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2D numerical investigation of segmental tunnel lining behavior

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ABSTRACT

The application field of shield tunneling has extended in recent years. Most shield-driven tunnels are supported by segmental concrete linings. Although many well documented experimental, numerical and analytical results exist in literature concerning the functioning of segmental tunnel linings, their behavior under the influence of joints is still not clear.

This paper presents a numerical study that has been performed to investigate the factors that affect segmental tunnel lining behavior. Analyses have been carried out using a two-dimensional finite difference element model. The longitudinal joint between segments in a ring has been simulated through double node connections, with six degrees of freedom, represented by six springs. The proposed model allows the effect of not only the rotational stiffness but also the radial stiffness and the axial stiffness of the longitudinal joints to be taken into consideration. The numerical results show a significant reduction in the bending moment induced in the tunnel lining as the joint number increases. The tunnel behavior in terms of the bending moment considering the effect of joint distribution, when the lateral earth pressure factor K_0 is equal to 0.5, 1.5 and 2, is almost similar and differs when K_0 is equal to unity. It has been seen that the influence of joint rotational stiffness, the reduction in joint rotation stiffness under the negative bending moment, the lateral earth pressure factor and Young's modulus of ground surrounding the tunnel should not be neglected. On the other hand, the results have also shown an insignificant influence of the axial and radial stiffness of the joints on segmental tunnel lining behavior.

1. Introduction

The shield-driven tunneling method is widely adopted for the construction of urban underground tunnels in soft ground due to its flexibility, cost effectiveness and the minimum impact on the ground surface. Concrete segmental linings, which are generally made up of a sequence of rings placed side-by-side (Gruebl, 2006), are commonly used in most shield-driven tunnels. These rings are divided into sectors that are called segments. These segments are assembled to form a circle, multi-circle or another shape. A single circular tunnel can be considered the most useful shape as it fulfills the normal requirements of a construction process.

Because of the geometry of the lining rings and joint distribution, segmental linings show a fully three dimensional (3D) behavior, but it is often considered a two dimensional (2D) calculation scheme, in order to reduce the calculation times. This assumption permits the influence of the calculation parameters to be pointed out but it also results in some drawbacks.

One of the most important factors in designing a segmental tunnel lining is the influence of the segmental joints on its overall behavior. In structural analyses, a segmental joint can be considered as an elastic pin and its stiffness characteristics are influenced by rotational stiffness K_{RO}, axial stiffness K_A, and radial stiffness K_R. The K_{RO} value is defined as the bending moment-per-unit length required to develop a unit rotation angle along the joints of the assembled segments. Similarly, axial stiffness, K_A, and radial stiffness, K_R, are defined as the axial force and the shear force-per-unit length required to develop a unit axial and radial displacement at a given joint, respectively.

In the literature, the effects of segmental joints on tunnel lining behavior are usually considered in both indirect and direct methods. As far as indirect methods are concerned, the tunnel structure is perceived as a rigid lining ring embedded on a continuous ground model (Muir Wood, 1975; Einstein and Schwartz, 1979; Duddeck and Erdmann, 1985; Takano, 2000). The effect of joints is usually taken into account through a reduced rigidity of the tunnel structure. The ground–structure interaction is usually considered by means of so-called bedded ring models, in which the ground reaction is taken into consideration by means of discrete springs according to Winkler's theory (e.g. Schulze and Duddeck, 1964). These simplified analytical methods can neither take into

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account the complexities of the joint characteristics, including joint stiffness and joint distribution, nor analyze complex situations of the surrounding ground (e.g. tunnel excavated through different ground layers). In direct methods, segmental joints are added directly to the tunnel lining structure (Lee et al., 2001; Blom, 2002; Ding et al., 2004; Naggar and Hinchberger, 2008). Ding et al. (2004) proposed a numerical method in which joint behavior is simulated by means of all three joint stiffnesses, that is, the rotational stiffness, the axial stiffness and the radial stiffness. However, the influence of joint stiffness has not been investigated in detail. Apart from the Ding et al. method (2004), most direct models consider joint behavior through rotational springs at the joints. In addition, these methods cannot be applied to cases in which the joint distribution is asymmetrical to the vertical axis of the tunnel.

Several model tests had recently been carried out to examine the influence of joints on lining behavior. Lu et al. (2006) conducted an experimental study to investigate the load carrying capacity of a fully segmental reinforced concrete lining with an outer diameter of 15.0 m. A great deal of useful information was obtained; unfortunately, however, the influence of segmental rotational stiffness was not explored in detail. Teachavorasinskun and Chub-Uppakarn (2008) performed a series of laboratory tests which were carried out on a scaled segmental tunnel (ϕ = 15 cm) made from PVC, in order to estimate the applicability of the simple beam support in terms of the bending moment reduction factor. However, the influence of the surrounding ground on the calculated results was not considered.

Apart from the joint characteristics, another parameter that has a considerable effect on the structural response of a segmental tunnel lining is the ground–structure interaction. This interaction defines the boundary condition of the tunnel structure and it affects the response of the tunnel lining.

In numerical analyses, two main techniques are applied to model the ground–structure interaction. The first technique involves the use of discrete springs and is based on Winkler's theory, which focuses on the structural behavior of the segmental lining (Blom, 1999; Oreste, 2007). The second approach uses the full ground model using finite elements (Kasper and Meschke, 2004, 2006). Although heavy computational efforts are required, the second approach generally provides more accurate results.

Using the first method, Teachavorasinskun and Chub-Uppakarn (2010) conducted a numerical study using a finite element analysis program on the influence of joint rotational stiffness, the joint number and the ground subgrade modulus on the bending moment. However, the interaction between the ground and the tunnel lining was taken into account only with regard to a set of normal subgrade reaction springs, and not tangential ones. The external loads were imposed vertically and horizontally to simulate the action of the earth pressures in corresponding directions (the lateral earth pressure factor was put equal to 0.5 and the depth equal to 20 m).

As far as the second method is concerned, Hefny and Chua (2006) numerically studied the influence of the joint number, joint orientation, lateral earth pressure factor, and tunnel depth on the bending moment induced in a 6 m diameter segmental tunnel lining, using a finite element analysis program. In their analyses, the stiffness of the segmental joint was not considered. Arnau and Molins (2011a, 2011b) carried out a real scale test on an experimental tunnel section of the new Line 9 of the Barcelona underground metro system. The section was composed of 15 rings built using only steel fibers as the reinforcement. The contact between the longitudinal joints was modelled using unilateral interface elements located at one side of plastic packer elements. The in situ measurements and the results of the numerical simulation were similar in terms of displacements, joint closures and crack patterns.

This paper presents a 2D numerical analysis of the segmental tunnel lining behavior in which the effects of the joint stiffness, Young's modulus of the ground and the lateral earth pressure factor are taken into consideration using a finite difference element program. A bilinear model, in which the rotational stiffness characteristics are assumed, allows the joint behavior to be modeled in a more realistic way. The influence of certain characteristics including the rotational stiffness, the axial stiffness and the radial stiffness of longitudinal joints on the tunnel behavior, with respect to the effect of the packing material, is considered in detail. The presented model is here used for the parametric analyses of a shallow tunnel in conditions in which the ground loads increase in depth due to the effect of the gravity field. In addition, this model allows the complete interaction between the tunnel lining and the surrounding medium to be taken into account through the normal and tangential connections.

2. Numerical modeling

Fig. 1 shows a 2D numerical model which uses the plane–strain conditions. It has been used to quantify the behavior of a segmental tunnel lining. The whole tunnel is simulated, due to the arbitrary distribution of the joints along the tunnel wall boundary. Parameters from the Bologna–Florence high speed railway line tunnel project in Bologna have been adopted in this numerical modeling (Croce, 2011). This case is named the reference case.

It is assumed that the behavior of the tunnel structure is linear-elastic and that of the ground is governed by an elastic perfectly-plastic constitutive relation, which is based on the Mohr–Coulomb failure criterion. The properties are given in Table 1.

In this study, numerical simulations have been performed by means of the FLAC^{3D} finite difference element program (Itasca, 2009), which provides flexible features for the analyses of joint parameters. The volume under study is discretized into hexahedral zones. The tunnel segments are modeled using the embedded liner elements. These elements are used to model thin liners (based on the classical Kirchhoff plate theory) for which both normal-directed compressive/tensile interaction and shear-directed frictional interaction with the host medium occurs (Itasca, 2009). This kind of liner element provides two links on each node. The first link

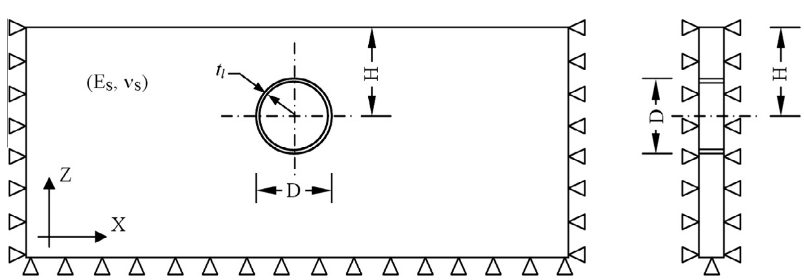

Fig. 1. The plane strain model under consideration.