Assessment on Segment Joint to Improve Soil-Tunnel Interaction

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Abstract. The bending moment of tunnel lining can be influenced by non-uniform ground pressures and joint eccentricities. Influence of joint interaction that induces flexural moment behaviour in segmental tunnel lining was investigated for the project Circle Line Stage 3 (C852), Serangoon Interchange Station. By considering behaviour of segment joint (which can affects the tunnel circumferential and longitudinal safety in overall), the tunnel lining behaviour and displacement of the ground surrounding the tunnel were evaluated. The segment joint modelling in simplified dual-jointed model and in fully soil-tunnel model were developed to assess the effect of segment joint on the overall tunnel response. Ground deformation or settlement trough at the ground surface resulted from the effect of tunnel construction and interaction between soil, tunnel, segment joints and ring joints was predicted. Results showed that with different use of segment joints give different longitudinal settlement. Hinge-nonlinear model together with separated rings model lead to the highest resemblance of surface settlement pattern to the field data when compare to tie model.

1 Introduction

The bending moment of tunnel lining can be influenced by non-uniform ground pressures and joint eccentricities. Under installation and ground static loads, the initial tunnel lining is typically subjected to decrease by 0.5% of its original diameter [1]. Shahrour *et al.*[2] mentioned that plastic deformations induce an important reduction in the seismic-induced bending moment in the tunnel, while the soil dilatancy moderately affects the bending moment in the lining. The consideration of the elastoplastic behaviour of the soil material leads to a reduction of about 50% in the bending moment.

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As joints in a tunnel lining evidently affect the tunnel behaviour [3-9], segmental joint needs to be less stiff and shall possessed more deformation than the main portion [6]. The stiffness of the tunnel joints is comprehensively influenced by many factors such as; 1) thrust force level of the segment joints, 2) the remaining longitudinal force and 3) property of the packer material, etc. presenting a non-linear characteristic [10]. Hence, Xiaochun *et al.* [11] specifically mentioned that the most influence factor impudence the bending moment is the rotational joint stiffness, K_{θ} . To carry out the joint rotational calculation, one has to understand the forces and rotation degree or joint interfaces in the joint. Segment's joint interfaces are usually taken as a reduced area, which tangential forces are assumed to be induced in a concentrated way [12]. Joints that are relatively rotating to each other act as a hinge between the adjoin segments, allowing only a limited angle of rotation between them. The segment has resistance against the rotation and bending moment is induced. It is crucial to zoom into rotational stiffness as previous researchers have stated that each longitudinal joint treated to have a unique value for the rotational stiffness but in realistic in verily change non-linearly [13].

Regarding to the tunnel's joint configurations, Hudoba [3], El Nagggar and Hinchberger [14] and Do *et al.* [9] emphasized the necessity of using a full 3D numerical model to obtain an accurate estimation of the structural forces induced by a different joint configurations including modern tunnel practice; a staggered tunnel lining configurations. In general, a lining built with straight longitudinal joints (uncoupled hinge ring) resulted to the high bending moments which gave conservative results [5]. On the other hand, staggered joint lining with larger number of ring types, *i.e.*, have smaller difference in the reference angles between successive rings will caused to a significant decrease of induced bending moment in lining [9]. This is due to the smaller span of concrete lining affected by the segment joints in the successive rings. As a result, tunnels possess better flexibility, particularly in terms of global support tunnel structure.

Do *et al.* [9] investigated on a staggered tunnel model with three different reference joint angles (angle of joint closest to the tunnel crown, in clockwise direction). When analysed with free ring joint, it was found out that the assignation of the free joint at the ring's joint led to none different observation in the final settlement. Whilst, for tunnel staggered joint configuration in which the ring joint were assigned with similar joint properties of segment joint, configured with two and three different reference angles; variation of induced structural forces in the successive rings can be seen. It was reported that the bending moment for two successive rings have difference maximum bending moment of 26.1%. Nonetheless, less impact were observed in normal forces, longitudinal forces and normal displacement which reported for approximately 1.8, 3.4 and 0.7 %, respectively. Do *et al.* [9] also reported in their parametric studies of joint pattern effect; the continuous lining and straight joint segmental tunnel lead to similar structural forces in successive rings. In terms of bending moment results, Do *et al.* [9] stated that tunnel lining with segment joint located at tunnel crown had depicted lower maximum bending moment, meanwhile the tunnel lining with reference joint (closest joint to the tunnel crown in clockwise direction from tunnel crown), influence of joint in reducing the maximum bending moment are greater than in the case which joint is situated near a point where bending moment is equal to zero. This phenomenon occurred due to the different joint pattern leading to different lining stiffness when compare to the successive rings alongside the tunnel axis. Load in the ring transfer from the stiffer to the softer ring (*i.e.*, with the lateral earth pressure factor is taken to be 0.5). The findings on bending moment for the case of a reference joint located at the tunnel crown were in accordance to Hudoba [3] and Klappers *et al.* [5]. Both studies were carried out via three-dimensional numerical models where low bending moment was obtained.

To sum up, staggered lining with a larger number of rings types is estimated to cause smaller changes of bending moment due to smaller span of lining affected by segment joints in the successive ring. On the other hand, the global support structure will be more flexible ascribed by the effects of joint configurations and properties and stiffness of the lining in successive ring is not uniform. As variation in lining stiffness occurred, load (ground) will be transferred from stiffer to softer ring and vice versa. Excessive increment or decrement in bending moment will lead to excessive deflection in precast concrete lining and lead to crack. This allowed dissipation of pore water pressure. The tunnel will act as drained structure and finally lead to an excessive ground settlement. Thus, it is agreed that tunnel and ground interaction is needed for interactive design approach. Detail research on how much lining changed in curvature will affect the stress distribution in medium around the tunnel and vice versa. The structural efficiency of lining and joint leads to resource efficiency. Therefore, to sum up, it is a necessity to obtain an accurate estimation of the structural force induced by staggered segmental tunnel lining. This paper will discuss the development of segment joint modelling in order to improve soil-tunnel interaction.

2 Segments Joint Model Development of Tunnel Lining in Geotechnical Field

The effects of segmental joints to tunnel lining behaviours have been greatly discussed in the literatures. Initial efforts had been reported by taking tunnel structure as a rigid lining ring embedded on a continuous ground model, introducing the flexibility ratio and reducing the rigidity of the tunnel structure [15,16]. Some other studies have suggested that segmental joints can be directly added to the tunnel lining structure [9,10,12,13,14,17] by considering the continuous ring with reduced rigidity (applying a reduction factor to the bending rigidity of the actual tunnel lining). With this concept, the moment capacity of joint is less than the moment capacity of segments body. Lee *et al.* [17] had proposed the flexural joint stiffness, K_θ and found out that K_θ is highly variable, highly depends on the properties of packer and bolts and also influenced by the geometry of end rib of lining segments and subjected forces. When subjected to a positive bending moment, the value of K_θ is higher than when it is subjected to a negative bending moment.. Blom [13] attempted to solve the joint stiffness-rotations relationship and successfully addressed a solution; however, it is limited to single ring and respective cases only. Do *et al.* [9] developed a 3D tunnel numerical model by including a set of segment's joint stiffness, lining joint pattern and the construction tunnel process (*i.e.*, grouting pressure, jacking forces) however the only coefficient of joint stiffness were adopted.. Yanzhi *et al.* [10] presented their work regarding an elastic equivalence method by assuming the orthotropic material behaviour for the Shanghai Yangtze River tunnel lining in a 3D shell-spring model by using effective rigidity ratio, η of 0.68. They empirically achieved good agreement for average values of internal forces for middle tunnel sections. Although good results obtained, the linear coefficient adopted by previous researcher limits the discussion for linear and homogeneous soil only.

3 Case Study

A fully numerical tunnel lining with appropriate soil model was modelled based on the construction tunnel profile of Circle Line Stage 3 (C852), Serangoon Interchange Station (Figure 1). Tunnels of 6.35 m in diameter with 1.4 m width and 0.275 m thickness were

modelled as a full ring and assigned with rings's joint and segment's joint interactions. Five standard segments with opening angle of 67.5° were used to represent the ring. Key segment was introduced to complete the whole ring. Klappers *et al.*[5] once have mentioned that a lining which is built with straight longitudinal joints (uncoupled hinge ring) gave a very high bending moments and conservative results. While smaller bending moment measured in the coupled rings, *i.e.*, staggered lining [9]. Therefore, in order to investigate the effectiveness of segments with the proposed joint model, a series of three staggered ring model are used herein (after Do [18]). Three successive staggered rings at angle of 11.25° rotated clockwise were developed followed by all-at-once tunnel model with the length of 22.4 m in longitudinal axis (excavation length in y-direction). Total length of tunnel was equivalence to 19 rings. Three successive staggered rings with all-at-once lining (3S+AAO) were chosen in order to discuss the effect of stress distribution in tunnel lining in global [9].

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). One could also see that the 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 [19]. 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.

Fig. 1. 3D model of soil-tunnel system with respective boundary condition and meshing

3.1 Tunnel lining and soil properties

For the tunnel properties, Mroueh and Shahrour [20] had mentioned that neglecting the structural stiffness in the tunnelling-structures analysis will yield a significant overestimation of internal forces in the structural members. Thus, a simple model of lining material model is suffice to give appropriate results for the structural forces [21]. Therefore, in this study, the lining was simulated by using Isotropic linear elastic model. The model was used with Young Modulus, E_L of 33 GPa and Poisson’s ratio, ν 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 are tabulated in Table 1.

Table 1. Details of the ground properties for every layer of soil model in MRT Singapore[22]

Soil layer	Soil type	Young Modulus, E_s (kPa)	Bulk density, γ (kN/m ³)	Poisson’s ratio, ν_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

3.2 Interaction Model in Full Soil-Tunnel Model

In full soil-tunnel model, three different interaction models were assigned; i) ring’s joint interaction, ii) segment’s joint interaction and iii) soil-tunnel interaction. For simplification, ring’s joints were modelled as tie constraints at the periphery of both rings, assigned as surface to surface contact (Figure 2(a)). Recent model of ABAQUS software allowed for shell-solid surface to surface interactions [19]. 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 [19]. In this interaction modelling, 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 [23].

In addition, the segment’s joint in generally can be left out from simulating it as a continuous ring or it can be modelled as a hinge or be given a rotational stiffness [24]. To have more certainty in model, a parametric model via tie constraints, spring and hinge type of interactions were investigated 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. Whilst, the investigation of spring segment’s joint was

carried out to compare the results with the previous reported findings. Hinge was assigned to perform as in ABAQUS, properties of moment-rotation can be embedded in the model appropriately (Figure 2(c)). It should be note that a series of unchained wire are assigned first at the respective nodes at both segment to join the segments prior of assigning the hinge properties. 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. In order to understand the hinge model capacity in ABAQUS, a rigid model hinge followed by hinge with initial linear stiffness ranged from 1000 Nm to 1000 kNm was analysed. Then nonlinear hinge model were carried out with respective laboratory findings (the nonlinear joint stiffness data from moment-rotation results). For comparison purposes in the full soil-tunnel model development, a hinge-model and tie-model were simulated for segment joint. The obtained results were presented and discussed in next sections.

Figure 2. (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 at two different wire link node-to-node position in tunnel lining.

4 Results

Results were mainly discussed the findings of segment joint modelling in simplified dual-jointed model and fully soil-tunnel model behavior.

4.1 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 [25]. Hinge with nonlinear 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.

4.2 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.

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 Circle Line Stage 3, Serangoon Interchange Station, MRT Singapore (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).

Surface settlement induced by tunnelling was validated and compared with data from a case study. Tie-model depicted heaving due to simplification of joint model, *i.e.*, continuous tunnel model. FEM-hinge-nonlinear of three staggered and all-at-once model (3S+AAO) demonstrated a match maximum settlement to the monitoring data at a distance of 20 m for about 32 mm of surface settlement. This results depicts almost similar to the steady state results obtained by BOTDR that had been measured in the circumferential ring of R540 and surface settlement observed from settlement marker of G2407 in the case study [26]. The improved hinge-nonlinear model of 19 rings (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 10 m of cutter head distance. However, due to limited computer capacity, simulated model was abruptly stopped at ring 19. This cause to a monolithic settlement pattern, not a sudden drop reading like had been observed in field data. Hence, the surface settlement in the longitudinal direction reported here is in well agreement to the cumulative Gaussian S curve proposed by Peck [15].

5 CONCLUSIONS

This paper presented the development of segment joint modelling in order to improve soil-tunnel interaction. Six different segment joints were modelled and the effects of joints were observed. Hinge model that anticipated the nonlinear moment-rotation findings led to the most matched results to the laboratory testing. The respective model then extended to a full soil-tunnel simulation model. Ground deformation or settlement trough at the soil ground surface were measured which located at the parallel location to the top of tunnel crown, resulted from the effect of tunnel construction together with soil-tunnel, segment and ring joint interactions. Results showed that with different use of segment joints give different longitudinal settlement. Hinge-nonlinear model lead to the highest resemblance of surface settlement pattern to the field data when compare to tie model.

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