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Calibration and performance of two different constitutive models for rockfill materials

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Abstract

In this paper, two different concepts for the constitutive modeling of the mechanical behavior of creep-sensitive rockfill materials are presented. Specifically, the performance of an extended generalized plasticity model proposed by Wang is compared with a simplified version of the hypoplastic constitutive model for weathered rockfill materials proposed by Bauer. Both models can reflect the influence of the mean stress on the incremental stiffness, the peak friction angle, and the dilatancy angle. The so-called *solid hardness* defined for a continuum description and originally introduced by Bauer is embedded in both models. Hydrochemical, thermal, and mechanical weathering are usually caused by environmental changes and are taken into account in a phenomenological description with an irreversible and time-dependent degradation of the solid hardness. A degradation of the solid hardness is usually accompanied by creep deformation of the stressed rockfill material. It is shown that appropriate modeling of creep deformation requires at least a unified description of the interaction between the time-dependent process of degradation of the solid hardness and the stress state. In this context, the solid hardness can be understood as a key parameter for describing the evolution of the state of weathering of the rockfill material. Particular attention is also paid to the necessary procedure for determining the constitutive constants of the two different constitutive models. Finally, the performance of the two different constitutive models is demonstrated by comparing the results obtained from numerical simulations with experimental data from the creep-sensitive rockfill material.

Keywords: Rockfill material; Creep; Generalized plasticity; Hypoplasticity; Constitutive model

1. Introduction

The adaptation of the parameters of a constitutive model to experimental data is called calibration, and from a mathematical point of view it is an inverse problem. The existence and uniqueness of a solution are of fundamental importance to the practical application of a material model. For more sophisticated constitutive models, a higher number of parameters are usually involved in the constitutive equations in a nonlinear manner. Without knowledge of the physical scope of the values of the parameters, the application of standard optimization procedures can fail. Therefore, the formulation of appropriate functions for the calibration procedure plays an important role (e.g., Bauer, 1996). The type and number of experiments necessary for calibration can also be determined according to the calibration equation derived from the constitutive model. It is worth noting that the application of a particular material model is not independent of the question as to whether the experiments necessary for the calibration can be carried out. This is not only a question of the equipment of the laboratory, but also a question of uncertainties of specimen

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sampling, the pre-compaction of the material at the construction site, financial aspects, and time can play a role as well. For a more refined constitutive modeling of microstructure effects, the task of calibration can be rather complex and the number of necessary experiments is usually much higher than for simple material models. If sufficient data are not available, some parameters have to be estimated or a simplified constitutive model has to be used instead. In order to evaluate the performance and physical limitation of a material model under consideration, the values of the constitutive parameters obtained should also be controlled by comparing the results of the numerical simulation of element tests with the corresponding laboratory experiments and, if available, with data from field tests.

The present paper focuses on constitutive modeling and calibration of coarse-grained and weathered rockfill materials, which can show pronounced density, pressure, and rate-dependent mechanical properties. In particular, weathered and soft rockfill materials can exhibit pronounced creep deformations, which can be explained by the process of progressive weathering accompanied by grain crushing and plastification of interparticle contacts of the stressed rockfill material (Alonso and Cardoso, 2010). As a consequence of the degradation of the solid hardness, delayed deformations can be observed even when the stress state is kept constant (Oldecop and Alonso, 2007). In rockfill dams, post-construction settlements have been recorded over decades (Sowers et al., 1965; Scherard and Cooke, 1987; Brauns et al., 1980; Soriano and Sanchez, 1999; Naylor et al., 1997; Wang, 2000; Zhou et al., 2007, 2011; Yin, 2009). The process of degradation of the solid hardness is mainly influenced by the history of mechanical, thermal, and chemical weathering, the mineralogical composition of the grains, the micro-crack distribution within the particles, the hydro-chemical reaction of the pore fluid at crack tips, and the local stress concentrations (e.g., Brauns et al., 1980; Li, 1988; Alonso and Oldecop, 2000; Oldecop and Alonso, 2001, 2007; Fang, 2005; Ovalle et al., 2013, 2015). Various constitutive models for simulating the mechanical behavior of rockfill materials have been developed based on the framework of continuum theories such as nonlinear elasticity, elastoplasticity, generalized plasticity, and hypoplasticity (e.g., Duncan and Chang, 1970; Justo and Durand, 2000; Oldecop and Alonso, 2001, 2007; Xiao et al., 2011; Zhang et al., 2007; Bauer, 2009; Sun and Huang, 2009; Bauer et al., 2012; Wang et al., 2014; Fu et al., 2014).

The aim of the present paper is to compare the performance of the extended generalized plasticity (EGP) model proposed by Wang et al. (2014) with a simplified hypoplastic model for rockfill materials, which is based on the original model by Bauer (2009). Both models can reflect the influence of the mean stress on the incremental stiffness, the peak friction angle, and the dilatancy angle. Furthermore, in both models, the so-called *solid hardness* is considered as a key parameter for describing the state of weathering and the time-dependent degradation of the rockfill material. In contrast to the hardness of a single grain, the solid hardness introduced in the constitutive models is defined for an assembly of rockfill particles under isotropic compression. The solid hardness was originally introduced by Bauer (1996) as a material constant for unweathered granular materials and then extended by Bauer in 2009 to a more general concept for modeling creep and stress relaxation of coarse-grained, weathered, and moisture-sensitive rockfill materials. The suitability of the solid hardness as a key parameter for reflecting the compression behavior for a wide range of pressures was also verified by discrete element simulations, e.g., for unbreakable granular materials (Oquendo et al., 2009), for an assembly of two-dimensional (2-D) breakable discs (Fu et al., 2012), and for arbitrarily shaped three-dimensional (3-D) particles (Laufer, 2015). While in the original generalized plasticity model the isotropic compression curve in the semi-logarithmic representation is described by a constant inclination, the more consistent compression law described by Bauer (1996) was adopted into the concept of generalized plasticity for modeling rockfill materials by Chen et al. (2011). Although the solid hardness is a key parameter in both models, the functions proposed for modeling the degradation of the solid hardness are different.

The paper is organized as follows: In section 2, the EGP model proposed by Wang et al. (2014) is outlined for the case of monotonic loading under axisymmetric stress conditions. The model is calibrated based on the experimental results from Fu and Ling (2009) with coarse-grained broken sandstone, which was also used in the Cihaxia concrete face rockfill dam. The results obtained from numerical simulations of triaxial compression tests under different lateral stress states and creep tests under different deviatoric stress states are compared by means of experiments. In section 3, the hypoplastic constitutive equations relevant to axisymmetric stress paths are presented. Calibration and numerical simulations are outlined for the same material and stress paths as those carried out for the generalized plasticity model. The performance of the two different models is compared and discussed in section 4. Finally, conclusions are given in section 5.

Throughout the paper, bold lowercase italic letters denote vectors, bold uppercase italic and Greek letters denote second-order tensors, and bold uppercase italic letters with ~ above the letters denote fourth-order tensors. Indices on vector and tensor components refer to an orthonormal Cartesian basis $\mathbf{e}_i$ ($i = 1, 2, 3$). Operations and symbols are defined as follows: $\boldsymbol{A}\otimes\boldsymbol{B} = A_{ij}B_{kl}\mathbf{e}_i\otimes\mathbf{e}_j\otimes\mathbf{e}_k\otimes\mathbf{e}_l$, $\boldsymbol{A}\boldsymbol{B} = A_{ik}B_{kj}\mathbf{e}_i\otimes\mathbf{e}_j$, $\tilde{\boldsymbol{A}}:\boldsymbol{B} = A_{ijkl}B_{kl}\mathbf{e}_i\otimes\mathbf{e}_j$, $\boldsymbol{A}:\boldsymbol{B} = A_{ij}B_{ij}$, and $\mathrm{tr}\boldsymbol{A} = A_{ii}$. Here, the summation convention over repeated indices is employed. A superposed circle denotes an objective time derivative, e.g., $\overset{\circ}{\boldsymbol{A}}$, and a superposed dot denotes the material time derivative, e.g., $\dot{\boldsymbol{A}} = \mathrm{d}\boldsymbol{A}/\mathrm{d}t$. For the EGP model in section 2, the sign convention in soil mechanics is adopted, i.e., compressive stress and strain are positive. On the other hand, for the hypoplastic model in section 3 compressive stresses and strains and their rates are taken as negative as in the sign convention of rational continuum mechanics. Moreover, in hypoplasticity, logarithmic strains are used, but in all figures the numerical results are presented in engineering strains.