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Effects of fracture distribution and length scale on the equivalent continuum elastic compliance of fractured rock masses

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ABSTRACT

Fracture systems have strong influence on the overall mechanical behavior of fractured rock masses due to their relatively lower stiffness and shear strength than those of the rock matrix. Understanding the effects of fracture geometrical distribution, such as length, spacing, persistence and orientation, is important for quantifying the mechanical behavior of fractured rock masses. The relation between fracture geometry and the mechanical characteristics of the fractured rock mass is complicated due to the fact that the fracture geometry and mechanical behaviors of fractured rock mass are strongly dependent on the length scale. In this paper, a comprehensive study was conducted to determine the effects of fracture distribution on the equivalent continuum elastic compliance of fractured rock masses over a wide range of fracture lengths. To account for the stochastic nature of fracture distributions, three different simulation techniques involving Oda's elastic compliance tensor, Monte Carlo simulation (MCS), and suitable probability density functions (PDFs) were employed to represent the elastic compliance of fractured rock masses. To yield geologically realistic results, parameters for defining fracture distributions were obtained from different geological fields. The influence of the key fracture parameters and their relations to the overall elastic behavior of the fractured rock mass were studied and discussed. A detailed study was also carried out to investigate the validity of the use of a representative element volume (REV) in the equivalent continuum representation of fractured rock masses. A criterion was also proposed to determine the appropriate REV given the fracture distribution of the rock mass.

1. Introduction

Rock masses inevitably contain fractures with varying fracturing intensity over a wide range of length scales. Fracture geometry has often very complex patterns, and fracture distributions and properties are strongly dependent on the length scale. Since the mechanical stiffness and strength of fractures are much lower than those of the rock matrix, the overall mechanical response of fractured rock masses is controlled by the fractures. Fractures contribute additional displacements to the rock mass, and owing to the complicated fracture geometry, the mechanical response is generally anisotropic even if the surrounding rock matrix behavior is isotropic. In addition to the mechanical behavior, geometrical distribution of fractures in a rock mass and corresponding fracture properties including length, orientation, frequency and stiffness, are key factors that control the mechanical behavior of fractured rock masses. Developing a comprehensive relation between fracture geometry and the overall mechanical characteristics of fractured rock masses is challenging because of the generally complex nature of fracture patterns and distributions.

Since the 1950s, several numerical procedures have been developed for modeling the mechanical behavior of fractured rock masses and the effect of different fracture patterns. The most rigorous approaches are the distinct fracture network (DFN) model and distinct element method (DEM). In DFN and DEM, individual fractures in a rock mass are modeled explicitly as distinct features that deform in the normal and shear directions. These methods can be used to precisely determine the explicit behavior of fractured rock masses. In many cases, however, considering all the individual fractures by the DFN and DEM models is computationally impossible as well as practically unachievable due to the lack of reliable data on fracture distribution and pattern. Thus, these simulation techniques are typically used only for defining the mechanical behavior of major faults and fractures as individual features (Guvanasen and Chan, 2000), as well as the small (e.g. core) scale mechanical behavior of rocks (Esmaieli et al., 2015).

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An alternative approach to modeling of fractured rock masses is to average the mechanical contributions from the fractures to obtain an equivalent continuum representation of the rock mass stress–strain behavior. Equivalent continuum models (ECMs) assume that a sufficiently large representative element volume (REV) exists, and that this REV contains "a sufficient number of representative fractures in a rock mass over which the fractures' stress–strain behavior can be averaged". Since the initial concept of ECM was first developed by Eshelby (1957), different numerical approaches based on ECMs have been introduced. The three most general ECMs for the mechanical analysis of fractured rock masses are the smeared crack model, multilaminate model, and anisotropic constitutive model. All the three modeling techniques have found wide use in different applications. In the smeared crack model (Rashid, 1968; Rots, 1991; De Borst et al., 2004), fractured rock mass deformations are obtained from superposition of rock matrix and fracture deformations. In the multilaminate model (Zienkiewicz and Pande, 1977), fracture deformations are added to the intact rock deformation using a viscoplastic formulation. Both methods are generally applicable for relatively simple fracture geometries since local stresses and deformations along fracture planes need to be transformed to the global axes in every time step. In anisotropic constitutive models, the strength and deformability of fractured rock masses are modeled using orthotropic stress–strain relations. Cai and Horii (1992), Oda (1982, 1988), Oda et al. (1993), and Yoshida and Horii (1998) have proposed anisotropic constitutive models that can simulate the effects of fracture geometries using compliance tensor formulations.

Despite its simplicity, there are two important issues that have not been completely addressed in the use of ECMs. These issues are related to: (1) the sensitivity of fractured rock mass equivalent continuum properties to fracture geometry and distribution, and (2) the dependency of the fracture geometry and behavior on the length scale and the volume of the rock mass. The sensitivity of the calculated compliance values to fracture geometry is an important issue since fracture geometry and distribution are inherently uncertain and stochastic in nature. The expected length scale dependency of ECMs stems primarily from their formulation, which assumes the existence of an REV. The REV of a fractured rock mass is qualitatively defined as "the smallest volume of the rock mass that is large enough relative to the characteristic scale of the fractures in the volume". However, there is currently no rigorously quantitative criterion for establishing the REV of a rock mass given the fracture geometry.

The main objective of the research presented in this paper is to critically evaluate the sensitivities of the elastic compliance tensor calculated from Oda's formulation (Oda, 1982, 1988; Oda et al., 1993) to the variability in fracture distribution and length scale, and to propose a method to quantify these sensitivities. An extensive parametric study is conducted to evaluate the dependence of rock mass compliance on fracture geometrical parameters, and the results are used to establish relationships between fracture geometry variations and rock mass elastic compliance. The dependence of fractured rock mass elastic compliance on length scale is investigated by calculating equivalent continuum elastic parameters over different sampling volumes of rock mass. To ensure that the results are valid for a wide range of fracture geometries and distributions, a large number of fracture geometry realizations are generated using a combination of Monte Carlo simulation (MCS) and probability distribution functions (PDFs). In addition, to ensure that they are geologically realistic, the fracture geometrical parameters are based on field data obtained from different sources in studies of fracturing from various geological fields.

The focus of the study is on fractured rock mass elastic behavior. Although fractured rock masses are expected to behave non-elastically in general, the study of elastic behavior is important in geophysical characterization where elastic response determines the propagation of seismic waves in fractured rock formations. Future extension of the study will be for nonlinear and elasto-plastic behavior of fractured rock masses. Two-dimensional (2D) elastic mechanical behavior is assumed based on the following justifications: (1) fracture data particularly from field studies of rock exposures are predominantly 2D; (2) most rock mechanical models for different applications (e.g. tunneling and excavations, and slope stability) remain 2D; and (3) interpretation and visualization of results in three-dimensional (3D) are difficult, and as a consequence 2D slices are often used to present 3D results. 2D results can provide valuable insights that can be extrapolated to 3D problems and be easily interpreted without being bogged down by the need to use complicated visualization techniques. A comprehensive parametric study is conducted using Oda's analytical compliance tensor formulation. Once the fracture geometries and mechanical properties have been collected, Oda's formulation generates crack tensors, which is combined with the fracture stiffness parameters and yields a homogenized elastic compliance tensor for a fractured rock mass. Since the crack tensor formulation has a summation form, all the generated fracture geometries can be effectively considered in the entire compliance tensor calculation.

2. Methodology

Three techniques were used for analyzing the effects of fracture geometrical distribution and length scale on fractured rock mass elastic properties: (1) Oda's elastic compliance tensor formulation; (2) Different PDFs to generate geologically realistic fracture geometries based on in-situ data from different field studies; and (3) MCS to generate stochastic realizations of fracture geometry and assemble the results of the compliance calculations from different randomly generated realizations. These techniques are described below.

2.1. Elastic compliance tensor for fractured rocks

Oda's compliance tensor formulation (Oda, 1982, 1988; Oda et al., 1993) suggests a way to express the geometry of complicated fracture systems in tensorial form and to deal with any fractured rock mass as a mechanically equivalent continuum. To apply Oda's compliance tensor formulation for fractured rock masses, the following assumptions are made: (1) The position of a fracture corresponds to its centroid, and the centroids are evenly distributed in the entire rock sample (i.e. fracture locations are assumed to follow a Poisson distribution). (2) The fracture is assumed to have a planar shape. Thus, the surface area of a fracture and volume of fractured rock under plane strain conditions can be converted to length of fracture and cross-sectional area of rock outcrop, respectively, due to the unity width of the sampling area. (3) The mechanical behavior of fractures is assumed to be elastic. (4) Fractures are persistent and there are no stress concentrations at fracture tips and intersections. Based on these assumptions, it is commonly assumed that a fracture plane can be replaced by an elastically equivalent set of parallel plates connected by two elastic springs in normal and shear directions. The formulations of the stiffness of the two springs are discussed below.

On the basis of these assumptions, Oda et al. (1993) has suggested the following equivalent continuum compliance tensor equation for fractured rock masses: