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Soil-tunnel interaction modelling for shield tunnels considering shearing dislocation in longitudinal joints

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ABSTRACT

The existing longitudinal structural model of shield tunnels usually simplify the tunnel as a Euler-Bernoulli beam on elastic foundation, which ignores the shearing dislocation between rings. To model the dislocation between rings, this paper proposed a soil-tunnel interaction model based on the Timoshenko beam simplified model (TBSM) of tunnel on Vlasov foundation. The governing differential equation and the closed-form solution for TBSM on Vlasov foundation subjected to any given pressure are derived with consideration of two types of boundary conditions. The proposed model was adopted to analyze the behaviors of a shield tunnel subjected to external forces transferred from surcharge load on the ground surface. Factors influencing the longitudinal behavior of shield tunnels are discussed. The factors include the equivalent of shear stiffness, location of load application, and the rotational stiffness of the joint between tunnel and station. The results indicated that Euler-Bernoulli beam model underestimates deformation and overestimates the internal forces in the tunnel structure. When the load application is close to the station, with the decrease of the distance between the load and the station will lead to a slightly decrease of the maximum settlement of the tunnel, and an increase of the maximum internal forces and the maximum joint deformation. A stiffer joint between tunnel and station will cause greater internal forces at the location of joint.

1. Introduction

Shield tunneling method has been widely utilized in soft deposits due to the following many advantages: highly safe construction efficiency, and less environmental impacts (Shen et al., 2016; Liu et al., 2018; Cheng et al, 2017b). The lining of a shield tunnel is composed of precast reinforced concrete segments connected by steel bolts (Cheng et al., 2017a). During long-term operation, shield tunnels often suffer from differential settlement to cause joint opening (Shen et al., 2014; Wu et al., 2017) and longitudinal structural deformation due to the effect of uneven subsoils, nearby construction (Chai et al., 2018), land subsidence (Shen and Xu, 2011; Shen et al., 2013), traffic loading, and groundwater leakage (Mair and Taylor, 1997; Mair, 2008; Wu et al., 2013; Huang et al., 2015). Large longitudinal deformation will inevitably result in a series of problems such as deformation of joints, cracks of concrete segments, groundwater leakages, distortion of track, which may threaten safety during train running (Shen et al., 2015; Wu et al., 2015). The differential settlement and longitudinal deformation of shield tunnels during operation has drawn more and more attention (ITA, 2000; Zhang et al., 2018).

In the last three decades, many attempts have been made to establish a soil-tunnel interaction model for longitudinal analysis (Liao et al., 2008; Huang et al., 2015; Ren et al., 2018). The most common way is to consider the tunnel/soil interaction problem as a beam structure on elastic springs, which is a one-dimensional problem. For tunnels, typical structural models include beam-spring model (Koizumi et al., 1988) and longitudinal continuous model (Shiba et al., 1988). The beam-spring model considers the ring as an one-dimensional short beam, and the joints as the spring elements to resist axial, shear forces, and rotational moment (see Fig. 1(a)). The longitudinal continuous model, however, considers the tunnel as a homogenous beam with reduction stiffness (see Fig. 1(b)). Compared with the beam-spring model, the longitudinal continuous model is much simpler in computation, making it widely used in soil-tunnel interaction analysis.

For the longitudinal continuous model, the previous studies commonly considered a tunnel as a continuous Euler-Bernoulli beam

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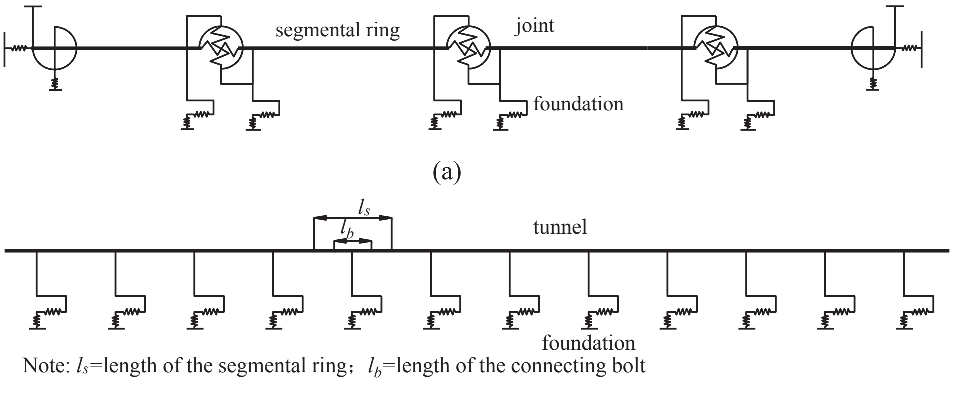

Fig. 1. Longitudinal structural model: (a) beam-spring model; (b) longitudinal continuous model.

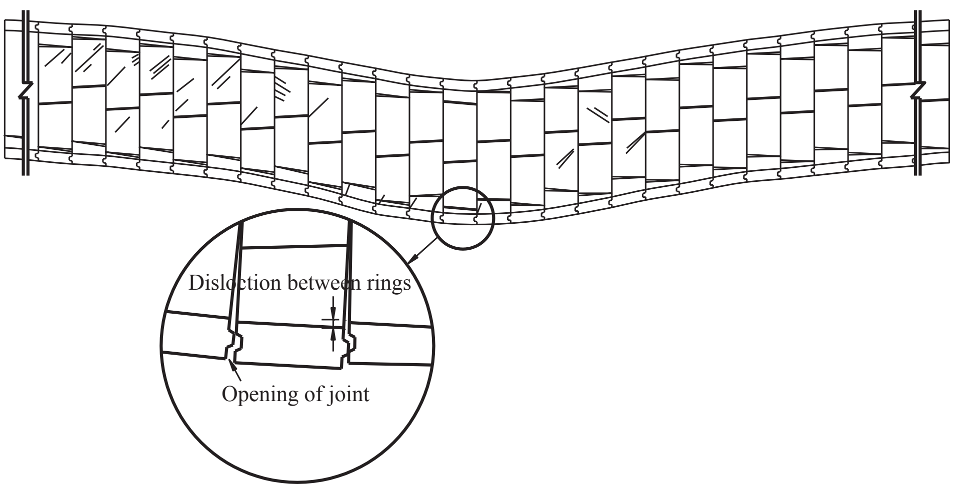

Fig.2. Longitudinal deformation of a shield-driven water pipeline in Shanghai (recreated based on the data from Liao et al., 2008).

(Bogaards and Bakker, 1999; Huang et al., 2012, 2015; Talmon and Bezuijen, 2013 Cheng et al, 2017b), which considered the longitudinal deformation as a pure bending deformation with opening of the joints. However, it is widely observed that shearing dislocation between rings occurs during long-term operation of shield tunnels (Wang, 2009; Shen et al., 2014; Wu et al., 2015). Fig. 2 shows the structural deformation of a shield-driven water pipeline in Shanghai, China. As shown in Fig. 2, the joint deformation includes both opening of joint and dislocation between rings. Such deformation reflects a flexure deformation under bending moment, and a shear deformation in longitudinal direction. The traditional Euler-Bernoulli model only accounts for flexural deformation under bending and fails to capture the shearing-induced dislocation between rings. A soil-tunnel interaction analysis based on this structural model will give inaccurate results. Wu et al. (2015) proposed a Timoshenko beam simplified model (TBSM), in which the tunnel is simplified as a continuous Timoshenko beam with equivalent flexure stiffness $(EI)_{eq}$ and shear stiffness $(\kappa GA)_{eq}$. TBSM presents the deformation behavior of shearing dislocation reasonably well. However, Wu et al. (2015) did not provide the analysis method for soil-tunnel interaction, which limits the application of TBSM.

There have been many constitutive models that attempt to simulate the actual behavior of foundation soils. However, these models are difficult to use for analytical analysis of structure/soil interaction problems due to the complex calculations involved. Therefore, some simple elastic foundation models, such as Winkler model and two-parameter models, continue to be widely used (Han and Frost, 2000; Yin, 2000a,b; Li et al., 2016). The Winkler model is the simplest representation of a foundation response. It idealizes the foundation to consist of closely spaced independent springs (Winkler, 1867). The shortcoming of this model is that it does not account for the shear strains in the ground. To address this shortcoming, some two-parameter models that are capable of considering the interaction among the discrete springs have been proposed, such as Vlasov model, Hetenyi model, Pasternak model (Vlasov and Leontev, 1966; Hetenyi, 1946; Pasternak, 1954). These models are therefore expected to better capture the soil response via selection of appropriate soil parameters (Jin et al., 2016, 2017; Yin et al., 2018).

This paper aims to establish a soil-tunnel interaction model by combining the TBSM proposed by Wu et al. (2015) with the Vlasov foundation model. A closed-form solution of a shield tunnel on Vlasov foundation subjected to arbitrary pressure loading will be derived. With the proposed model, the effect of the equivalent shear stiffness, the location of load application, and the rotational stiffness of the joint between tunnel and station on the longitudinal behavior of the tunnel structure are discussed.

2. Brief introduction of TBSM

2.1. Shearing-dislocation deformation of shield tunnels

Fig. 3 plots the modes of longitudinal deformation of a shield tunnel. The lining is a composite structure consisting of segmental rings and circumferential joints. Since the joints have a lower stiffness than the segmental rings, joint deformation is the main element causing longitudinal deformation. In view of different joint deformation types, longitudinal deformation can be identified as following two modes: *i*)