3D Modelling of concrete tunnel segmental joints and the development of a new bolt-spring model

Fei Wang[1], Hongwei Huang[2], Kenichi Soga,[3] Zili Li[4*]

1. Shanghai Institute of Disaster Prevention and Relief, Tongji University, Shanghai, 200092, China;
2. Department of Geotechnical Engineering, Tongji University, Shanghai, 200092, China;
3. Department of Civil and Environmental Engineering, University of California, Berkeley, 760 Davis Hall 94720-1710, Berkeley, USA;
4. Civil, Structural and Environmental Engineering, School of Engineering, University College Cork, Cork, Ireland;

*Corresponding author: Zili Li, zili.li@ucc.ie

ABSTRACT

In a segmental metro tunnel, it is widely observed that cracks, water leakage and other structural defects usually appear at segmental joint section of a smaller stiffness than main tunnel segment section. In this study, a 3D finite element analysis was conducted to simulate a typical concrete segmental joint explicitly using 3D continuum elements, and the performance of 3D continuum model was validated against laboratory tests available in literature. Since such continuum model may cost excessive computational time when a large-scale tunnel structure is analysed, a new bolt-spring model was developed to simplify the structural features of concrete segmental joint. In the bolt-spring model, the interaction between bolt and segment was modelled by a set of normal springs and shear springs: the stiffness of the normal springs is mainly determined by the bolt itself, whilst the shear springs take account of bolt-segment friction, interaction and shear resistance of the bolt. In the meanwhile, the interaction between two adjoining tunnel segments is explicitly modelled using contact elements. The proposed bolt-spring model is able to simulate the details of joint deformation and contact pressure between segments more realistically than previously available by conventional methods (e.g. continuous ring, beam-spring model (BSM)), where segment-segment interaction is not explicated modelled. Compared to the continuum model, the bolt-spring model saves up to 90% computational time without compromising numerical accuracy. Furthermore, this paper compared the mechanical behaviour of a concrete joint against that of a cast-iron one with particular emphasis on the development of different bolt-spring models.

Key words: concrete segmental joint, bolt-spring model, 3D continuum model, computational cost, joint distortion

1. INTRIDUCTION

In many big cities, metro tunnels usually continue to settle and deform after construction due to soil consolidation, adjacent deep excavation, surface building surcharge and many other factors (Soga et al., 2017). The variation in ground conditions and building environment along a metro line may inevitably cause differential settlement of the tunnel along the rail track direction. In Shanghai metro, for example, the maximum differential tunnel settlement has built up to as much as 295mm near the People's Square Station in 2010 (Shen et al., 2014).

Excessive differential tunnel settlement often leads to water leakage, concrete cracks, significant segment distortion and other structural defects (Wright, 2010), which may pose a risk to tunnel integrity (e.g. cracks) and even railway operation (e.g. train derailment). The differential settlement and associate lining distresses (e.g. water infiltration) are commonly observed at the bolted joints between tunnel segments in a tunnel lining (Shen et al., 2014), where the joint stiffness is generally much smaller than the main segment section (Li et al., 2014). Hence, it is essential to pay extra attention on the joint between segments when structural performance of a segmental tunnel is analysed.

Over the past decades, there have already been a large number of experimental and numerical analyses on the mechanical behaviour of concrete segmental joint (e.g. Teachavorasinskun et al., 2010; Ding et al., 2013; Jin et al., 2017). In most of the previous numerical studies, a concrete segmental joint was either 1) incorporated into a continuous tunnel ring with a stiffness reduction (Wood, 1975; ITA, 2000; Koyama, 2003; Li et al., 2015b) or 2) simplified using a beam-spring model (BSM), where a segmental joint is modelled as a rotational / shear spring, while beam or shell elements are used to simulate tunnel segments (Murakami and Koizumi, 1980; RTRI, 1997; Zhu et al., 2006; Klappers et al., 2006).

Previous segmental joint models, nevertheless, fail to represent the 3D joint behaviour in a precise manner, which are important for accurate analyses of 3D tunnel lining behaviour: for instance, in the beam-spring model (BSM) approach, beam elements for tunnel lining can hardly consider the crack development around the bolt hole due to stress concentration at a joint; the spring elements between segments may fail to represent the segment-segment contact pressure distribution realistically. Considering these limitations, some recent investigations model the bolt between segments as 3D continuum element with detailed structural features, and a brief review of their research works is summarised in Table 1: As a pioneer, Gu (2011) conducted a 3D finite element analysis of two concrete tunnel rings with explicit modelling of segments and bolts using 3D continuum element. In his study, the modelling of detailed features in a segmental joint enabled to present the tunnel deformation explicitly, and examine the effect of contact imperfections at the joint on the development of tunnel structure force as well as joint opening. The computed results, however, were not validated against either field or experimental measurements. In addition, the use of 3D continuum bolt model also allowed Jin et al. (2017) to directly compare the rotational behaviour of two types of segmental joints under bending moment in a water-conveyance tunnel, explicitly showing the 3D contact pressure between segments. The finite element results were validated against experimental data and highlighted the effect of the bolt arrangement and gaskets between segments on the joint bending stiffness. Following the principle of precise 3D joint modelling, Gong et al. (2018, 2019) conducted a dedicated investigation of gasket between segments through both physical laboratory tests and 3D finite element modelling using ABAQUS software. The 3D finite element model was validated against the experimental data, and then adopted to comprehensively examine the effect of the joint opening, the joint offset and the gasket hardness on the contact pressure distribution at the gasket interface. Besides concrete segmental joint, structural performance of cast iron joints in old tunnels of London Underground was also studied by Tsiampousi et al., (2017) using 3D bolt continuum model, which enabled to overcome the limitations of typical experimental tests and evaluate the effect of boundary condition and loading scenarios on the joint bending behaviour.

Up to date, the 3D continuum bolt model has been adopted in some studies for specific investigation of segmental joints, and subsequently may also be used for structural analysis of multiple tunnel rings behaviour. For example, Shi et al. (2016) modelled the bolt explicitly in continuous contact interface between tunnel segments to investigate the stress development and dislocation at the joint in a segmental tunnel lining subject to adjacent deep excavation, whereas the computed results were not compared against field measurements. The computational cost of such model, however, may be prohibitively expensive if a large-scale tunnel structure (e.g. cross passage section) is performed (Li, et al. 2016).

Different from 3D continuum approaches, Li et al. (2014) proposed an innovative bolt-spring model to simulate segmental joints in old cast-iron tunnel lining at London Underground. In the bolt-spring model, tunnel segments were modelled explicitly using solid elements, whilst the interaction between bolt and segment was modelled by a set of normal springs and shear springs. The proposed bolt-spring model for cast-iron joints was validated against laboratory test data and compared against conventional beam-spring model. This model was later adopted for the analysis of complex tunnel behaviour at cross passage tunnel sections in London Underground (Li et al., 2015 & 2016). Nevertheless, similar innovative model for segmental joints in modern reinforced concrete tunnel has not yet been comprehensively proposed in literature, to the authors' best knowledge.

In this paper, a 3D continuum model of concrete segmental joint was developed and then validated against laboratory test results available in literature. Since the 3D continuum model requires significant computational resources when a large-scale tunnel lining is analysed, a bolt-spring model was developed to simulate concrete segmental joints as realistically as possible without compromising computational cost. The bolt-spring model includes both normal spring model for the joint rotational behaviour and shear spring model for the shear resistance at the joint.

2. 3D CONTINUUM MODEL FOR CONCRETE SEGMENTAL JOINT

In an underground tunnel lining subject to earth pressure, a segmental joint is usually compressed by axial tunnel hoop thrust and also subject to both bending moment and shear load between segments. Likewise, the mechanical behaviour of a concrete segmental joint is discussed herein in two aspects, respectively: one is for the joint bending behaviour and the other is for the shear behaviour. In each section, a laboratory test on a typical concrete segmental joint in Shanghai metro is introduced first, followed by description of the corresponding 3D finite model continuum model and the computed FE results are tested against the experimental data.

2.1 Bending behaviour

2.1.1 *Laboratory* test

Figure 1 shows a full-scale laboratory bending test on a typical tunnel segmental straight joint in Shanghai metro (Chen et al., 2010; Cao et al., 2010). The bending test was conducted on two jointed half-segments under both horizontal forces for axial compression and vertical forces for bending moment at the joint, while the end of the tunnel segments was constrained by rigid steel supports. The two concrete tunnel segments are connected by an inclined standard Grade 6.8 steel bolt of 575 mm effective length.

In total, four loading cases were considered based upon typical scenarios of earth pressure surrounding the tunnel as given in Table 2 and Figure 2: Case B1 & B2 were for the negative bending moment under small eccentric axial compression (see Figure 2a); Case B3 & B4 were for the positive bending moment under large eccentric axial compression (see Figure 2b). To take account of tunnel structural behaviour at different depth, bending moment smaller than 450 kNm/m was adopted in Case B1 & B3 for shallow tunnel section, while bending moment greater than 580 kNm/m was considered in Case B2 & B4 for deep tunnel section. In each test, the target axial compression was applied at the start and remained constant throughout, followed by the increasing bending moment up to the target value along 10 incremental steps. For each loading case, three identical tests were repeated under exactly the same condition as to minimize experimental errors.

The joint opening between segments was recorded by displacement gauges and the readings were then converted to a rotational angle at the joint using the equation below:

$$\theta = \frac{\Delta V}{h} \quad (1)$$

Where θ is the rotational angle between segments at the joint, ΔV is the rotational angle between segments, h is the thickness of the tunnel segment

2.1.2 Finite element model

Based upon the laboratory test described above, a 3D finite element analysis was conducted to investigate the bending behaviour of concrete tunnel segmental joint. Considering symmetry, a 1/2 FE model was performed using ABAQUS 6.12 (ABAQUS Inc. 2012) as shown in Figure 3. In this model, the concrete of tunnel segment was considered as a linear elastic-plastic strain hardening material, based upon Saenz (1964)'s concrete constitutive model as shown in Figure 4 and Equation 2 below:

$$f = \frac{A}{1 + B\varepsilon + C\varepsilon^2 + D\varepsilon^3} \quad (2)$$

Here, A, B, C, D are the model parameters determined by fitting experimental test data as shown in Figure 4.

For simplicity, one multilinear approximate Line OBCD' proposed by Zhang (2000) and Zhang *et al.* (2003) was adopted in this FE model (see the red line highlighted in Figure 4) and the properties of concrete are given in Table 3. The end of concrete segments was tied to the steel support, which was modelled as fixed rigid body. The constitutive model of Grade 6.8 inclined bolt between segments was considered as linear elastic-perfectly plastic material and the mechanical properties are listed in Table 4 (Moster 2010, Theodorou 2003). Both tunnel segment and bolt were modelled explicitly using 3D C3D8R 8-node linear solid elements, and typical numbers of elements were 5380 for one segment and 2028 for each bolt.

2.1.3 Model validation

Figure 5a shows the development of rotational angle at the segmental joint with increasing negative bending moment for Case B1 & B2. In general, the rotational angle builds up linearly with negative bending moment with a constant bending stiffness of approximately 1.05×10^6 kNm / (Ring × rad) up to the angle of -0.001 rad, and then the stiffness decreases gradually due to plastic strain development. The moment-rotation curves computed from finite element analysis show good agreement with experimental data for both shallow tunnel section Case B1 and deep tunnel section Case B2.

When the segmental joint is subject to positive bending moment in Case B3 & B4, the moment-rotation curves for positive bending moment condition are shown in Figure 5b. Due to axial compression between segments, the rotational angle increases linearly proportional to bending moment load until up to approximately 0.0006 rad, where plastic strain occurs in the concrete compression zone at the joint section. Once the bending moment increases up to the yield point, plastic strain develops substantially within the compression zone and the joint section stiffness decreases substantially with increasing joint opening. As the joint rotates significantly up to about 0.02 rad, the joint stiffness increases slightly when the two segments contact at the tip of caulking groove between segments, whereas further significant rotation beyond 0.03 rad is unlikely allowed in practice for the sake of tunnel stability.

One major advantage of the 3D FE model over conventional methods (e.g. beam-spring model (BSM) approach) is the capability of simulating contact between segments realistically. Figure 6 shows the development of segment-segment contact pressure contours in Case B1 under constant axial load of 200 kN/m but increasing negative bending moment: (a) under zero bending moment, (b) under -191 kNm/m, (c) under -382 kNm/m. As the joint gradually opens with increasing bending moment, the contact pressure between segments changes along the height; greater pressure concentrates near the tip of segment above the caulking groove, whilst negligible pressure appears above the bolt hole as the two segments are detached. In each contour, the contact pressure is uniform across the width of the tunnel segment, suggesting a uniform joint opening along the segment width direction with little distortion.

2.2 Shear behaviour

2.2.1 *Laboratory* test

In addition to bending moment tests, full-scale laboratory shear tests on the same Shanghai metro concrete tunnel segmental joint were analysed as shown in Figure 7 (Li et al., 2011; Cao et al., 2010). In these tests, one tunnel segment was placed between two fixed half-tunnel segments. The concrete, bolt and other materials were the exactly same as those in the bending test described earlier. Likewise, there were 4 loading cases conducted in the shear tests as listed in Table 5: Case S1 & S2 were for the shear load in longitudinal direction along the railway track (see Figure 7a), while Case S3 & S4 were for the shear load between segments within a tunnel ring (see Figure 7b). During the loading process, the segments were first loaded under the target axial compression throughout the test, and the shear load was then applied incrementally until the displacement between segments built up to 6mm. Similar to the bending tests, three identical tests were conducted under exactly the same condition for each loading case.

2.2.2 Finite element model

Based upon the joint shear test configuration above, a 3D finite element model was proposed aiming to further investigate the fundamental mechanism of joint shear behaviour as shown in Figure 8. In particular, the details of the inclined bolts were explicitly modelled as shown in Figure 8b and the maximum clearance between the bolt and bolt hole is 8 mm. In this finite element analysis of shear test, the constitutive models and element types of concrete and bolts were the same as those adopted for the bending test. The friction coefficient between concrete segments was set to be 0.65 according to the range reported by Li et al. (2011).

2.2.3 Model validation

Figure 9a shows the development of shear force with relative displacement between segments in longitudinal direction for Case S1 & S2. The shear force firstly increases linearly with the displacement and then yields due to the friction between the bolt head and the segment within the displacement of 1~2 mm. The greater the axial compression between segment is, the higher the initial yield load becomes due to the higher friction between the bolt and the segment. After the initial yielding, the displacement increases under small shear force until the bolt touches the bolt hole after the clearance between them is used up. The computed load-displacement curves from the 3D FE model match well with the experimental data from the laboratory shear tests before the bolt touches the bolt hole; although the laboratory shear test finished at the displacement of 6 mm, the FE model enables to further investigate the joint shear behaviour under larger displacement: after using up the clearance, the shear load continues to build up gradually under a further incremental displacement of about 4 mm, where the bolt and concrete starts to yield. In general, the load-displacement curve may be divided into three stages of different stiffnesses as marked in Figure 9.

Similar load-displacement relationship was observed in the joint shear test between segments in radial direction within a ring for Case S3 & S4 as shown in Figure 9b; the computed results generally show agreement with the experimental data except a small discrepancy at the initial stiffness stage. It is likely that the boundary of the laboratory shear test could hardly be completely fixed so that the tunnel segments at the two sides moved together with the middle segment and in turn led to a smaller relative displacement between segments than the computed results. In general, the proposed 3D continuum bolt finite element model is able to simulate the joint shear behaviour both in longitudinal direction and radial direction realistically.

In particular, the bolt between segments plays a very important role on the joint shear behaviour. Figure 10 shows the local Mises stress contours of the bolt model at different displacements for Case S1. Before the bolt touches the bolt hole (0~2mm), the joint shear resistance is mainly contributed by the friction between the bolt head and the segment, and as such that the bolt stress with increasing displacement are negligible (Figure 10a&b). After using up the clearance, the bolt stress increases dramatically, in particular at the interface between segments (Figure 10c&d). As shear displacement continues to increase more than 8mm, large plastic shear bolt distortion develops at the interface. Hence, the behaviour of bolt largely determines the shear load-displacement curves in Figure 9.

3. BOLT-SPRING MODEL FOR CONCRETE SEGMENTAL JOINT

3.1 Continuum model versus bolt-spring model

In a tunnel segmental joint test, the 3D continuum model described above is able to consider structural features as realistically as possible in agreement with the laboratory test data. Due to complex segment geometry, such 3D continuum model usually requires large number of elements, irregular mesh and contact interaction particularly around the bolt holes (see Figure 3b & 8b). The calculation of continuum model in turn may require prohibitively expensive computational cost, when a large-scale tunnel lining is analysed. In the interest of computational time, Li et al. (2014) proposed a new bolt-spring model for cast-iron tunnel segmental joint in old London underground tunnels. In the bolt-spring model, the bending and shear behaviour of each individual bolt is modelled as a set of normal springs and shear springs, respectively, whilst the segment-segment interaction is explicitly modelled using contact elements. The properties of the bolt-springs and contact interface between segments can be referred to standard codes. In summary, the spring-contact model is able to provide more realistic solution and require much fewer laboratory tests than the conventional beam-spring or shell-spring models (Li et al. 2014).

In this study, the bolt spring model for a concrete segmental joint is developed in a similar manner. In the next sections, the performance of the bolt-spring model with regard to rotational behaviour and shear behaviour will be evaluated against 3D continuum model, respectively.

3.2 Rotational bolt-spring model

Figure 11 shows the rotational bolt-spring model for concrete tunnel segmental joint: the bolt connecting two segments is simplified as either one or a group of springs. The normal stiffness of an individual spring is solely determined by the bolt geometry and property based upon the equations below:

$$K_n = \frac{F}{n\Delta L} = \frac{EA}{L} \tag{3}$$

$$\varepsilon = \frac{n\Delta L}{L} = \frac{F}{EA} \tag{4}$$

Where K_n is the stiffness of each individual normal spring, n is the number of normal springs, F is the axial load, ΔL is the elongation of normal spring, E is Young's modulus of bolt, A is cross section area of bolt, L is the length of bolt, and ε is the axial strain in bolt. Since a bolt doesn't sustain hoop thrust between two segments when a joint is compressed, the normal spring only sustains tension but zero compression as shown in Figure 12a.

A 3D finite element analysis of a concrete segmental joint was conducted to evaluate the performance of the rotational bolt-spring model against the continuum model as shown in Figure 13. This 3D model is composed of two concrete segment tunnels connected by two standard M30 bolts in the joint section, which is subject to both axial compression in the horizontal direction and bending moment similar to the loading cases in Table 2: B1 & B2 under negative bending moment; B3 & B4 under positive bending moment. In particular, Figure 14 shows the continuum element bolt model, the single spring model and the nine springs-group spring model at the joint section, respectively. In all the three models, hand hole at the joint section is modelled explicitly, whereas the bolt hole is only modelled explicitly in continuum element model as to consider the clearance between the bolt and bolt hole as shown in Figure 15. The interface between two tunnel segments is modelled by surface to surface contact available in ABAQUS Inc. 2012. For the normal behaviour, hard contact type between segments is adopted, which prevents two segments from penetrating into each in compression, but allows them to separate when subject to tension. The material properties of concrete and the bolt continuum model in this FE model are given in Table 3 & 4 the same as adopted in the last section. For the single spring model, the load-displacement curve is determined by the axial bolt stiffness using Equation 3 & 4, whereas for the nine springs-group model, the stiffness of each individual spring is 1/9 of the single spring one.

Figure 16 compares the computed joint bending stiffness between continuum model and two bolt-spring models under negative bending moment. The bending moment increases linearly under small rotation within 0.0001 rad, and gradually decreases up to 0.0007 rad. Both two bolt-spring models (i.e. single spring model and nine spring model) show the same joint stiffness with the continuum model. When a joint is under positive bending moment, the nine-spring model can match well with the continuum bolt model throughout the loading process, whereas the single spring model is only able to simulate the joint bending realistically before the yielding point, but underestimates the bending capacity at the large rotation. Compared to continuum model and 9 spring model, the contact forces between segments in a single spring model is more localised and significant, resulting in greater plastic strains concentration in concrete and therefore smaller joint bending stiffness. In summary, both single spring model and nine springs-group model are able to simulate the joint bending behaviour realistically similar to the continuum model, although the single spring model may underestimate the bolt stiffness after the joint opening develops at large rotational angle.

3.3 Shear bolt-spring model

In terms of shear behaviour for the bolt-spring model, the sliding friction between segments is simulated explicitly as the segments are modelled by solid elements, whereas the shear spring between segments takes account of the shear resistance between the bolt and segment interaction. Li et al. (2014) points out that shear spring stiffness for a cast-iron joint can be determined at three stages: 1) At the first stage of shearing, the shear resistance is contributed by the bolt-segment friction and the maximum friction value can be defined by multiplying the bolt pretension force with the friction coefficient; 2) After using up the clearance, the shear spring stiffness builds up substantially as the bolt compresses the concrete around the bolt hole under a further displacement. 3) Both the bolt and the cast iron around the bolt hole yields at large shear displacement, and nevertheless, the joint is still able to sustain increasing shear resistance with a smaller stiffness.

In a segmental tunnel lining, shear resistance between segments is mainly transmitted by segment-segment friction and bolt-segment interaction at local joint sections. Based upon the laboratory shear tests described earlier, a local joint section is modelled explicitly to specifically investigate the shear behaviour between segments as shown in Figure 17. In this FE model, axial compression is applied at the end of the segments in the horizontal direction; in the vertical direction, the base of the left segment is fixed, whilst a uniformly-distributed pressure is applied on the top surface of the right segment to generate a shear load between the two segments. Similar to the rotational bolt-spring model, the analysis of shear bolt-spring model comprises 3D bolt continuum model, single spring model and nine-spring model.

The springs are placed in the two shear directions between segments, while their stiffnesses can be divided into four stages as shown in Figure 12b, different from the three-stage bolt-spring shear model for a cast-iron joint noted by Li (2014) described earlier; the main difference starts from the second stage: when the steel bolt touches the concrete bolt hole after the clearance is used up, the shear force in the bolt-spring model increases significantly by a further displacement of approximate 8 mm until some plastic strain develops around the bolt hole. As the plastic zone propagates in both the bolt and the concrete bolt hole, the joint can still sustain greater shear force but with a smaller stiffness in the third shearing stage, and finally fails at 35mm, which is then assumed to be levelling off for the sake of computational stability. In summary, the stiffness of an individual shear spring can be determined based upon the equations below:

$$K_s = \begin{cases} \frac{\mu P}{nc},\ 0 \leq \mathrm{d} \leq \mathrm{c} \\ Bolt\ - Segment\ interaction \\ (see\ Figure\ 18),\ \mathrm{c} < \mathrm{d} \leq \mathrm{failure} \end{cases} \quad (5)$$

Where K_s is the stiffness of each individual shear spring, d is the shear displacement, n is the number of shear springs, P is the bolt pretension / preload, μ is the friction coefficient between the bolt end and tunnel segment, c is the bolt clearance between the bolt core and bolt hole. After using up the bolt clearance, the K_s has to be determined by either 3D continuum simulation or experimental test as to take account of different types of concrete tunnel segmental joints.

Figure 18 compares the shear force-displacement relationship predicted by the bolt-spring model against that by the 3D bolt continuum model. Both the single spring model and nine-spring model match well against the 3D bolt continuum model at the first stage of shearing due to the bolt-segment friction, although differ slightly after the bolt hole-bolt clearance is used up since the second stage.

Besides the model accuracy evaluation, the computational cost of the proposed bolt-spring models is compared against 3D continuum model under bending moment as listed in Table 6. To facilitate the comparison, all the simulations were performed in the same desktop with 8 cores processors, 16 GB RAM and 500 GB hard disk. In general, a 3D continuum model requires significantly longer time an order of magnitude more than that for the single bolt-spring model. Instead, the nine-spring model only doubles the computational time for a single bolt-spring model and also produces accurate prediction in agreement with the results from 3D continuum model as discussed earlier. When a large-scale tunnel analysis is performed, both the single spring model and nine-spring model may be adopted to simulate tunnel behaviour realistically without compromising computational cost.

3.4 Concrete segmental joint versus cast-iron segmental joint

The bolt-spring model was originally developed based upon joint behaviour in a cast-iron tunnel lining in London Underground. Li et al. (2014) highlighted that when a cast-iron segmental joint is bent, the joint opens more at the edge along the width of the flanges than the middle as shown in Figure 19a. The precise modelling of such joint distortion behaviour requires 13 springs or more springs to consider the bolt bending behaviour, whereas a single spring model severely under-predicts the joint bending stiffness as shown in Figure 19b.

When a concrete segmental joint is bent, the joint opening is relatively uniform across the width of the tunnel segment (see Figure 6). That is, little bending distortion develops along the width of the segment as noted in Figure 20. Unlike the joint distortion in a cast-iron joint, the use of fewer springs (e.g. single spring model) is able to simulate the flexural behaviour of a concrete segmental joint until subject to significant bending moment. In such condition, large distortion develops at the joint and hence the nine-spring model enables to simulate the bending distortion along the width of the segment more realistically than that by the single spring model.

When subject to shear load, both cast-iron joint and concrete joint shear behaviour are determined by bolt-segment friction, segment-segment friction, clearance between the bolt and bolt hole and bolt shear stiffness, which can be realistically considered by shear springs model. The comparison between Figure 21 for cast-iron joint and Figure 18 for concrete joint shows their main difference in shear behaviour, particularly at the second stage where the bolt interacts with the bolt hole after the clearance is used up; in a cast-iron joint, the shear load increases significantly within 1mm due to contact interaction between rigid steel bolt and cast-iron bolt hole, whereas the shear load in a concrete joint builds up gradually under a larger incremental displacement of about 8 mm, as the steel bolt compresses relatively flexible concrete bolt hole around. Even after some plastic strain propagates around the bolt hole, the concrete joint is still able to sustain greater shear load with a smaller stiffness at the third shearing stage until failure, whereas the cast-iron joint can hardly provide more shear resistance after the yielding of the steel bolt between segments at the end of the second shearing stage.

Another distinct characteristic of concrete joint behaviour different from cast-iron one is the interaction mechanism between joint rotational behaviour and shear behaviour, depending on the joint composition and structural features. Most cast-iron segmental joints in London Underground and other old infrastructures are comprised of two tunnel segments with flat contact surface jointed by a straight bolt in between. Li et al. (2014) demonstrated that if the bolt in a typical cast-iron joint is dislocated as shown in Figure 22, the influence is rather small on the joint bending behaviour and as such no need to change the stiffness of normal springs for joint rotational behaviour. Compared to old cast-iron joint, there are many more different types of modern concrete segmental joints with various geometries and structural features, including curved bolt, inclined bolt, trapezoidal tunnel segment, joint sealant and etc. as shown in Figure 2 & 23. If large tunnel deformation occurs, various interaction mechanisms are likely to occur between joint rotational behaviour and shear behaviour. The rotation-shear interaction may vary significantly from one type of concrete joint (e.g. inclined bolt) to another (e.g. curved bolt), while their relationship can be derived from experimental tests and a series of 3D bolt-continuum models proposed in this study.

4. CONCLUSION

This paper conducted a series of 3D finite element analyses of concrete segmental joint under bending moment and shear load, respectively, and the computed results were compared against laboratory experimental data. Furthermore, a bolt-spring model was then developed to simplify the bolt behaviour in segmental joint as one or a group of springs: joint bending behaviour is considered by normal springs, while joint shear behaviour is simplified as shear springs in two shear directions. The results of the proposed bolt-spring model are validated against those by continuum model. Some parametric analyses are performed, including 9 springs vs single spring, concrete segmental joint vs cast-iron joint, different types of concrete joints with various structural features and etc. The conclusions from the 3D finite element models are as follows:

(1) The flexural behaviour of a concrete segmental joint is governed by the segment geometry at the joint section. In this study, when a segmental joint is loaded under negative bending moment, the rotational angle first builds up linearly with a constant bending stiffness and then the stiffness decreases gradually due to plastic strain development. Subject to positive bending moment, the rotational angle increases linearly until the development of plastic strain in concrete at the compression zone between tunnel segments. As the joint continues to rotate significantly, the stiffness increases slightly when the two segments start to contact at the tip of caulking groove in between.

(2) The shear behaviour of a concrete segmental joint can be generally divided into three stages: 1) the friction between bolt and segment 2) the shear resistance of the bolt after using up the bolt clearance 3) the bolt and concrete develop plastic strain at significant shear displacement.

(3) Both the one spring model and nine spring model is able to simulate the flexural and shear behaviour of concrete segmental joint realistically in agreement with the continuum bolt model, although the single spring model may underestimate the bolt stiffness after the joint opening develops at large rotational angle. Compared to the continuum bolt model, the bolt-spring model significantly saves computational time without compromising model accuracy.

(4) The normal bolt-spring model for a concrete joint differs from the one for a cast-iron joint mainly due to their difference in tunnel segment geometries and the deformation mode under bending moment. Compared to distortion at a cast-iron joint subject to bending moment, the rotational behaviour of a concrete segmental joint is more uniform along the width. Hence, as many as 13 normal springs are required to simulate the bolt distortion in a cast-iron segmental joint subject to bending moment realistically, whereas only a single normal spring is sufficient to model the flexural behaviour of a concrete segmental joint accurately.

(5) In terms of shear behaviour, the interaction between bolt and bolt hole plays an important role in the bolt-spring shear stiffness at shear stage 2 after the clearance is used up. Given the comparable bolt and tunnel segment dimensions, a concrete joint usually shows a smaller shear stiffness than a cast-iron joint, as the steel bolt compresses relatively soft concrete bolt hole in the former one but hard cast-iron bole in the latter. As the plastic strain propagates around the concrete bolt hole, the concrete joint can still sustain larger shear load although with a smaller stiffness.

(6) The composition of most old cast-iron joints is similar with relatively simple structural features, whereas various modern concern tunnel linings comprise many different types of segmental joints. For a typical old cast-iron joint, the influence of bolt shear displacement on the joint bending behaviour is generally negligible. In contrast, for a variety of concrete joints, the interaction between rotational behaviour and shear

behaviour differs from one to another, and their relationship can be derived from experimental tests and the 3D bolt continuum models proposed in this study.

ACKNOWLEDGEMENT

This research is sponsored by the National Natural Science Foundation of China (No. 5150080691, No. 51708564 and No. 51608539).

REFERENCES

American Concrete Institute (ACI), 2011, Building Code Requirements for Structural Concrete and Commentary, USA.

ABAQUS Inc., 2012. ABAQUS User's Manual, Version 6.12. SIMULIA. www.simulia.com

Cao, H., Shen, W., 2010. Ultra large and long shield tunnel design – Shanghai Yangtze River tunnel design, China Architecture & Building Press, Beijing (in Chinese)

Chen Z., Yang, Z, Li, D., 2010. Study on Mechanical Properties of Longitudinal Joint of Segmental Lining of Shanghai Yangtze River Tunnel, Underground Engineering and Tunnels, Vol. 4, pp. 17-19. (in Chinese)

Ding, W.Q., Peng, Y.C., Yan, Z.G., Shen, B.W., Zhu, H.H., Wei, X.X., 2013. Full-scale testing and modeling of the mechanical behavior of shield TBM tunnel joints. Struct. Eng. Mech. 45 (45), 337–354. http://dx.doi.org/10.12989/sem.2013.45.3.337.

Gong, C., Ding, W., Soga, K., Mosalam, K., Tuo, Y., 2018. Sealant behavior of gasketed segmental joints in shield tunnels: An experimental and numerical study. Tunnelling and Underground Space Technology, Vol. 77 pp. 127–141

Gong, C., Ding, W., Soga, K., Mosalam, K., 2019. Failure mechanism of joint waterproofing in precast segmental tunnel linings. Tunnelling and Underground Space Technology, Vol. 84, pp. 334-352.

Gu, L., 2011. Influence of Installation Errors on Performance-based Evaluation Index of Shield Tunnel in Soft Clays. Master's dissertation, Tongji University.

Jin, Y., Ding, W., Yan, Z., Soga, K., Li, Z., 2017. Experimental investigation of the nonlinear behavior of segmental joints in a water-conveyance tunnel, Tunnelling and Underground Space Technology Vol. 68 pp. 153–166

Klappers, C., Grubl, F., Ostermeier, B., 2006. Structural analyses of segmental liningcoupled beam and spring analyses versus 3D-FEM calculations with shell elements. Tunn. Undergr. Space Technol. 21 (3/4), 254–255.

Li, D., Chen, Z., Yang, Z., 2011. Test and Analysis of Shear Performance of Circumferential Joint of Segment Ring in Shanghai Yangtze River Tunnel, Underground Engineering and Tunnels, Vol 1 pp. 15-17 (in Chinese)

Li, Z.*, Soga, K., Wang, F., Wright, P., Tsuno, K., 2014, "Behaviour of cast-iron tunnel segmental joint from the 3D FE analyses and development of a new bolt-spring model", Tunnelling and Underground Space Technology. 41, 176-192.

Li, Z., Soga, K., & Wright, P., 2015a. Behaviour of cast-iron bolted tunnels and their modelling. *Tunnelling and Underground Space Technology, 50*, 250-269. doi: 10.1016/j.tust.2015.07.015

Li, Z., Soga, K., & Wright, P., 2015b. Long-term performance of cast-iron tunnel cross passage in London clay. Tunnelling and Underground Space Technology, 50, 152–170. doi: 10.1016/j.tust.2015.07.005

Li, Z., Soga, K., & Wright, P., 2016. Three-dimensional finite element analysis of the behaviour of cross passage between cast-iron tunnels. Canadian Geotechnical Journal, 53 (6), 930–945. doi: 10.1139/cgj-2015-0273

Moster, T.C., 2010. Rotation stiffness of single-bolt sleeve connections. Master's dissertation, University of Milwaukee-Wisconsin, USA, P.34-35.

Murakami, H., Koizumi, A., 1980. On the behaviour of transverse joints of a segment. Proceedings of JSCE, No.296, pp.73-86. (in Japanese)

Saenz, L.P., 1964. Discussion of the paper equation for the stress-strain curve of concrete. Journal of the American Concrete Institute Proc., Vol.61, No.9, pp.1229-1235.

Shen, S., Wu, H., Cui, Y., & Yin, Z., 2014. Long-term settlement behaviour of metro tunnels in the soft deposits of Shanghai. Tunnelling Underground Space Technology, 40, 309–323.

Shi, C., Cao, C., Lei, M., Peng, L., Ai, H., 2016. Effects of lateral unloading on the mechanical and deformation performance of shield tunnel segment joints, 51, pp. 175-188.

Soga, K., Laver, R., **Li, Z.*.** (2017) Long-term tunnel behaviour and ground movements after tunnelling in clayey soils, Underground Space, Vol 2, 149-167,

Teachavorasinskun, S., Chub-uppakarn, T., 2010. Influence of segmental joints on tunnel lining. Tunn. Undergr. Space Technol. 25 (4), 490–494. http://dx.doi.org/10.1016/j.tust.2010.02.003.

Theodorou, Y., 2003. Mechanical properties of grade 8.8 bolts at elevated temperatures. Master's dissertation, University of Sheffield, UK.

Tsiampousi, A., Yu, J., Standing, J., Vollum, R., Potts, D., Behaviour of bolted cast iron joints. Tunn. Undergr. Space Technol., Vol. 68, pp. 113-129

Wright, P. (2010). Assessment of London underground tube tunnels –Investigation, monitoring and analysis. Smart Structures and Systems, 6, 239–262.

Zhang, H., 2000. Research on the loading test and structural models of prefabricated segment reinforced by secondary lining, PhD dissertation, Tongji University, China.

Zhang, H., Zhang, Z., Wang, J., 2003. 3-D FEM analysis on prefabricated segment joints of shield tunnel. Journal of Shanghai Jiaotong University, Vol.37, pp.567-569.