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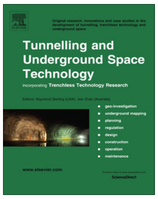

A mine shaft case study on the accurate prediction of yield and displacements in stressed ground using lab-derived material properties

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ABSTRACT

Continuum models provide a useful tool for the prediction of stress re-distribution due to excavation and induced yielding, and are used as a key analysis tool in the design of many underground excavations. Recent developments in the study of rock strength and post-yield behaviour have played a key role in improving our understanding of how plastic constitutive models can also be used to practically replicate observed phenomena in brittle rocks. In particular, new models for rock dilatancy can help to improve the applicability of plastic constitutive models as a predictive tool for excavation design. In this study, laboratory data for a heterogeneous, brittle, conglomerate unit from a mine shaft has been analysed. Using parameters from this analysis, brittle strength and dilatancy models have been implemented in a finite-difference code to predict not only stress re-distribution and yield around the shaft, but also to obtain realistic displacement values. Comparison of the modelling results to displacements measured using borehole extensometers show that the constitutive model and lab-derived parameters used were effective in predicting the rockmass behaviour. Parameters were further optimized through back analysis. One interesting finding of this analysis is that the in-situ rockmass dilation decay rate (as a function of plastic strain) appears to be faster than estimated based on laboratory data, which may be indicative of the influence of rockmass-scale natural fractures and other geological structures on the dilation decay process. It also appears possible to model the in-situ dilation decay rate using a single parameter, instead of separate parameters for unconfined and confined conditions. To conclude the study, more numerical results obtained using alternative dilatancy models are presented to illustrate the problem of non-uniqueness in plasticity back analyses.

1. Introduction

In the field of rock mechanics, numerical models have seen increasing use in recent years. Sophisticated discontinuum and hybrid continuum/discontinuum codes have shown significant promise in replicating observed behaviours in rocks and rockmasses (Diederichs, 2003; Eberhardt et al., 2004; Cai, 2008; Elmo and Stead, 2009; Mahabadi et al., 2010). Still, in cases where there is no significant influence of discrete structures on the failure mode of a rockmass, continuum models can provide useful information about stress and strain distributions induced by various loading conditions (Jing, 2003; Hoek, 2007; Diederichs, 2007). Because of their relative simplicity and ease of implementation, these models are still used in practical engineering analyses today.

For excavations in stressed ground, elastic continuum models can provide useful information about stress re-distribution and highlight potentially problematic areas. 2D and 3D elastic models produced using various approaches (such as the Boundary Element Method (BEM), Finite Element Method (FEM), and Finite Difference Method (FDM)) are commonly used in preliminary investigations for the design of underground works (Jing and Hudson, 2002). In the realm of continuum models, plasticity theory provides a practical alternative to linear elastic behaviour.

Numerically defining the behaviour of a rock or rockmass in a plasticity context requires the definition of three distinct components: (1) a stress/strain relation for elastic conditions; (2) a yield criterion which establishes which stress states correspond to elastic conditions, which correspond to plastic conditions, and which cannot be sustained by the material of interest; (3) a stress/strain relation for plastic conditions (Lubliner, 1990). Broadly speaking, our understanding of the last component is poorer than that of the first two. This is partly due to the increasing behavioural

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complexity that is encountered at larger strains (i.e. during/past yield) and also to an increasing sensitivity of the observed behaviour to the system's boundary conditions (Diederichs, 2003; Diederichs et al., 2004).

Much research was conducted in the 1990s into the accurate prediction of the yield of rocks and rockmasses. Work by Hoek et al. (1998, 2002) and Marinos and Hoek (2000) focussed on the strength of rockmasses where deformation is controlled by shear slip along pervasive pre-existing structures. In parallel work by Martin and Chandler (1994), Martin (1997), and Diederichs (1999) provided increased insight into the mechanisms underlying the fracture and yield of intact rock and sparsely fractured rockmasses. Since then, the cohesion-weakening–friction-strengthening (CWFS) and damage-initiation-spalling-limit (DISL) strength models for intact rock have been shown to accurately represent rock yield observed in highly stressed excavations (Hajiabdolmajid et al., 2002; Diederichs, 2007; Edelbro, 2009; Zhao et al., 2010).

With respect to the post-yield stress/strain relationship for rocks, recent developments have resulted in a number of alternative models. In particular, many of these models focus on alternative formulations for the dilation angle, ψ, which uniquely controls post-yield deformation in Mohr–Coulomb plasticity (Hill, 1950). Based on work focussed primarily on soils and rocks under significant confinement, Vermeer and de Borst (1984) suggested that the use of a constant dilation angle less than the friction angle is appropriate for general use. Since then, Detournay (1986) and Cundall et al. (2003) have proposed models accounting for the dependencies of post-yield dilatancy on accumulated damage and confining stress, respectively. Alejano and Alonso (2005) proposed a model for strain-weakening rocks which accounts for both of these factors, and Walton and Diederichs (2014) showed that for approximately circular excavations under approximately hydrostatic stresses, a constant dilation angle can provide results which approximate those obtained using this model. Zhao and Cai (2010) proposed a model for brittle rocks, and demonstrated its ability to replicate observed displacements in-situ using a back analysis (Zhao et al., 2010). Walton and Diederichs (2015) have since developed an alternative model for brittle rocks, which requires a smaller number of parameters to define (hereafter referred to as the "W–D model").

Post-yield dilation of rocks can control the evolution of yield zones in numerical models, and also directly controls the equilibrium displacements obtained. As such, it is of great importance that models for rock dilation are properly validated against in-situ data. Once a methodology for modelling brittle rock failure in a plasticity framework is formalized, it can serve as a useful tool for the design of underground works and support systems within a wider design program.

In this study, strength and post-yield dilatancy models from the literature are used in a continuum model to obtain rockmass yield patterns and displacements around a mine shaft (10 m diameter) in stressed ground. By using material parameters derived from standard uniaxial and triaxial compression tests, the authors hope to demonstrate the capability of existing characterization and modelling capabilities with respect to predicting in-situ rockmass behaviour. It should be noted that all of the data used in this study was collected as a part of normal mining operations prior to any research considerations, meaning that the procedure used could be easily applied to practical problems.

2. Rock and rockmass data

In the area of the mine shaft being modelled, the rock type is a matrix supported conglomerate, which has a propylitic alteration. The clasts vary in shape from subangular to rounded, and are commonly 1–3 cm large (although they can be as large as 10 cm in diameter in some cases). They are derived from a number of different primary lithologies, including feldspar porphyry, diabase, quartzite, and limestone. As can be seen in Fig. 1, this unit is highly variable.

2.1. Geotechnical properties

As would be expected from an examination of Fig. 1, the geotechnical properties of the conglomerate unit are highly variable. This is particularly true at low confining stresses, where failure is dominated by extensile cracking; in this case, the locations of particularly strong/weak clasts and orientations of veins can have a significant influence on the stress/strain behaviour of a lab sample (Lan et al., 2010; Ghazvinian et al., 2013). What must be considered is that although the sample scale heterogeneities are large enough to result in significant variability in the data, the overall average behaviour observed in the lab should still be relevant to the behaviour of a rockmass. This is because anomalously strong/weak heterogeneities at the cm-scale are not expected to govern the material behaviour at the excavation scale.

With respect to the Young's modulus (see Fig. 2), a confined value of ~60 GPa appears reasonable, although the stiffness at lower confinement is expected to be significantly lower (Arzua and Alejano, 2013; Walton et al., 2014a). For lower confining stresses expected near an excavation (i.e. $\sigma_3 < 10$ MPa), a value between 40 GPa and 50 GPa may be more representative. The Poisson's ratio is relatively consistent, with a mean value near 0.2–0.25 for most confining stresses, with greater variability observed at low confinement.

The strength properties of the conglomerate were determined using least-squares linear regression (Mohr–Coulomb model) and least-squares regression with a Hoek–Brown model. The Mohr–Coulomb parameters are $c = 18.5$ MPa and $\phi = 50°$, and the Hoek–Brown parameters are UCS = 94.7 MPa and $m_i = 24.8$ (see Fig. 2).

Given the relatively high value of m_i for the conglomerate, as well as the relatively high GSI value (discussed below), it was

Fig. 1. Examples of two different end-members of conglomerate grain structure in laboratory testing samples.