Discrete modelling jointed rock slopes using mathematical programming methods

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A B S T R A C T

In this paper, a mathematical programming based discontinuum approach is developed for modelling jointed rock slopes. The formulation naturally leads to a standard second-order cone program, which can be solved using efficient optimisation solvers, and a purely static method is derived that does not require artificial damping parameters. Notably, the approach provides somewhat of a unification of two distinct discontinuum approaches: the soft-particle model and the hard-particle model. A series of numerical examples are conducted to validate the proposed approach. The soft-particle model is more versatile than the hard-particle model while the hard-particle model is more efficient.

1. Introduction

The stability analysis of jointed rock slopes is challenging, mainly because of the existence of the discontinuities introduced by joints or faults. Because of its importance, the problem has been widely studied and a large number of models have been proposed. Although limit equilibrium methods [1–3] have traditionally been employed, and are effective in slope stability analysis, they require a priori assumptions regarding the force distributions as well as the shape and location of the failure surface. As a consequence, little information about the actual failure mechanism can be obtained. To better simulate the failure mechanism and overall deformation pattern, various numerical models have been proposed in recent decades, including the finite element method (FEM) [4], the boundary element method (BEM) [5], the discrete element method (DEM) [6] and discontinuous deformation analysis (DDA) [7]. The FEM has been widely employed for slope stability analysis (e.g., [8,9] and [10]) with good results, but to model pre-existing discontinuities it is generally necessary to use joint (or interface) elements. Since these elements can lead to difficulties involving remeshing and convergence issues [11], the extended finite element method (XFEM) [12] has subsequently been proposed. This procedure has been applied to model pre-existing discontinuities and crack propagation in jointed rock masses with some success [13,14]. To model discontinuous materials under large deformation efficiently, discontinuum approaches may be used. There are essentially two types of these approaches: the soft-particle model and the hard-particle model [15–17]. The soft-particle model (e.g., the conventional DEM originally developed by Cundall and Strack [6]) considers overlap at the contact points between particles to simulate particle elasticity. This approach is now used widely in the rock mechanics community. Since pre-existing discontinuities and the growth of cracks can be represented explicitly and conveniently, the interaction of these phenomena can be modelled in a straightforward manner [18–20]. The influence of joints’ geometrical and mechanical behaviours on jointed rock slopes’ stability are investigated as well [21,22]. Furthermore, modelling the complete failure process of a slope is now possible [23,24].

The second discontinuum approach is the hard-particle model e.g., contact dynamics [25,26]. In contrast to the soft-particle model, the overlap is not allowed at contacts (i.e., particles are perfectly rigid) and non-smooth contact laws are used. Furthermore, damping coefficients or local elastic parameters are not necessarily required in the model [16] and large time steps can be employed because of the adoption of implicit time discretisation [26]. Numerous studies have been performed using this model and it has proven to be very successful in modelling granular materials (e.g., [27–31]). Although this discontinuum approach has the potential for modelling jointed rock masses, it has rarely been used for this purpose. One study was performed by Rafiee et al. [32], but all results were limited to Fig. 3 in this reference.

This work further develops the discontinuum approach based on mathematical programming [33–39] for modelling jointed rock slopes. A series of variational formulations are developed for the statics and dynamics of jointed rock slopes. The frictional contact problem for rock
blocks is first considered. To model failure of intact rock materials, a polygonal discretisation is used which is based on the Voronoi diagram. The variational formulation is developed based on the rigid-body-spring network [40]. All the formulations developed can be cast into standard second-order cone programs, which can be solved conveniently using advanced optimisation algorithms. A number of very efficient and robust second-order cone programming codes have been developed recently, including MOSEK [41] and SeDuMi [42], which are ideally suited to the proposed formulations. It is notable that this approach is more general than the conventional DEM because it incorporates both the hard-particle and the soft-particle models. Thus, these two models can be implemented for jointed rock slopes and their results are compared. Another distinct feature is that the purely static formulations, dedicated to modelling quasi-static problems, can be formulated.

This paper is organised as follows. In Section 2, formulations for frictionless blocks with the hard-particle model are developed and then extended to the frictional case. These formulations are further extended to the soft-particle model in Section 3. To model intact rock materials, the governing equations for the bonded block model with the modified Mohr-Coulomb failure criterion are summarised in Section 4. Implementation details are presented in Section 5. In Section 6, the proposed approach is validated with four examples by comparing the numerical results with analytical solutions and experimental observations. Results from the soft-particle model and the hard-particle model are also compared. Moreover, the capability of the proposed approach with the soft-particle model is tested with a jointed rock slope containing two sets of non-persistent joints. Finally, some conclusions are drawn in Section 7.

2. Frictional blocks with the hard-particle model

The formulations developed in this section are aimed at describing sticking, sliding and separating of rock blocks. For clarity, the variational formulations for frictionless blocks are developed first and only the translational degrees-of-freedom are considered. Then, the governing equations are extended to handle frictional blocks by accounting for tangential forces and the rotational degrees-of-freedom.

2.1. Frictionless blocks with the hard-particle model

2.1.1. Equations of motion

The equations of motion for a single block i are given by:

\[
m_i \ddot{v}_i = f_{ext}^i
\]

where \(m_i\) is its mass, \(\dot{v}_i\) is its linear velocity, \(f_{ext}^i\) is the external force vector acting on it. 
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