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Model test study on effective ratio of segment transverse bending rigidity of shield tunnel

Ye Fei *, Gou Chang-fei, Sun Hai-dong, Liu Yan-peng, Xia Yong-xu, Zhou Zhuo

Chang'an University, Shaanxi Provincial Major Laboratory for Highway Bridge & Tunnel, Xi'an 710064, China

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ABSTRACT

The effective ratio of the transverse bending rigidity has an important influence on internal force of segmental ring, and that is an important parameter in shield segment design with average uniform rigidity ring. Based on tensile tests and similarity theory (at the joint area, similarity relation is achieved from the model tunnel which has the same rigidity ratios with the prototype tunnel), three kinds of segmental ring test models made of PMMA (to simulate segment) and aluminum welding wire (to simulate bolt) are used to carry out the model test, which include straight-jointed ring, stagger-jointed ring and uniform ring. Through changing the number of spring gaskets, the different bolt pre-tightening forces of straight-jointed and stagger-jointed ring are obtained. The multi-stage loading test on straight-jointed ring, stagger-jointed ring and uniform ring under different bolt pre-tightening forces are carried out with a homemade loading device. The variation values of horizontal and vertical diameter of straight-jointed and stagger-jointed ring are compared respectively, and then it is concluded that the range of the effective ratio of the transverse bending rigidity value is between 0.09 and 0.23 under straight-jointed condition, 0.30 and 0.80 under stagger-jointed condition. The contrast analysis on the effective ratio of the transverse bending rigidity values under different load levels with different bolt pre-tightening forces and different assembly modes shows that value of the stagger-jointed segmental ring is obviously lager than that of the straight-jointed segmental ring, and that difference decrease gradually with the load increasing.

1. Introduction

The shield-driven tunneling method is widely adopted for the construction of city subway tunnel, municipal tunnel and underwater tunnel, due to its flexibility, cost effectiveness and the minimum impact on surrounding soil. As the lining of a shield-driven tunnel is not a continuous ring structure due to the existence of joints, the effect of the joints on internal forces and displacements should be taken into consideration in the design of tunnel lining. Shield tunnel segments are often articulated or coupled at the longitudinal and circumferential joints. Therefore, not only the characteristics of the concrete segments influence the structure but also the mechanical and geometrical characteristics of the joints strongly affect the structural behavior of the tunnel lining (Klappers et al., 2006). Hudoba (1997) had taken into consideration the effects of the segment ring joints in his study. Gruebl (2012) pointed out that the determination of loads during ring erection, advance of the TBM, earth pressure and bedding of the articulated ring is difficult, and the ring model and the design input values must be studied carefully according to the parameters of the surrounding soil. Through diagrams for the hoop forces, bending moments and radial displacements, Duddeck and Erdmann (1982) illustrated the differences in the design values evaluated for three different models – the continuum model, the Muir Wood design model and the bedded beam model without bedding at the crown region. With respect to the actual design methods for the shield tunnel linings, the loads acting on the tunnel linings should be firstly determined, and then the material and the cross-sectional dimensions of the segments are determined by structural analysis. It is, therefore, very significant to choose an appropriate design model (or method) for the determination of the internal forces in each part of a segment and its interaction under different loads. There are a number of design models suggested by ITA (ITA, 2000). Lee et al. (2001) classified all tunnel lining design methods into four major types: (a) empirical design methods based on past tunneling practices; (b) design methods based on in-situ measurement and laboratory testing; (c) circular ring in elastic foundation method; and (d) continuum mechanics models including analytical methods and numerical methods.

As for the shield tunnel linings, the segment structure was often been separated into two plane problems along transverse and

* Corresponding author. Address: School of Highway, Chang'an University, Nan Er Huan Zhong Duan, Xi'an 710064, Shaanxi, China. Tel.: +86 29 82338926; fax: +86 29 82334838.

E-mail address: xianyefei@sohu.com (F. Ye).

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longitudinal direction in design or study process, although it was a 3D structure apparently (Liao, 2002; Liao et al., 2008). In transverse direction, the segmental circular lining system is usually designed in the plane strain condition (ITA, 2000; Bakker, 2003; BTS, 2004; Huang et al., 2012), and the third method "circular ring in elastic foundation method" in aforementioned models is by far most commonly adopted for design purposes. There are a number of proposed structure models so far in accordance with the treatment of the joints of segments, the corresponding structural models are shown in Fig. 1 (Koyama, 2000).

(1) Uniform rigidity ring, the circumferential joint is assumed to have the same rigidity as that of the segment, the moment for the design of joint is overestimated and that occurring at the segment cannot be calculated correctly. Therefore, it is difficult to compute the bending moment at the joint area.
(2) Average uniform rigidity ring, an average uniform rigidity ring model was proposed in order to make up for the faults of the uniform rigidity ring model. Two factors (the effective ratio of the transverse bending rigidity η and the additional rate of bending moment ξ) were applied to this model. The decrease of the bending stiffness at the joint is considered as the decrease of the ring, accordingly, the equivalent stiffness of the segmental ling ring is ηEI ($\eta \leqslant 1$). Under the condition of stagger-jointed assembly, $(1+\xi)M_0$ (M_0 is the moment in tunnel lining without joint) is adopted as the main moment for the segment and $(1-\xi)M_0$ is taken as the design moment of the joint (shown in Fig. 2, Peck et al., 1972; Muir Wood, 1975; JSCE, 1977; Koyama, 2003).
(3) Multi-hinge ring, the rigidity of the joint is ignored, and the joins are assumed as hinges. As a non-static structure, the lining ring can turn to a static structure only with surrounding pressures including soil resistance around the lining structure. Therefore, the surrounding pressures condition and soil resistance has an important influence on stress, deformation and performance of the segmental lining ring, and this model is only suitable for hard stratum (Tang, 1988).
(4) Beam-spring model, the segments are modeled as beams and the joints are simulated by the rotation of springs, and their rigidities are expressed by the constants of the springs concerning the bending moments. The model can be subdivided into beam-spring (I) and (II) according to whether the relative displacement between the two neighboring rings in the longitudinal direction is to be considered or not (Zhu and Tao, 1998; Koyama, 2003; Hu et al., 2009).

The average uniform rigidity ring model is often used in today's segment structure design of shield tunnel, in which the value of the effective ratio of the transverse bending rigidity is crucial, as low value may lead to unnecessary waste in the segmental lining design process, while high value may result in hidden trouble of insufficient bearing capacity of the segmental lining. Furthermore, the value of the effective ratio of the transverse bending rigidity has an important influence on internal force of segmental ring, and the rationality of that directly determines whether the stress and deformation behavior of the tunnel lining is truly displayed by the average uniform rigidity ring model (Koyama and Nishimura, 1998). Presently, the study on the effective ratio of the transverse bending rigidity concentrates on the value and influence factors, with the research methods of theoretical analysis and model test. Muir Wood (1975) proposed experiential formula for calculating the effective ratio of the transverse bending rigidity considering the effects of segment number and joint stiffness. Based on the hypothesis of ellipsoid deformation, Liu and Hou (1991) deduced the calculation method of stiffness reduction coefficient of segment ring with joints in contrast to continuous ring. Lee and Ge (2001) calculated the effective ratio of the transverse bending rigidity of average uniform rigidity ring method with the multi-hinge ring model, and proposed the fitting formula of the effective ratio of the transverse bending rigidity and various parameters (including the radius of tunnel, lining thickness, strata resistance coefficient, and joints stiffness ratio) under the condition of straight-jointed assembly. Zhong et al. (2003) obtained the value of the effective ratio of the transverse bending rigidity through calculating the maximum horizontal displacement with average uniform rigidity ring and beam-spring model separately. Therefore, they put forward the simple determination method of the effective ratio of the transverse bending rigidity η, after summarizing the bending stiffness ratio λ between bending rigidities of segments and that of joints of Chinese subway tunnels. They considered that segment assembly mode, such as the straight-jointed assembly and stagger-jointed assembly, has a small influence on transverse bending rigidity of segmental ling structure. Taking Shanghai subway tunnel as the research object, Xu (2005) and Huang et al. (2006a) analyzed the value of the

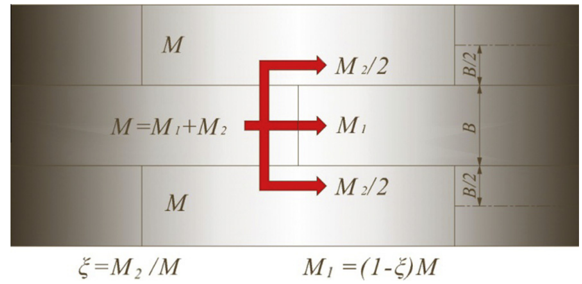

Fig. 2. Concept of the additional rate of bending rigidity (Koyama, 2003).

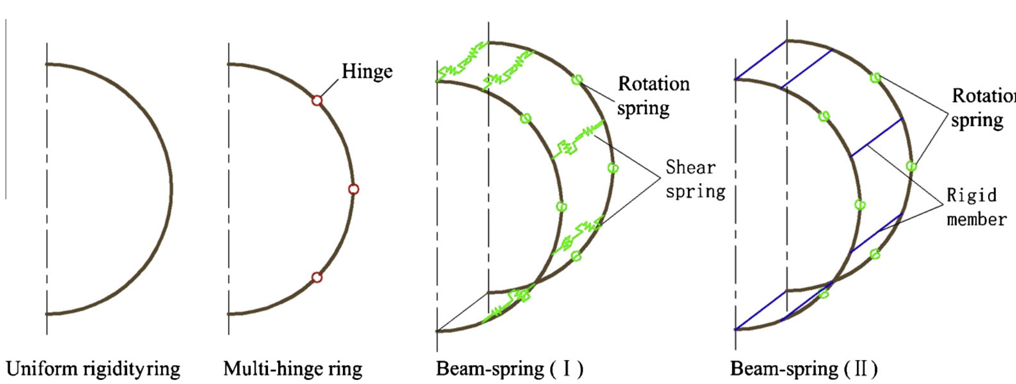

Fig. 1. Structural models of the segment ring (Koyama, 2000).