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Normal and shear resistance of longitudinal contact surfaces of segmental tunnel linings

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ABSTRACT

Stiffness of contact points has a significant effect on the internal forces and structural design of segmental lining of mechanically bored tunnels. Recent research on the effect of contact points in the structural analysis of segmental lining can be categorized into: (1) using hinges at contact points (HL model), (2) reducing liner rigidity (RR model), (3) using effective moment of inertia for liners (EMI model), (4) using rotational springs at contact points (BRS model), and (5) developing a comprehensive 3D model for segmenting contact locations. The present study tried to develop a precise contact model based on experimental direct shear tests (DST) on the concrete samples of contact points in segments. By selecting the normal stress between 0.25 and 2 MPa, about 90 tests were performed on the grooved cubic samples with and without gasket. As the practical outcome of this study, the contact shear and normal reaction moduli k_s and k_n were related to contact normal stress via two linear regression equations considering R^2 of 99%. For evaluating the proposed method, finite element models of an urban tunnel liner were developed using the concept of beam on elastic foundation considering the proposed contact model of the present study (beam-contact springs (BCS)), the results of which were compared with those of the conventional contact models. Results demonstrated that the proposed model of this research had the highest correspondence with reduced RR, HL, EMI, BRS, and comprehensive coverage, respectively.

1. Introduction

Segmental lining has been extensively applied in mechanized shield tunneling in recent years, and the shield tunneling method has been widely adopted for designing and constructing urban underground tunnels in soft grounds due to its flexibility, cost effectiveness, minimum impact on urban traffic, and settlement risk on surface structures. A large part of the cost of shield tunneling construction is related to segment manufacturing; hence, efficient design of these elements can considerably affect total construction cost. In this regard, understanding the actual behavior of the segmented liner under surrounding loads is an important issue from both structural analysis and design standpoints. In other words, as the lining of a shield tunnel cannot be assumed as a continuous ring due to the existence of longitudinal joints, effect of segment-to-segment contact should be properly considered during its structural analysis in order to access the realistic values of internal forces and displacements.

In this paper mechanical behavior of longitudinal joints in segmental lining was studied in order to find a definite relationship between stiffness of contact points and normal stress in contact locations. For this purpose, direct shear test (DST) apparatus was utilized for testing real concrete samples in order to obtain normal and shear stiffness coefficients of longitudinal contact surface of the segmental lining. According to the standard of International Society of Rock Mechanics [1], the tests were performed on the concrete samples of the segment contact surface in two cases of with and without gasket. In this manner, 46 concrete samples were prepared from both A and B segments (two consecutive segments with a shared contact surface in the same ring, as shown in Fig. 1). The samples were tested under different normal stresses (σ_n) of 0.25–2 MPa and variation of normal and shear stresses ($\Delta\sigma_n$, $\Delta\tau$) were recorded based on normal and shear displacements ($\Delta\delta_n$, $\Delta\delta_s$). Consequently, the values of $k_n = \Delta\sigma_n/\Delta\delta_n$ and $k_s = \Delta\tau/\Delta\delta_s$ as normal and shear reaction moduli were presented as a function of σ_n. At the final stage, the derived equations for the normal and shear reaction moduli were converted into normal and shear stiffness and were implemented at the contact point of a numerical example as a case study of an urban tunnel. Results of numerical models including the liner internal forces and deformations were obtained using the

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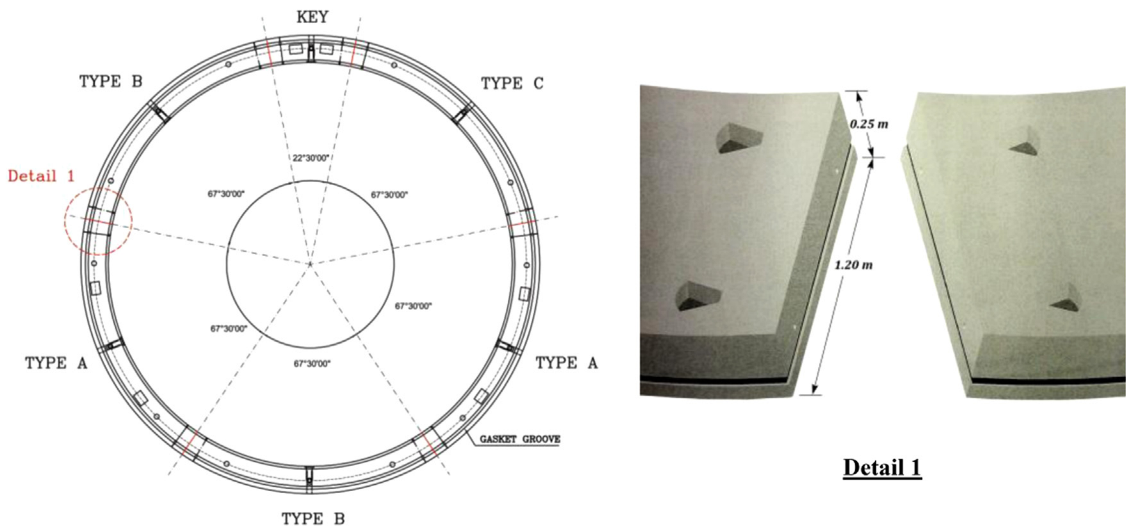

Fig. 1. Geometry and arrangement of the segments in a ring.

contact model developed in the present study, called beam-contact springs (BCS), and compared with those obtained by implementing other methods such as united lining (UL), reduced rigidity of lining (RR), hinged lining (HL), effective moment of inertia (EMI), and beam-rotational spring (BRS).

2. Literature survey

Reviewing the available technical literature on this issue reveals four main categories of contact models for assessing the effects of longitudinal joints on liner internal forces as follows:

Using hinges at liner contact points (HL model): In this method, segments are modeled using beam elements considering perfect hinges in their contact locations. Assuming perfect joints in the liner causes a pure axial force in the joint location without any bending moment. The joint behavior in this model cannot consider the flexural behavior of segment-to-segment contact area and leads to the transfer of bending moment to segments. This method usually causes more bending moment in the liner than other contact models. Tang [2] and Zhong et al. [3] have utilized this method for structural analysis of segmental lining.

Reducing liner rigidity (RR model): Some researchers and societies such as Morgan [4], Peak et al. [5], Japan Society of Civil Engineers (JSCE) [6], Ranken et al. [7], Einstein and Schwartz [8], Yuen [9], Ogawa [10], Liu and Hou [11], Lee and Ge [12], Blom [13], and El Naggar et al. [14] have considered segmental tunnel lining as a continuous ring with discounted rigidity by applying a reduction factor, $\eta \leq 1$, to the bending stiffness (EI) of liners.

Using effective moment of inertia of liners (EMI model): Muir Wood proposed this method for the segmental lining of tunnels considering the same length for each segment in the case of segment number of $n>4$ and introduced the effective moment of inertia of liners, I_e, as follows [15]:

$$I_e = I_j + (4/n^2)I \quad (1)$$

where I_j is moment of inertia of liners in the joint location (effective contact area) and I is moment of inertia of liners.

This method has been used by Lee and Ge [12], Hefny and Tan [16] and Hefny and Chua [17] as a simple methodology for determining the stress induced in jointed lining without incorporating the joints into structural analysis. In another work, Hefny et al. proposed the maximum and minimum equivalent moment of inertia for the liners of jointed shallow tunnels as follows [16]:

$$I_{e,\ max}/I = 429.01n^{-4.6023} \quad (2)$$

$$I_{e,\ min}/I = 159.19n^{-4.2734} \quad (3)$$

where $I_{e,max}$ and $I_{e,min}$ are effective moment of inertia of lining with respect to critical and most favorable orientation of joints, respectively, and I is moment of inertia for non-jointed lining.

Using beam rotational spring model (BRS model): In this model, segments are modeled by beam elements and longitudinal joints using rotational springs. Many researchers have proposed various values for rotational stiffness, k_θ. For instance, Mashimo and Ishimura suggested the range of 32–127 MN m/rad for this parameter [18]. Lee et al. proposed the range of 4–30 MN m/rad for such stiffness, which was based on the field measured values reported by Chen and Zhou in Shanghai subway tunnel [19]. Koyama proposed three diagrams for bending moment versus rotational angle ($M-\theta$) behavior of contact joints in segmental lining [20]. In their study, approximate values of rotational spring stiffness k_θ as the slope of $M-\theta$ diagrams varied from 15 to 150 MN m/rad. Teachavorasinskun and Chub-uppakarn, according to the experimental tests and FEM modeling, suggested the range of 1–3 MN m/rad for k_θ [21]. In another study, Arnau and Molins presented the rotational stiffness of segments as 50 and 100 MN m/rad with respect to two values of compressive stress as 1.5 and 3 MPa in the contact location [22]. Do et al. simulated segment connections with perfect hinges, reduced lining thickness in the narrowest part of the joint, and consequently calculated the bending moment of yielding condition (M_{yield}) as about 150 kN m/m [23]. This moment was in agreement with the maximum permitted angular rotation of 0.01 rad ($\approx 1\%$) in the joint location. Based upon the reported values of M_{yield} and the permitted rotation, rotational stiffness coefficient was calculated as about 100 MN m/rad/m based on $0.8(M_{yield}/\theta)$. Overall, based on the aforementioned works, it seems that it is impossible to propose a unique value for rotational spring stiffness and this parameter can be selected in a wide range of 1–150 MN m/rad.

By summarizing the above-mentioned models, it could be stated that the first method does not simulate properly the actual construction conditions and considers joints as a hinge while ignoring partial moment transmitting capacity. On the other hand, although effective bending rigidity must only affect contact points, in the second model, it affects the entire lining by ratio of the bending rigidity [20]. In the third model, it is assumed that all segments have the same length in a ring, which is not correct in