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A dissolution-diffusion sliding model for soft rock grains with hydro-mechanical effect

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ABSTRACT

The deformation and failure of soft rock affected by hydro-mechanical (HM) effect are one of the most concerns in geotechnical engineering, which are basically attributed to the grain sliding of soft rock. This study tried to develop a dissolution-diffusion sliding model for the typical red bed soft rock in South China. Based on hydration film, mineral dissolution and diffusion theory, and geochemical thermodynamics, a dissolution-diffusion sliding model with the HM effect was established to account for the sliding rate. Combined with the digital image processing technology, the relationship between the grain size of soft rock and the amplitude of sliding surface was presented. An equation for the strain rate of soft rocks under steady state was also derived. The reliability of the dissolution-diffusion sliding model was verified by triaxial creep tests on the soft rock with the HM coupling effect and by the relationship between the inversion average disjoining pressure and the average thickness of the hydration film. The results showed that the sliding rate of the soft rock grains was affected significantly by the waviness of sliding surface, the shear stress, and the average thickness of hydration film. The average grain size is essential for controlling the steady-state creep rate of soft rock. This study provides a new idea for investigating the deformation and failure of soft rock with the HM effect.

1. Introduction

Deformation and failure of soft rock affected by hydro-mechanical (HM) effect are one of the most important issues in geotechnical engineering field. The deformation and failure of soft rock such as crack propagation, shear zone deformation, and creep are closely related to grain sliding at meso-scale. In order to understand the meso-mechanism of soft rock deformation and failure, it is necessary to understand the grain sliding of soft rock with the HM effect. Many studies have been carried out by focusing on the sliding of brittle rock grains and crystalline material grains, including elastic-, diffusion- and dislocation-coordinated grain slidings. The former two grain sliding phenomena mainly occur in low stress state and the third one mainly occurs in high stress state. This article deals with the diffusion-coordinated grain sliding in the low stress condition, in which diffusion is considered around the sliding surface. Conventionally, the grain sliding rate was the focal point in the previous studies.

Gifkins and Snowden (1966) derived the diffusion-coordinated sliding rate for the step-shaped grain sliding, but they only considered the boundary diffusion, ignoring the body diffusion. Ashby et al. (1970) and Ashby (1972) established a diffusion-coordinated grain sliding model with introduction of a saw-toothed sliding surface. In this model, the grain sliding rate with low degree of waviness was derived. Additionally, they discussed the behavior of atoms surrounding the sliding surface when the crystalline grains slid, and found that if the crystal contains significant defects, the predications of grain sliding rate and creep rate are in accordance with the classical results. Subsequently, Ashby and Verrall (1973) established a diffusion-coordinated grain deformation model in the condition of tensile stress. In this model, interaction among grains has been taken into consideration, and it was found that the grains do not exhibit apparent deformation in the direction of tensile stress. Yang and Wang (2004) assumed that the model proposed by Ashby and Verrall (1973) was not repeatable, and they proposed a nine-grain sliding model in consideration of different distances between grains. The molecular dynamics was employed for the simulation with this model, and it was observed

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that the grain creep rate is positively correlated with stresses. Raj and Ashby (1971) proposed a grain sliding model by taking into consideration both boundary and body diffusions, based on which the sliding and strain rates were derived. Meanwhile, a three-dimensional sliding model was proposed, and the obtained results accorded with the conclusions of Gifkins and Snowden (1966). Rutter and Mainprice (1979) studied the sliding of quartz-sandstone grain under the HM effect, and derived the sliding rate of quartz grains under shear stress. The theoretical results have also been verified by the stress relaxation experiments on sandstones. Morris and Jackson (2009a, b), Lee and Morris (2010) and Lee et al. (2011) modified the grain sliding model proposed by Raj and Ashby (1971), by considering the grain boundary. With this model, both elastic- and diffusion-coordinated grain slidings were discussed and the first- and second-order solutions were achieved. It was shown that the sliding rate varies with the positions of grain boundary. Jackson et al. (2014) discussed the difference and relations between the elastic- and diffusion-coordinated grain slidings, and validated the conclusions of Lee and Morris (2010) through experiments. Korla and Chokshi (2014) observed the deformation of crystalline materials as well as the sliding of internal grains under stresses using scanning electron microscope (SEM) and electron back-scattering diffraction (EBSD), and derived an continuity equation describing the grain sliding. Mancktelow and Pennacchioni (2004) found that quartz grains in aqueous conditions were different from those in anhydrous conditions, and that the quartz sliding was hindered significantly in the anhydrous conditions.

Recently, relative research has been conducted mainly in the following three respects:

(1) The impact of other substances on the grain sliding. Dobosz et al. (2012) used the finite element method (FEM) to simulate the case that the second substance was added at the boundary of grains, and they found that the grain sliding apparently enhanced the material's hardening. In order to observe the phenomena of coupling and sliding between particles, Schäfer and Albe (2012a) simulated the case that other substances were dispersed at the boundaries between crystal grains by the molecular dynamics theory. In addition, the uniaxial tension test was also conducted. It was shown that the solutes at the boundaries were conducive for the sliding between crystal grains. Du et al. (2011) also conducted simulations based on the molecular dynamics theory, and found that grain sliding was more significant when some other substances were present. Schäfer and Albe (2012b) simulated the variation in solution concentration of other substances using the large-scale atomic/molecular massively parallel simulator (LAMMPS), and found that the grain sliding was thus considerably influenced. Molodov et al. (2011) studied the grain sliding within aluminium specimens and found that the increase in concentration of other substances accelerated their migration rate at the boundary of crystal grains, and thereby enhanced the sliding rate.

(2) The coupling of grain rotating and sliding. Kim et al. (2010) proposed a rotating-sliding coupling model of regular-hexagon-grain. In comparison with the sliding rates of cases with or without grain rotating, it was found that by considering the grain rotating, the diffusion-coordinated sliding rate was relatively large. Ovid'ko and Sheinerman (2013) carried out a similar study through discrete element numerical simulation, considering the coupling effect of grain rotating and sliding. According to the stress–strain curve obtained from the uniaxial compression test, the ductility of materials was obviously improved due to the coupling effect of grain rotating and sliding. Since the variations in grain rotating, sliding and deformation can be well detected by the EBSD, Bird et al. (2015) used the EBSD to observe the structures and orientations of crystalline, and put forward an improved grain sliding model to reveal the impact of grain rotating on material creep.

(3) The impact of grain sliding on crack propagation. Ovid'ko et al. (2011) proposed a new crack propagation model by taking into account the crystal grain sliding under stresses. The stress intensity factor of cracks was derived. It was indicated that the grain sliding and migration facilitate the crack propagation. Fang et al. (2014) established a two-dimensional model containing initial cracks, considering the diffusion-coordinated grain sliding. It was revealed that the stress intensity factor increased with the decrease in grain size. Ovid'ko and Sheinerman (2012) established a crystalline solid model with pre-cracks, and it was found that the fracture toughness of cracks was enhanced due to the grain rotating around the cracks, which was consistent with the findings from the previous studies (Cheng et al., 2010; Liu et al., 2011).

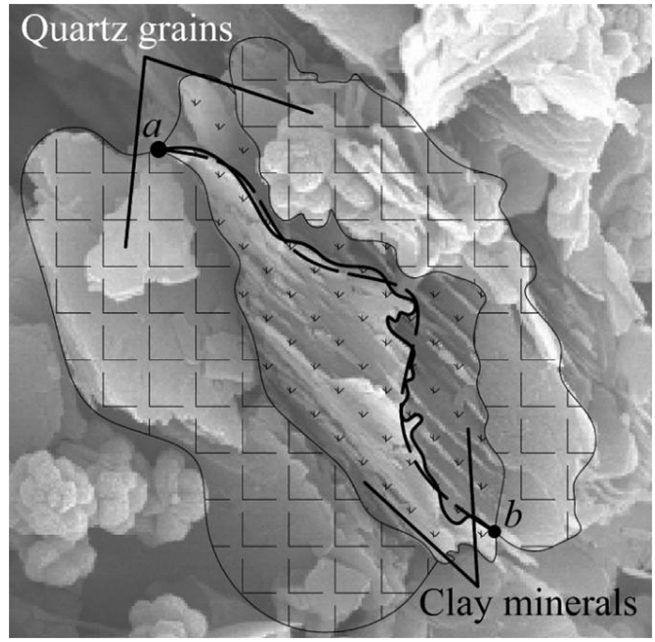

Fig. 1. Typical distribution and shape of red bed soft rock grains (Zhu, 2009).

There are distinct differences between soft and brittle rocks. The soft rock is rich in clay minerals. When it contacts with water, significant physico–chemical reactions take place, and it is thus much easier to induce disasters. With the hydro-mechano-chemical coupling effect, the sliding of soft rock grains is different from that of brittle rock grains. However, rare research has been conducted with respect to the sliding of soft rock grains under the hydro-mechano-chemical effect.

The objectives of this study are to conduct laboratory experiments on the red bed soft rock from South China, and discuss the dissolution and diffusion of soft rock grains with the HM effect. Based on the cosine sliding surface, the equations of continuity, mechanical equilibrium and chemical potential balance of the soft rock dissolution and diffusion are established. Combined with the Einstein-Stokes equation, the equation for the grain sliding rate can be established. Finally, a dissolution-diffusion sliding model of soft