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Modeling the particle breakage of rockfill materials with the cohesive crack model

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ABSTRACT

A practical combined finite–discrete element method was developed to simulate the breakage of irregularly shaped particles in granular geomaterials, e.g., rockfill. Using this method, each particle is discretized into a finite element mesh. The potential fracture paths are represented by pre-inserted cohesive interface elements (CIEs) with a progressive damage model. The Mohr–Coulomb model with a tension cut-off is employed as the damage initiation criterion to rupture the predominant failure mode occurs at the particle scale. Two series of biaxial tests were simulated for both the breakable and unbreakable particle assemblies. The two assemblies have identical configurations, with the exception that the former is inserted with CIEs and is breakable. The simulated stress–strain–dilation responses obtained for both assemblies are in agreement with experimental observations. We present a comprehensive study of the role of particle breakage on the mechanical behavior of rockfill materials at both the macroscopic and microscopic scales. The underlying mechanism of particle breakage can be explained by the force chain in the assemblies.

1. Introduction

Rockfill material is increasingly used in many geotechnical engineering applications, particularly in high rockfill dams. In contrast to sand and gravel, rockfill grains generally possess a lower crushing strength and are subjected to a higher contact force due to their larger size and coarse gradation. The role of particle breakage in the mechanical behavior of granular geomaterials has been experimentally investigated by many researchers [1–4].

In parallel with experimental studies, another contribution to this field comes from the numerical modeling of granular materials using the discrete element method (DEM). Previously published works regarding DEM and particle breakage were mainly concerned with the breakage of subparticles that are joined by bonding or cohesive forces [5–11]. Another approach is to replace the particle fulfilling a predefined failure criterion with an equivalent group of smaller particles [12–15]. Both techniques for a particle breakage simulation are mainly employed, with either discs in 2D or spheres in 3D. For particles with general shapes, the realization of particle breakage follows the idea proposed by Potapov and Cambell [16]. In their simulations, a breakable particle is created by bonding unbreakable and nondeformable subparticles via cohesive bonds; if the bond between these subparticles breaks, breakage occurs [17,18].

A natural evolution of the DEM is to accurately replicate the deformability and crushability of real granular materials and to provide a robust model for contact interaction that is insensitive to the complexity of the considered particle shape. For these reasons, Munjiza et al. proposed a method that merges the capabilities of the finite element method (FEM) with discrete element implementations [19]. In the combined FDEM, each particle is discretized into a finite element mesh, and the deformation is solved computationally according to the rheological behavior of the material, where the particle movements and interactions are handled as they would be in the DEM [20]. One of the remarkable benefits of this combination is its ability to handle the contact interactions of particles with arbitrary shapes, independent of the contact configuration. This combined FDEM has been applied to granular materials by several researchers [21–25]. In addition to the combined FDEM, the multi-particle finite element method (MPFEM) and meshed discrete element method (MDEM) also allow for finite element simulation at the particle scale [26,27]. Basically, the combined FDEM, MDEM, and MPFEM have similar theoretical backgrounds.

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The main purpose of this paper is to develop a practical combined FE/DE method for modeling particle breakage in granular geomaterials, e.g., rockfill materials. Our method uses the cohesive interface element (CIE) in the general-purpose finite element software ABAQUS to model potential particle fracture or fragmentation. First, densely packed polygonal particles are prepared to represent the rockfill sample. The CIEs are inserted into the initial FE mesh of each particle using a specially designed and efficient algorithm. Then, the cohesive crack model and a progressive damage model are introduced. Once the initial damage criterion is satisfied, the CIE starts to degrade and gradually loses its carrying capability. Finally, two series of biaxial tests are simulated with both the breakable and unbreakable particle assemblies. The input parameters of these simulations are chosen on a purely empirical basis and without calibration to any specific type of parent rock. The simulation results are analyzed on both the macro- and micro-scales to investigate the role of particle breakage in the mechanical behavior of rockfill materials.

2. Combined finite–discrete element method

In the combined approach, each particle is discretized into an FE mesh, as shown in Fig. 1. These meshes define the shapes of the discrete elements. The contact between the interacting particles is defined commonly in DEM. Once the contacts have been detected, a linear contact model is employed to calculate both the normal and tangential contact forces between two particles. The normal component is linear-elastic with a no-tension limit, and the shear component is linear-elastic with a Coulomb friction limit.

In this paper, the combined FDEM-based simulations of granular materials are performed using the explicit module of ABAQUS [28]. The explicit integration scheme and general contact capability of this module make it appropriate for a large number of actual and potential contacts for particles undergoing large deformation. In addition, the ABAQUS software provides the user with an extensive array of secondary development interfaces that allow them to adapt ABAQUS to their particular analysis requirements. A user-defined CIE with the theoretical formulation described below was developed and implemented into ABAQUS using the user defined element subroutine. Several python scripts were also developed to facilitate the pre- and post-processing processes.

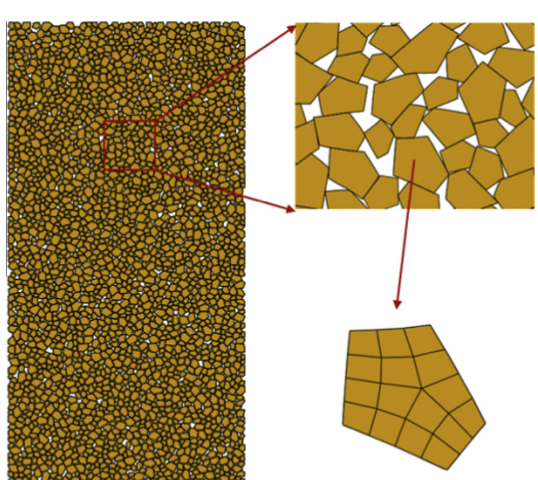

Fig. 1. Typical particle assembly used in combined FDEM simulations.

3. Particle breakage with the cohesive crack model

3.1. Modeling procedures

The proposed method includes the following steps:

- Generating a realistic description of the particle assembly for discrete modeling. A Voronoi tessellation-based approach is adopted to generate the 2D assembly of polygonal particles [29]. Because the simulated particle breakage patterns are dependent upon the initial FE mesh of particles, the selection of the element type is relevant to the accuracy of the simulation. Compared with the use of quadrilateral elements, the simulated breakage patterns of an FE mesh with triangular elements have less mesh sensitivity. However, the locking problem arising from linear triangular elements reduces the simulation accuracy. In this paper, quadrilateral elements are preferred in a fine FE mesh so that the particle breakage can be simulated with adequate accuracy and relatively less mesh sensitivity.
- Compressing the initially loose particle assembly until the desired void ratio is reached. This process is accomplished using a combined FDEM simulation.
- Inserting CIEs into the initial FE mesh of the dense particle assembly using a python-based computer program. This paper uses four-node CIEs with zero in-plane thickness. The FE mesh of a single particle is taken as an example to clarify the method used to realize this procedure (Fig. 2). The details of the cohesive element insertion algorithm can be found in the study by Yang et al. [30].
- Numerical simulations of biaxial tests of the polygon assemblies are performed using the ABAQUS/Explicit solver. The detailed modeling procedures will be discussed later.

3.2. Cohesive crack model

The cohesive crack model assumes the existence of a fracture process zone (FPZ) in front of the crack tip, in which energy dissipation occurs during fracture, as illustrated in Fig. 3. In the FPZ for a 2D case, tractions exist in the normal direction t_n and shear direction t_s across the crack surface, and the corresponding relative displacements are δ_n and δ_s. The nonlinear relationship between relative displacement and traction inside the FPZ is characterized by the cohesive crack model. Fig. 4 shows a typical bilinear traction–separation response. A linear elastic traction–separation law is assumed to model the initially undamaged material prior to damage. Once damage is initiated, the failure of the elements is characterized by the progressive degradation of the material stiffness, which is driven by a damage process.

The initial CIE stiffness is defined by the Young's modulus and elastic shear modulus of the intact material. The initial normal stiffness k_n^0 and shear stiffness k_s^0 should be large enough to

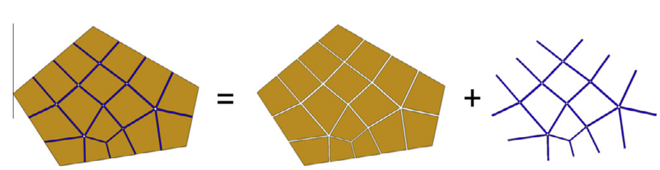

Fig. 2. Inserting CIEs in the initial mesh (which is exaggerated for clarity).