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On the importance of advanced constitutive models in finite element simulations of deep tunnel advance

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ABSTRACT

In a numerical study of deep tunneling, considering a stretch of the Brenner Base Tunnel, the influence of the employed constitutive models for rock mass and shotcrete on the predicted mechanical behavior of a tunnel structure is investigated. Departing from the standard numerical model, commonly employed in engineering practice, the complexity of both the constitutive models and the securing measures is increased gradually. The respective predicted responses of the tunnel structure are assessed and they are compared with available measurement data from the tunnel construction site. The numerical results, computed on the basis of the advanced material models, provide important insights into potential failure mechanisms of a deep tunnel structure.

1. Introduction

Together with advanced exploration and monitoring techniques, numerical simulations are valuable tools for the design and construction of tunnels. In tunnels with high overburden, the high prevailing geostatic stresses are strongly redistributed during the excavation process, leading to structural changes frequently inducing damage of the rock mass (Yang et al., 2003; Egger, 2000). To prevent a tunnel structure from severe damage or collapse effective flexible securing measures, like rock anchors, steel arches and a primary shotcrete lining, can be installed. Hence, in numerical simulations of tunnel advance appropriate constitutive models for both the rock mass and the installed securing elements, which are able to represent the main features of material behavior, are of special importance.

In standard numerical models of tunneling, based on the Finite Element Method (FEM) within the continuum approach for representing the rock mass, commonly a linear-elastic perfectly-plastic constitutive model for rock mass and a linear-elastic material model for shotcrete are employed in engineering practice (Negro and De Queiroz, 2000). Typically, the former is characterized by a Hoek and Brown (1980) or Mohr-Coulomb type failure criterion and a non-associated flow rule, whereas for the latter an artificially low Young's modulus of shotcrete is applied for considering the time-dependent material behavior of shotcrete at least in an approximate manner (Pöttler, 1990). However, the simplified assumptions inherent in these models like neglecting the nonlinear material behavior in predominantly hydrostatic compression, ignoring permanent strains in the pre-peak region of the stress-strain curves and neglecting softening beyond the peak of the stress-strain curves, are in contrast to the experimentally observed behavior of rock and shotcrete. In addition, for the latter the temporal evolution of stiffness and strength as well as shrinkage and creep play an important role.

To overcome the mentioned shortcomings of the linear-elastic perfectly-plastic material models for rock, only few constitutive models have been proposed so far, which at least address some of these effects (Dragon and Mroz, 1979; Kawamoto et al., 1988; Lade and Kim, 1995; Swoboda et al., 1998; Pourhosseini and Shabanimashcool, 2014). Within this context, a damage plasticity model for rock was proposed by authors of the present study in Unteregger et al. (2015), herein denoted as the RDP (Rock Damage Plasticity) model. In addition to strain hardening it represents strain softening behavior, which may have a significant impact on the stability of a tunnel profile during tunnel advance due to potential localization of deformation into shear bands.

In the past, the formation of shear bands was studied in the context of borehole breakout phenomena occurring in petroleum engineering, reported in Vardoulakis et al. (1988), Crook et al. (2003), and Zervos et al. (1998). Some researchers considered softening behavior of rock as a material property, e.g., in the vicinity of the excavation of a borehole (Alonso et al., 2003; Lee and Pietruszczak, 2008), leading to axisymmetric distributions of stresses and deformations and, thus, precluding the formation of shear bands. However, strain softening is rather a structural phenomenon with the strains localizing into narrow zones. In this context, a suitable regularization technique is needed for obtaining

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objective numerical results upon mesh refinement. For regularizing the softening behavior of rock or soil during borehole excavation, the crack band approach (Crook et al., 2003), the strong discontinuity approach (Callari, 2004; Callari and Armero, 2002; Hauseux et al., 2016), the Cosserat continuum (Papanastasiou and Vardoulakis, 1992), or gradient-enhanced models (Varas et al., 2005) were employed. In the hydraulic fracturing context, the extended finite element method (Weber et al., 2013; Bendezu et al., 2017), the phantom-node method (Wang, 2015), or phase-field models (Wilson and Landis, 2016) were applied. Varas et al. (2005) investigated the effect of strain localization in rock mass on the ground response due to unloading during a circular excavation process without considering a supporting structure. Strain localization in the context of the excavation of a shallow tunnel in soil was analyzed in Schuller and Schweiger (2002) using the multi-laminate framework assuming cohesive-frictional softening behavior for the soil and a linear-elastic material model for shotcrete. In Salehnia et al. (2015), the evolution of strain localization around a gallery was studied by a coupled hydro-mechanical analysis, also employing a linear-elastic model for the concrete lining.

Compared to linear-elastic shotcrete models with an artificially low Young's modulus for shotcrete (Pöttler, 1990), which are commonly employed in engineering practice, advanced shotcrete models basically provide time-dependent stress-strain relations, like the shotcrete models by Meschke (1996) and Schädlich and Schweiger (2014) and the recently proposed shotcrete damage plasticity (SCDP) model by authors of this contribution (Neuner et al., 2017). Common features of the latter models are the representation of the temporal evolution of material stiffness and strength in terms of the shotcrete age, the application of a yield surface for delimiting the domain of elastic material behavior and consideration of hardening and/or softening material behavior, the latter being regularized within the framework of the FEM by means of the specific fracture energy and a characteristic element length. Main differences of the advanced shotcrete models are related to the applied type of the flow rule and to the employed theory for modeling creep. Their performance was compared in Neuner et al. (2017) on the basis of an axisymmetric benchmark example of deep tunnel advance.

In most of the case studies related to numerical simulations of tunneling, the constitutive behavior of rock mass and shotcrete is simplified by means of linear-elastic perfectly-plastic models, or more advanced constitutive models are only employed for one of them, i.e., either the rock mass or the shotcrete lining. However, for the numerical analysis of potential collapse of a tunnel structure, advanced constitutive models for both materials are inevitable. To the authors' best knowledge, the application of advanced constitutive models for the surrounding rock mass, including softening, as well as for the shotcrete, including time-dependent effects and softening material behavior, has not been presented so far. This motivates the present study by addressing the influence of such advanced models on the predicted behavior of a deep tunnel structure of the Brenner Base Tunnel. Departing from the standard numerical model, commonly employed in engineering practice, which is characterized by a linear-elastic perfectly-plastic constitutive model for the rock mass and a linear-elastic shotcrete model, the complexity of both the constitutive models and the securing measures is increased gradually. The respective predicted responses of the tunnel structure are assessed and they are compared with available measurement data from a tunnel construction site.

The paper is organized as follows: At first, in Section 2 the employed constitutive models for rock mass and shotcrete are summarized briefly. Subsequently, in Section 3 the numerical study is outlined and in Section 4 the initial boundary value problem of deep tunnel advance together with the excavation and securing procedure is described. The numerical results are presented and discussed in Sections 5–7 and conclusions from the presented results are drawn in Section 8.

2. Constitutive models

In this section, the constitutive models for rock and shotcrete, applied in the numerical simulations, are summarized briefly. All constitutive models were implemented by the authors of the present contribution into the finite element package Abaqus/Standard v6.14-1 (Abaqus, 2015) by the provided user material interface (UMAT). The respective rate equations were integrated using the Backward Euler scheme within the return mapping algorithm (Simo and Hughes, 2006) and the system of nonlinear equations is solved by Newton's method.

2.1. Linear-elastic perfectly-plastic model for rock mass

A linear-elastic perfectly-plastic material model for rock mass, referred to in the following as rock plasticity (RP) model, is considered as a reference model and as a representative of elastic-plastic models commonly employed in engineering practice. The stress–strain relation is expressed as $\boldsymbol{\sigma} = \mathbb{C}\colon(\boldsymbol{\varepsilon}-\boldsymbol{\varepsilon}^{\mathrm{p}})$, in which $\boldsymbol{\sigma}$ is the Cauchy stress tensor with tensile stresses defined as positive quantities, $\mathbb{C}$ the fourth order elastic stiffness tensor, $\boldsymbol{\varepsilon}$ the total strain tensor and $\boldsymbol{\varepsilon}^{\mathrm{p}}$ the plastic strain tensor.

To delimit the elastic domain, the Hoek-Brown yield criterion (Hoek and Brown, 1980) in the smooth version proposed by Menétrey and Willam (1995) is employed (cf. Fig. 1a). It is expressed in terms of the Haigh-Westergaard coordinates of the stress tensor, i.e., the mean stress σ_{m}, the deviatoric radius ρ and the Lode angle in the deviatoric plane θ, as

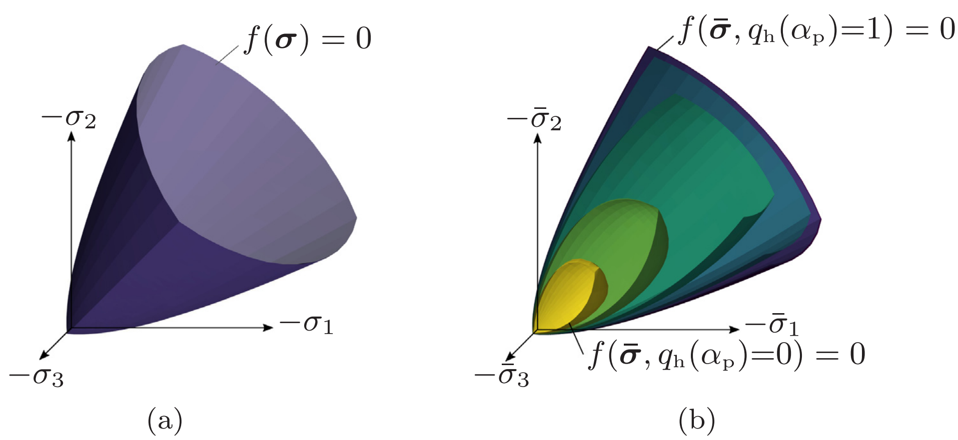

Fig. 1. (a) Yield surface of the smoothed Hoek-Brown criterion and (b) cut through the evolving yield surface of the RDP model during strain hardening in the principal stress space.