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A novel method for modeling the 3D discrete fracture network from a single 2D exemplar

Huaiguang Xiao[1,2], **Lei He**[1*]

[1] School of Civil Engineering, Southeast University, Nanjing, Jiangsu 211189, China
[2] School of Civil and Environmental Engineering, University of Technology Sydney, Ultimo, NSW, 2007, Australia
[*] Correspondence author: helei_civil@seu.edu.cn

Abstract. Fracture network modeling is an important prerequisite for studying many rock mechanics and permeability topics. At present, the fracture morphology in the most discrete fracture network (DFN) models is expressed by Euclidean geometries. In order to improve the accuracy of natural fracture description, this paper proposes using the block texture synthesis method to generate large-scale models of 2D fractured coal rock. The results show that these large-scale models remain the original texture or fracture structures from the exemplars. In addition, this paper presents using the idea of physical cover to transform exemplar that is used to generate 3D DFN models. The results show that the fracture density of the 3D DFN model generated by uncovered fracture structures is low. In contrast, the fracture structures with texture or random coverage can generate high-quality 3D DFN models. Furthermore, compared with the traditional DFN model, the texture-based DFN model has an excellent restoration of natural fractures in orientation, roughness, fluctuation, aperture, density, and connectivity. Therefore, the texture-based DFN method can provide a new idea for constructing 3D DFN models.

1. Introduction

Rock is one kind of discontinuous material, and its fractures generally exist in rock mass at any scale. As a kind of weak interface and channel, the fracture has an important effect on the mechanical stability of rock and the connectivity of the fluid system. Therefore, fracture modeling is an essential prerequisite for studying academic (the mechanism of rock cracking [1] and flow path [2]) and engineering problems (surrounding rock support [3], inrush water [4]) of rocks. Scientific fracture network models can provide a reliable basis for studying these problems.

At present, the Monte Carlo method is the main method for fracture network modeling [5,6]. This method firstly uses artificial (scanline [7] and window measurement [8]) or non-artificial (photogrammetry [9], laser scanning [10]) methods to conduct statistics on 2D fracture parameters (such as orientation, size, shape, aperture, density, spacing) from rock outcrops. Then, these parameters are extracted into function distributions (such as lognormal distribution, exponential distribution, uniform distribution). Finally, these function distributions representing fracture characteristics are reproduced into 2D or 3D space to generate 2D or 3D DFN models. In addition, in order to generate discrete fracture networks with natural fluctuation and shape, some scholars [11,12] construct 3D DFN models by reproducing palaeo-stress from the perspective of geo-mechanics. Although the geomechanical method can obtain relatively natural fracture networks, it can only restore geological conditions with simple stress history.

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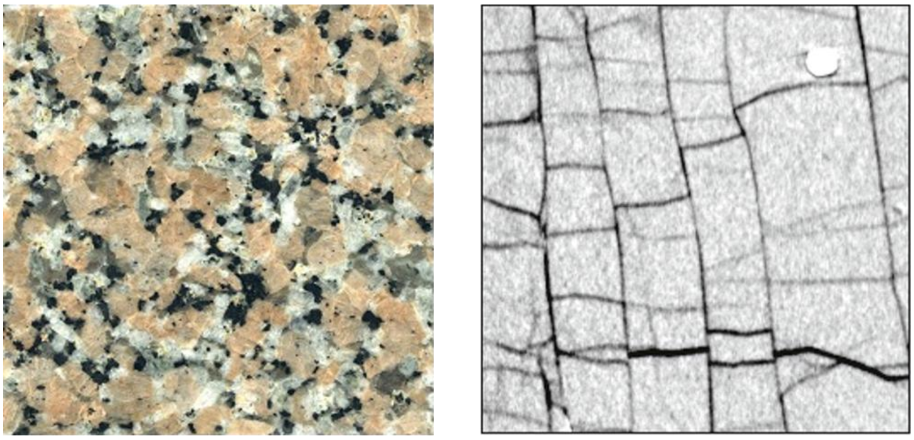
The modeling method based on image texture has been well studied in the field of computer graphics, which provides solid theories and algorithms of texture synthesis [13-16]. In recent years, some scholars have also introduced the texture synthesis method into the modeling of rock materials. For example, Xiao et al. [17] used the texture synthesis method to build 2D digital granite models whose reliability has been proved in terms of color space, geometric parameters, and mechanic properties. Xiao et al. [18] used the digital twin modeling method to generate the 3D digital model of porous sandstone from a single 2D image. The synthetic model can well show the morphology of the solid grain phase and better reflect the natural fracture morphology. However, there are rare studies to model fracture networks based on texture. This is because the proportion of fracture structure is very lower than the matrix of the rock. In order to increase the proportion of fracture structure, this paper intends to transform texture images using the idea of physical cover to generate high-quality DFN models.

2. Materials and methods

2.1. Materials

Two types of rocks have been adopted in this paper: sanbao red granite and fractured coal rock [19], as shown in Figure 1. The side length of the maple red granite is 120 mm. The mineral grains, including orthoclase, plagioclase, quartz, mica, are visible to the naked eye. The side length of the porous sandstone is 1.5 mm. The side length of the fractured coal rock is about 4 mm. The fracture is very developed which can be used to generate 3D fracture networks. The image resolution of these three samples is processed as 256×256 pixels to improve the processing efficiency of the algorithm.



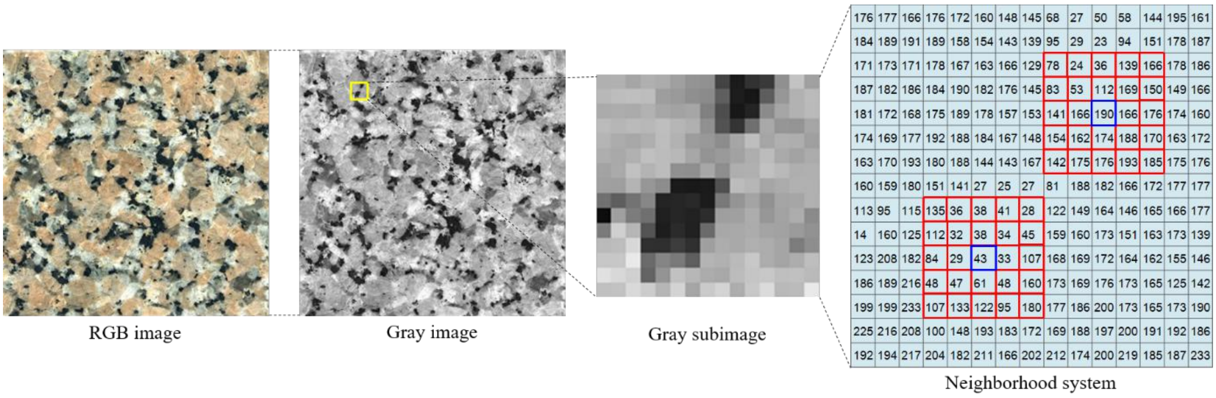
(a) (b)

Figure 1. Rock materials. (a) sanbao red granite (b) fractured coal rock

2.2. Methods

2.2.1. 2D texture synthesis based on blocks. Markov random field is a probabilistic graph model that can be used to model the distribution of variables with correlations. Markov random field has two characteristics in the image texture synthesis method: stationarity and locality [20]. Stationarity refers to the certain similarity between texture blocks. Locality means that a pixel is only determined by its surrounding pixels. As shown in Figure 2, the center pixel marked by the blue box line is determined by the neighborhood pixel marked by the red box line.

In this research, the image is assumed to have Markov random property so that the new texture structure can be generated by the neighborhood matching principle. The main steps of the 2D synthesis method based on texture blocks are as follows. Firstly, the exemplar is divided into many texture blocks whose size depends on the texton size [17]. Then, the texture blocks are recombined together using the principle of neighborhood matching. Finally, the minimum curve error method is used to eliminate the obvious quilt. The detailed principle can be referred to [14].



$$\begin{bmatrix} 78 & 24 & 36 & 139 & 166 \\ 83 & 53 & 112 & 169 & 150 \\ 141 & 166 & & 166 & 176 \\ 154 & 162 & 174 & 188 & 170 \\ 142 & 175 & 176 & 193 & 185 \end{bmatrix} \rightarrow \begin{bmatrix} & & & & \\ & & & & \\ & & 190 & & \\ & & & & \\ & & & & \end{bmatrix}$$

Figure 2. Neighborhood system of pixels in the image

2.2.2. Synthesis 3D model from a single image. The 3D texture synthesis method in this paper is learned from the literature [15,16]. The core concept is that three orthogonal slices in the 3D model determine a central pixel, and the three orthogonal neighborhoods in the 3D model are matched with the neighborhoods in the exemplar.

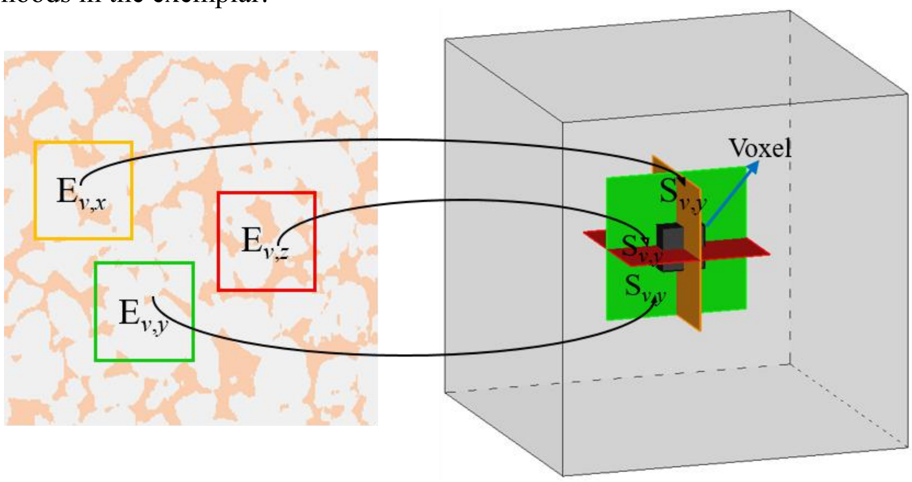


Figure 3. Matching law of neighborhood between the 2D exemplar and 3D synthetic model [18]

2.2.3. Fracture structures with coverage. As mentioned in the introduction section, compared with other phases, the proportion of fracture in the images cannot meet the requirements of the 3D texture synthesis method. Inspired by the physical coverage in the numerical manifold method, the fracture structure can be added in texture images to improve the relative proportion of fractures.

A large-scale granite sample of 3840 pixels representing an actual physical scale of 1800 mm is generated from maple red granite samples (256 pixels). As shown in Figure 4, an oblique crack with 17 pixels run the whole image, whose size is 3840 pixels. The image of 3840 pixels was subsampled to 256 pixels. The texture is not too clear, and the width of the crack is about 1 pixel.

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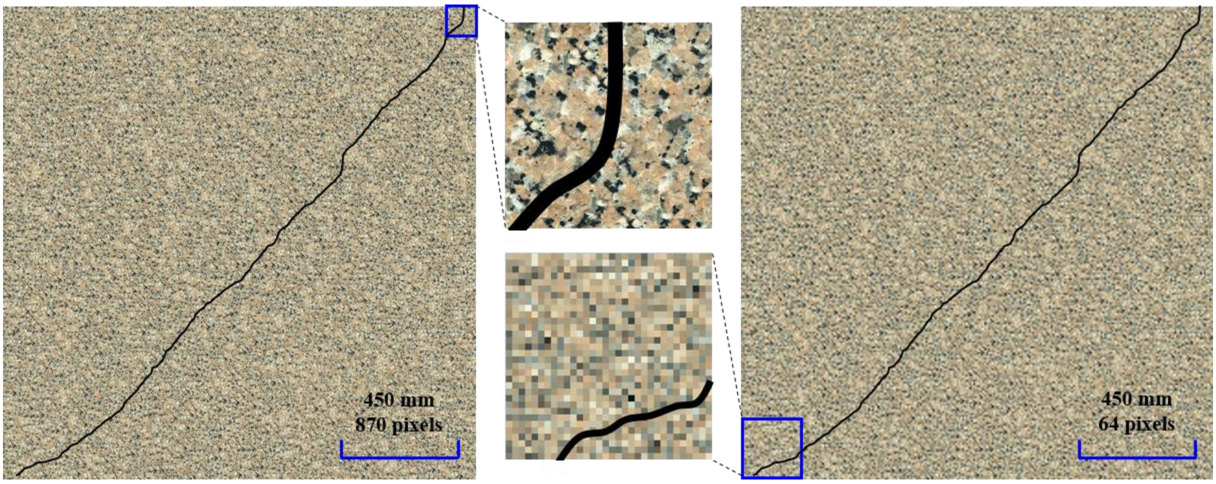

Figure 4. The relationship between mineral grains and fracture under different resolutions

3. Results

3.1. 2D DFN model by texture synthesis method

The traditional DFN model has regular shapes, equal aperture, no undulation or roughness, no relationship between fracture sets. By contrast, the DFN based texture remains the morphology of fractures and the connective relationship between fracture sets, as shown in Figure 5.

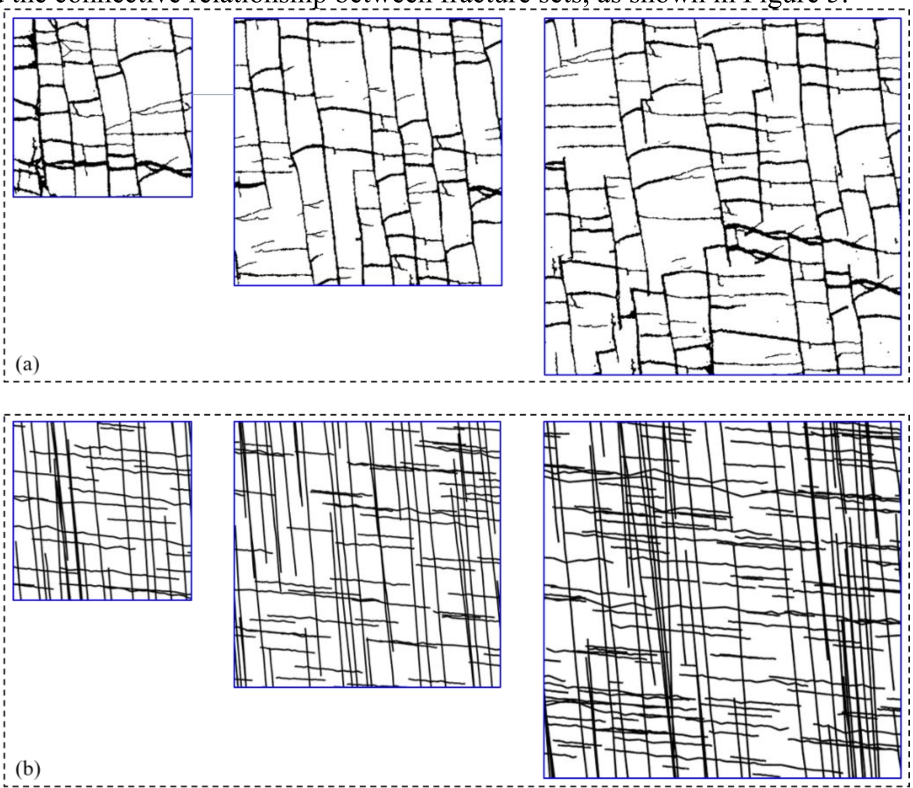

Figure 5. Synthetic models of different sizes. (a) The left image is the original fracture network with 256 pixels and 4 mm, and the middle (384 pixels) and right (512 pixels) images are synthesized from the original exemplar. (b) The left (256 pixels), middle (384 pixels) and right images (512 pixels) are DFN models based on the Monte Carlo method.

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3.2. 3D DFN model generated based on a single 2D exemplar

Compared with the DFN model based on the Euclidean geometry, this texture-based DFN model texture shows the natural fracture characteristic. As shown in Figure 6, three kinds of fracture network models were obtained by 3D reconstruction of uncovered, texture and random covered fracture structures. The 3D DFN model generated by texture can show the following characteristics: two fracture sets (the same as the traditional DFN model); fracture shapes are irregular and varied (different from those of disks or polygons in the traditional DFN model); the fracture surface has obvious undulation (different from the complete flatness of the traditional DFN model); the fracture aperture fluctuates significantly (completely different from the equal aperture of the traditional DFN model); the connectivity between fracture sets is maintained (different from the weak mathematical connections between traditional DFN fracture sets).

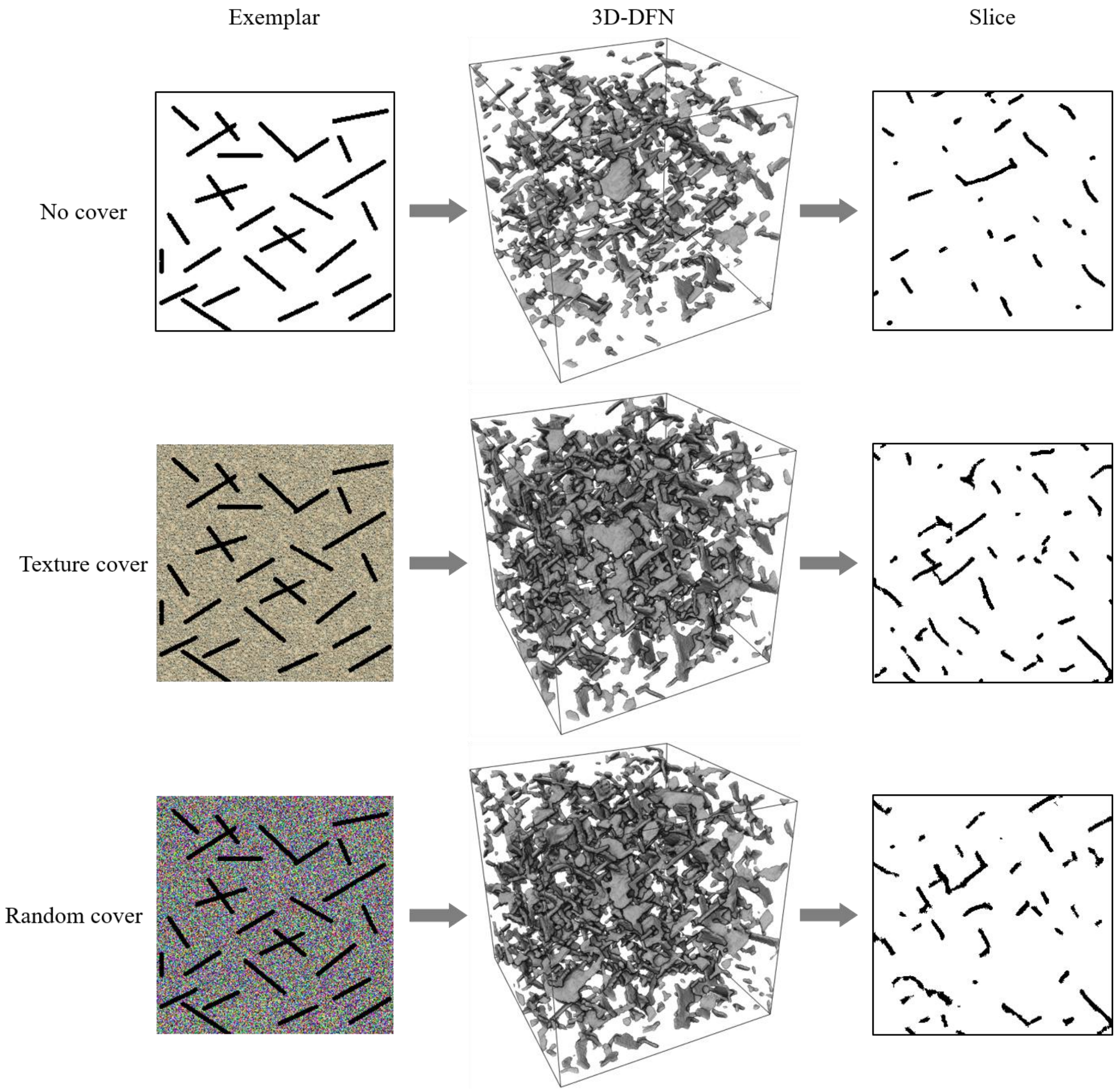

Figure 6. 3D DFN from a single 2D exemplar with different coverages

Compared with the 3D DFN models generated by the textured covered fracture structures, the DFN model with no cover has less fracture density. The result shows that when the proportion of fractures is low compared with other phases, the generation proportion of fracture in the 3D model is low. It can

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also be seen from the slice image that the proportion of fractures is low. Therefore, although the DFN model with no cover presents a complex natural morphology, the low density in the 3D DFN model will greatly affect the mechanical or permeability characteristics. The 3D DFN model is generated by covered real granite texture, which may represent the natural state of fractures. This model has a good restoration in terms of the density and complexity of fractures. However, it is not easy to obtain the natural rock texture because most grain size is small, and the rock surface texture is not clear. This paper attempts to generate 3D DFN models with completely random lattices as the mathematical coverage. The result shows that the DFN model generated by completely random coverage has a high degree of consistency with the texture coverage model.

4. Discussions

In this paper, a 2D DFN method is proposed to replicate and recombine the texture blocks to generate 2D DFN. The distribution and morphology of fractures can restore the natural morphology of exemplars. In addition, this paper proposes to use the idea of physical coverage to solve the problem of a low proportion of fracture in the image. Compared with the traditional DFN model, the model presented in this paper can represent the fracture morphology and be used for mechanical or permeability analysis. In addition, the natural DFN model in this paper can be directly applied to lattice Boltzmann permeability calculation. Further research will verify the reliability of the texture-based DFN model with the natural rock.

5. Conclusions

This paper proposes a method to generate 2D DFN models based on texture blocks and generate 3D DFN models based on physical covering ideas. It is more natural and effective to obtain the DFN model by block texture method based on Markov random field principle. The random coverage can replace the texture coverage to generate 3D DFN models. The texture-based DFN model can provide a new idea for generating natural fracture structures and a lattice model for the numerical simulation to study the mechanics and permeability mechanism of rock materials.

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