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Particle simulation of thermally-induced rock damage with consideration of temperature-dependent elastic modulus and strength

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ABSTRACT

Based on the particle simulation method, a thermo-mechanical coupling particle model is proposed for simulating thermally-induced rock damage. In this model, rock material is simulated as an assembly of particles, which are connected to each other through their bonds, in the case of simulating mechanical deformation, but connected to each other through thermal pipes in the case of simulating heat conduction. The main advantages of using this model are that: (1) microscopic parameters of this model can be directly determined from the related macroscopic ones; (2) the temperature-dependent elastic modulus and strength are considered in an explicit manner, so that thermally-induced rock damage can be realistically simulated in a thermo-mechanical coupling problem. The related simulation results from an application example have demonstrated that: (1) the proposed model can produce similar behaviors to those observed in experiments; (2) the final failure is initiated from the outer surface of the testing sample and propagates toward the borehole; (3) microscopic crack initiation and propagation processes can be reasonably simulated at the cooling stage.

1. Introduction

Understanding thermally-induced rock damage is of great importance and significance for both scientific research and engineering application. For example, in underground mining engineering, because most of the near-surface mineral deposits (<1000 m) have been exploited, many underground mines involve deep mining (>1000 m). South African mines have been excavated at depths greater than 4000 m below the ground surface level. Due to the existence of a geothermal gradient, the temperature at about 4000 m depth can reach around 120 °C with an average geothermal gradient of 30 °C/km. On the other hand, clean, renewable and safe, geothermal energy extraction has the potential to be one of the most important energy resources in the world. With this new technology, large fractures have to be created to guarantee maximum interaction between cold water with hot dry rock (HDR), so that hot water is pumped for utilization. To increase the geothermal energy extraction from a HDR system, a series of secondary thermally-induced fractures should be generated, resulting in an effective fracture network for water flow. This fracture network allows cold water to flow deeply into the reservoir matrix where the geothermal energy is stored [9]. Thus consideration of thermally-induced rock damage has a large impact on the development of geothermal energy extraction technology.

A large amount of research, theoretical, experimental and numerical, has been carried out in an attempt to understand thermally-induced rock damage over the past decades [3,11,13,14,18]. Although many researchers simulated thermally-induced rock damage at sample-length scales [10,15–18,20,21], they mostly treated the rock as a continuum or a discontinuum with pre-existing flaws or fractures, so that the traditional finite element method (FEM), finite difference method (FDM) or boundary element method (BEM) can be used. However, such a treatment cannot simulate the predominant mechanism of rock failure processes associated with microscopic crack initiation, propagation and coalescence. To simulate the rock failure processes more realistically, the discrete element method (DEM) is widely used in many geotechnical problems during the past four decades [6,12,19,33,34]. Not only can the DEM be used to deal with mechanical problems, it can be extended to solve heat conduction problems in granular materials [8,22,23]. However, although many studies have paid attention to simulation of heat conduction, most neglected the simulation of thermally-induced rock damage in the rock mass. In recognizing this point, some researchers used the DEM-based commercial software (known as the PFC2D) to simulate thermally-induced rock damage [1,2,24]. However, microscopic crack initiation and propagation at the cooling stage of rock is not simulated [24]. Although it has been recognized that this limitation could be overcome by introducing particle clusters to represent more

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realistic grain shapes [24], no further work has been devoted to simulating microscopic crack initiation and propagation at the cooling stage until now. On the other hand, in previous publications, the macroscopic parameters (i.e. elastic modulus, both tensile strength and shear strength) are treated as constants, so that the corresponding microscopic parameters (i.e. contact stiffness, both normal bond strength and tangential strength) are also constants. This may be reasonable for either a pure mechanical system or a thermo-mechanical coupling system with small changes of temperature. However, if the temperature change is large, this simplification may be questionable, depending on how temperature affects the macroscopic parameters of the material within a thermo-mechanical coupling system. For example, experimental studies of Westerly granite indicate that its dimensionless elastic modulus reduces by 70% at 500 °C [11]. Meanwhile, the tensile strength of Westerly granite reduces from 13.8 MPa at room temperature to about 7 MPa at 500 °C [11]. Such large decreases in the elastic modulus and strength should certainly affect thermal and mechanical processes and therefore, must be considered in the thermo-mechanical modeling. Since the particle simulation method has been widely used to simulate mechanically-induced rock damage problems at laboratory-, engineering-, and geological-length scales associated with microscopic crack initiation and propagation [25–31], it is desirable to extend the existing particle simulation method from a purely mechanical system to a thermo-mechanical coupling system, so as to simulate thermally-induced rock damage problems associated with microscopic crack initiation and propagation. In addition, the effect of temperature on the macroscopic parameters (i.e. elastic modulus and bond strength) in the particle simulation model must be considered. This means that the corresponding microscopic parameters (i.e. contact stiffness, both normal bond strength and tangential strength) in the particle simulation model should be expressed as the functions of temperature.

Keeping the aforementioned considerations in mind, this paper is arranged as follows. In Section 2, the thermo-mechanical coupling problem to be simulated using the particle simulation method is described. In Section 3, an application example is given to investigate thermally-induced rock damage using the proposed thermo-mechanical coupling particle model. Finally, some conclusions drawn from this study are given in Section 4.

2. Simulation of thermal and mechanical coupling processes

2.1. Simulation of the mechanical deformation process

The particle simulation method [25–31] treats the material as an assembly of particles, which can interact with each other through their contacts and links (represented by bonds). The motion of the particle is controlled by Newton's second law, while the contact force is governed by a force–displacement law. Since the particle can straightforwardly be associated with large displacements, including block rotations, fracture opening and complete detachments, microscopic crack initiation, propagation and coalescence can be traced and simulated automatically. For this reason, it is desirable to extend the existing particle simulation method from a purely mechanical system to a thermo-mechanical coupling system, so as to simulate thermally-induced rock damage associated with microscopic crack initiation and propagation. Thus, the corresponding formulation of the thermo-mechanical coupling particle model based on the particle simulation method is described below.

In the thermo-mechanical coupling particle model, the normal and tangential contact forces are calculated using Eqs. (1)–(4):

$$F^n_{mechanical}(T)=\begin{cases}K^n(T)U^n & (U^n\geqslant \bar{U}^n)\\ 0 & (U^n<\bar{U}^n)\end{cases}\quad\text{(before the normal contact bond is broken)}$$
$$F^n_{mechanical}(T)=\begin{cases}K^n(T)U^n & (U^n\geqslant 0)\\ 0 & (U^n<0)\end{cases}\quad\text{(after the normal contact bond is broken)}\tag{1}$$

$$\Delta F^s_{mechanical}(T)=\begin{cases}-k^s(T)\Delta U^s & (U^n\geqslant \bar{U}^n)\\ 0 & (U^n<\bar{U}^n)\end{cases}\quad\text{(before the normal contact bond is broken)}$$
$$\Delta F^s_{mechanical}(T)=\begin{cases}-k^s(T)\Delta U^s & (U^n\geqslant 0)\\ 0 & (U^n<0)\end{cases}\quad\text{(after the normal contact bond is broken)}\tag{2}$$

$$K^n(T)=\frac{k_n^{(A)}(T)k_n^{(B)}(T)}{k_n^{(A)}(T)+k_n^{(B)}(T)}\tag{3}$$

$$k^s(T)=\frac{k_s^{(A)}(T)k_s^{(B)}(T)}{k_s^{(A)}(T)+k_s^{(B)}(T)}\tag{4}$$

where $F^n_{mechanical}(T)$ is the mechanical, temperature-dependent, normal contact force at a contact between two particles; U^n is the normal displacement at the contact; $\bar{U}^n$ is the critical normal displacement corresponding to the contact bond breakage at the contact in the normal direction; $\Delta F^s_{mechanical}(T)$ is the corresponding mechanical incremental tangential component of the temperature-dependent contact force; ΔU^s is the corresponding mechanical incremental tangential displacement at the contact; $K^n(T)$ is the temperature-dependent contact normal stiffness; $k^s(T)$ is the temperature-dependent contact tangential stiffness; $k_n^{(A)}(T)$ and $k_n^{(B)}(T)$ are the temperature-dependent normal stiffness of particles A and B; $k_s^{(A)}(T)$ and $k_s^{(B)}(T)$ are the temperature-dependent tangential stiffness of particles A and B, respectively. The constitutive behavior at a contact between two particles is shown in Fig. 1(a).

In a purely mechanical system, if two circular particles in contact have the same normal and shear stiffnesses, then the values of these stiffnesses are equal to twice the macroscopic elastic modulus of the material [29]. Similarly, in the thermo-mechanical coupling system, if two circular particles in contact have the same normal and shear stiffnesses, then the values of these stiffnesses should be a function of temperature as follows:

$$k_n(T)=k_s(T)=2E(T)\tag{5}$$

where $E(T)$ is the temperature-dependent elastic modulus of the particle material.