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Complex aperture networks

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ABSTRACT

A complex network approach is proposed for studying the shear behavior of a rough rock joint. Similarities between aperture profiles are established, and a functional complex network—in each shear displacement—is constructed in two directions: parallel and perpendicular to the shear direction. We find that the growth of the clustering coefficient and that of the number of edges are approximately scaled with the development of shear strength and hydraulic conductivity, which could possibly be utilized to estimate and formulate a friction law and the evolution of shear distribution over asperities. Moreover, the frictional interface is mapped in the global–local parameter space of the corresponding functional friction network, showing the evolution path and, eventually, the residual stage. Furthermore, we show that with respect to shear direction, parallel aperture patches are more adaptable to environmental stimuli than perpendicular profiles. We characterize the pure-contact profiles using the same approach. Unlike the first case, the later networks show a growing trend while in the residual stage; a saturation of links is encoded in contact networks.

1. Introduction

A thorough understanding of the behavior of rock joints or fault surfaces is paramount for the study of abrupt motion, seismicity or flow patterns in geomaterials. The evolution of macroscopic friction in frictional interfaces originates from a sequence of contact area variations [1–3]. The formation and rupture of new contact areas (∼bonds/junctions) between two surfaces result in stick–slip motion. Classic characteristics of stick–slip motion include fast frictional strength drop and the release of energy as spikes in ultrasonic waveforms. Recent findings suggest that stick–slip motion is related to the collective interactions of contact areas (Refs. [1–10]). Dissecting the aforementioned collective behavior into a list of interacting units, using complex networks, provides a new mathematical–statistical framework for analyzing a wide range of complex systems [11–17]. In the geosciences, complex earthquake networks, climate networks, volcanic networks, and river networks, which require large-scale measurements, have been taken into account. On a smaller scale, topological complexity has been evaluated with regard to the gradation of soil particles, fracture networks, and apertures of fractures, and the mechanical behavior of granular materials [18–36].

When considering the direct relationship between void spaces and contact areas, one may be interested in considering the induced topological complexity of the opening elements (i.e., apertures) in the fracture treatment. Using linear elastic fracture mechanics, we know that aperture patterns generally are the indexes for the available energy in the growth of a rupture and the eventual fracture length. Also, variations of fluid flow features are controlled directly by aperture patterns. Owing to the complexity of aperture patterns, the understanding and characterization of the features of energy release

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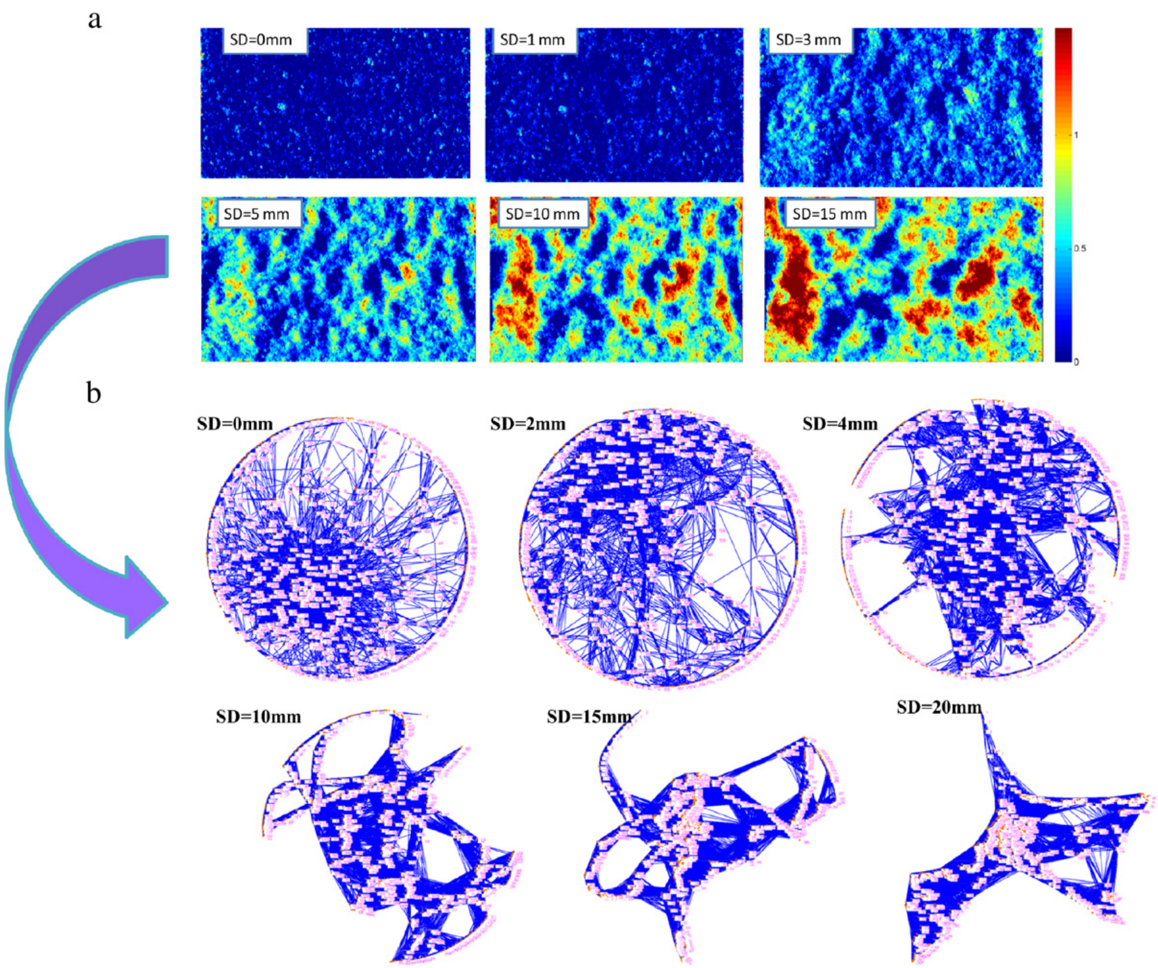

Fig. 1. Methodology for extracting aperture networks from: (a) the evolution of apertures through 20 mm shear slip of an interface; each pixel corresponds to a relative contact area (i.e., aperture); (b) visualization of the similarity matrix and functional friction networks achieved.

and fluid flow are of primary interest in this study. The current work will elaborate upon the Euclidean measure of an aperture network, addressing new aspects, such as: the resolution effect, the local–global (c–k) space of complex aperture networks, and stair-like profiles (contact profiles). We will show the scaling of the development of the frictional forces with the attributes of the proper networks, which will give the approximate evolution of the shear stresses acting on the profiles. The next section details our methods and covers the general aspects of network measures. Subsequently, the results of experiments on a rock joint and the complex networks arranged are shown.

2. Networks on apertures

To set up a network on the apertures of a joint – or, more generally an interface, under a certain amount of normal stress – we consider patches (or profiles) of elements where each profile is a line with an extra dimension corresponding to the aperture magnitude (i.e., $2 + 1$D). Each element on the profile is a pixel with a certain dimension, indicating relative contact area or aperture size. For apertures with zero magnitude, the terms contact areas and asperities are used.

In the aperture patterns, we consider each aperture profile as a node. We define X-profiles as the aperture profiles perpendicular to the shear direction and Y-profiles as those parallel to the shear direction. To draw an edge between two nodes, a relationship (or, in general, a relationship matrix) should be defined (Fig. 1). By assuming that there are some hidden metrics between two nodes, or similar functionality between two profiles, the similarity between the nodes is captured. As the simplest metric for a certain profile's state (X or Y), the Euclidean distance, we will have

$$\mathrm{d}_{Euc.} = \sqrt{\sum_{p,q=1}^{n_p} (p(x_1, x_2, \dots, x_n) - q(x_1, x_2, \dots, x_n))^2}, \qquad (1)$$