segmental tunnel lining which each of it consists of 5 standard segments and 1 key segment to complete a single tunnel lining. Each standard segment was built with opening angle of 67.5° while key segment with opening angle of 22.5° was used to complete a set of ring. Furthermore, each ring was rotated 11.25° in clock wise direction from previous lining to present actual condition of tunnel lining installation. Hence, 19 tunnel linings which equivalent to 22.4 m aligned in Y-direction were placed 23 m from the ground surface to the centre of tunnel.

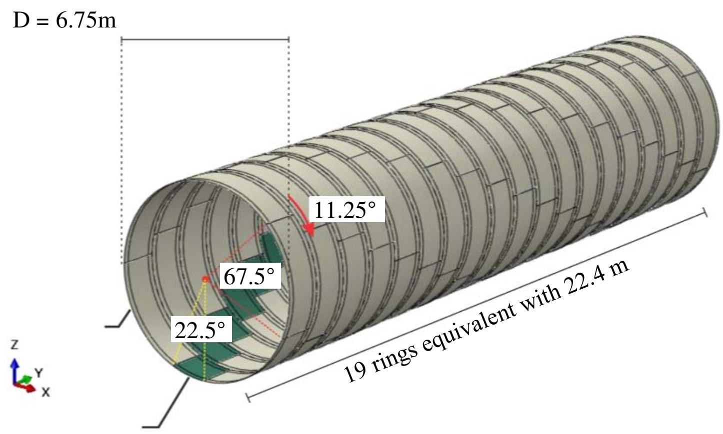


Figure 1. Staggered segment model using shell element

Tunnel lining was simulated as isotropic linear elastic model, in which 33 GPa of Young Modulus and 0.2 of Poisson ratio was used. Tie interaction between each lining were simulated to prevent pore fluid flow entering the tunnel and dual-hinge-joint segment model were placed in Y-direction connecting each segment in single ring to simulate ring joints (Figure 2). Elasticity of the hinge was assumed as Uncoupled with Modulus of 24.5 MPa. The mesh tie constraints method called "master-slave" was used to simulate soil-tunnel interaction in which lining acted as master surface and soil bodies as slave surface. Interaction property with tangential behaviour of 0.35 was adopted for this simulation.

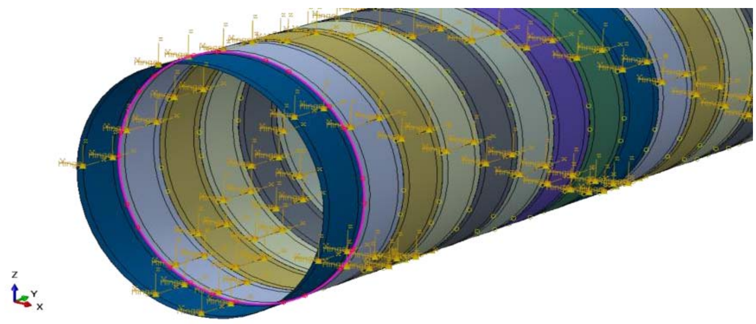


Figure 2. Dual hinge-joint segment interaction and tie ring interaction applied in tunnel lining

3.2 Soil properties and boundary conditions

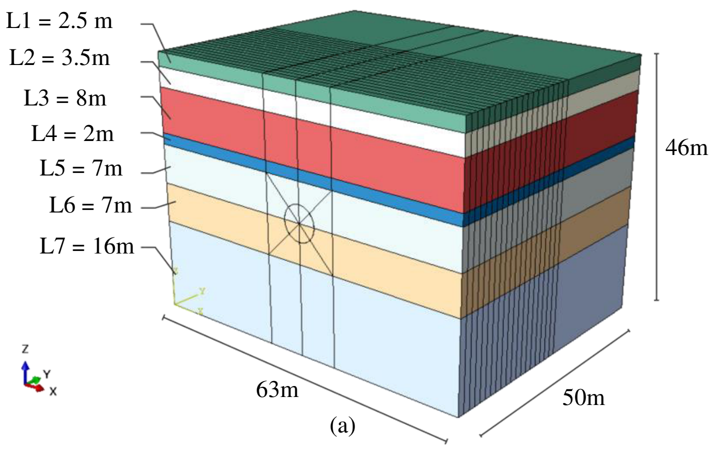
The entire soil model was assigned with specific properties based on Table 1. A body of soil which has dimension of 63 m x 50 m x 46 m were constructed (Figure 3). Three different conditions of soils will be modelled. Original soil condition consists of 7 layers of material follows the soil properties of case study. Each layers of material adopted presented in Table 1.

In the second model, Clay soil model will be modelled using properties of Fluvial clay (L3) properties and overlaid by 16 m thick Bukit Timah Granite G2 (III) will be used as bedrock. Third model (Sand soil) will be constructed with the same dimension as clayey soil model which is 40 m thick with properties taken from original Fluvial sand (L4) and overlaid with 16 m thick of bed rock.

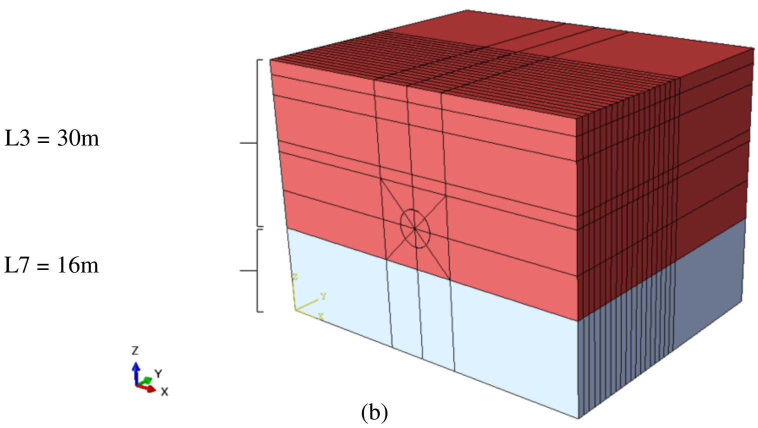
A gravity load of 10 kN was applied to all model to simulate gravity. Furthermore, geostatic stresses were assigned in each layers based on effective stress of each layer. Water table was assigned 2.5 m from ground follow the real case study. Void ratio was set to be 1 for the whole model to avoid discrepancies of the model.

Table 1. Soil Properties taken from Circle line stage 3 (C852), Serangoon Interchange Station [8]

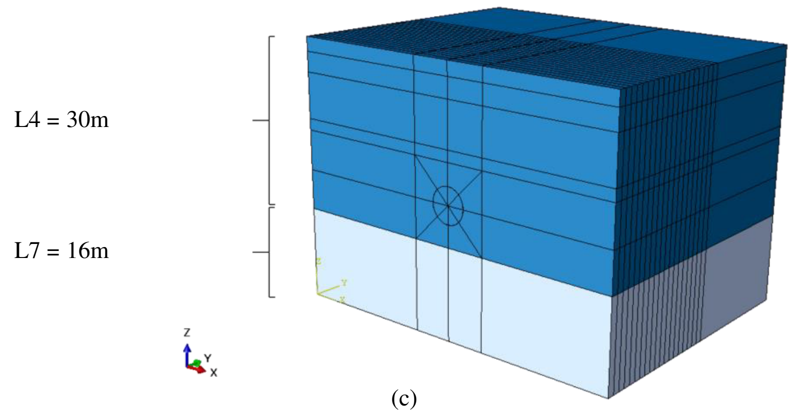
Soil layer	**Soil type**	**Young Modulus, E_s (kPa)**	**Bulk density, γ (kN/m³)**	**Poison's ratio, v_s**	**Angle of friction, ϕ (°)**	**Cohesion, *c* (kPa)**
L1	Fill	7000	19	0.333	30	0.3
L2	Estuarine	3000	15	0.35	20	0.3
L3	Fluvial clay	3000	19	0.35	22	0.3
L4	Fluvial sand	7000	20	0.32	32	0.3
L5	Bukit Timah granite formation, G4 (VI)	59200	20	0.333	30	2
L6	Bukit Timah granite formation, G4 (v)	86400	20	0.3	35	2
L7	Bukit Timah granite formation, G2 (III)	3500000	23	0.32	35	400



(a)



(b)



(c)

Figure 3. Soil block model (a) Original case study model, (b) Clay model and (c) Sand model

Boundary condition of tunnel excavation was changed along the progression of tunnel construction. Bottom boundary of the model was assigned as fixed in all direction to prevent any movement and fixed along the tunnel construction. However, each side of soil model boundaries were allowed to move vertically (Z-axis). During each excavation step, surface of the excavated soil was set to be fixed. It was then deactivated in the next lining installation step. FEM models were simplified in which the lining has the same dimension with excavation size. Results were compared with site monitoring result.

4. Result

In general, result from FEM shows different amount of settlement with site monitoring result (Figure 4).

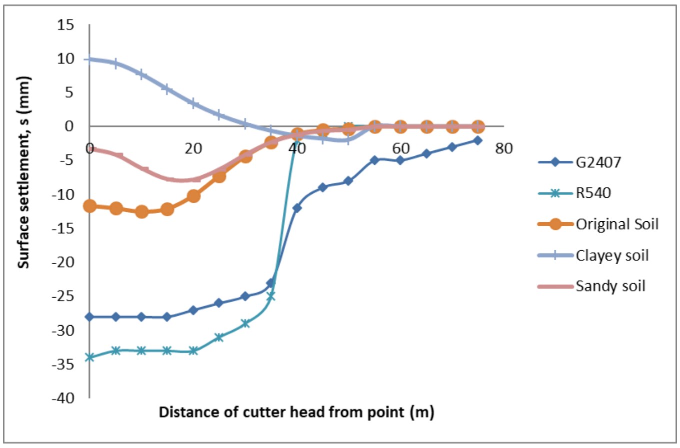


Figure 4. Results of tunnel induced ground settlement from FEM and site monitoring. (Note that G2407 was surface settlement measured by settlement marker on OT tunnel and R540 was settlement reading at the specific rings [9])

Based on Figure 4, some differences in maximum settlement were found between FEM (*i.e.,* original soil model) and field data result (*i.e.,* G2407 and R540), in ratio of 1:2. Original soil and settlement monitoring data depicted similar pattern of settlement but the FEM model did not captured the sudden settlement at the distance of 40 m from starting point. This might due to the simplification of FEM model in which, at first, diameter of excavation were assumed to be similar with the lining size. In the actual situation, excavation diameter is always slightly bigger than the lining diameter that allows volume loss occurring during excavation. In second, FEM analyses were modelled in greenfield condition which not showing the effect of external loading from surrounding buildings (*i.e.,* actual conditions).

Using the similar analysis approach, in order to increase understanding of soil properties effect in ground settlement due to tunnel excavation, further analysis were carried out with two different type of soil; sandy and clayey soil. From the analysis, results show some distinctive behaviour between sand and clay model in terms of settlement. In the sand model, a similar pattern like the original soil model was captured, but with some heaving effects from the beginning of excavation until 10 m length. It reaches the maximum settlement up to 8 mm, and then continued to decrease in values until the end. In contrary to that, heaving was also unexpectedly seen in clay soil model. A 10 mm of heaving found at the start of tunnel excavation up to 10 meter of excavation length. A set of concrete lining was placed in the saturated clay immediately after the excavation. Clay with full of water (saturated) were then induced with some pressure by the weight of concrete lining. This action caused the water pressure to move upward and caused heave.

5 Conclusions

This paper presents another development of FEM in soil-tunnel interaction in which hinge model of 19 rings were modelled in three different soil conditions. Construction of Circle line stage 3 (C852), Serangoon Interchange Station was used as a case study to model the original soil condition. The analysis were then followed by modelling clay and sand separately to understand each soil type behaviour in terms of settlement induced by tunnel excavation on a segmental lining model.

Model using original case study and sand model gave similar result patterns. However, clay model showed heaving at the beginning of construction up to until 10 mm of tunnel excavation. This distinctive behaviour of clay was caused by the excessive water pressure which was caused by the pressure induced by the weight of concrete and moving the water pressure toward the ground. One could conclude that, the elastic settlement profile occurred due to selected parameters of soil and Mohr Coulomb model.

In the future, soil modelling study by using hardening soil model or Camclay model should be carried out to bring more comprehensive results.

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