International Journal of Rock Mechanics & Mining Sciences 83 (2016) 170–173

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Short communication

Closure model with asperity interaction in normal contact for rock joint

Zhi Cheng Tang [a,f], Cai Chu Xia [b,c], Yu Yong Jiao [d], Louis Ngai Yuen Wong [e,f,*]

[a] Faculty of Engineering, China University of Geosciences, Wuhan, Hubei 430074, China
[b] College of Civil Engineering, Shaoxing University, Shaoxing 312000, PR China
[c] Department of Geotechnical Engineering, Tongji University, Shanghai 200092, PR China
[d] State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, China
[e] Department of Earth Sciences, The University of Hong Kong, China
[f] Formerly School of Civil and Environmental Engineering, Nanyang Technological University, Block N1, 50 Nanyang Avenue, 639798 Singapore, Singapore

ARTICLE INFO

Article history:
Received 16 August 2015
Received in revised form
21 December 2015
Accepted 23 December 2015
Available online 16 January 2016

Keywords:
Rock joint
Closure deformation
Asperity interaction
Morphology component

1. Introduction

In jointed rock mass of low matrix permeability, rock joints are the dominant pathways for fluid flow and solute transport. An in-depth understanding of fluid flow or solute transport characteristics of rock joint under loading is therefore an important practical issue in many rock engineering applications, such as CO_2 sequestration and underground nuclear waste repository. Studying the mechanical or hydro-mechanical behavior of rock joint at a small scale in laboratory is a prerequisite to comprehensively understand the in situ mechanical or hydro-mechanical behavior of a jointed rock mass. It has long been recognized that the roughness influences the mechanical or hydro-mechanical behavior of rock joint. Thus, numerous definitions and measurement techniques of surface roughness have been developed in the past forty years. According to the International Society for Rock Mechanics (ISRM),[1] roughness comprises large-scale (waviness) and small-scale (unevenness/asperity) components. However, several researchers have stressed that joint surfaces only show roughness across all length scales.[2–4] These contradicting concepts might be due to the observation of different scale joints.[5] The former is usually restricted to small rock joints ($<1\,m^2$). In the present study, we focus on the effect of normal loading on the closure deformation of rock joint at a laboratory scale. Hence, the ISRM suggested method is used to describe the surface roughness.

Numerous researchers have investigated approaches for incorporating the effect of asperity contacts. The notable early effort along this line can be traced to the work of Greenwood and Williamson.[6] The recent developments of rock joint contact modeling can be classified into direct simulation using equivalent method [7–9] and statistical method.[10–14] Several researchers, such as Hopkins,[7] Pyrak-Nolte and Morris,[15] Lee and Harrison [8] and Petrovitch et al.,[16,17] account for roughness and deformation implicitly by numerical work. In these models, rock joints only contain roughness component. However, there are a few reports [18,19] documenting the research on the influence of waviness component on the closure behavior of rock joints based on Greenwood and Williamson model.

According to Hopkins,[7] mechanical interaction of deformed asperity caused by normal loading has a great influence on the overall closure behavior of a rock joint, which was ignored by most of the above approaches. To further understand the closure behavior of rock joint, an improved Xia model [18] with the inclusion of asperity interaction is proposed in the present study.

* Corresponding author at: Department of Earth Sciences, The University of Hong Kong, China.
E-mail address: lnywong@hku.hk (L.N.Y. Wong).

http://dx.doi.org/10.1016/j.ijrmms.2015.12.006

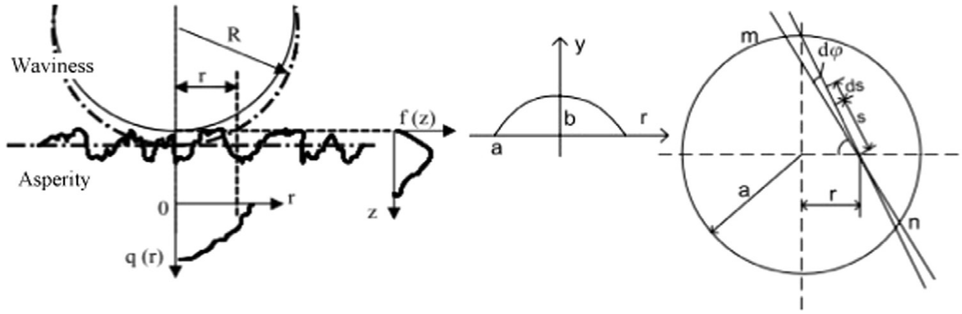

Fig. 1. Conceptual scheme for the contact between a “waviness” and an “unevenness” (modified from[18]).

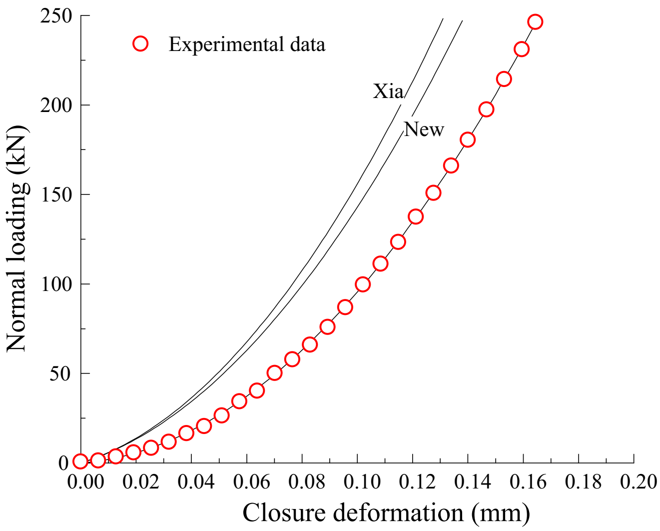

Fig. 2. Comparison of theoretical curves and experimental data for rock joint.

2. Theoretical closure model for rock joint

In the Greenwood and Williamson model,[6] when the separation between the mean plane of a rough surface and the contacting rigid plane is d, and an asperity of height z is compressed by $(z-d)$, then a force acting on the deformed asperity is given by $P_1=\frac{4}{3}E'\sqrt{\beta}\,(z-d)^{\frac{3}{2}}$, where $E'=\frac{E}{2(1-\nu^2)}$, E is the Young's modulus, ν is the Poisson's ratio; β is the root mean square radius of peaks. Adding these individual forces by a statistical averaging approach as performed in the Greenwood and Williamson theory or by direct addition in a numerical simulation, gives the total force acting on the rough surfaces. At light load, the mechanical interaction between deformed asperities has little effect on the overall closure deformation due to the relatively few asperities in contact. As load increases, the number of contacting asperity increases and for heavier load, the distribution of contacting asperity can be treated as uniform over the apparent contact area. According to Timoshenko and Goodier [20] and Ciavarella et al.,[21] the average deformation over a compact area A due to a uniform pressure p_{nom} acting on that area is $\frac{p_{nom}\sqrt{A}}{E'}$. Thus, the height of each asperity is in effect reduced from z to $(z-\frac{p_{nom}\sqrt{A}}{E'})$ and the corresponding force becomes $P_2=\frac{4}{3}E'\sqrt{\beta}\,(z-\frac{p_{nom}\sqrt{A}}{E'}-d)^{\frac{3}{2}}$. As the pressure distribution of asperity contact is relevant to the asperity deformation $u(r)$, the asperity pressure $q_a(r)$ at the contact area can be obtained as follows according to all of the above considerations and the Greenwood and Williamson model [6]:

$$q_a(r)=\frac{4}{3}\eta E'\sqrt{\beta}\int_0^{u(r)}\left[u(r)+\frac{p_{nom}\sqrt{A}}{E'}-z\right]^{\frac{3}{2}}f(z)dz \tag{1}$$

where, η is the mean peak density of unevenness in composite topography of a joint; $f(z)$ is the height distribution function of the asperities with the topographical height z as the independent variable.

Eq. (1) is an iterative expression and can be solved with high accuracy by using the Greenwood and Williamson model to estimate the mean pressure $p_{\rm nom}$ by the first iteration.

To analyze the contact behavior between a “waviness” surface and an “unevenness” surface as shown in Fig. 1, waviness is simplified by a periodic function and has identical amplitude. The load applied to each peak of waviness can be solved according to static equilibrium and deformation compatibility of the contact area. When an external load P is applied to a waviness surface, the pressure distribution of contact area for waviness $q_w(r)$ is determined by[18]

$$q_w(r)=\frac{P}{\pi c}\left(\frac{1}{r^2+4b^2}-\frac{1}{a^2+4b^2}\right) \tag{2}$$

where, r is the distance from the contact center, shown in Fig. 1; a, b are the radius of circular contact area and a special curve, respectively, shown in Fig. 1; $c=\ln(\frac{a^2+4b^2}{4b^2})-\frac{a^2}{a^2+4b^2}$.

and at the center of contact area $(r=0)$, the pressure is given by[18]

$$q_w(0)=\frac{a^2P}{4\pi b^2c\left(a^2+4b^2\right)} \tag{3}$$

Waviness deformation $w(r)$ and asperity deformation $u(r)$ is determined by.[18]

Table 1
Morphology parameters of artificial rock joints.[19]

Dislocation (mm)	Group I				Group II			
	η (mm^{-2})	β (mm)	e_0 (mm)	R (mm)	η (mm^{-2})	β (mm)	e_0 (mm)	R (mm)
5	0.1666	6.3248	1.36	∞	0.0970	5.1626	2.18	141.8
10	0.1727	6.2276	1.93	∞	0.0950	5.4584	2.66	144.3
15	0.1738	6.443	2.24	∞	0.0955	5.3642	3.02	143.7

e_0: initial aperture.