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DEM investigation of weathered rocks using a novel bond contact model

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ABSTRACT

The distinct element method (DEM) incorporated with a novel bond contact model was applied in this paper to shed light on the microscopic physical origin of macroscopic behaviors of weathered rock, and to achieve the changing laws of microscopic parameters from observed decaying properties of rocks during weathering. The changing laws of macroscopic mechanical properties of typical rocks were summarized based on the existing research achievements. Parametric simulations were then conducted to analyze the relationships between macroscopic and microscopic parameters, and to derive the changing laws of microscopic parameters for the DEM model. Equipped with the microscopic weathering laws, a series of DEM simulations of basic laboratory tests on weathered rock samples was performed in comparison with analytical solutions. The results reveal that the relationships between macroscopic and microscopic parameters of rocks against the weathering period can be successfully attained by parametric simulations. In addition, weathering has a significant impact on both stress–strain relationship and failure pattern of rocks.

1. Introduction

Weathering of rocks is a process of the disintegration of rocks through contact with the Earth's atmosphere, biota and water. Weathering is common in nature and may deteriorate not only physical properties of rocks (e.g. density, void ratio, and hydraulic properties), but also the mechanical properties (e.g. reduction in strength over time). Hence, it is of great significance to understand the long-term mechanical behavior of rocks to achieve economically and mechanically adequate designs for structures involving rock masses in the entire life cycle, such as high rock slopes, and underground radioactive waste deposit.

Presently, the phenomenon of rock weathering has been extensively studied using experimental approaches, which, however, fail to determine the weathering time due to the long-time span and the error from dating methods. Instead, degree of weathering is generally used for classification. Gupta and Rao (1998, 2000) investigated the physico-mechanical properties of rocks under different degrees of weathering and presented the relations between the indices. Tugrul (2004), Beavis et al. (1982), and Irfan and Dearman (1978) also experimentally studied the physico-mechanical properties of a variety of weathered rocks classified by the degree of weathering.

Merely a minority of researchers estimated the weathering time using isotopic dating method. Sunamura (1996) summarized the rate of coastal tafoni development. Hachinohe et al. (2000) studied the rate at which the thicknesses of weathered zones increase and the strengths of weathered rocks decrease. Based on this work, they proposed an approach for predicting rock strength at a given depth and weathering time. In addition, Oguchi et al. (1999) examined four dated lava domes made of porous rhyolite and performed a series of experimental tests to investigate the evolution rules of rock properties, and Matsukura et al. (2002) investigated the same material with emphasis on the effect of weathering on strength anisotropy.

The aforementioned efforts have demonstrated that the weathering process impacts not only the strengths of rocks, but also their deformation behaviors. The authors believe that the variations of rock behaviors are closely related to the change of microstructure and micro-properties. However, it is still extremely difficult to detect the evolution of microstructure during weathering using any available experimental technique. Alternatively, the distinct element method (DEM) equipped with a proper bond contact model for rocks stands out as a powerful tool to study the

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macroscopic and microscopic characteristics of weathered rocks. This approach was originally proposed by Cundall and Strack (1979) based on the discrete mechanics, and is widely applied in the field of geotechnical engineering due to its capacity of modeling heterogeneous, discontinuous materials subjected to large deformation and related macroscopic behaviors with microscopic mechanisms. Recently, the method has been introduced into the field of rock mechanics and shows a great potential. Potyondy and Cundall (2004) proposed the bonded particle model (BPM) to model Lac du Bonnet granite. Wang and Tonon (2009) subsequently proposed the three-dimensional (3D) bond model to study the triaxial behaviors of the same material. Jiang et al. (2013) developed a novel bond contact model for rocks on the basis of experimental investigation and theoretical analysis, and reproduced adequately the mechanical behaviors of typical rocks such as the Lac du Bonnet granite.

Several researchers made valuable contributions to DEM analyses of rock weathering. Calvetti et al. (2005) modeled the degradation of strength due to weathering by means of continuous and discrete approaches. Utili and Nova (2008) established a contact bond model based on two micromechanical contributions (i.e. intergranular friction and cohesive bond force) and modeled the evolution of natural cliffs subjected to weathering as an example. However, the evolution of rock strength applied in the study was based on the research conducted by Kimmance (1988), where the strength was not related to weathering time, resulting in an unclear relationship between rock slope stability and time period. Nevertheless, these studies remain preliminary by using simple contact models of rocks.

In this paper, time-dependent weathering laws were established for rock mechanical properties (strength and deformation parameters), and their relations with the evolution of microscopic parameters were investigated by deploying a novel contact model for rocks (Jiang et al., 2013). This study aims to enhance the understanding of weathering of rocks from a microscopic point of view, and to promote future investigations including rock properties prediction and practical engineering modeling. Although this paper presents the results derived from porous rhyolite as an example, the presented methodology and qualitative relationship are applicable to other types of rocks weathered in different circumstances.

2. Evolution laws of macroscopic mechanical properties of rocks due to weathering

Although weathering may give rise to a variety of changes on rocks, this paper regards the degradation of rock mechanical properties as the overall impact of weathering on the basis of available research findings without distinguishing different mechanisms. Oguchi et al. (1999) performed a series of unconfined compression tests and Brazilian tests on the porous rhyolite subjected to different weathering times over 40 thousand years, and the strengths obtained against the weathering time are listed in Table 1.

In the light of the formula presented by Sunamura (1996), an exponential function ($y = ae^{-bx}$) is selected to fit the experimental data. The relationships between normalized strengths and weathering time are shown in Fig. 1, and the corresponding equations are given as follows:

Table 1
Compressive and tensile strengths of porous rhyolite at different weathering times (Oguchi et al., 1999).

Weathering time (ka)	Compressive strength (MPa)	Tensile strength (MPa)
1.1	15.3	1.97
2.6	13.7	2.11
20	5.9	0.47
40	4	0.24

$$\sigma_c/\sigma_{c0} = e^{-0.0404t} \tag{1}$$

$$\sigma_t/\sigma_{t0} = e^{-0.0643t} \tag{2}$$

where σ_c is the unconfined compressive strength (MPa); σ_t is the tensile strength (MPa); σ_{c0} and σ_{t0} are the maximum compressive and tensile strengths (MPa), respectively; and t is the weathering time (ka).

Fig. 1 shows that rock strengths decrease significantly at the initial stage of weathering, and the degradation rate decreases with increasing weathering time, which can be adequately captured by the exponential function. Besides, the degradation rate of tensile strength is greater than that of compressive strength. It is noted that although both lithology and weathering environment may impact the behaviors of weathered rock, the general trend can be featured by the same function with different fitting constants.

Unfortunately, Oguchi et al. (1999) provided no experimental data of deformation parameters. Thus, the experimental observation reported by Gupta and Rao (2000) is used instead to establish the evolution law of deformation parameters. They tested strengths, elastic modulus and Poisson's ratio of weathered granite, basalt and quartzite at different weathering grades. In this study, we select the data of basalt and estimate the weathering times for each weathering grade using Eqs. (1) and (2), assuming the same weathering laws as porous rhyolite (Table 2). Although two different calculated values can be obtained from Eq. (1) or Eq. (2), the discrepancy is small and the adjusted value is observed to fit both curves of Eqs. (1) and (2) (Fig. 2).

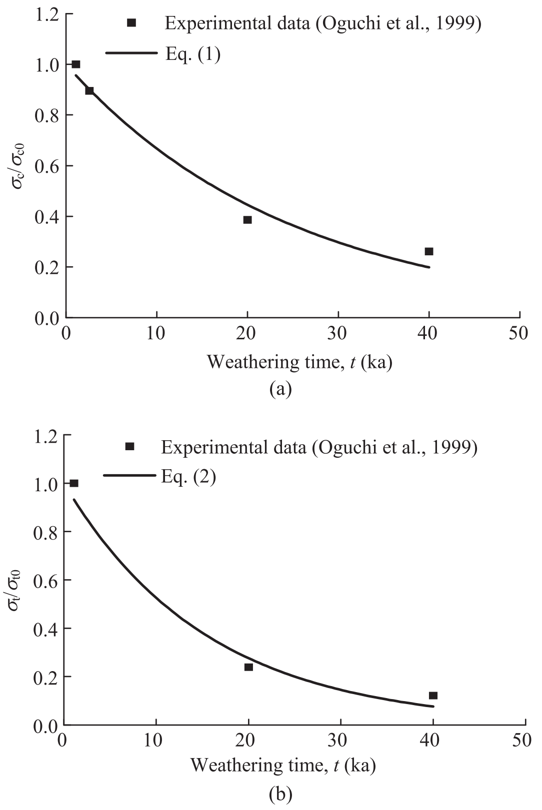

Fig. 1. Evolution laws of (a) unconfined compressive strength and (b) tensile strength.