3D Numerical Model of Soil-Tunnel Interaction Induced by Segment Joint Parameter

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Abstract. In a shallow tunnel, tunnel construction will triggers a chain of ground movements, resulting in settlements at the ground surface, which become more significant with the decrease in tunnel depth. Therefore, by considering behaviour of the segment tunnel joints (can affect the integrity of tunnel in both circumference and longitudinal directions), the surface settlement trough were investigated. Initial model of dual segmental tunnel lining was model and validated with laboratory test to gain nonlinear response of segment joint. Then, a soil-tunnel simulation model was developed with various segment joint parametric models for Singapore Circle Line Stage 3 (C852) project. Results showed that with the use of flexible segment joints that allow movement (hinge-nonlinear model) in staggered ring tunnel model, the ground deformation depicted higher resemblance of surface settlement pattern to the field data. Steady state settlement was observed after 10m of cutter head distance.

1. Introduction
Soil-tunnel interaction is uncertainty phenomenon. Tunnel excavation causes relaxation of in-situ stress, which is only partially restricted by the insertion of the tunnel support. In fact, it is not possible to create a void instantaneously and provide an infinitely stiff lining to fill it exactly. Hence, a certain amount of the deformation of the ground will take place at the tunnel depth, which triggers a chain of movements, resulting in settlements at the ground surface, which become more significant with the decrease in tunnel depth. In mean time, non-uniform ground pressures and joint interaction induced tunnel lining movement (i.e., bending moment). Lots of researchers agreed that joints in a tunnel lining evidently affect the tunnel behaviour [1-7]. Therefore, segmental joint needs to be less stiff and shall possess more deformation than the main portion [4]. Yanzhi et al. [8] reported that the stiffness of the tunnel joints is comprehensively influenced by many factors such as; 1) thrust force exerted during tunnel advancement, 2) the remaining longitudinal force and 3) property of the packer material, etc. presenting a non-linear characteristic. Hence, Xiaochun et al. [9] specifically mentioned that the most influence factor impudence the bending moment is the rotational joint stiffness, $K_\theta$. It is crucial to zoom into rotational stiffness as previous researchers have stated that each segment joint treated to have a unique value for the rotational stiffness but in realistic in verily change non-linearly [10].

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Recent approach has led researchers to conduct more detailed investigations on the impacts of joint rotational to the global behaviour of the tunnel lining. Blom [10] presented a visualization of three stages behaviour of segment joints for tangential bending moments as a function of the rotation. Respective researcher proposed a direct closed solution by introducing reduction factor, $\zeta$ ($EI_{eq} = \zeta EI_{full, hom}$) that considers the global influence of segment joint and is valid for single ring consideration with segment joint is in stage of closed joints. This solution is also accounted for non-linear segment joint conditions. Despite the proposed solutions are fit for linear and multi-linear models, however, Blom’s solution is only ideal for single ring problems. In addition, the model of the solution was only based on the soil as radial spring and was derived only for the case of full slip soil-lining interfaces.

Therefore, it is important to carry out detail research on how much joint in lining affect the stress redistribution in the medium around the tunnel. This paper will discuss the development of segment joint model nonlinearly and tunnel model in order to improve soil-tunnel interaction. Nonlinear joint model and staggered ring tunnel model was simulated in the soil block to help investigate the global behaviour of ground. This is crucial because in-depth understanding of joint behaviour will contribute to an improved understanding of tunnel lining as a whole.

2. Simulation Model
Simulation model has been divided into two main phases; i) model development of dual-segment model (parametric analysis of joint model), ii) soil-tunnel model development.

2.1 Model Development

has been divided into two main phases; i) model development of dual-segment model (parametric analysis of joint model), ii) soil-tunnel model development. Dual-segment model consist of half segment tunnel lining jointed with parametric segment joint (hinge, spring and tie constrains) and verified with laboratory work [11, 12]. A series of dual segment model itself in early had been validated with empirical solution and single tunnel lining model, respectively. In soil-tunnel model, two types of segment’s joint has been developed and embedded in a full tunnel lining together with soil tunnel model. Simulation model was developed based on the constructed tunnel profile of Singapore Circle Line Stage 3 (C852) project at Serangoon Interchange Station. Non-linear segment’s joint model was adopted from Jusoh [11,12] by means hinge non-linear model and was compared to tie model (to represent continuous ring condition). Respective tunnel of 6.35 m outer diameter with 1.4 m width and 0.275 m thick segmental linings were modelled as a full ring and assigned with ring’s joint and segment’s joint connections. Five standard segments with opening angle of 67.5° were used to assemble the ring. Key segment was introduced to complete the whole ring. A series of three staggered ring model are used herein (follow [13]). Three successive staggered rings at angle of 11.25° rotated clockwise were developed followed by all-at-once tunnel model (3S+AAO) with the length of 22.4m in longitudinal axis (excavation length in y-direction). Total length of tunnel was equivalence to 19 rings. Another tunnel model consist of 19 rings tunnel model was also has been developed.

2.2 Mesh assignation
The entire soil and tunnel model was discretized. Solid element of 8-node brick linear hexahedron (C3D8P) with trilinear displacement and trilinear pore pressure was assigned to the soil model. In this case, the soil mesh was assigned to be well matched to the tunnel excavation length of 1.4 m in y-direction (which resembling the ring’s width). Denser meshing was assigned at the respective axes so that the mesh of tunnel lining with segment’s joint can be also accounted. A total of 9680 of solid elements with 10994 of total nodes were assigned. Pore pressure elements were used to model the soil (solid continuum element type) in geostatic analysis [14]. A total of 1522 linear quadrilateral shell elements of S4R were assigned to the tunnel lining model with the total number of nodes are 1832. Meshing of tunnel lining model initially had been validated with initial work in Jusoh [11,12].
2.3 Tunnel lining and soil properties

For the tunnel properties, the lining was simulated by using isotropic linear elastic model. The lining was assigned with Young Modulus, $E_l$ of 33GPa and Poisson’s ratio of 0.2. This full soil-tunnel model was designated with appropriate boundary condition and mesh. Figure 1 presents the soil-tunnel lining model developed in ABAQUS 6.10. Different colour schemes were used to represent the different type of soil. Selection of the developed model size (i.e., boundary of model) is discussed in the next section while the details on the assigned soil properties are tabulated in table 1.

| Table 1. Summary of the adopted soil properties |
|-----------------------------------------------|
| Soil layer | Soil type | Young Modulus, $E_s$ (kPa) | Bulk density, $\gamma$ (kN/m$^3$) | Poisson’s ratio, $v$ | Angle of friction, $\phi$ (°) | 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 Tannik granite formation, G4 (VI) | 59200                      | 20                            | 0.333           | 30              | 2               |
| L6        | Bukit Tannik granite formation, G4 (V) | 86400                      | 20                            | 0.3             | 35              | 2               |
| L7        | Bukit Tannik granite formation, G2 (III) | 3500000                   | 23                            | 0.32            | 35              | 400             |

2.4 Interaction analysis in full soil-tunnel model

In full soil-tunnel model, three different interaction analyses were studied; i) ring’s joint interaction, ii) segment joint interaction and iii) soil-tunnel interaction. Ring’s joints were modelled as tie constraints at the periphery of both rings, assigned as surface to surface contact (see Figure 2(a)). Recent model of ABAQUS software allows for shell-solid surface to surface interactions [14]. Therefore, soil-tunnel coupling was accomplished by surface to surface contact algorithm by linking the contact interaction property and penalty friction of tangential behaviour adopted as 0.35 (Figure 2 (b)). The mesh tie constraints method called “master-slaves” was used to model the interaction between both lining and soil [14]. In this interaction analysis, the displacement and pore pressure of the “slaves” surface were set to be equal to the value of the master surface to which it is the closest. In general, the master surface is a surface of stiffer body or coarser mesh and vice versa for slave surface [15].

Figure 2. Interaction model, (a) Tie constrain of surface to surface type is assigned at the ring’s joint, (b) Soil-tunnel interaction “master-slaves” formulation with surface to surface contact algorithm with contact interaction property, penalty friction of tangential behaviour; ‘master’ was represent by red
colour and ‘slave’ in purple and (c) Segment joint assigned with hinge nonlinear or tie constrain at two different wire link node-to-node position in tunnel lining

To have more certainty in model, a parametric model via tie constraints, spring and hinge type of interactions were investigated initially in dual-segment joint model to model the segment to segment interactions. The tie constraints of segment’s joint were performed as tie (assigned as penalty type), representing the continuous ring condition. Tie and spring model did not require any stiffness joint data (with spring model allowed changes in boundary conditions), whereas for hinge model; rigid, linear and nonlinear joint stiffness properties shall be assigned (figure 4(c)). Non-linear hinge model was carried out with respective laboratory findings (the non-linear joint stiffness data from moment-rotation results)[11]. The obtained results were presented and discussed in next subsections.

3. Results and discussion

In this section, the results are discussed mainly based on the segment joint modelling in dual-jointed segment model and in fully soil-tunnel model.

3.1 Dual-jointed segment results

In simplified dual-jointed segment tests, tie constraints, spring and hinge type of interactions were investigated and verified with laboratory findings [16]. Hinge with non-linear angular joint stiffness properties (H-NL) showing the closest moment response in dual-jointed segments in which it was later selected to be adopted in the soil-tunnel model.

3.2 Soil-tunnel model results

After successfully model the interaction of simplified segment-to-segment model, the H-NL model was then adopted in the segment joint of a fully soil-tunnel numerical model. Tie constraints segment’s joint were also adopted to show the comparison (i.e., represent continuous ring condition). Instead of 3S+AAO model, a fully staggered 19 rings model had also been designated. Figure 3 presents the results of the surface settlement which were later compared with field data.

Surface settlement induced by tunnelling was validated and compared with data from a case study where the behaviour of full tangential bending moment tunnel was investigated. Field data showed sudden drop reading occurred at 38 to 40 m from tunnel start point due to construction process. This was due to nature of tunnelling process. As cutter head of tunnel construction is stopped at the final ring, different face pressure in the ground surrounding occurred, thus lead to obvious effect on settlement trough here. However, tunnel model via simulation possess slightly different in trend (lower initial surface settlement) but still obey general trend and gave good agreement to the cumulative Gaussian S-curve proposed by Peck [17]. This is due to the tunnel lining installation [18], effect of boundary fixities and material properties in tunnel lining.

When compared to the continuous ring model (tie-model), FEM-hinge model demonstrated well agreement in term of maximum settlement (suppose a steady state surface settlement) at a distance of 20m for about 32mm of surface settlement, almost similar to the steady state results obtained by Brillouin Optical Time Domain Reflectometer (BOTDR) or sometimes referred to as the Optical Fiber Strain Analyzer which has been measured in the tunnel ring of R540 in the case study and surface settlement observed from settlement marker of G2407 [19]. In the opposite, a simplified adopted joints of tie-model lead to unexpected heave measurement of surface settlement at the tunnel excavation range of 0 to 20 m. This unexpected heave due to due to segment's joint properties (i.e., tie) act as continuous lining create buoyancy effect in lining. Another improved model with separated rings model (instead of all-at-once model) lead to higher resemblance of surface settlement pattern to the field data, with steady state settlement observed after 10m of cutter head distance. However, due to limited computer capacity, simulated model was abruptly stopped at ring 19, causing to monolithic (not a sudden drop reading) effect observed in field data. Nevertheless, one could see that this
improved model (FEM-Hinge-model of 19 rings), presented more convincing results which depicted steady state surface settlement after 10 m at the distance of cutter head and ahead and shows almost similar pattern of settlement profile such as reported in G2407 [19].

4. Conclusions
This paper presents the development of segment joint modelling in order to improve soil-tunnel interaction. Various type of segment joints were modelled in initial dual-segment model and the effects of joints were observed. Hinge model that anticipated the non-linear moment-rotation reveals the results most matching to the field measurement. The respective model then extended to a full soil-tunnel simulation model. Ground deformation or commonly represented by a settlement trough at the ground surface as resulted from the effect of tunnel construction together with soil-tunnel, segment's and ring's joint interactions were measured parallel at the top of tunnel crown. Results showed that the flexible segment joint with non-linear properties induced higher resemblance of surface settlement pattern to the field data, with steady state settlement observed after 10m of cutter head distance.

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Figure 3. FEM results of three staggered and all-at-once tunnel (3S+AAO) of hinge-model, tie-model and FEM results of 19 rings hinge-model compared to field data of Outer bound tunnel (OT) at R530 –R540 of Singapore Circle Line Stage 3 (C852) project. (Note: G2407, G2408 and G2419 were surface settlement that measured by settlement marker on OT tunnel; and R530 and R540 were settlement reading at the specific rings; measured by BOTDR)
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