International Journal of Rock Mechanics and Mining Sciences 110 (2018) 120–132

Contents lists available at ScienceDirect

International Journal of Rock Mechanics and Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Three-dimensional bonded-particle discrete element modeling of mechanical behavior of transversely isotropic rock

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ARTICLE INFO

Keywords:
Transversely isotropic rock
Discrete element method
Smooth-joint contact model

ABSTRACT

This paper presents the three-dimensional bonded-particle discrete element modeling of mechanical behavior of transversely isotropic rock as an extension to the previous work conducted in two dimensions (Park B, Min K-B. Bonded-particle discrete element modeling of mechanical behavior of transversely isotropic rock. Int J Rock Mech Min Sci 2015a;76:243–55). Systematic verifications of the elastic and strength anisotropy were performed by comparing the numerical results with the analytical solutions, which indicated that there was good agreement with appropriate consideration of overlapping ratio of smooth-joint contacts. Two validation cases are presented in this study. First, the three-dimensional bonded-particle DEM model successfully captured the monotonic and concave variations of elastic and strength anisotropy and Brazilian tensile strength anisotropy observed in the laboratory tests of Asan gneiss, Boryeong shale, and Yeoncheon schist. Improved match in Brazilian tensile strength was attributed to higher average coordination number in three-dimensional numerical model than that in two-dimensional model whereby leading to higher interlocking. The second validation case was conducted against CIU (isotropically consolidated undrained triaxial) and Brazilian tensile strength tests of a Tertiary shale from the Norwegian Continental Shelf (NCS). The three-dimensional bonded-particle DEM modeling of the triaxial tests with different initial effective confining pressures showed that the peak strength at failure provided by the numerical model reasonably simulated the strength variation as well as the various elastic moduli with respect to the inclination angles. Brazilian tensile strength of the numerical model was in range of the laboratory data. Furthermore, the numerical model produced similar post failure patterns as exhibited on the disk-shaped NCS shale, e.g., axial splitting and crushing failure. The results demonstrated that the three-dimensional bonded-particle DEM model with embedded smooth-joint contacts is a viable model for emulating the mechanical behavior of transversely isotropic rock with the potential of enhanced predictive capability of anisotropic numerical model.

1. Introduction

Anisotropic rock presents one of the most distinct challenges of engineering rock mechanics.[1] Among the many forms of anisotropic models, a transversely isotropic (TI) model, in which one set of weak planes possesses full rotational elastic symmetry around one axis, is known to be the most relevant for many types of rocks.[1,2] Especially in sedimentary and metamorphic rocks that contain weak cohesive planes, such as bedding, foliation, or schistosity, the direction normal to the weak planes can be regarded as the axis of rotational symmetry, so transverse isotropy is pertinent to modeling these types of rocks.[3]

Since the existence of a set of weak planes makes the mechanical behavior of a TI rock substantially vulnerable to the stress applied at the boundary, predicting the deformation and strength of anisotropic rock observed in situ is challenging in many geomechanics applications, e.g., wellbore stability analyses in shale formation. Therefore, a thorough understanding of the effects of the weak cohesive planes is necessary to investigate the anisotropic mechanical behavior. Since previous studies on the mechanical behavior of anisotropic rock have focused more on experimental observations,[2,4–7] there is a need for research on the numerical approach in order to be able to predict anisotropic behavior in large-scale engineering problems.

The bonded-particle discrete element method (DEM) is a powerful approach for simulating the dynamic behavior of materials for given boundary conditions without the need to establish the constitutive law.[8,9] The main advantage of bonded-particle DEM is its ability to take

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https://doi.org/10.1016/j.ijrmms.2018.07.018
Received 22 May 2017; Received in revised form 9 July 2018; Accepted 31 July 2018
1365-1609/

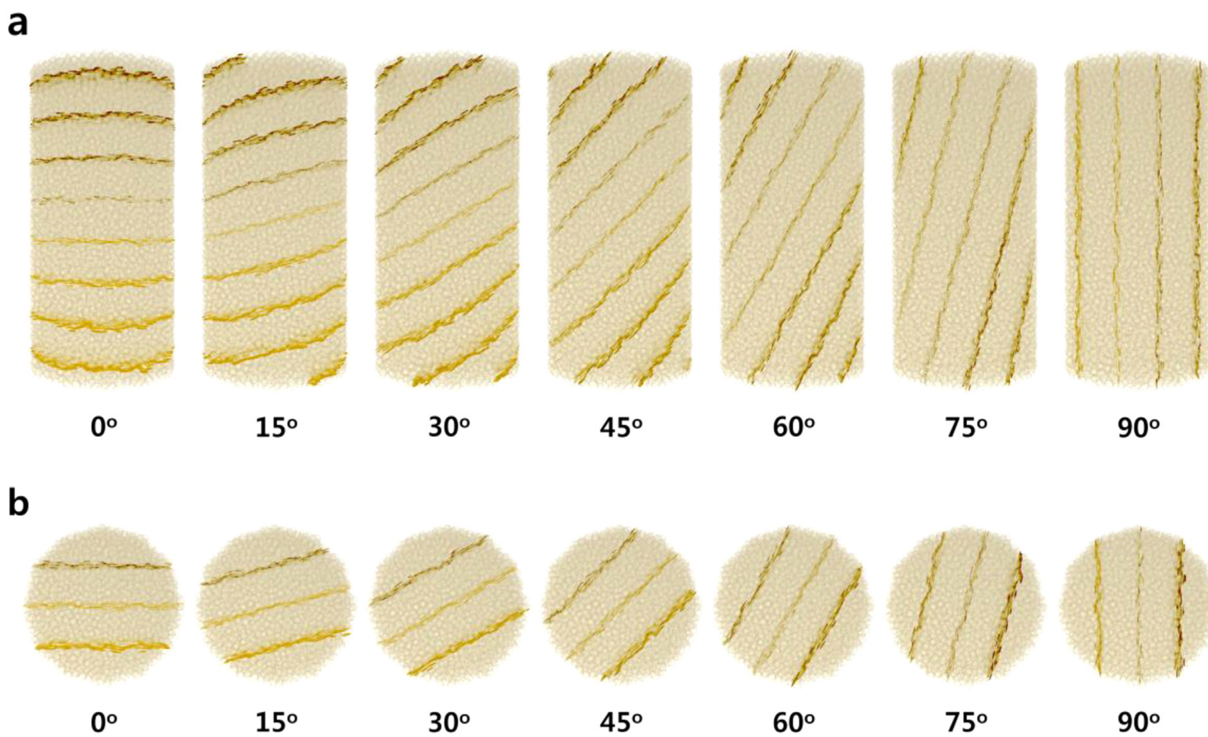

Fig. 1. Transversely isotropic rock specimens with seven different inclination angles. Smooth-joint contacts are inserted into bonded-particle model at 9.5 mm intervals: (a) cylindrical specimens for compressive strength test (16,179 particles, D = 38 mm, L = 76 mm), and (b) disk-shaped specimens for Brazilian tensile strength test (4013 particles, D = 38 mm, thickness = 19 mm).

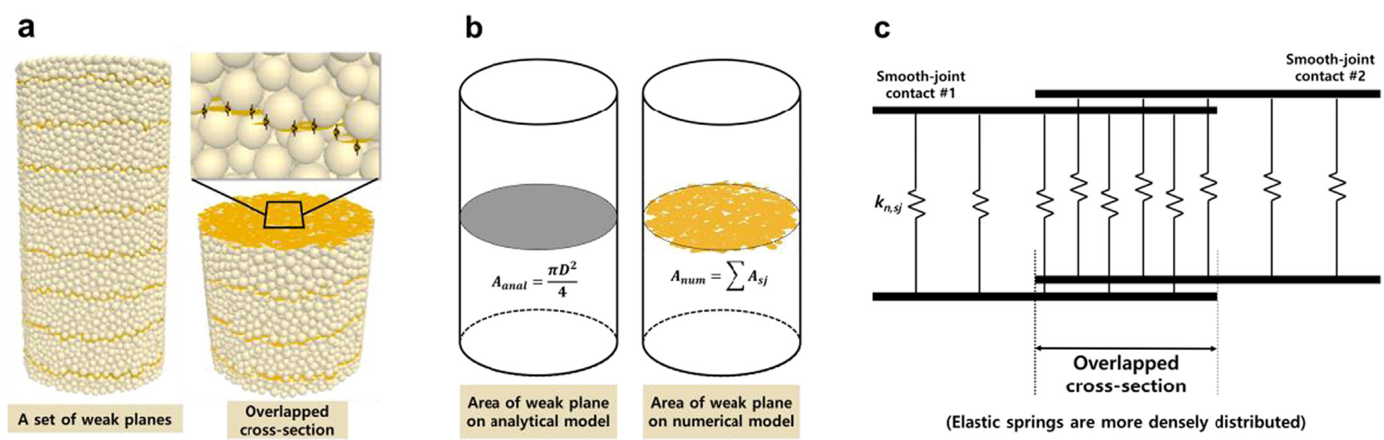

Fig. 2. (a) Three-dimensional transversely isotropic model embedding a set of horizontal weak planes, which have rough surface comprised of densely overlapped smooth-joint contacts, (b) definition of the area of weak plane observed from analytical model and numerical model, and (c) normal stiffness ($k_{n,sj}$) of elastic springs uniformly distributed on smooth-joint contacts connected in parallel on the overlapped cross-section.

into account the evolving micromechanisms of progressive rock failure. Applications of bonded-particle DEM have been expanded into the modeling of large-scale, complex rock masses, in which natural fractures are taken into account using the discrete fracture network (DFN) model by means of the "smooth-joint contact model" (SJM).[10] Although the fractured rock mass behavior mostly has described the natural fractures that normally are separated from one another with very low mechanical properties, it is necessary to emulate the behavior of the weak cohesive planes *within* the intact rock, such as the bedding planes embedded in TI shale.

Recent studies have shown that the two-dimensional bonded-particle DEM model can simulate the elastic and strength behavior of TI rocks effectively.[11–19] These studies have shown that the behavior of weak cohesive planes can be modeled by the smooth-joint contact model or aligned contact angles to model TI rocks. Park and Min[15,16,19] conducted laboratory-scale DEM modeling of TI rock with systematic verification of its elastic and strength properties, including validation against the laboratory observations. Moreover, as an extension to large-scale foundation and borehole problems, the stress redistribution in the discontinuum DEM model resulting from the applied line load and borehole excavation compared well with both analytical solutions and the results of the continuum finite element model.

Duan and Kwok[13,14] proposed an inherent anisotropic model in which intrinsic anisotropy was imposed by replacing the parallel bonds that dipped within a range of angles with smooth-joint contacts, and they showed how the micro-parameters affected the mechanical behavior of the anisotropic model with different anisotropy angles. In addition, these authors observed the development of stress-induced borehole breakout in an anisotropic rock formation model at the laboratory-scale.[18] Several recent studies have shown that two-