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Generic strength model for dry jointed rock masses

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A R T I C L E I N F O

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A new nonlinear thermo-mechanical model for heavily jointed rock masses is presented. The model describes poroelasticity, shear-enhanced compaction and brittle–ductile transition in dry porous rocks. The key input parameters of the model, such as elastic moduli, tensile and compressive strength are expressed as functions of the reference porosity of the rock. These functions are based on empirical data for limestones and sandstones and assume that the medium is isotropic. The effect of joints is modeled by scaling down the key model parameters. The scaling rules are found with the help of explicit numerical modeling of randomly jointed media.

1. Introduction

Modeling thermo-mechanical response of jointed rock masses is of practical importance for rock engineering, (e.g., excavation of tunnels and caverns), petroleum engineering (e.g., oil and gas production), civil and defence engineering (e.g., structural integrity assessment and penetration resistance for deeply buried targets), and astrophysics (e.g., asteroid and comet impacts). Due to the heterogeneous nature of rock materials it is a challenge to model mechanical response even for lab-scale rock samples. Rocks exhibit strongly nonlinear behavior, anisotropy and rate dependence. Over the years numerous models have been developed describing experimental data on triaxial compression and extension for various porous rocks (Roscoe and Burland, 1968; Schwer and Murray, 1994; Fossum and Brannon, 2004; Shao and Henry, 1991; Xie and Shao, 2006; Shao et al., 2006; Papamichos, 1999; Hashiguchi and Mase, 2007). Most of these models use incremental hypoelasticity and an associative flow rule applied on a cap-like yield surface. Very often stress return algorithms are implicit and require special care to avoid instabilities (Crouch and Tahar, 2000; Hofstetter et al., 1993). Despite the fact that some of these models have been very successful in matching quasistatic triaxial tests, they are not easily extended to high pressure regimes, where material can undergo phase transitions,

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melting and chemical transformations. Also, implicit update algorithms used in many models make them impractical for large-scale calculations.

The model presented in this paper assumes nonlinear isotropic material response. It is hyperelastic in the sense that the Cauchy stress can be expressed using derivatives of the Helmholtz free energy. The model uses an explicit algorithm to advance evolution equations for history dependent variables such as porosity, hardening parameter and damage in a way that is consistent with the yield surface. The stress state is then reconstructed as a sum of the volumetric stress, found using equations of state (EOS), and the deviatoric stress proportional to the elastic distortional deformation tensor (Rubin et al., 1996, 2000). By using wide-range EOS accounting for melting and phase-transitions, the model is applicable to problems involving shock waves.

Because rock properties may vary significantly from sample to sample, it can be very useful to parametrize the key model parameters such as Unconfined Compressive Strength (UCS), the initial bulk modulus and the crush pressure in order to capture this variability. Parametrization of the yield surface as a function of the reference porosity or the grain size has been used in the past (Aubertin and Li, 2004; Sheldon et al., 2006). In the current model not only the yield surface but also the elastic moduli are expressed as functions of the reference porosity of the rock.

It is well known that the mechanical properties of jointed rock masses are quite different from those of rock samples. Therefore, building a good model for intact rocks may not be good enough for large-scale calculations. The presence of thin structures in rock masses such as faults, joints and bedding planes adds another level of complexity, because one needs to resolve phenomena on multiple spacial scales in the numerical simulations. Validation of numerical results for rock masses is not always available, since large-scale *in situ* tests are expensive and in some cases not possible. *In situ* tests generally provide information on P-wave and S-wave velocities as well as the joint spacing but not on the failure surface for the rock masses. Numerical modeling can help to study and analyze responses of jointed rock masses measured in experiments. In explicit methods the rock mass is presented as an assembly of intact blocks and joints. One of the most popular explicit methods used in rock mechanics is the distinct element method (DEM) where the rock blocks and the joints are modeled separately (Cundall and Hart, 1992; Morris et al., 2004; Heuze and Morris, 2007). The DEM approach is quite expensive computationally but can be used to calibrate phenomenological continuum models both for porous rock samples and *in situ* blocky rock masses (Cho et al., 2007; Kulatilake et al., 2001). The advantage of DEM is that it can deal with large deformations of rock masses (block separation, splitting, etc.) in a natural way. The disadvantages are difficulties in modeling nonpersistent joints and cracks. Alternative methods to model discontinuous media include the discrete-continuum approach (Lin and Cheng, 2006), XFEM (Belytschko and Gracie, 2007) where the finite elements containing the joints are treated in a special way, and the "thin" elements used to model joints (Desai et al., 1984; Wang et al., 2003).

Effects of discontinuities have been also studied in numerous analytical models. Gerrard (Gerrard, 1982) and Fossum (Fossum, 1985) derived equivalent elastic properties for jointed rock assuming that both joints and the rock are elastic materials. Cai and Horii (1992) derived equivalent stress–strain response for jointed rock masses by assuming that the rock is elastic while the joints are elasto-plastic. They also accounted for the interactions between the joints. Models developed for granular materials (Nicot and Drave, 2005; Zhu et al., 2006) are more focused on intergrain contacts. Nicot and Drave (2005) derived homogenized properties for an assembly of sphere-shaped grains with compliant contacts and Morh–Coulomb friction. Zhu et al. (2006) developed a continuum model which uses intergrain contact distribution described by the fabric tensor to model plasticity along the contact plains. The micro-mechanical approaches used in these works relates the material structure (fabrics) and its mechanical properties. None of the models mentioned above assume that significant plastic deformation or damage, such as grain fracture, can occur at the subgrain scale.

The main focus of this work is on rock response at high pressures where the rock blocks can be plastically deformed, and sliding at the joint can be significant. In these cases plastic deformations and damage of the material within the blocks is captured by the constitutive model for intact rock. Contact algorithms are applied to provide a robust method for explicit modeling of jointed rock.

For large scale simulations it is not practical to count every single joint in the problem explicitly. When the wave length is much larger than the joint spacing it may be appropriate to use homogenization