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Effects of spatial correlation property of microstructure on the pulverising performance of rock prisms

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ABSTRACT

Ore rocks are commonly identified as heterogeneous materials, that is, their various micro-structures are characterized by inherent natural randomness. Reasonably, heterogeneity is an important factor that controls damage initiation, fracture propagation, and in turn final breakage failure or fragmentation process within raw rocks. This paper focuses on the internal spatial variability in terms of mineral distribution, and the objective is to numerically investigate the effects of different randomness feature of fine-scale structure, as described by variable magnitudes of spatial correlation length parameter, on the rolling compression induced breakage failure of individual rock specimen on a horizontal table. A simple and direct algorithm was developed to generate specimens characterized by random fields of prescribed spatial correlation, which are obtained by a weighted average of random fields without spatial correlation. The finite element method with conversion to the smoothed particle hydrodynamics method was adopted to simulate the progressive deformation, fracture and final breakage failure by roller compression. From parametric study results, it was found that the spatial correlation length parameter value can significantly influence the breakage failure and the corresponding size reduction efficiency for ore rock prisms. Specifically, the progressive fragmentation patterns, and the characteristic size of main broken pieces show obvious length value-related distribution features. The numerical study given in this paper can definitely help understanding the pulverizing mechanism of various polycrystalline particles in roller mills and the optimization of the grinding works for better efficiency.

1. Introduction

In principle, quasi-brittle materials such as concrete and natural ore rocks are usually characterized by heterogeneous fine-scale structures. To begin with, natural mineral aggregates formed under the process of metamorphism, weathering, transportation or sedimentation are composed of various fractions of materials. Furthermore, existence of numerous random distributed micro-cracks and tiny holes also contributes to the explicit non-homogeneity of these materials. Nevertheless, the distribution pattern of macro mechanical properties are by no means completely tangled or disorganized. It is noteworthy that there often exists spatial correlation of local continuity in terms of material properties, which means that mechanical properties of discrete elements are significantly correlated with respect to spatial distance in the random field.

In recent years, the randomness feature of natural geomaterials has attracted much attention and many research works have been carried out in the literature, particularly on the size and shape effects of compression strength (Hudson et al., 1971; Tuğrul and Zarif, 1999), rock fragmentation and failure modes under static or dynamic loads (Liu et al., 2002; Villeneuve et al., 2012), as well as development of variable digital image processing (DIP) techniques for numerical representation of fine-scale heterogeneity (Kemeny et al., 1993; Lenoir et al., 2007). Even though the contribution of spatial correlation character has been omitted, almost all of these studies have clearly shown the significance of fine-scale heterogeneity character on the prediction of fracture development and final failure patterns.

While in terms of microstructures in multiphase composites, spatial correlation of local continuities cannot be overlooked. For example, different concrete batches and the variability of workmanship may lead to spatially varying concrete quality and concrete cover, which will as a consequence influence the likelihood and extent of corrosion-induced cracking of a concrete surface

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(Vu and Stewart, 2005). In the region of biological and non-biological structures, semi-flexible fibre networks exhibit long-range power-law spatial correlations of the density and elastic properties which can be simulated by the stochastic finite element techniques (Hatami-Marbini and Picu, 2009; Heussinger and Frey, 2006). In this regard, to investigate the mechanical behaviour of natural or artificial materials, the existence and resulting effects of spatial correlation should be underlined to a certain extent. Griffiths and Fenton (2004) developed random finite element method (RFEM) incorporating such a spatial correlation length character of soil strength properties for slope stability analysis. Their findings indicate that simplified probabilistic analysis ignoring spatial variability can lead to unconservative estimates of the probability of failure. Tang et al. (2010) considered the spatial correlation character of concrete materials based on an equivalent probabilistic model. Their results clearly show that when the spatial correlation of the fine-scale material property is weaker, a comparatively larger scatter is shown in the softening stage response and in the failure pattern during the uniaxial compression tests. Interestingly, the mean values of compressive strength present only insignificant changes.

In this paper, to simulate the local distribution continuity of fine-scale mineral components within ore rocks, an efficient and practical algorithm was developed for generating three dimensional random fields of spatial correlation, which is an extension of the method by the authors (Tang et al., 2014). Coal material was taken as an instance in this study, and typical cubic coal samples were generated by the method considering an impurity component of variable spatial correlation length factors. Parametric numerical studies of rolling compression tests were conducted on the generated numerical coal prisms, and the effects of variable spatial correlation length factors of coal material on its pulverizing induced breakage response were investigated.

2. Numerical algorithm for spatial correlation

The main implementation flowchart for generating numerical samples that are characterized by spatial correlation feature is shown in Fig. 1. Not losing generality, a particular case of ore material made up of two constituent components was chosen for the purpose of simplicity. Firstly, the algorithm for one-dimensional case was described, and then an extension to a more general three-dimensional case was presented.

2.1. One-dimensional case

Firstly, an integer array A of given length n, comprising elements $a_i = \pm 1, i = 1, 2, \ldots, n$, was generated in complete random order, in which 1 and -1 indicate two constituent components respectively. The corresponding volume fraction of each component is prescribed as w $(0 < w < 1)$ and $1 - w$ respectively. Hence, the statistical expectation value can be derived as follows:

$$\langle a_i a_{i+d} \rangle = \frac{1}{n}\sum_{i=1}^{n} a_i a_{i+d} = \begin{cases} 1, & d = 0 \\ 2w - 1, & d \neq 0 \end{cases} \tag{1}$$

where d indicates the spatial distance between elements a_i and a_{i+d}.

In order to introduce spatial correlation, a Markovian correlation function, $f(k) = e^{-\frac{k}{\Theta}}$ was adopted in this study. As introduced in references (Tang et al., 2010; Griffiths and Fenton, 2004), the chosen correlation function is characterized by exponentially decaying, where Θ denotes the spatial correlation length parameter and $|k|$ indicates the effective distance of the centroids of two number elements. The Θ parameter represents the correlation degree between elemental points in space, here equivalently as the distance along the one-dimensional axis. A smaller Θ factor

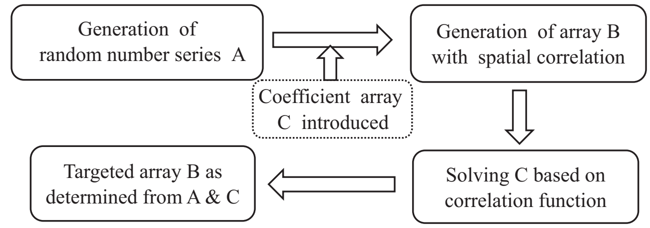

Fig. 1. The flowchart of the numerical algorithm.

indicates that the random field varies smoothly whereas a larger value implies a more intense variation.

Secondly, a new array B representing spatial correlation can be formulated based on linear products of A elements, the correlation function $f(k)$ above and undetermined coefficients. The comprising elements of B array are defined as:

$$b_i = \sum_{k=-n}^{n} c_{|k|} a_{i+k} f(|k|) \tag{2}$$

where c_k $(k = 0, 1, \ldots, n)$ denotes the unknown coefficients which are to be determined based on the above-mentioned spatial correlation function $f(k)$ in the following step, and they form the C array in Fig. 1. To endow the B array elements with spatial correlation, here, one-dimensional, a sequence of nonlinear equations on the basis of correlation functions can be formulated:

$$\begin{aligned} \langle b_i b_{i+k} \rangle &= \frac{1}{n}\sum_{i=1}^{n} b_i b_{i+k} \\ &= \frac{1}{n}\sum_{i=1}^{n}\left(\sum_{p=-n}^{n} c_p a_{i+p} f(p)\right)\left(\sum_{q=-n}^{n} c_q a_{i+k+q} f(q)\right) \\ &= f(k) \quad (k = 0, 1, 2, \ldots, n) \end{aligned} \tag{3}$$

Combining Eqs. (1)–(3), the following equations can be derived:

$$\begin{aligned} \langle b_i b_i \rangle &= c_0^2 f(0)^2 + 2(c_1^2 f(1)^2 + c_2^2 f(2)^2 + \ldots + c_n^2 f(n)^2) = f(0) \\ \langle b_i b_{i+1} \rangle &= c_n c_{n-1} f(n) f(n-1) + c_{n-1} c_{n-2} f(n-1) f(n-2) \\ &\quad + \ldots + c_1 c_0 f(1) f(0) + c_0 c_1 f(0) f(1) + \ldots \\ &\quad + c_{n-1} c_{n-2} f(n-1) f(n-2) + c_n c_{n-1} f(n) f(n-1) \\ &= \sum_{i=-n}^{n-1} c_{|i|} c_{|i+1|} f(|i|) f(|i+1|) = f(1) \\ < b_i b_{i+2} >&= \sum_{i=-n}^{n-2} c_{|i|} c_{|i+2|} f(|i|) f(|i+2|) = f(2) \\ < b_i b_{i+3} >&= \sum_{i=-n}^{n-3} c_{|i|} c_{|i+3|} f(|i|) f(|i+3|) = f(3) \\ &\;\;\vdots \\ < b_i b_{i+n} >&= \sum_{i=-n}^{0} c_{|i|} c_{|i+n|} f(|i|) f(|i+n|) = f(n) \end{aligned} \tag{4}$$

It can be seen that the above Eq. (4) are nonlinear containing $n + 1$ undetermined coefficients c_k $(k = 0, 1, \ldots, n)$. As $n + 1$ equations are available in total, generally the solutions are available. The above equations have been implemented into the Matlab software and the solutions can be directly obtained.

Finally, with the solutions of undetermined coefficients, i.e., C array members, the targeted array B can be obtained according to Eq. (2). The value of B array member would appear as a series of real numbers. Through additional mapping manipulation back to ±1 according to given corresponding ratios of constituent