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Validation of Monte Carlo simulation for discontinuity locations in space

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ABSTRACT

Baecher disk model is the most commonly accepted and widely used 3-D discontinuity network model (3DDNM). Monte Carlo simulation (MCS) for discontinuity locations is an important step for constructing Baecher disk model. Uniform distributions are usually used to simulate the locations, based on the assumption that trace spacings along a sampling line (SL) obey an exponential distribution. However, no researchers have validated whether the trace spacings simulated using aforementioned method obey the observed exponential distribution in the field. The aim of this study is to perform the validation using a hypothetical 3DDNM. This study includes a brief review of the MCS procedure for discontinuity locations, construction of a hypothetical 3DDNM, and the goodness-of-fit test procedure for simulated trace spacings along SL. Seven sampling line groups (SLG) are used, and each SLG contains twenty SL having a same direction vector. The possible points of intersection between each SL and all simulated discontinuities are obtained, the spacings of those points are calculated, Kolmogorov–Smirnov tests are used to test the goodness-of-fit to the spacings along different SL, and the theoretical values and simulated values of parameter λ of exponential distributions for different SL are also calculated. The results show that: (a) for all SL the trace spacings obey exponential distributions at the 5% significance level; (b) for all SLG the simulated values of λ fluctuate around their theoretical values, and the mean simulated values are very close to its theoretical values; (c) therefore, it is valid to use uniform distributions to simulate locations in space for those discontinuities, whose observed trace spacings follow exponential distributions. The validation procedure developed in this study are also applicable to 3DDNM constructed for field cases.

1. Introduction

“Discontinuity” is usually used to describe any separation in a rock mass having zero or low tensile strength [1], including most types of joints, weak bedding planes, weak schistosity planes, weakness zones, and faults [2]. Discontinuities have significant influence on the properties of rock masses as follows: the deformation [3,4], strength [5,6], permeability [7,8], stress–strain relation [9], and the failure [10,11]. The main properties of discontinuities to be determined are orientation, size, frequency, surface geometry, genetic type, and infill material [12,13]. Since discontinuities are hidden in the actual rock masses, it is extremely difficult to investigate all of them and their properties in three dimensions [14]. In addition, discontinuities are generally developed in rock masses randomly and in sets [15]. Therefore, it is widely accepted to infer discontinuity characteristics from data sampled at exposed rock faces (including both natural outcrops and tunnel walls) and/or in boreholes [14,16–22], and then three-dimensional (3-D) discontinuity network models (3DDNM) [23–30] can be constructed. Dershowitz and Einstein [25] provided an excellent review of the development of these 3DDNM. Among these models, Baecher disk model [23] is most commonly accepted, and widely used by large number of researchers (e.g., references [21,24,27–30,31–37]).

One of assumptions of Baecher disk model is that the center points of discontinuities are randomly and independently distributed in space forming a Poisson process [23]. The assumption leads to an exponential distribution of trace spacings along a sampling line (SL), in agreement with many reported field studies (e.g., references [15,23,38,39]). Therefore, numerous researchers (e.g., references [20,21,23,24,27–36]) used uniform distributions to simulate the discontinuity locations. Thus the simulation procedure is also very simple and convenient. However, some researchers may ignored that the prerequisite of using uniform

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Nomenclature

(x_i, y_i, z_i)	components of C_i in (x, y, z) coordinate system
(x_{il}, y_{il}, z_{il})	components of P_{il} in (x, y, z) coordinate system
(x_l, y_l, z_l)	components of P_l in (x, y, z) coordinate system
(x_{lk}, y_{lk}, z_{lk})	components of P_{lk} in (x, y, z) coordinate system
$(x_{lk+1}, y_{lk+1}, z_{lk+1})$	components of P_{lk+1} in (x, y, z) coordinate system
3-D	three-dimensional
3DDNM	3-D discontinuity network model(s)
B	breadth of the interested block
C_i	center point of discontinuity i
D	diameter of discontinuity
D_i	diameter of discontinuity i
d_{ili}	distance between P_{il} and C_i
D_n	maximum difference between the empirical cumulative frequency and theoretical cumulative distribution function
D_n^{α}	critical values at significance level α.
$E(\cdot)$	expected value of the function within the parentheses
H	height of the interested block
i	discontinuity number
$\boldsymbol{i}$	mean unit normal vector of the discontinuity set
K–S	Kolmogorov–Smirnov
L	length of the interested block
l	a sampling line
$\boldsymbol{l}$	upper unit vector along the SL l
MCS	Monte Carlo simulation
m	meter(s)
m^2	square meters
N	total number of simulated discontinuities in the interested block
$\boldsymbol{n}$	unit normal vector of discontinuity
$\boldsymbol{n_m}$	mean unit upper normal vector of the discontinuity set
P_{il}	point of intersection between sampling line l and discontinuity i
P_l	a point on the sampling line l
P_{lk}, P_{lk+1}	two adjacent points of intersection on l
SL	sampling line(s)
SLG	sampling line group(s)
s_{lk}	kth spacing along $\boldsymbol{l}$ or spacings of P_{lk} and P_{lk+1}
s_m	spacing along the mean normal vector of the discontinuity set
s_{mk}	kth spacing along $\boldsymbol{n_m}$
t	parameter of the parametric equation
u_{xi}, u_{yi} and u_{zi}	generated random numbers distributed according to the uniform (0,1) distribution
α	significance level
α_l	plunge of the sampling line l
β_l	trend of the sampling line l
γ_{ml}	angle of intersection between $\boldsymbol{n_m}$ and $\boldsymbol{l}$
δ_i	dip angle of discontinuity i
δ_m	mean dip angle of the discontinuity set
θ_i	dip direction of discontinuity i
θ_m	mean dip direction of the discontinuity set
λ	parameter of an exponential distribution
λ_m	value of parameter λ of the exponential distribution followed by the spacings along the mean normal vector of the discontinuity set or one-dimensional density of discontinuities along the mean normal vector of the discontinuity set
λ_v	3-D density of discontinuities

distribution to simulate locations is that the observed trace spacings obey exponential distributions in the field, and no researchers have validated whether the simulated trace spacings using uniform distribution to simulate locations obeys the observed exponential distribution in the field. The aim of this study is to perform the validation using a hypothetical 3DDNM.

2. Review of the MCS procedure for discontinuity locations

In Baecher disk model [23] discontinuities are assumed as thin circular disks, hence their locations can be descripted by the coordinates of center points of circular disks. Assume that we need to generate a set of discontinuities in a $B \times L \times H$ block (Fig. 1), in which the east direction (E) and north direction (N) are the positive directions of the x-axis and y-axis, respectively. The number of generated discontinuities in the interested block (Fig. 1) is controlled by only one parameter, the 3-D density (denoted as λ_v) that specifies the average number of distribution center points within unit volume of rock mass [35].

As stated previously, the uniform distributions can be used to simulate the coordinates of center points as follows:

$$\begin{cases} x_i = Bu_{xi} \\ y_i = Lu_{yi} \\ z_i = Hu_{zi} \end{cases} \quad (1)$$

where u_{xi}, u_{yi} and u_{zi} are generated random numbers, which are distributed according to the uniform (0,1) distribution; i is the serial number of generated discontinuity, and can be equal to 1, 2, ..., and N. Note that N is the total number of generated discontinuities in the interested block and can be expressed as:

$$N = BLH\lambda_v \quad (2)$$

λ_v cannot be directly measured in field, and would be usually inferred from one-dimensional density. According to Kulatilake et al. [27], the λ_v can be estimated by

$$\lambda_v = \frac{4\lambda_m}{\pi E(D^2)E(|\boldsymbol{n} \cdot \boldsymbol{i}|)} \quad (3)$$

where λ_m is the one-dimensional density along the mean normal vector of the discontinuity set, and is equal to the reciprocal of

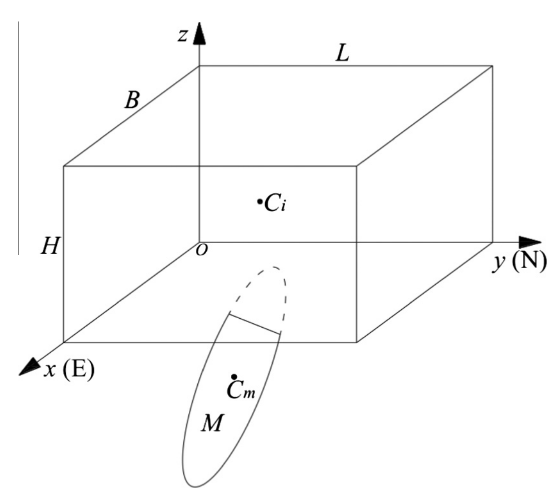

Fig. 1. Cartesian coordinate system (x,y,z) and the interested block.