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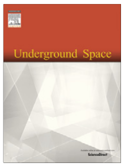

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A holistic approach for the investigation of lining response to mechanized tunneling induced construction loadings

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Abstract

Design methods for segmental tunnel linings used in mechanized tunnel constructions typically employ numerical bedded beam models and/or classical analytical solutions for the determination of structural forces (i.e. moments and shear and axial forces) and simple load spreading assumptions for the design of the reinforcement in joint areas. However efficient such methods may be, many physical details are often overlooked and/or oversimplified in the process of reducing the actual structure to a structural beam model, e.g. analytically derived loadings are employed, the grouting and ground reactions are reduced to a spring bedding, and the confinement due to grouting at the longitudinal joint is largely not considered in reinforcement design. Such a design process is not able to account for, or predict, the susceptibility of tunnel linings to often observed damages that, although they may not be structurally relevant, lead to serviceability or durability issues, such as crack development or chipping at the segment corners. Numerical methods, such as the Finite Element Method, provide an opportunity to model the segmental tunnel lining and its response to the entire TBM construction process and to explicitly model the crack development within individual segments using modern methods to model the discontinuities in structures. In this contribution, a holistic modeling procedure for the representation of the tunnel lining within the tunneling process is proposed and compared to traditional lining models. A 3D process oriented Finite Element model is used to calculate the predicted forces on the tunnel lining and the obtained results are compared with those generated by traditional methods. Subsequently, the predicted deformations are then transferred to a detailed segment model in which the nonlinear response of the segment at the longitudinal joint is modeled using an interface element based approach to simulate concrete cracking.

Keywords: Mechanized tunneling; Segmental tunnel linings; Finite element method

1. Introduction

The most commonly used structural models for determining structural ring forces in tunnel linings in modern tunnel engineering practice are numerical bedded beam models (FHWA, 2009; German Tunnelling Committee (DAUB), 2013; Städing, 2007). Analytical solutions to this problem, whether continuum based (Ahrens et al., 1982) or beam based (Schulze and Duddeck, 1964a), may also be used for this purpose, and provide a valuable reference point for the evaluation of obtained structural forces using other methods. Analytical models often used to generate a preliminary design concept (Blom, 2002). However, because pronounced simplifications are involved in numerical or analytical beam models, many common models neglect or are unable to account for certain design details, such as the allowable crack width in the lining segments.

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These simplifications made in the construction of structural models for tunnel linings occur primarily on two levels. First, the interactions between the lining and the surrounding structures are simplified. In bedded beam models (Schulze and Duddeck, 1964a), the structural interaction between the tunnel lining and the grout and soil is reduced to being represented by an elastic bedding, whereas in continuum models often only elastic ground deformations are considered (Ahrens et al., 1982). Loadings are typically derived from either undisturbed in-situ stresses, or from pre-existing analytical solutions. Secondly, the structure of the lining is simplified, as the lining and corresponding segments themselves become idealized as beam structures. Such an idealization produces a model which only yields stress resultants and deformations to be used as design parameters, rather than more precise local stresses and strains. Even though these parameters may be sufficient to determine the structural stability of the tunnel lining, other factors that may lead to serviceability or durability issues, such as local chipping or cracking of the segments, cannot be predicted or accounted for.

In this contribution a holistic multi-level method for the simulation of segmental tunnel segments that addresses the issues mentioned above is proposed. In order to accurately evaluate the interactions of the tunnel lining with the surrounding ground and structures,“ekate ”, a 3D process-oriented finite element (FE) simulation tool (Nagel et al., 2009) based on the FE code KRATOS (Dadvand et al., 2010) is used. This model explicitly accounts for the advancement and ring building process during the construction of a machine driven tunnel. It is therefore able to account for the effects of time-dependent processes, such as grout hardening, and how these influence the deformations and structural forces experienced by the tunnel lining. In order to evaluate the reliability of this model, the moments, axial forces, and radial deformations are compared to those derived from other structural models, i.e. an analytical continuum model, an analytical bedded beam model and a numerical beam-and-spring model, which are known to show different results due to varying underlying assumptions (Kämper et al., 2016; Smarslik et al., 2017; Zhao et al., 2017). In order to investigate the detailed response of the individual segments to radial tunnel loadings, the radial deformations resulting from the 3D simulation are applied to a detailed FE segment model in a displacement controlled loading process. Specifically, the segment response in ring direction is investigated. The segment model is constructed using a mesh in which non-zero thickness interface elements placed between standard geometrically linear finite elements (i.e. bulk elements) in order to account for cracking in the concrete segment, as per Zhan (2016). The geometry of the segment is explicitly modeled, and therefore the correct stress distribution and cracking response in the radial and circumferential directions are captured. This provides a crack width which may be used as a serviceability parameter for design.

Within the context of this contribution two goals are addressed. The aim is to firstly examine the validity of using a full scale 3D process oriented tunnel model for extracting the structural forces needed for tunnel lining design, and, secondly, to introduce a new holistic modeling concept in which the segment response to tunnel loadings is investigated on multiple simulation scales.

2. Commonly used analytical methods for the determination of lining forces and deformations

The first solutions to the tunnel lining problem were introduced in the early part of the 20th century. As a result, language barriers inhibited a great deal of communication between scientific communities (e.g. between english and german speakers). This problem continues to this day as, typically, german authors and english authors continue to favor referencing different sources, e. g. for the continuum solution, german speaking communities reference Ahrens et al. (1982), whereas english speaking communities tend to reference other sources, e.g. Wood (1975). Although the authors of this paper have attempted to include as many sources as possible, the sources given are (naturally) biased towards german-language literature, however, a good overview of german structural models for tunneling linings written in the english language is provided in Duddeck and Erdmann (1985).

The analytical models for determining lining forces are generally continuum models, e.g. Schmid (1926), Voellmy (1937), Wood (1975), Ahrens et al. (1982), and Einstein and Schwartz (1979), in which the tunnel lining (or lining like structure), is assumed to be bedded within an elastic domain, but unidimensional beam models, e.g. Schulze and Duddeck (1964a), Windels (1967), and Hain and Horst (1970), in which the differential equations for a 2D bedded beam are explicitly solved, exist as well. The different methods for representing the lining and ground, including methods to account for the lack of support at the tunnel crown, are depicted in Fig. 1.

Continuum solutions for the tunnel lining problem, derived from the theory of elasticity, were first proposed by Schmid (1926) and Voellmy (1937) and later models are modifications thereof. Both of these solutions, however, rely on significant simplifications. In Schmid (1926), the lining is assumed to be very thick and therefore very stiff, and in Voellmy (1937) the tangential transfer of forces between the lining and ground is neglected. A full solution to the problem was formulated by Ahrens et al. (1982). This solution includes the tangential contact forces between the lining and ground and includes modifications to the solution to take into account the weak bedding at the crown of the tunnel for shallow tunnels (i.e. if the depth of the tunnel is less than two times its diameter). Additional modifications to account for segmentation of the lining have been proposed in Blom (2002), and a method based on discontinuous slender arches has been proposed in Zhang et al. (2017).

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