Longitudinal deformation pattern of shield tunnel structure and analytical models: a review

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ABSTRACT

This paper gives a general review on the deformation pattern of the longitudinal structure of shield tunnel and the existing analytical models. Based on the previous studies, two longitudinal deformation modes are identified: i) bending deformation mode, and ii) dislocation mode. The longitudinal deformation of tunnel should consist of both flexural deformation under bending and dislocation between segmental rings under shear force. The existing analysis models of longitudinal structure mainly include i) segment ring-joint model and ii) longitudinal equivalent continuous model. The former can theoretically reflect the features of the tunnel structure. However, it is difficult to be applied in tunnel analyses as some of the parameters (e.g. joint stiffness) are difficult to determine in engineering practice and the calculation is very complicated. By contrast, the longitudinal continuous model is clearer in concept and simpler in calculation, which makes it widely adopted by researchers. The existing longitudinal continuous model follows the Euler-Bernoulli theory and therefore only considers the flexural deformation under bending; the dislocation between segmental rings is not taken into account. Elastic foundation model is widely used in the analysis of the interaction of tunnel and soil. Typical elastic foundation models include Winkler model, elastic continuous medium model, and two-parameter model. Winkler model is the most popular model due to its simplicity in calculation. Two parameters model, which considers the continuity of soil, is more accurate than Winkler model.

Keywords: shield tunnel, longitudinal deformation, calculation models, review

1 INTRODUCTION

The construction of urban rail transit has been carried out on a large scale in large and middle inshore cities. The soil in these cities is almost soft soil deposit, which is characterized by high compressibility, high sensitivity, high sensitivity, and low shear strength. The metro tunnels in soft soil are generally constructed with the shield-driven method. The lining of shield tunnel is a flexible structure with segment joints, and can produce longitudinal deformation in soft soil layer easily. Even though emphasis has been put on the design of the longitudinal deformation, effective design of the construction in the tunnel longitudinal structure has not been carried out, and the current design is still a horizontal design of some typical profiles which are selected in longitudinal. Therefore, it is of great importance to study longitudinal deformation pattern of shield tunnel, which includes three aspects, longitudinal deformation modes, calculation model of shield tunnel in longitudinal direction and calculating model of interaction of soil and tunnel.

This paper is a review of longitudinal structure

deformation of shield tunnel and analytical models. This objectives of this paper are as follows: (i) to investigate the longitudinal deformation mode of shield tunnel; (ii) to discuss the existing calculation models of shield tunnel deformation in longitudinal direction; (iii) to introduce the existing calculating model of interaction between soil and tunnel.

2 LONGITUDINAL DEFORMATION MODE

Shield tunnel linings are composed by a number of precast concrete segments, which are connected by steel bolt. The joint between the segments is the weakest part of the tunnel structures. When an external load is applied to the tunnel structure, the deformation of the joints is much greater than that of the segments. The deformation of joints causes the deformation of tunnel structure. The exact understanding of the longitudinal deformation modes of tunnel is of great importance for the internal force analysis and the waterproof design of tunnel structure.

In the previous studies, two longitudinal deformation modes have been identified for tunnel

Fig. 1. Longitudinal deformation modes of tunnel.

structure: bending deformation mode and dislocation mode. Fig. 1 illustrates the two deformation mode. In the bending mode, segments rotate around the center of the deformation curve, which causes the compression of the concrete segments in the inner edge and the opening of the joints and the tension of bolts in the outer edge. In the dislocation mode, deformation curve of tunnel is accumulated by the differential settlement of adjacent segmental rings. The segment rings does not rotate in rigidity.

Most of the previous studies on the longitudinal deformation of shield tunnel are based on the bending mode. Zheng et al. (2005) obtained the limit tension force of the bolt and the critical curvature of tunnel before the waterproof failure based on bending deformation mode. On the basis of bending deformation mode, Zhou and Yuan (2009) calculated the opening of the joints of the cross-river tunnel under different curvatures and obtained the limit value according to the waterproof standard of shield tunnels in Shanghai. Wang and Huang (2013) analyzed the reliability of the opening of joints based on bending mode. Huang et al. (2012) analyzed that transversal flattening deformation and the additional internal force caused by longitudinal deformation of tunnels based on bending mode.

However, some other studies give different viewpoints on longitudinal deformation mode of tunnel. Wang (2009) analyzed the relationship between the opening of the joint and the sealing effect of the gasket embedded in joints according to the two deformation modes. By comparing with the field observation of groundwater leakage in tunnels of Shanghai, they believed that tunnel deformation between segmental rings is dominated by the deformation mode of dislocation. Liu et al. (2013) pointed out that the tunnel is fixed to the working shaft in both two ends, the longitudinal distance of the tunnel cannot extent, and

therefore, no bending of the segmental rings could occur. Tunnels can only deform by dislocation between the segmental rings. Fan (2009) conducted numerical simulation found by 3D FEM and found that longitudinal deformation was composed of bending deformation and dislocation. When the rings are jointed in alignment, the tunnel is dominated by bending deformation, while in a staggered arrangement the tunnel is dominated by dislocation between rings.

3 CALCULATION MODEL OF SHIELD TUNNEL IN LONGITUDINAL DIRECTION

The longitudinal calculation models of tunnel can be divides into the following two types according to the previous literatures: i) segmental ring-joint model, in which the segmental rings and the joints are modelled separately; ii) longitudinal continuous model, in which the joints and the segmental rings are assumed to be continuous structure. The classification of the two calculation models is tabulated in Table 1.

3.1 Segmental ring-joint model

Segmental ring-joint model can be further divided into the following types: i) beam-spring model proposed by Koizumi et al. (1988), which considers the bending and shearing effect of segmental lining using beam element, and simulates the confining effect of bolts between rings using tension, shear and rotation springs, as shown in Fig. 2; ii) beam-joint element model proposed by Zhu et al. (1994), which introduces the Goodman element for modelling the joint; iii) shell-spring model, in which 3D segmental ring model are established and the bolts are modelled by springs; iv) 3D skeleton model, in which each segment and bolt are modeled accurately. The shortcoming of using the segmental ring-joint model is that complex calculation needs to be conducted, and the stiffness of spring is difficult to determine.

3.2 Longitudinal continuous model

Longitudinal continuous model was first proposed by Shiba et al. (1989). In this model the tunnel is regarded as a homogeneous ring in transversal direction. In the longitudinal direction, the tunnel composed of joints and segments is equivalent to a continuous beam, which has a uniform stiffness and structural characteristics. Longitudinal continuous model includes the following two forms: i) one-dimensional simplified equivalent beam model which ignores the influence of transversal deformation (see Fig. 3); ii) three-dimensional equivalent cylindrical shell model proposed by Liao et al. (2002) (see Fig. 4). The former is much simpler and has been widely adopted in longitudinal analyses.

The longitudinal equivalent bending stiffness is the most important factor of longitudinal continuous model and can affect the calculation accuracy of model. There are three typical methods to calculate the equivalent

Fig. 2. Beam-spring model (Xu, 2005).

Fig. 3. One-dimensional equivalent continuous mode.

Fig. 4. Three-dimensional equivalent continuous model.

Table 1. Calculation model of shield tunnel in longitudinal direction.

Mode	Classification	
Segment annulus- joint model	1D	Beam-spring model
		Beam-joint element model
	3D	Shell-spring model
		3D skeleton model
Longitudinal continuous model	1D	Equivalent beam model
	3D	Equivalent cylindrical shell model

bending stiffness: i) the method proposed by Shiba et al. (1989), in which the stiffness of the whole tunnel is regarded as the stiffness at the joint. Obviously, this method overestimates the influencing range of the joint and therefore predicts a smaller bending stiffness of the tunnel; ii) the method proposed by Murakanu and Koizumi (1978), in which the bending stiffness is calculated by combining the rotational stiffness of joint with the bending stiffness of segmental rings. Some of the critical factor needs to be determined based on library test, such as the rotational stiffness of the joint; iii) the modified method proposed by Liao (2002), which is based on Shiba et al. (1989) and Murakanu and Koizumi (1978), taking account of the influencing range of the joint.

Obviously, the existing longitudinal continuous model follows the Euler-Bernoulli theory, in which the cross section of the beam remain plane section and is perpendicular to the neutral axis under deformation. That is only the flexural deformation under the effect of

bending is considered. The dislocation between segmental rings is not taken into account.

4 CALCULATING MODEL OF INTERACTION OF SOIL AND TUNNEL

The response of soil to external load is an important factor influencing the soil and structure interaction. Many researches have been conducted on the soil characteristics including elastic, consolidation, creep, failure behavior. Some constitutive models that well presents the soil stress-strain relationship has been proposed on the basis of experiment. However, it is difficult to obtain the analytical solutions for interaction between soil and structure based on these models. Elastic foundation model is an idealize soil model, by which the interaction analysis for soil and structure can be conducted by simple calculation, and therefore has been adopted by many researchers. Table 2 lists the existing elastic foundation models.

Fig. 5 give an illustration on the soil model proposed by Winkler (1867). Winkler model assumes that the displacement at any point on the soil surface is proportional to the stress on the point, which is irrelevant to the stresses acting on the other points. The surface settlement of soil occurs only in the loading area. Since the soil is a continuous medium, the surface

Table 2. Elastic foundation models.

Model type		Model description
Winkler model		The soil is composed of a series of independent springs.
Elastic continuous medium model		The soil is expressed by a completely continuous elastic half space.
Two-parameter model	Filoncnko-Borodich model	Interaction between the springs was added to the Winkler model (Such as elastic film, elastic beam, pure shear layer).
	Hetenyi model	
	Pasternak model	
	Vlazov model	some simplified assumptions are introduced on the basis of elastic continuous medium model

Fig. 5. Winkler foundation model.

settlement occurs not only in the loading zone, but also in the area out of the loading zone. In elastic continuum medium model, the soil is expressed by completely continuous elastic half space. The feature of soil is expressed by the properties of elastic modulus and Poisson's ratio. Compared with Winkler model, elastic continuous medium model is more accurate about the description of soil properties. However, the mathematical form of this model is very complex. It often needs to solve the integral equation or integro-differential equations. In light of the inaccurate description of Winkler model on the soil behavior and the calculation complexity of the elastic continuous medium model, different types of two-parameter models were proposed. Some of the two-parameter models add interaction between the springs to Winkler model by elastic film, elastic beam or pure shear layer, e.g. Filoncnko-Borodich model, Hetenyi model, Pasternak model. Some others introduced simplified assumptions into elastic continuous medium model, e.g. Reissner model (Reissner, 1958). The characteristic equations of these models can transform into each other in certain conditions.

5 CONCLUSION

The following conclusions can be drawn:

- 1) Longitudinal deformation of tunnel is composed by flexural deformation under bending and dislocation under shear force.
- 2) As compared with the segmental ring-joint model, longitudinal continuous model is clearer in concept and simpler in calculation, and is widely adopted in the internal forces and deformation analysis of tunnel. However, longitudinal continuous model only considers the flexural deformation under bending; the dislocation between segmental rings is not taken into account.
- 3) Elastic foundation model is widely used in the analysis of the interaction of tunnel and soil. Typical elastic foundation models include Winkler model, elastic continuous medium model, and two-parameter model. Winkler model is the most popular model due to its simplicity in calculation. Two parameters model, which considers the continuity of soil, is more accurate than Winkler foundation model.

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