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A self-consistent model with asperity interaction for the mechanical behavior of rock joints under compressive loading

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1. Introduction

The contact behavior of rock joint remains a challenging issue in the field of rock mechanics. The Greenwood-Williamson (GW) model[1,2] is the foundation of many theoretical models for the contact behavior of rock joints, in which the contact of each individual asperity obeys the Hertz theory. In the GW model, the rough surface is treated as a population of isolated spherical asperities with identical radius and their heights follow a Gaussian distribution with respect to a mean plane. However, the GW model neglects several key points influencing the contact behavior of rock joints under compressive loading: (1) the complex surface geometries which includes small-scale roughness component and large-scale waviness component,[3–5] (2) the contact state between the upper and the lower blocks of a rock joint,[5,6] (3) the deformation caused by the bulk substrate deformation,[3,4,7] and (4) the deformation caused by the asperity interaction during the process of normal loading.[3,4,7] Several theoretical/analytical contact models were developed to capture the closure behavior of a rock joint under compressive loading through contact theory or elastic theory, in which we can highlight the models proposed by Xia et al.[5] and Tang et al.[8–10] due to the mentioned limitations existing in GW model were at least partly solved. Besides, the superposition principle in linear elasticity was also used to consider the contact behavior of rock joints,[7,11] in which the asperity was simplified as cylinder.

Recently, Wang et al.[12] developed a self-consistent model for the elastic contact of rough surfaces to account for the asperity interaction through the Boussinseq's solution. However, both the complex geometries of joint morphology and the contact states between the two blocks of a rock joint can hardly be considered by the Wang model. To seek a possible solution for the challenging issue, we try to apply the Boussinseq's solution to describe the closure process of rock joints under compressive loading. For comparison, both the experimental results and the theoretical curves predicted by the proposed model and three available models are given.

2. New contact model accounting for asperity interaction

As stated in the self-consistent model proposed by Wang et al.,[12] the elastic contact of rough surfaces can be viewed by a representative asperity with an effective contact radius a and the influence of other asperities which is accounted for by assuming an effective elastic field outside the territory of the representative asperity with radius b. The model assumes that the mean pressure outside the radius b is consistent with that inside. The effective contact radius a can be determined by Eq. (1) and the relation between a and b is given by Eq. (2).

$$a = \frac{3}{4}\sqrt{\pi R \sigma_s} \tag{1}$$

$$\left(\frac{a}{b}\right)^2 = \frac{A}{A_0} \tag{2}$$

where, R is the curvature of the representative asperity, σ_s is the root mean square roughness of the rough surface, A is the real contact area of the two contact surfaces and A_0 is the nominal contact area of the surfaces.

If the pressure over the contact region ($r \le a$) is denoted as $p(s)$, the mean pressure $\overline{p}$ outside the radius b is consistent with that inside, which is applied throughout the region $r > b$ (as shown in Fig. 1) and can be given by Eq. (3). According to the classical Hertz contact theory,[13] the contact force between two rough surfaces, f_1, can be given

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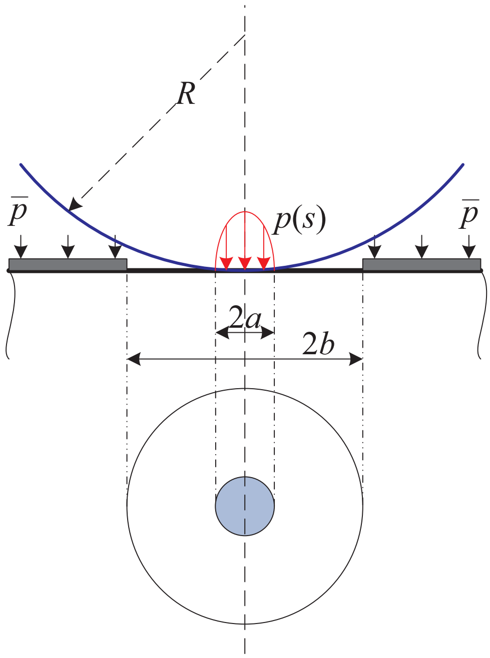

Fig. 1. Self-consistent model for the contact of two rough surfaces (modified from[12]).

by Eq. (4). The solution neglected the effect of asperity interaction under the normal loading. To overcome the limitation, Wang et al.[12] proposed a self-consistent solution for the elastic contact of rough surfaces to account for the asperity interaction, given by Eq. (5), which was on basis of the Boussinesq's solution for a concentrated normal force acting on a half-space. However, the substrate deformation, one of the important factors influencing the contact behavior of rock joint,[4,5,8] cannot be considered by the Wang model. Here, we applied the model proposed by Tang et al.[8] to consider the effect, as given in Eq. (6). Thus, the total contact force F of two rough surfaces can be viewed as the sum of f_2 and f_3, as given in Eq. (7).

$$\overline{p} = \frac{1}{\pi b^2}\int_0^a p(s)2\pi s\,ds \tag{3}$$

$$f_1 = \int_0^{2\pi}\int_0^a \frac{p(s)s}{\sqrt{s^2 + r^2 - 2rs\cos\theta}}\,d\theta ds \tag{4}$$

$$f_2 = \overline{p}\int_0^{2\pi}\int_0^b \frac{s}{\sqrt{s^2 + r^2 - 2rs\cos\theta}}\,d\theta ds \tag{5}$$

$$f_3 = \frac{4}{3}E'\eta\beta^{1/2}\int_d^\infty [g(z-d)]^{3/2} f(z)dz \tag{6}$$

$$F = f_2 + f_3 \tag{7}$$

where E' is the Hertz elastic modulus, η is the areal density of asperities, β is the root mean square radius of peaks, $f(z)$ is the distribution function of the asperity heights, and $g(z-d)$ is the function of the applied displacement $(z-d)$.

The proposed model can be solved by an iterative method. Firstly, we need to apply a small initial displacement δ to the contact surfaces, and then the area ratio $\left(\frac{a}{b}\right)^2$ can be determined based on the composite topography of the rock joint. According to the applied initial displacement δ, we can calculate the contact force f_3 by using the approach proposed by Tang et al.[8] Then the averaged pressure $\overline{p}$ across the real contact area can be determined. On the other hand, to solve the integral equation, Eq. (5), we should first check whether the stress distribution, $\overline{p}$, is reasonable or not. If the value $\overline{p}$ is larger than a proper one, the pressure at the contact fringe will ascend to infinity,[13] implying the unreasonable contact outside the contact region. Otherwise, the pressure will appear negative at the contact fringe, which is physically unreasonable for the Hertz contact. For a reasonable value of $\overline{p}$, we can calculate the contact force f_2. By using the above mentioned iteration method to seek the proper value of $\overline{p}$, we can obtain a finite positive pressure in the whole contact region. Thus, we treat the sum of f_2 and f_3 as the contact force of two rough surfaces and the corresponding normal displacement is the closure deformation. The flowchart of the iterative algorithm is shown in Fig. 2.

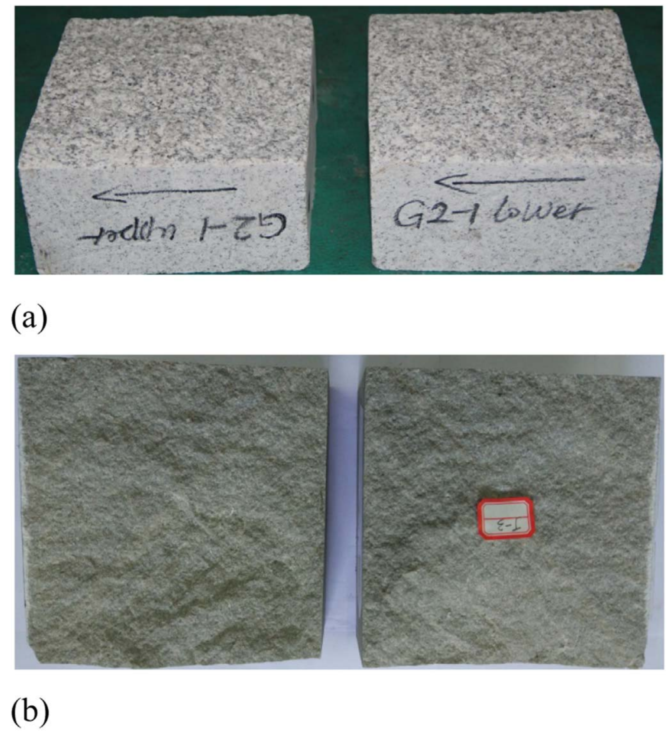

Fig. 2. The main procedure for solving the model.

3. Experimental verification

3.1. Rock joints

To obtain fresh, un-weathered and perfect matedness samples, several intact rock blocks were split and two of them were selected to perform the following closure deformation test. The selected samples are shown in Fig. 3. The granite is composed of feldspar, quartz and black micas with a medium grain texture. The sandstone is dominantly composed of feldspars and quartz with fine sandy texture, cemented by calcium carbonate. The size of the samples is 150 mm length, 150 mm width and 150 mm height. Cylindrical samples with a diameter of 50 mm and a height of 100 mm were used to obtain the main mechanical parameters, such as the Young's modulus, Poisson's ratio, uniaxial compression strength, listed in Table 1.

Prior to closure test, the topography of the two joints were measured by an advanced stereo-topometric scanning system 3D CaMega. The system has the advantages of high precision, good repeatability and high measurement speed. The resolution of the spatial location of each sampling point in three-dimensional space along x, y, and z direction is ± 25 µm. To capture the topography of the joint surfaces precisely and also avoid time-consuming task in the process of point clouds data analysis, the sampling interval is selected as 0.5 mm in both x and y direction in the present study. Several morphological parameters are listed in Table 2.

As stated by Xia et al.,[5] contact state between the upper block and the lower block of a rock joint is an important factor influencing its