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A statistical meso-damage mechanical method for modeling trans-scale progressive failure process of rock

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ABSTRACT

Starting from the concept of Representative Volume Element (RVE) at the mesoscopic scale, a statistical meso-damage mechanical method (SMDMM) is developed to model the trans-scale progressive failure process of rock, based on the statistical and continuum damage mechanics theory and the finite element method (FEM). The proposed mesoscopic constitutive law of RVE is established within the framework of elastic–brittle-damage theory in which the double damage functions correspond to a tensile and compressive damage surface. A statistical approach is employed to describe the mesoscopic heterogeneity of rock material. The damage evolution and accumulation of mesoscopic RVEs is used to reflect the macroscopic failure characteristics of rock. The global stress and strain fields are solved by the FEM. An element represents a RVE, the initiation and propagation of meso-macroscopic trans-scale cracks and their interaction are manifested by removing the failed elements. Numerical analyses are carried out on a few groups of laboratory-scale rock specimens and the effects of RVE size, material homogeneity and quasi-static loading step length are investigated. Finally, a full-scale Atomic Energy of Canada Limited (AECL) Mine-by test tunnel is simulated. The proposed SMDMM is calibrated and validated for its trans-scale modeling capability to reproduce the shape and size of excavation damage zone profile around the tunnel. Accordingly, the simulation results are compared with experimental observations and numerical results predicted by other models. It is shown that the SMDMM has good performance for modeling the rock failure process from meso- to engineering/field-scale.

1. Introduction

Rock has composite or heterogeneous microstructures with a variety of pre-existing or stress-induced defects, in the form of pores, microdamages, grains, minerals, etc. Rock deformation-damage-failure process is a macroscopic catastrophic process due to accumulation of a great number of microdamages and their trans-scale nonlinear propagation. The multi-scale characteristics and the relationships among different scales of rock are shown in Fig. 1. The essence of rock failure can hardly be understood and the failure mechanism cannot be revealed in-depth only by the macroscopic phenomenological approach. Explanation of high-level characteristics by low-level characteristics becomes an effective way to understand the complex failure process of rock. In recent years, studies on rock failure by physical experiments and numerical simulations have gradually changed from macro- to meso-, microscopic and trans-scale levels, which have become the frontier of fundamental researches in rock mechanics [1–6]. Experimental multi-scale observations of rock failure at laboratory scale indicate that the macroscopic behaviors and the failure process are closely related to mesoscopic damage evolution. The root cause and law of the multi-scale correlation need to be explained by trans-scale analyses [4]. Although the trans-scale failure process of rock has been investigated by physical experiments, numerical reproduction and prediction of these phenomena still remains a big challenge [7,8]. Currently, numerical modeling of the trans-scale progressive failure process of rock has become one of the main trends in numerical simulation of fracture [6–8]. Over the past few years, various numerical models have been continuously proposed [9–19], which can be classified into the three categories:

1. Discontinuum-based models. These models can directly and explicitly permit cracks development of localization and coalescence, but are dependent on the predefined flaws or network of discontinuities and limited by the state of computing technology as to the size of problem to be dealt with. Therefore these models have limited capacity in trans-scale simulation.

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2. Continuum-based models. Depending on whether to consider the physical degradation behavior of individual microcrack, continuum-based models can be subdivided into two categories: the phenomenological models and the micromechanics-based models. The phenomenological models usually require complex constitutive laws to account for the purely macroscopic damage evolution and strength weakening of rock and could not capture the transition from the continuum to discontinuum behaviors. Therefore these models cannot reflect the complete trans-scale failure process involving crack initiation, propagation and coalescence. Micromechanics-based models describe the mechanical degradation effect at the micro- or mesoscopic level, with the behavior of microdefects distributed throughout the material. When dealing with material deformation and fracturing process indirectly by continuum-based models, some special techniques are required to overcome the difference between the continuity state of a problem and randomness and discontinuity of crack propagation under the theoretical framework. As a result, various new methods have been continuously developed. The continuum-based numerical methods are relatively mature and can be easily implemented. It is an alternative to explicit treatment of cracking by discontinuum-based models. The continuum-based models have attracted a lot of attentions nowadays [6].
3. Hybrid models. Hybrid models were developed to take advantages of both continuum and discontinuum-based models. Although hybrid models could be successful in simulating internal crack propagation, and capable to reflect the main characteristics of the damage and fracturing process, the presence of pre-existing flaws (or special crack elements) is always required. Especially, the bottleneck in computational efficiency still exists. For instance, Lisjak et al. [19] recently employed a coupled finite-discrete element model (FEM/DEM) to simulate the damage process during excavation of a two-dimensional (2D) circular opening. The total number of 2D triangular (T3) elements was 160,000, resulting in a total computation time of approximately 4 days on an Intel Core i7-920 2.67 GHz CPU with RAM 8 GB. Therefore, the hybrid models may not be suitable for analysis of large-scale engineering problems.

In situ and engineering/field-scale tests are often used to assess the state-of-the-art in numerical modeling approach, and the capability of numerical models [20]. For instance, the Mine-by experiment (MBE) tunnel of Atomic Energy of Canada Limited (AECL) Underground Research Laboratory (URL) is a well-known test model for assessing the performance of numerical modeling of the complex progressive failure process of brittle rock. Based on the observations during the MBE, several shortcomings of different continuum-/discontinuum-based models were identified. According to the numerical simulation results, Hajiabdolmajid et al. [21] summarized that most models failed to predict both the shape and extent of the failure zones developed around the MBE tunnel. It was hoped that, by advancing the understanding of the progressive failure process, numerical models can be further developed or refined to be predictive tools later [20,22].

In this paper, a general framework based on the statistical meso-damage mechanical method (SMDMM) is introduced to model the trans-scale progressive failure process of rock. The mesomechanical aspects, as well as the damage mechanics, are considered in the SMDMM. The macroscopic mechanical behaviors are traced by propagation and accumulation of mesoscopic factures, with the FEM as a basic field solver. The SMDMM is programmed and implemented into the self-developed software, Rock Failure Process Analysis (RFPA) version 2.0 code. Starting from the concept of Representative Volume Element (RVE), the mesomechanics-based damage constitutive law of RVE is proposed. The double damage descriptions are formulated to include two degradation paths due to compressive and tensile stress fields. A statistical approach based on the Weibull distribution is employed in the macroscopic model to consider the effects of meso-level heterogeneity of RVE properties. Numerical simulations are then performed to investigate the failure process of laboratory-scale specimens with or without pre-existing cracks under uniaxial compression. The effects of RVE size, homogeneity index and quasi-static loading step length on the macroscopic strength, failure mode and crack propagation pattern are then discussed. Finally, in order to further verify the applicability of the SMDMM to engineering-scale rock masses, the full-scale MBE tunnel is simulated to assess the trans-scale modeling capability of the SMDMM in capturing the extent and profile of the failure zone around the tunnel. Accordingly, the simulation results are compared with the findings in the previous relevant studies.

2. Statistical meso-damage (SMD) model

2.1. Representative volume element (RVE)

For rock, damage is not only a state, but also a micro- to macroscopic trans-scale process. The internal microscopic and mesoscopic defects are the initial damage for the stages thereafter. Propagation of initial defects and initiation of mesoscopic cracks are the damage evolution process. However, as illustrated in Fig. 1, under a state far from equilibrium, there is no simple and direction relation between the microscopic mineral atomic, molecular level and the macroscopic level [23]. Macroscopic nonlinearity and damage are the most intuitive and empirical understanding of rock material. The stress–strain relations are usually expressed by multi-parameter phenomenological constitutive laws. In fact, the separation process essentially occurs at micro-scale. However, it brings huge mathematical complexity and challenge to numerical simulation (in terms of both software and hardware). A practical and feasible way is to establish the bridge between the micro- and macro-scales through an intermediate scale, i.e., the mesoscopic scale [12,23–25]. The meso-scale can be a bridge connecting the microscopic essence and the macroscopic representation, and a key intermediate role for trans-scale correlation. On one hand, the relationship between the mesoscopic evolution and the macroscopic rock behaviors shall be traced from the details of the evolution process. This can help to explain the macroscopic mechanical behaviors from the trans-scale viewpoint in terms of failure mechanism, as well as to avoid computational complexity. On the other hand, the material structure can be considered, including the mesoscopic physical properties of various materials. This can provide certain physical background for the damage variable and the damage evolution equations. The mesoscopic model-based method can be a bridge between the physical mesoscopic structure and the macroscopic representation. The mineral structures smaller than the mesoscopic level, such as the original cavity, cements and crystal, are not considered in meso-scale, instead, they are considered as inclusions in the RVE. The initial defects and material matrix are generalized into mesoscopic equivalent RVEs by statistical homogenization so as to reflect the mesoscopic constitutive relation and physical properties, as shown in Figs. 1 and 2a. The following assumptions are made: (1) the RVE is the smallest volume reflecting the statistical average of material properties, is the smallest cell for mesoscopic damage analysis. The damage evolution starts from the RVE level and is irreversible. (2) The RVE is isotropic and only has one damage mode at a moment. (3) The damage evolution of RVE is a function of stress–strain state.