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Improved analytical model for circumferential behavior of jointed shield tunnels considering the longitudinal differential settlement

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ABSTRACT

Differential settlements of the shield tunnel along the longitudinal direction can significantly affect the circumferential behavior of segmental lining, degrading both the structure safety and serviceability. In this paper, the authors introduce both the shearing effect and flattening effect on the tunnel cross section, which was caused by the longitudinal differential settlement, into an existing analytical model of jointed shield tunnels. An example is then presented to illustrate the variation of the circumferential behavior of segmental lining, including both the structure safety and serviceability, along the longitudinal position. Finally, a series of parametric studies are performed to investigate how factors such as tunnel longitudinal settlement, property of surrounding ground, and the design parameters of segmental lining affect the circumferential behavior of the segmental lining.

1. Introduction

The progress in advancing shield-driven machines and construction technologies has made shield tunneling one of the most popular methods used in the construction of urban tunnels, particularly for tunnels in soft soils. The segmental lining of these shield tunnels constructed with shield-driven machines is often designed with the assumption of a plane strain condition, a prerequisite that is valid when no variation of the design parameters (e.g., soil parameters, ground water level, and embedded depth, surcharge load) exists along the longitudinal direction (Wood, 1975; ITA, 2000; Lee et al., 2001; Koyama, 2003). However, such a prerequisite may not always be satisfied; many factors such as the longitudinal variation of tunnel alignment, the spatial variability of soil properties, the differential consolidation of the ground, and the nearby underground construction (e.g., tunneling) can cause the longitudinal variation of tunnel design parameters. One significant consequence, caused by the longitudinal variation of the tunnel design parameters, is the longitudinal differential settlement of shield tunnels (referred to herein as the vertical displacement of the tunnel structure), which is a particularly serious event in soft soils. The Metro Line 1 in Shanghai, China is one such example, with the accumulated longitudinal settlement occurring over the past 15 years plotted in Fig. 1, reached a maximum of 300 mm, and severe differential settlements were noted. In such a circumstance, the effect of tunnel longitudinal differential settlement on the circumferential behavior of segmental lining cannot be neglected.

Though it is widely acknowledged that the effect of tunnel longitudinal differential settlement on the circumferential behavior of segmental lining must be considered in the analysis and design of shield tunnels (e.g., ATRB, 2000; ITA, 2000), very few studies have been undertaken to elucidate this effect. Among these studies, Liao et al. (2005) developed a 1-D analytical model to analyze the effect of the longitudinal shear force increment, arisen from the longitudinal differential settlement, on the tunnel cross section through the longitudinal shear transfer (LST) mechanism. This 1-D shearing effect model was subsequently extended to account for the 3-D behavior of shield tunnels by modeling the segmental lining with cylindrical shells (Liao et al., 2008). Later on, the effect of the longitudinal bending moment on the tunnel cross section, known as the flattening effect, was studied by Huang et al. (2012). While the shearing effect and the flattening effect were analyzed separately in the previous studies, these two effects should be modeled simultaneously to investigate how the circumferential behavior of segmental lining is affected by the longitudinal differential settlement of the tunnel. However, a tunnel analytical model to account for the effect of tunnel longitudinal differential settlement on the circumferential behavior of segmental lining, including both

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the structure safety and serviceability, has not been developed. Furthermore, a framework for evaluating the longitudinal variation of the circumferential behavior of segmental lining based upon the observed tunnel longitudinal differential settlement is needed.

Therefore, the objective of this paper is to develop an improved analytical model of jointed shield tunnels, which considers explicitly the effect of tunnel longitudinal differential settlement on the circumferential behavior of segmental lining. This paper is organized as follows. First, we describe an improved tunnel analytical model with explicit consideration of the longitudinal differential settlement, primarily through the shearing effect model and the flattening effect model. We next present an example to illustrate how the circumferential behavior of segmental lining varies along the longitudinal direction with a tunnel longitudinal settlement curve. Finally, we conduct parametric analysis to investigate how the circumferential behavior of segmental lining is affected by different factors, including tunnel longitudinal differential settlement.

2. Improved analytical model for the circumferential behavior of segmental lining considering longitudinal settlement

In the current practice, the segmental lining of jointed shield tunnels is often designed based upon the results of analysis of a few typical tunnel cross sections assuming a plane strain condition (ITA, 2000). For a typical tunnel cross section, as plotted in Fig. 2 and subjected to the circumferential loads defined in Appendix A, the internal forces and convergence deformation of segmental lining can readily be computed with the existing analysis methods such as that proposed by Lee et al. (2001). In this paper, the authors describe the simultaneous incorporation of the shearing effect (Liao et al., 2005) and the flattening effect (Huang et al., 2012) into the existing analytical model, for purpose of improving the model for the designing of jointed shield tunnels.

2.1. Shearing effect model and flattening effect model

In the subsequent analysis of tunnel *longitudinal* performance, the following sign conventions are adopted: the settlement is assumed as positive when it moves downward; the longitudinal bending moment is treated as positive when the tunnel invert would be subjected to the longitudinal tension; and the longitudinal shear force is regarded as positive when it exhibits a clockwise rotation. As mentioned above, the effect of tunnel longitudinal differential settlement on the circumferential behavior of segmental lining can be modeled by considering the shearing effect and the flattening effect, both of which are represented with the additional loads on the tunnel cross section, as shown in Fig. 3. According to Liao et al. (2005), the additional load on the tunnel cross section from the shearing effect (p_s) is expressed as (see Fig. 3(a)):

$$p_s = \frac{R^2 t \sin\varphi}{I_L} \Delta Q_L \tag{1}$$

where R is the radius of the segmental lining, taken as the average of the outer radius (R_o) and inner radius (R_i); t is the thickness of segmental lining; φ is the circumferential angle measured from the tunnel crown; ΔQ_L is the longitudinal shear force increment per unit length caused by the longitudinal differential settlement; and I_L is the inertia moment of the tunnel cross section in the longitudinal performance analysis, defined as:

$$I_L = \frac{\pi}{4}\left[\left(R + \frac{t}{2}\right)^4 - \left(R - \frac{t}{2}\right)^4\right] \tag{2}$$

The additional load on the tunnel cross section from the flattening effect (p_f) is expressed as (see Fig. 3(b); Huang et al., 2012):

$$p_f = \frac{M_L}{I_L} \kappa R t \cos\varphi \tag{3}$$

where M_L is the longitudinal moment of the shield tunnel caused by the longitudinal differential settlement, and κ is the curvature of the tunnel longitudinal settlement.

For simplicity, the longitudinal structure of the jointed shield tunnel is usually approximated as a slender elastic beam in the context of tunnel longitudinal performance analysis (e.g., Shiwa et al., 1986; Talmon and Bezuijen, 2013), while the soil-structure interaction is modeled with Winkler (1867), Pasternak (1954), or Kerr (1965) model. In context of the elastic beam, M_L in Eq. (3) and ΔQ_L in Eq. (1) are computed respectively with the observed tunnel longitudinal settlement (w) as follows:

$$M_L = (\varsigma E I_L)\kappa \tag{4}$$

$$\frac{dQ_L}{dx} = \frac{d^2 M_L}{dx^2} \approx (\varsigma E I_L)\frac{d^4 w}{dx^4} \tag{5}$$

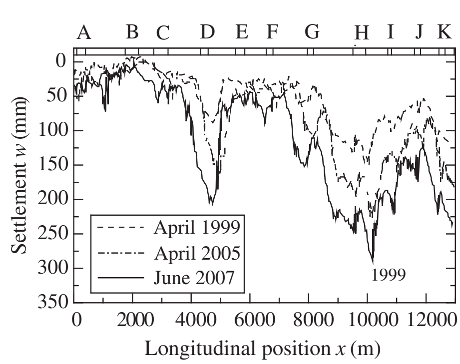

Fig. 1. Accumulated longitudinal settlement of the Shanghai Metro Line 1 (down line) (Note: A – Caobao Road; B – Shanghai Indoor Stadium; C – Xujiahui; D – Hengshan Road; E – Changshu Road; F – South Shanxi Road; G – South Huangpi Road; H – People's Square; I – Xinzha Road; J – Hanzhong Road; K – Shanghai Railway Station).

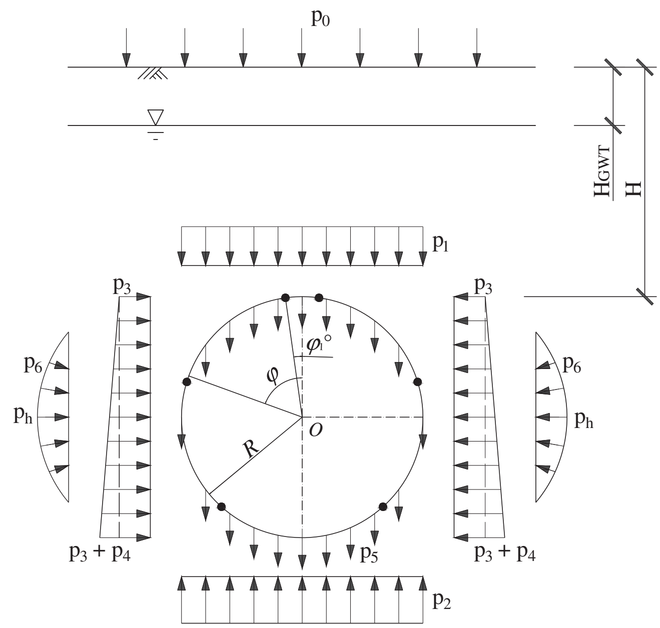

Fig. 2. The circumferential loads on the cross section of jointed shield tunnels (Gong et al., 2014).