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Verification of a laboratory-based dilation model for in situ conditions using continuum models

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ABSTRACT

With respect to constitutive models for continuum modeling applications, the post-yield domain remains the area of greatest uncertainty. Recent studies based on laboratory testing have led to the development of a number of models for brittle rock dilation, which account for both the plastic shear strain and confining stress dependencies of this phenomenon. Although these models are useful in providing an improved understanding of how dilatancy evolves during a compression test, there has been relatively little work performed examining their validity for modeling brittle rock yield in situ. In this study, different constitutive models for rock dilation are reviewed and then tested, in the context of a number of case studies, using a continuum finite-difference approach (FLAC). The uncertainty associated with the modeling of brittle fracture localization is addressed, and the overall ability of mobilized dilation models to replicate in situ deformation measurements and yield patterns is evaluated.

1. Introduction

Recently, numerical methods have become increasingly popular tools to analyze rock mass behavior. Computer programs which represent rock masses as continua and discontinua can be used to predict loads and displacements in rock structures and support or reinforcement systems or to verify hypotheses about observed behavior (back analysis). Although these tools are no longer restricted to research applications, models used in the study of civil and mining geotechnical structures are often limited in their complexity (i.e. elastic models for stress prediction). This is largely due to the questions about the validity of more complex models. In fact, the use of inadequate material models is one of the largest limiting factors in numerical analyses (Lade, 1993; Carter et al., 2008).

Continuum models are more commonly used than discontinuum models in rock engineering (even when they are not necessarily appropriate). The existing experience base in the geotechnical community with respect to modeling rock masses as continua is a major driver of this phenomenon (Bobet, 2010). Although rapidly evolving discontinuum and hybrid continuum/discontinuum modeling tools provide a valuable alternative to continuum models for some applications (see Jing (2003) and Bobet (2010)), it is important to continue to improve constitutive models for use in continuum models given their relative accessibility and ease of use.

One area of particular historical deficiency in terms of constitutive models for rocks and rock masses is their post-yield volumetric response to continued deformation. Correspondingly, the tendency of rock masses to dilate following yield has been a topic of increased research recently. Understanding this phenomenon may be integral in allowing for the accurate prediction of yield and ground movement; this is particularly true of more brittle rocks, which tend to dilate most significantly (Hoek and Brown, 1997).

In this study, different approaches for modeling dilative behavior are reviewed, and then used in a back analysis of extensometer data obtained from the Donkin-Morien Tunnel (Nova Scotia, Canada). One dilation model in particular is then applied to further case studies to illustrate its ability to successfully replicate displacements measured in situ.

2. Models for rock dilation

The tendency of rocks to expand under compression was first shown to be a true material property (rather than an influence of the testing system) by Cook (1970). Although the underlying mechanisms for this phenomenon are fundamentally brittle (see Brace et al. (1966) and Jaeger and Cook (1969)), different formulations based on plasticity theory have been developed over the

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years in an attempt to properly capture the macroscopic stress–strain behavior of rocks.

For a Mohr–Coulomb solid, the ratios of plastic strain components are controlled by the dilation angle, ψ. This parameter uniquely defines the stress gradient of the plastic potential function, which is in turn directly proportional to the plastic strain tensor for a material at yield. The connection to volumetric strain can be seen through the general definition of the dilation angle in terms of plastic strain increments (Vermeer and de Borst, 1984):

$$\sin\psi = \frac{\dot{\varepsilon}_{\mathrm{v}}^{\mathrm{p}}}{-2\dot{\varepsilon}_1^{\mathrm{p}} + \dot{\varepsilon}_{\mathrm{v}}^{\mathrm{p}}} \tag{1}$$

or, equivalently,

$$\dot{\varepsilon}_{\mathrm{v}}^{\mathrm{p}} = \frac{2\dot{\varepsilon}_1^{\mathrm{p}} \sin\psi}{\sin\psi - 1} \tag{2}$$

where $\dot{\varepsilon}_{\mathrm{v}}^{\mathrm{p}}$ and $\dot{\varepsilon}_1^{\mathrm{p}}$ are the volumetric and major principal plastic strain increments, respectively.

Early work on the post-yield deformation of plastic solids led to the concept of an associated flow, which requires the plastic potential surface to be coincident with the yield surface in stress space (in this case, the friction angle, ϕ, is equal to ψ). In this case, the plastic dissipation (energy loss) associated with post-yield deformation is zero. As the study of soil and rock plasticity progressed, it was noted by many that the adoption of an associated flow rule was inappropriate for granular materials which dissipate energy through frictional mechanisms (Roscoe, 1970; Price and Farmer, 1979; Vermeer and de Borst, 1984; Chandler, 1985). More recently, a number of authors have noted that for those materials, it is necessary not only to use a non-associated flow rule, but also to use a dilation angle which depends on confining stress and is mobilized as damage accumulates in rock; note that “damage” is commonly quantified in terms of the maximum plastic shear strain, γ^{p}, taken as the difference between the major and minor principal plastic strain components.

2.1. *Mobilized dilation models*

In the study of soil mechanics, there were early attempts to tie the mobilization of the dilation angle to the mobilization of friction over the course of deformation (see Rowe (1971)). Detournay (1986) extended this mobilized dilation concept to rock masses based on theoretical considerations, although his model for the dilation angle was independent of any change in the friction angle. Work by Ofoegbu and Curran (1992) represents one of the first mobilized dilation models which was developed based on the study of laboratory test data and accounts for both the confining stress and accumulated strain dependencies of rock dilatancy. Cundall et al. (2003) also proposed a model for post-yield dilatancy, although theirs was based solely on theoretical considerations.

The model proposed by Alejano and Alonso (2005) represented a major advancement in the study of rock dilatancy, both in that it is shown to fit data from a wide number of lithologies, and in that it requires only one parameter to define the dilation angle for all (σ_3, γ^{p}) conditions (σ_3 is the minor principal stress). In this model, the initial dilation angle following yield is taken to be the peak dilation angle, which is a function of the confining stress. As deformation continues, the dilation angle gradually decays from its peak value. Typical volumetric strain–axial strain plots obtained from laboratory compression tests are shown in Fig. 1, both for a material following the Alejano and Alonso (2005) model for dilation (AA), and for a material with a constant dilation angle.

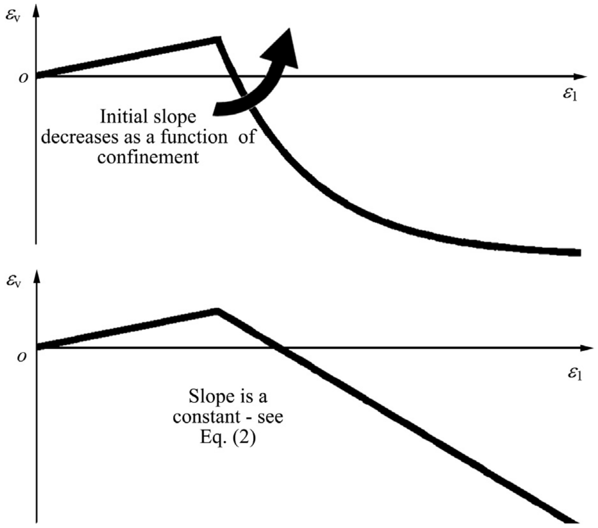

Fig. 1. Volumetric strain–axial strain curves for the Alejano and Alonso (2005) dilation angle model (top) and a constant dilation angle (bottom) (after Walton and Diederichs (2013)).

Based on a statistical analysis of in situ displacements predicted using the AA model for dilation and a variety of strength and stiffness parameters, Walton and Diederichs (2014) concluded that in many cases (particularly for near hydrostatic stresses), results obtained using the AA model can be approximated using a constant dilation angle. For preliminary models, they suggested a constant dilation angle value of

$$\psi = \phi_{\mathrm{Peak}}(\sigma_{\mathrm{crm}}/\sigma_{\mathrm{e\_t}} - 0.1) \tag{3}$$

where σ_{crm} is the rock mass strength at unconfined conditions, and $\sigma_{\mathrm{e\_t}}$ is the elastic tangential wall stress, which, for a circular tunnel, has a maximum value of

$$\sigma_{\mathrm{e\_t(max)}} = 3\sigma_1 - \sigma_3 \tag{4}$$

where σ_1 is the major principal stress.

The AA model has two major limitations. The first is that it was developed based solely on a selection of sedimentary rock data, and it has since been shown that the confinement-dependency of the peak dilation angle as predicted by their model is too large for crystalline rocks (Zhao and Cai, 2010; Arzua and Alejano, 2013; Walton and Diederichs, submitted for publication). The second is that the model is based on the assumption that yield in situ is coincident with peak strength as observed in laboratory tests. Although this assumption may be true for certain weaker rock masses, for rock masses which deform through brittle fracturing processes, a different definition of yield must be used (Martin, 1997; Diederichs, 1999; Diederichs and Martin, 2010).

In contrast to that of Alejano and Alonso (2005), the dilation angle model of Zhao and Cai (2010) defines the onset of unstable cracking (CD) as yield (which is consistent with the conclusions of Diederichs and Martin (2010) for brittle rocks). The model of Walton and Diederichs (submitted for publication) (WD) uses this same definition for yield, and obtains similar model fit qualities using a lower overall number of parameters.

Like the Zhao and Cai (2010) model, the WD model begins with a dilation angle of 0°, then mobilizes dilation to a peak value before initiating a gradual decay as predicted by the AA model. Although some dilatancy caused by crack opening can be observed, it is the dilatancy which mobilizes due to shear deformation of cracks that