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Estimation of the three-dimensional density of discontinuity systems based on one-dimensional measurements

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1. Introduction

Any separation in rock masses with zero or low tensile strength is usually denoted as "discontinuity" [1], which is a generalized term for most types of joints, bedding planes, schistosity planes, weakness zones, and faults.[2] The characteristics of a rock mass, mainly including deformation,[3,4] strength,[5,6] permeability,[7,8] stress-strain relation,[9] and failure,[10–12] are significantly influenced by discontinuity properties. These properties usually include orientation, size, density, genetic type (such as faults, geological contacts, tension joints, shear joints, dykes and so forth), infill material, and surface geometry.[13] Because rock masses are three-dimensional (3-D) in nature, we may have to characterize discontinuities in 3-D space.[14] Unfortunately, discontinuities are usually buried in actual rock masses, and difficult to directly measure all discontinuities and their properties in 3-D space. Therefore, it is widely accepted to infer discontinuity 3-D properties from one-dimensional (1-D) (e.g., sampled in boreholes) and/or two-dimensional (2-D) measurements (e.g., sampled on natural outcrops or tunnel walls).[14–23]

Discontinuity 3-D density, defined as the number of discontinuity centers per unit volume,[24] is of fundamental importance in considerations of rock mass properties before, during and after excavation.[16] It reflects the jointing of a rock mass in essence. It is also one of basic parameters for developing 3-D discontinuity networks.[14,24–26] As described above, 3-D density cannot be directly measured in field, and may have to be inferred from the corresponding 1-D or 2-D measurements (1-D or 2-D density and discontinuity orientations and sizes), where: discontinuity 1-D density (also called as linear frequency) is defined as the number of discontinuities intersected with per unit length of a line in a particular direction through the rock mass[16]; and 2-D density is defined as the number of trace midpoints per unit area of the exposure.[27]

With respect to estimating the 3-D density of discontinuity systems based on 1-D measurements, several researchers[24,28,29] have developed their relationship equations. Cacas et al.[28] proposed an empirical relationship equation as follows:

$$SD=2f \tag{1}$$

where S is the average discontinuity area, D is discontinuity 3-D density, and f is discontinuity 1-D density. U.S. National Committee for Rock Mechanics[29] suggested the following simple equation:

$$N_L=N_V A < cos\theta> \tag{2}$$

where N_L is discontinuity 1-D density along a scanline or borehole, A is mean discontinuity area, θ is the angle between the discontinuity poles and the scanline or borehole; $<\cos\theta>$ is the mean value of $\cos\theta$. Note that Eqs. (1) and (2) lack of rigorous mathematical derivation. Kulatilake et al.[24] developed a relationship equation, to date, which becomes the most widely used one for estimating the 3-D density of discontinuity systems based on 1-D measurements due to being based on rigorous mathematical derivation.

Note that Kulatilake et al.'s formula[24] is directly upon all the values of samples of discontinuity geometry properties including discontinuity

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orientations and sizes. However, in practical cases for some discontinuities with partly exposed facets or trace exposure, which will be described in detail in the next section, it might be not easy to directly sample their orientations and sizes, and one can only estimate their relevant numerical characteristics (e.g., mean value and variance) or related distribution parameters (e.g., the parameter λ for exponential distribution and the parameter K for Fisher distribution). Therefore, it is meaningful and necessary to establish a new formula for estimating the 3-D density of discontinuity systems with partly exposed facets or trace exposure based on 1-D measurements, which can directly reflect the relationship between discontinuity 3-D density and numerical characteristics or related distribution parameters of other discontinuity geometry properties. The aim of this study is to develop such a new formula for estimating the 3-D density of discontinuities with partly exposed facets or trace exposure which may not be done by Kulatilake et al.'s formula. In addition, based on the advantage of the new proposed formula, some suggestions for roughly estimating the 3-D density of the discontinuities for practice purpose are also discussed in this paper.

2. Two exposure scenarios of discontinuities

When exposed in an outcrop or cut, discontinuities in a rock mass manifest themselves in one of or in both two ways[30]: facet exposure and trace exposure.

2.1. Discontinuities with facet exposure

Discontinuities with facet exposure: on irregular rock excavation faces or outcrops, the actual faces of discontinuities are exposed. These discontinuity surfaces can be considered as "facets" (see cyan polygons in Figs. 1 and 2) on a cut precious stone. In the field the orientation of one discontinuity with facet exposure can be directly measured manually with a traditional compass, or can be directly computed using any three non-linear points on the discontinuity plane from LiDAR (light detection and ranging) scanners[31] or close-range digital photogrammetry,[32] both of which are used more and more in recent years. (a) When the facet is completely exposed (such as the cyan polygon in Fig. 1), the 3-D size of the discontinuity can be directly measured manually using a traditional steel tape, or can be directly computed using two points at the edge of the discontinuity plane from LiDAR scanners[31] or close-range digital photogrammetry[32]; and (b) when the facet is partly exposed (such as the cyan polygon in Fig. 2), the 3-D size of the discontinuity cannot be directly measured or computed, and one usually directly measured or computed the 2-D trace length of discontinuities (such as the yellow line in Fig. 2) and then inferred the distribution of the 3-D sizes of discontinuities. Many researchers[14,34–36] have developed the estimation method for 3-D discontinuity size from 2-D trace length. Note that in this situation one finally obtains not the 3-D size value of each discontinuity but the distribution and its related distribution parameters of 3-D discontinuity sizes.

Fig. 1. Two exposure scenarios of discontinuities: facet exposure (cyan polygon) and trace exposure (red line) (after Otoo et al.[30]). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

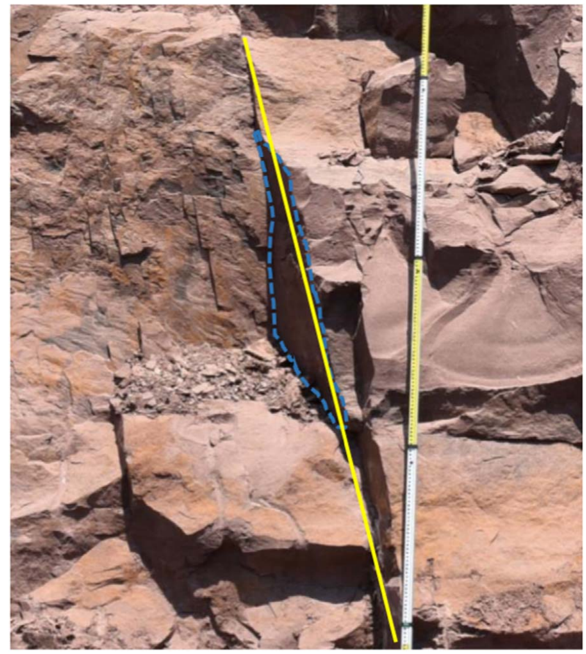

Fig. 2. A discontinuity with partly exposed facet (cyan polygon).

As described above, Kulatilake et al.'s formula is directly upon all the values of samples of discontinuity orientations and 3-D sizes, and therefore is practical for estimating the 3-D density of discontinuities with completely exposed facets and is not practical for discontinuities with partly exposed facets.

2.2. Discontinuities with trace exposure

Discontinuities with trace exposure: on flat planar rock excavation faces or outcrops, the intersection between the discontinuity plane and the planar rock excavation face or outcrop results in a visible line (discontinuity trace, see red line in Fig. 1 and black lines in Fig. 3) that lies on both planes. With respect to a discontinuity with trace exposure, using the traditional tools or LiDAR scanners or close-range digital photogrammetry, usually only its 2-D trace orientation and trace length can be directly measured or computed, and its 3-D orientation and size are very difficult to be directly obtained. Kemeny and Post[33] developed a computer approach for estimating 3-D discontinuity orientations from 2-D trace orientations: (a) assume that the orientations of discontinuities from a set follow a Fisher distribution; (b) sample the trace angles, which are measured in the plane of excavation faces or outcrops from horizontal, on one or more faces (excavation faces or outcrops) using the traditional tools or LiDAR scanners or close-range digital photogrammetry in the field; (c) calculate the statistical parameters of trace angles (mainly including mean, standard deviation, skewness, etc); and (d) apply a type of genetic algorithm called DE forms to find the optimum mean dip angle,mean dip direction, and Fisher constant K that match an observed distribution of discontinuity