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Studies on the key parameters in segmental lining design

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A B S T R A C T

The uniform ring model and the shell-spring model for segmental lining design are reviewed in this article. The former is the most promising means to reflect the real behavior of segmental lining, while the latter is the most popular means in practice due to its simplicity. To understand the relationship and the difference between these two models, both of them are applied to the engineering practice of Fuzhou Metro Line I, where the key parameters used in both models are described and compared. The effective ratio of bending rigidity η reflecting the relative stiffness between segmental lining and surrounding ground and the transfer ratio of bending moment ξ reflecting the relative stiffness between segment and joint, which are two key parameters used in the uniform ring model, are especially emphasized. The reasonable values for these two key parameters are calibrated by comparing the bending moments calculated from both two models. Through case studies, it is concluded that the effective ratio of bending rigidity η increases significantly with good soil properties, increases slightly with increasing overburden, and decreases slightly with increasing water head. Meanwhile, the transfer ratio of bending moment ξ seems to only relate to the properties of segmental lining itself and has a minor relation with the ground conditions. These results could facilitate the design practice for Fuzhou Metro Line I, and could also provide some references to other projects with respect to similar scenarios.

1. Introduction

The shield-driven tunneling method is widely used for the construction of urban underground tunnels in soft ground due to its advantages of flexibility, effectiveness and minimum impact on the ground surface. Most shield-driven tunnels are supported by segmental lining, which provides the structural capacity to resist the ground and water pressures, as well as the reaction frame to push the shield machine ahead. A certain number of segments are connected by longitudinal joints to form the ring, and then a number of rings are connected by circumferential joints to form the lining. The configuration of staggered joints, as shown in Fig. 1, is commonly used to improve the overall stiffness and minimize the water leakage of segmental lining (Guglielmetti et al., 2007; Maidl et al., 2012). The design of segmental lining is basically carried out by analytical methods or numerical methods, where the lining structure and the loading condition are simplified by designers.

There are generally two models for segmental lining, i.e. indirect-joint model and direct-joint model. The indirect-joint model regards the segmental lining as a ring of uniformity or a ring with multi-hinge, and some corrections are introduced to modify the influence of joints on lining behavior. The direct-joint model regards the segment, the longitudinal joint and the circumferential joint as beam (or shell), rotation spring and shear spring respectively, so that the lining behavior is determined by both segments and joints. On the other hand, there are generally two loading modes imposed by surrounding ground, i.e. active-loading mode and passive-loading mode. The active-loading mode assumes that the surrounding ground applies the earth/water pressures to the lining structure actively, which are calculated by theoretical or empirical formulas. The passive-loading mode takes the ground-lining interaction into account, and the earth/water pressures transferred to the lining are calculated through the displacement compatibility between ground and lining.

As for the indirect-joint model, the uniform ring model and the multi-hinge ring model are widely used in practice. The former is suitable for the shield-driven tunnel in soft ground, where many practices have been carried out and abundant experiences have been gathered among practitioners. The latter is suitable for the tunneling boring machine (TBM)-driven tunnel in hard rock, where the ground can stabilize itself and provide enough reaction to the lining. Both models introduce some corrections to modify the

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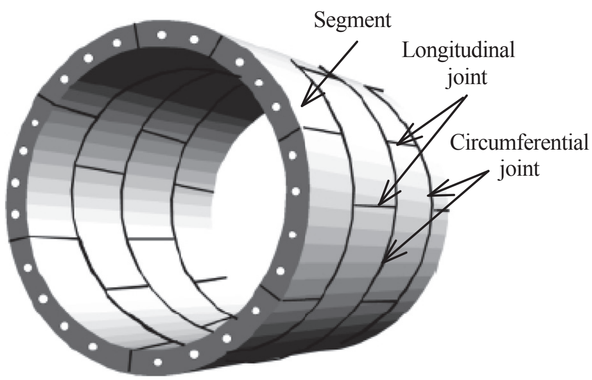

Fig. 1. Illustration of segmental tunnel lining.

influence of joints on lining behavior equivalently (ITA Working Group No. 2, 2000; Ding et al., 2004; Koyizumi, 2006; Wang, 2010; Gruebl, 2012).

As for the direct-joint model, the development of large-scale test rig for joint-connected segments and the development of computation capability in finite element analysis make it possible now to take the joints into account directly. The beam-spring model and the shell-spring model are receiving more attraction in practice nowadays. Many researchers have contributed their work to the following issues: the determination of joint stiffness and the real behavior of segmental lining (Hefny and Chua, 2006; Huang et al., 2006; Zhong et al., 2006; Teachavorasinskun and Chub-uppakarn, 2010; Arnau and Molins, 2011, 2012; Molins and Arnau, 2011; Do et al., 2013).

Although both the indirect-joint model and the direct-joint model are commonly used in practice, the relationship and the difference between them are rarely reported in the literature. In this article, the uniform ring model (a typical one based on indirect-joint model and active-loading mode) and the shell-spring model (a typical one based on direct-joint model and passive-loading mode) are thoroughly reviewed in Sections 2 and 3, respectively. Then they are applied to the engineering practice of Fuzhou Metro Line I in Section 4, where the key parameters used in these two models are focused. It is followed by further discussions in Section 5, and finally, some conclusions are summarized in Section 6.

2. Uniform ring model

2.1. Principle of uniform ring model

The uniform ring model regards the segmental lining as a ring of uniformity, and the calculation diagram is illustrated in Fig. 2 (ITA Working Group No. 2, 2000; Ding et al., 2004). In this figure, R_0 and R_c are the radii of extrados line and middle line of uniform ring, respectively; H and H_w are the overburdens of soil mass and the water head of groundwater, respectively; p_0 is the overload on ground surface.

Then the active loads applying on the uniform ring can be calculated by analytical or empirical formulas. The vertical earth pressure equals the total overburden weight or calculated by Terzaghi's formula, as shown in Eq. (1) or (2). Generally speaking, Eq. (2) is employed when the tunnel has a large overburden (i.e. $H>(3-4)R_0$) and the ground condition is good (e.g. stiff clay and dense sand), and Eq. (1) is suitable for other conditions. The vertical water pressure equals the total weight of groundwater above the uniform ring and calculated by Eq. (3). In absence of groundwater, γ_w can be set to zero in Eqs. (1)–(3).

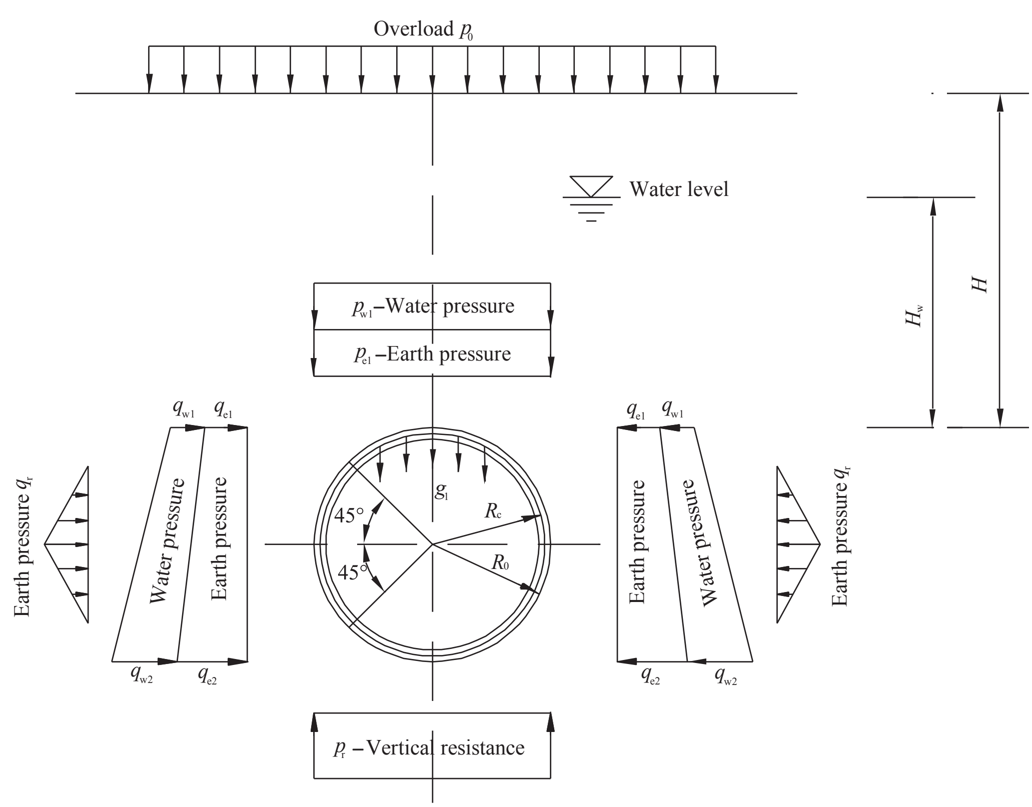

Fig. 2. Calculation diagram of uniform ring model (after Ding et al. (2004)).