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Influence of heterogeneity on rock strength and stiffness using discrete element method and parallel bond model

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ABSTRACT

The particulate discrete element method (DEM) can be employed to capture the response of rock, provided that appropriate bonding models are used to cement the particles to each other. Simulations of laboratory tests are important to establish the extent to which those models can capture realistic rock behaviors. Hitherto the focus in such comparison studies has either been on homogeneous specimens or use of two-dimensional (2D) models. In situ rock formations are often heterogeneous, thus exploring the ability of this type of models to capture heterogeneous material behavior is important to facilitate their use in design analysis. In situ stress states are basically three-dimensional (3D), and therefore it is important to develop 3D models for this purpose. This paper revisits an earlier experimental study on heterogeneous specimens, of which the relative proportions of weaker material (siltstone) and stronger, harder material (sandstone) were varied in a controlled manner. Using a 3D DEM model with the parallel bond model, virtual heterogeneous specimens were created. The overall responses in terms of variations in strength and stiffness with different percentages of weaker material (siltstone) were shown to agree with the experimental observations. There was also a good qualitative agreement in the failure patterns observed in the experiments and the simulations, suggesting that the DEM data enabled analysis of the initiation of localizations and micro fractures in the specimens.

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1. Introduction

This study explores the use of discrete element method (DEM) to capture the influence of weak interlayers on the overall response of heterogeneous rock specimens. The bonded particle model (BPM) proposed by Potyondy and Cundall (2004) was used to simulate the heterogeneous rocks made up of layers of two different lithological units with significant differences in strength and stiffness. A comparison of the DEM simulation data with the results from a prior experimental study (Tziallas et al., 2013) shows that the model can capture reasonably the variation of strength with increasing proportion of the weaker materials. The influence of relative strengths of lithological units of the heterogeneous rocks on the overall strengths and stiffnesses of the composite heterogeneous rock specimens was also investigated.

This paper first gives an overview of the mechanical responses of composite rocks, and then the simulation approach is presented. The analysis of the results also considers the overall material response prior to discussing the particle-scale mechanics.

2. Background

2.1. Mechanical behaviors of composite rocks

The composition and structure of rocks are altered by natural geological processes leading to the formation of heterogeneous rock masses with complex engineering behaviors. Heterogeneous rocks are usually of sedimentary origin and consist of relatively stronger and weaker rock alternately with varying thickness. Complex geological formations such as turbidites, flysch and molasses are typical examples of such rocks.

Researchers including Hoek (1968), Hawkes and Mellor (1970), Paterson and Wong (2005) and Kwaśniewski et al. (2012)

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amongst others have experimentally studied the failure modes of rocks. Tang and Hudson (2010) stated that the failure of brittle rocks under uniaxial compression was due to the expansion of the initial micro cracks to a major shear band, whereas in confined tests the failure can be attributed to the coalescence of the micro fractures into a critical shear failure zone. At higher confining pressure, the Young's modulus and the peak strength values of rocks are higher and a transition from brittle to ductile deformation occurs.

The effect of heterogeneity on the failure mode was studied by Liang et al. (2007) and Tziallas et al. (2013) through conducting uniaxial compression tests on the composite specimens with varying siltstone-sandstone ratios as illustrated in Fig. 1. They observed that the failure mode was affected by the proportion of the weaker materials (siltstone). For specimens with lower values of siltstone percentage, extensional fractures were formed throughout the specimens, whereas for specimens with higher values, the fractures were merely restricted to the weaker materials. Liang et al. (2007) conducted triaxial tests on composite specimens of anhydrite (stronger, harder component) and halite (weaker component) and they observed that there was a strain incompatibility along the interface leading to tensile or shear cracking in the harder component and more ductile deformation in the weaker component. Greco et al. (1991) also investigated the strength and failure mechanism of composite rock specimens subjected to uniaxial compression. According to their investigation, tests on specimens composed of discs of the same material resulted in lower uniaxial compressive strength (10% reduction) compared to continuous specimens. In their laboratory tests on composite specimens of shale and sandstone, Mohamed et al. (2007) studied the effect of the thickness of shale on the overall strength. They concluded that for specimens with shale percentage greater than 10%, the strength of the composite specimen was equal to the strength of the weaker material. Vergara et al. (2015) performed large-scale triaxial test on bedded sandstone–claystone specimens, and concluded that the failure of the bedded specimens occurred by a combined failure of both materials in a ductile manner. They also conducted a numerical analysis using a two-dimensional (2D) universal distinct element code (UDEC) to simulate the specimens composed of alternating layers of both materials with equal thickness. It was shown that when confining pressure was less than 15 MPa, the strength of the specimen was controlled by tensile failure of the harder rock, while under larger confining pressure, the strength was controlled by shear failure of the weaker rock. Lin et al. (2013) studied the anisotropic behavior of a layered rock mass under triaxial compression using a three-dimensional finite element method (3D FEM) for numerical analysis. Anisotropy due to the presence of bedding planes affects the failure pattern of transversely isotropic, heterogeneous rocks. The varying inclination of the bedding planes relative to the major loading axis affects both their strength and failure mode (Tien et al., 2006).

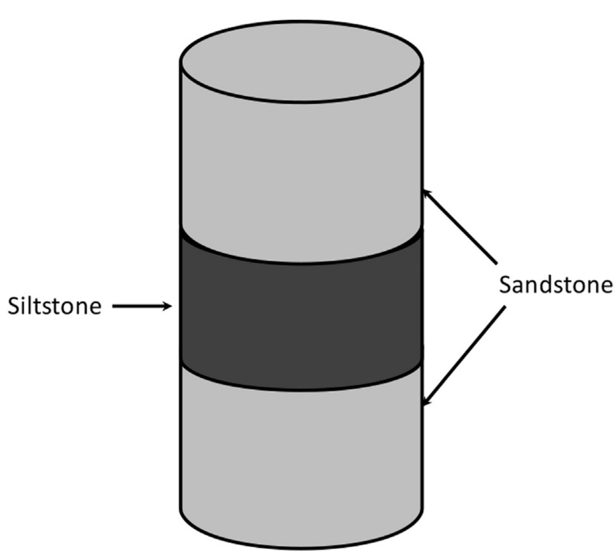

Fig. 1. Schematic of composite specimen configuration.

2.2. Use of bonded particle model to simulate the behavior of rock mass

The particulate DEM was originally proposed for fundamental simulations of unbonded granular materials by Cundall and Strack (1979). This algorithm can be applied to analyzing the behavior of rock mass using contact models that can transmit tensile forces. The parallel bond model (PBM), documented by Potyondy and Cundall (2004), is a relatively sophisticated bonding model that enables specification of tensile and shear strengths. The bonds are of finite size and thus there is moment transfer/resistance due to the normal and tangential components of the contact force. A number of studies have reported the use of this model to simulate rock mass behavior. Studies using 2D model such as Cho et al. (2007) provide useful qualitative insight into the model's behavior; however, effective models should reflect the 3D nature of the physical material. Potyondy and Cundall (2004) reported only limited success in simulating the behavior of Lac du Bonnet granite. However, Potyondy (2007) found that a modified PBM, the parallel-bonded stress corrosion (PSC) model, could successfully reproduce experimental data from static fatigue tests. Zhang et al. (2011) calibrated DEM specimens using the PBM along with a fracture model to capture the response of Yamaguchi marble and they succeeded in capturing the size dependency of the uniaxial compressive strength observed in laboratory tests. Cheung et al. (2013) performed a parametric study to illustrate how the PBM parameters influence the overall behavior, prior to describing a relatively successful calibration of the PBM to simulate the response of Castlegate and Saltwash sandstones; the load–deformation response of the model agreed with experimental data until the peak stress was mobilized. Nevertheless for the post-peak regime, the model was less successful.

There have been some 2D DEM simulations that have explored the issues of layering and inhomogeneity. Park and Min (2015) used a 2D DEM modeling approach that included embedded smooth joints to simulate the mechanical behavior of a transversely isotropic rock using the PBM. They compared the laboratory observations of model behaviors of three rock types (gneiss, shale and schist) and concluded that this modeling approach can successfully capture the failure patterns observed in anisotropic rock in which weak planes play a significant role. Hsieh et al. (2008) conducted 2D DEM simulations using the BPM to study the relationship between the macroscopic properties of sandstones and their petrographic or microscopic properties. Jeng et al. (2008) also used 2D DEM to create a model of layered rock. In their work, they captured experimental observations of the influence of the layer inclination on strength and stiffness. They also explored the influence of the relative strengths and stiffnesses of the two materials on the overall behavior. However, these results were not linked to experimental data. In addition, Abe and Urai (2012) studied a layered rock material using 2D DEM simulations. These earlier studies have demonstrated the potential of the model and the current contribution aims to further develop confidence in the PBM by demonstrating its ability to capture known response features of heterogeneous rock specimens. In particular, an in situ 3D material subjected to a 3D stress state is of interest, and therefore the earlier

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