Synthesis of numerical methods for the design of segmental tunnel lining

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Abstract. This paper presents a numerical study that aims to compare the behavior of the segmental tunnel lining using the direct, indirect and experimental methods. This model is based on a practical case applied in university of Tongji: a project of water conveyance tunnel. A reduction in the bending moment and increasing of the displacement in the tunnel lining is showed in numerical results, when taking into account the effect of the joints. It has been shown that the number of joints in the tunnel-lining structure highly affects the results in terms internal forces and displacements. Furthermore, the internal forces obtained by the continuous method are high compared to the other methods when the effects on segmental joints on tunnel lining behaviour are usually considered. Additionally, the bending moment of the direct method with behaviour of rotation spring linear and experimental method is comparable.

1 Introduction

The mechanized shield tunnelling method has become more and more popular for the construction of tunnels in recent periods due to its flexibility, cost effectiveness and minor trouble to the surrounding ground [19]. Because of the presence of joints between segmental linings driven in place by tunnelling operations, its design should take into account these discontinuities. Generally, the influence of joints on the internal forces and displacement is one of the main issues in the segmental lining design of shield-driven tunnels.

In order to describe the influence of joints in tunnels consisting of segments, various methods have been investigated in the literature, from theoretical to numerical (two-dimensional or three-dimensional) models, and compared to experimental data's with some accuracy (references).

Recently, a research program at Tongji University [22] has been conducted to study the three-dimensional effect through full-scale loading tests on a staggered-fabricated three-ring structure for rain-water storage and transportation tunnel. Based on their preliminary results, we propose in this paper a comparative numerical analysis of segmental lining modelled as uniform or discontinued segments, either by continuous, indirect and direct

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methods. In this model, in addition from the soil pressures and the normal external water, inner hydrostatic pressures will also applied during strong storms. Single-ring loading tests have been realized to evaluate under the designed loads the performance of the segmental lining. Results are compared with experimental results obtained from the project of Tongji University [22].

2 Survey of existing methods

There are two main analytical methods for taking into account the effects of joints between segments on tunnel behaviour: indirect and direct methods.

In indirect method, tunnel structure is perceived as a rigid lining ring embedded on a continuous ground model [1], [2],[3],[4],[6],[11]. The presence of joints causing a decrease in the rigidity of the structure, these methods simply consist in considering all the segments as a continuous beam ring with a reduced rigidity, i.e. by applying a reduction factor to the rigidity in bending of the elements of the tunnel. These simplified analytical methods cannot take into consideration the intricacy of the joint characteristics, including joint distribution and joint stiffness, nor analyze complex situations of the surrounding ground.

In direct method, the segments are modelled by beam elements linked together by a connection with rotation spring supposed to describe the joint [7], [9], [10], [12]. The behavior of the springs in rotation can be linear or nonlinear. [10] Proposed a numerical method where joint behaviour is assumed by means of all three joint stiffness's, that is, the rotational stiffness, the axial stiffness and the radial stiffness. On the other hand, these methods cannot be applied to cases in which the joint distribution is asymmetrical to the vertical axis of the tunnel [16].

To better understand the local behavior within the structures formed of segments, many experimental tests were conducted. They made it possible to highlight the role played by the joints and the technologies used [21], [20], [14]. For example, [5] performed various experimental tests on flat joints with a concrete-concrete interface (with and without bolts) and determined the experimental moment (M) - rotation (θ) relationship. Others like [17] have studied the flat bolted longitudinal joint structural behavior of Shanghai Metro Line No.13 with a full-scale test conducted continuously loading the joint until it is completely failure.

For example, In particular, they have shown that the bolt position along the surface contact influence the joint behavior but also its behavior itself. Other researchers [18] conducted a series of large-scale experimental trials on two types of seals used in a water transfer tunnel project. The main objective of this study was to better understand the mechanism of rotational behavior of these two types of joints in cases of negative and positive bending moment. This brief review of the experimental literature on complex structures provides a better understanding of the overall behavior of structures formed by segments and linked together by joints.

Concerning numerical approach, by using numerical tool, the Flac [15] modelled a tunnel for the railway line Bologna-Florence. A 2D model has been developed under condition of plane deformations. It is supposed that the behavior of the tunnel structure is linear elastic and that of the ground is defined by an elastic perfectly plastic constitutive relation, that is based on the Mohr–Coulomb failure criterion. A segmental joint can be simulated as an elastic pin and its stiffness characteristics are affected by rotational stiffness KRO, radial stiffness KR and axial stiffness KA.

Through of simplified FEM 3D analyses, [13] presented a numerical study. They studied the influence of joints (The joint are modelled with interface elements, indicated with springs). They calculated a range of rotational stiffness between 1000 and 3000 kN.m/rad, then a constant elastic rotational stiffness is used to model the joint. The interaction between the soil-structure is also taken into account through a set of normal reaction springs, without taking into account tangential springs. The authors investigate also the influence of longitudinal joins number and position in the transversal lining section.

To better understand the behaviour observed in experiments, [18] developed a three-dimensional finite element (FEM) model using ABAQUS (version 6.14). In particular, they took into account: the numbers of bolts, cast iron panels and initial conditions of contact between the different segments. The presence of gasket that produces a gap between the segments has an important influence on longitudinal joint rotation rigidity. They concluded to the presence of gaskets produces a space between the segments, this space have a significant influence on the longitudinal joint rotation rigidity.

3 Project background

The full-scale loading tests were carried out based on a pilot ‘deep tunnel’ under Suzhou River of Shanghai [22], which purpose to extenuate the waterlogging and ground overflow problems of this city during the heavy raining seasons. A tunnel length of 1.5 km has testing, and the average burial depth to the tunnel crown is about 50 m. Fig.1 show the cross-sectional layout of the lining structure that has a thickness 0.65 m and an inner diameter of 9 m. A single lining ring has a width of 1.5 m and composed of eight segmental blocks, including one key block (K), two adjacent blocks (AB) and five identical standard blocks (SB). The precast C60 concrete reinforced with steel fiber is adapted to lining structure. All this data is extracted from [22].

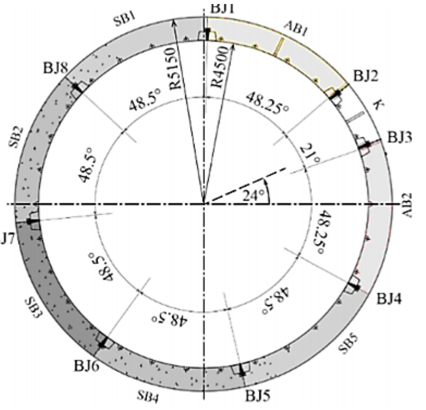

Fig.1. Cross-sectional layout of the lining structure

Fig.2. : Half-ring model

In the present study, a symmetrical half-ring model is used to reduce computation time (Fig.2.). In addition, the segments is modeled as a beam, it is fixed at one end and supported at the other (vertical displacement is zero and rotation are blocked).

Fig.3 presents the loads following up on the testing specimen considered in the present investigation extracted from experimental study [22] and the load symbols is given in Table 1.

Table 1. Load symbols

Symbols	Loads
p	Overburden earth pressure
(q1),(q2)	Lateral earth pressure
qw0	External water pressure
qwi	Inner water pressure
k	Coefficient of lateral resistance
δ	Deflection of segmental lining [−45°; 45°]
pk	Subgrade reaction pressure
g	Segment's self-weight

In the experimental installation [22], these mechanical loads are converted into 16 sets of concentrated loads, between then the 15 sets loads are symmetrically dispersed according to the vertical axis of the testing configuration and last one set of loading points uniformly distributed over the periphery of the testing configuration. This last, was used in the three-ring tests to apply the longitudinal thrust forces. But in this study, just the single-ring tests are investigated, so no longitudinal thrust forces were applied. Therefore, 15 sets loads are applied.

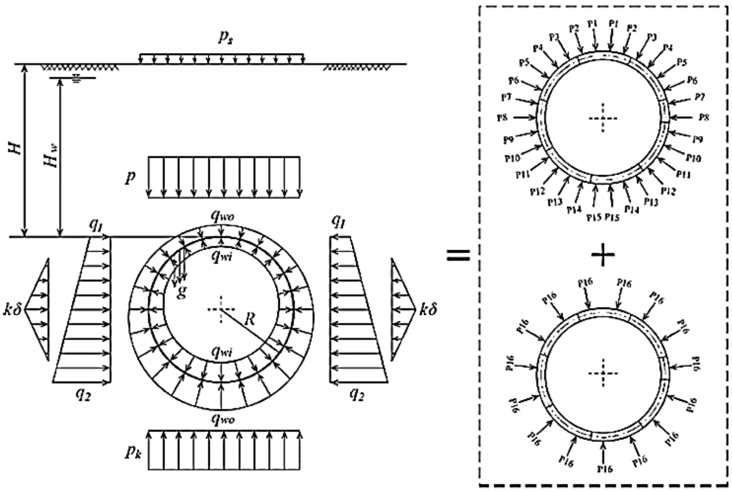

Fig.3. : Loads acting on the testing specimen [22].

4 Research methods

In view of different methods in literature, three methods of segmental linings were designed for this study as shown in. Several methods are investigated in this study: direct and indirect methods. The continuous method assumes the tunnel ring as continuous beam, without presence of joint. Direct and indirect methods are applied to determine the influence of joint in tunnel, by means of a finite element model and compared with an experimental result obtained from project of Tongji University [22].

As long as indirect methods are affected, the effect of joints is generally taken by a reduced rigidity of the tunnel structure; its value is between 0.25 and 1.

In direct methods, segments and joints are modelled as structural elements. Segments and joints are represented as structural beam elements and rotational springs respectively. The behavior of rotating springs is assumed linear with constant rotational rigidity 50000 KN.m/rad.

5 Results

The variation of displacement obtained throughout tunnel (fig.2) for the different methods is shown in fig.4. In this figure, the displacement increases throughout tunnel for indirect, direct and continuous methods. According to the indirect method, it is noted that as the joint stiffness factor increases, the displacement decreases. Because, more the joint stiffness factor, η is close to 1, more the model behaves like a continuous tunnel so has a lower displacement compared to the other method. Moreover, direct model is calibrated through the rotational spring value, to obtain the same maximum displacement that experimental study 8 cm (Fig.4).

The numerical results show a significant reduction of bending moment when the effect of distribution of joints is taken. It is observed that the bending moments obtained by the continuous method are higher than those of the direct and experimental methods where the effects on the joints between the segments are taken into account (Fig.5.). It is found that the bending moments of direct method and experimental method are comparable (Fig.5).

(In the figures, the simplified moments represent the ratio of the moment obtained from the calculation and maximum moment obtained in continuous method).

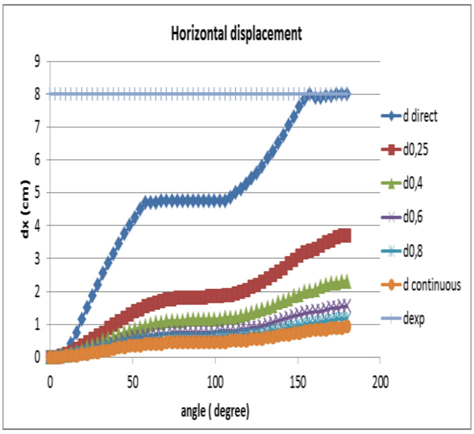

Fig.4.: Variation of displacement

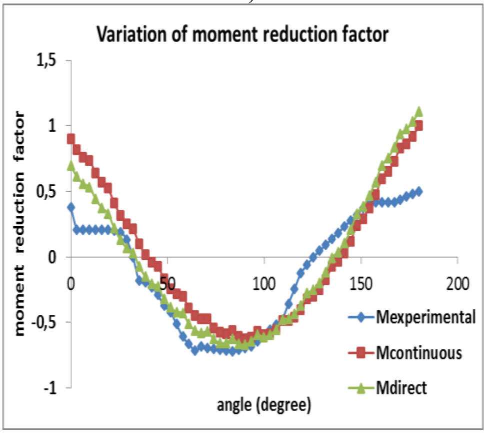

Fig.5. : Variation of moment reduction factor

Instead, it can be seen (Fig.6.) that the number of joints in a tunnel has a great influence on the results in terms of bending moment. Thus, when the number of joints increases, the bending moment increases.

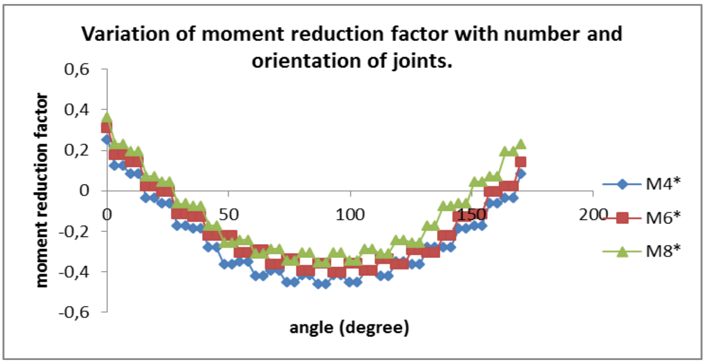

Fig.6. : Variation of moment reduction factor with number and orientation of joints.

The number of joints has an important effect on the displacement as a function of the joint rotational stiffness as illustrated in Figures 7 and 8. When the number of joints increases, the displacement is smaller. It can be noted that the influence of rotational rigidity in the range (4000 to 20000 KN.m / rad) is very important (Fig.7.) for the displacement (Fig.8.). The higher the rotational stiffness joint, the greater the displacement decreases sharply.

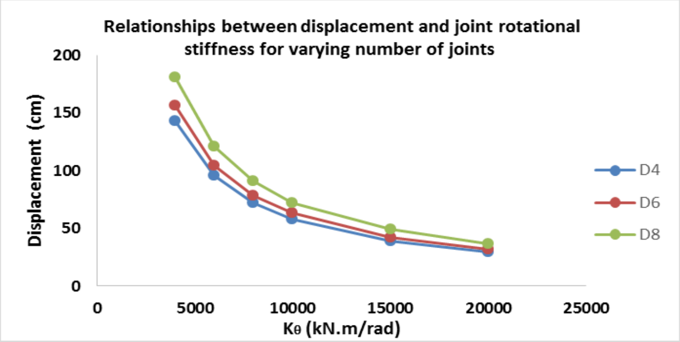

Fig.7. : Relationships between displacement and joint rotational stiffness for varying number of joints

6 Conclusion

In this study, a comparative numerical study for different methods, representing the segmental lining as a uniform or discontinued segment is presented. Different methods are applied on a finite element model and compared with the experimental results got in the project of Tongji University.

Based on the results, the numerical results show a significant reduction in the bending moment and increasing of the displacement in the tunnel lining taking into account the effect of the distribution of joints. Besides, the bending moment obtained by the continuous method are high compared to the other methods when the influence of segmental joints on tunnel lining behaviour is usually considered. Additionally, the bending moment obtained from the direct method (with law behaviour of rotation spring is linear) and experimental method are comparable. Furthermore, it has been shown that the number of joints in the tunnel-lining structure highly affects the results in terms bending moment and displacements.

In view of the results, it seems that taking into account of the rotation is primordial. It is then necessary to describe the joint behaviour in the most relevant way that is depending on the geometry and characteristics of joints. Our work aims to propose a friendly-method that is capable to take into account the complex local behaviour of joints by way of global approach with globalized parameters, without dealing with a complex three-dimensional and non-linear calculation.

Following the limitation of the current numerical methods, we propose to model the joint using the concept of macro-element, which consists in considering all material and geometrical nonlinearities of joints locally and transferring the local behaviour to some global structural parameters between linings, by concentrating them in a representative point and by formulating a three-dimensional law in generalized variables (moment and rotation).

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