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A hierarchical-fractal approach for the rock reconstruction and numerical analysis

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ABSTRACT

A novel reconstruction method is proposed to reconstruct porous rock model based on limited morphological information from experiments. X-ray Micro-CT observations and triaxial compressive tests are initially conducted to obtain the raw CT images and necessary mechanical parameters. Then, a hierarchical annealing algorithm is proposed to gain large profits in computational efficiency. Moreover, the fractal system control function with time variables and local histogram system control function are introduced to characterize the irregular and multi-scale features in rocks. Finally, the comparisons between the numerical results and experimental data show that the proposed novel reconstruction method has a powerful capacity to predict the properties of rocks for engineering purposes.

1. Introduction

In this planet, sandstone accounts for about ten percent of the sedimentary rocks. Most underground cavern groups run through sandstone strata. Specifically, sandstone is a clastic sedimentary rock composed mainly of sand-sized mineral particles or rock fragments. The major materials in sandstone are quartz or feldspar. There are various applications of sandstone, such as an aggregate for the base of roads, or a soil conditioner, or an essential component of concrete, or a building material. The pore structures play an important role in the application of sandstone. It has not only a direct relation to the porosity and permeability, but also has an indirect relation to the strength and elastic modulus of rocks. Various methods and technologies are developed to investigate the pore structures in rocks, such as Nuclear magnetic resonance (NMR),[1] Ultrasound tomography (UT),[2] Electrical Tomography (ET),[3] Micro-computed tomography (Micro-CT),[4] Focused ion beam (FIB),[5] Scanning electron microscopy (SEM),[6] or FIB-SEM.[7] Among these methods and technologies, the Micro-CT method seems to be the most preferred one for rocks. Compared with NMR, UT and ET, it has a higher resolution. Compared with FIB, SEM and FIB-SEM, it has no need to destroy the sample. The high resolution (um) is the main difference between the Micro-CT and the common CT. A lot of researches on the microscopic behaviours of rocks have already been done by CT method. Diaz et al.[8] employed the X-ray CT technology to study the roughness of open and closed joints in rock samples extracted at a rarely studied depth. Zhang and Sheng[9] investigated hydration-induced fracture propagation using CT lateral cross-section images and digital image processing techniques, including the reconstruction of core vertical cut faces and 3D fractures. Blaheta et al.[10] described procedures of numerical upscaling and experience with X-ray CT-based finite element (FEM) analysis of properties of geocomposites, and the upscaling technique is used to obtain the macro-level response of materials by loading test (representative) volumes with described micro-level structure. Raynaud et al.[11] developed an X-ray transparent triaxial cell that was included in a medical purpose X-ray scanner with a millimeter-scale volumetric resolution, and applied this technique to a porous calcarenite at low confining pressure. Raynaud et al.[12] used several observation methods, such as X-ray computed tomography, scanning electronic microscopy, quantitative image analysis of thin sections and mercury porosimetry, to study the deformation of Beaucaire marl.

The simulation result for rocks in microscopic scale by Micro-CT method seems to be accurate and reliable. However, the accuracy and reliability are somehow limited to the field of view of the Micro-CT scanning device. In other words, the depth and scope of study by Micro-CT method are limited to the observation range of the CT scanning device. Although the interior pore structure of the porous media such as rocks can be measured accurately by the Micro-CT scanning, the observation results are only responsible for the microscopic scanning zone in the sample, and these local results are not able to represent the characteristics of the whole sample, let alone provide a reliable basis for the prediction of the engineering zone under various geological conditions.

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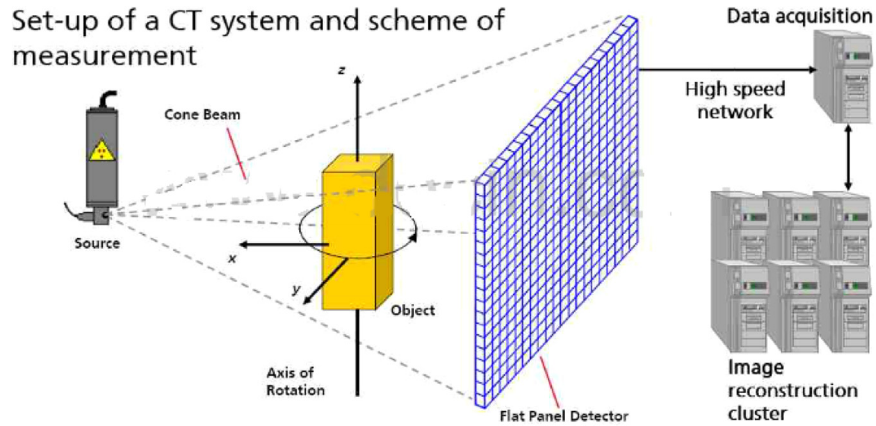

Fig. 1. Working principle of the X-ray CT observation.

Therefore, a more comprehensive method is required to characterize the various pore structures configuration in rocks. Several reconstruction methods are developed for this purpose, such as Geological process-based reconstruction method,[13,14] Gaussian Random Fields reconstruction method,[15–17] Multiple-point statistics reconstruction method[18–20] and Simulated annealing reconstruction method.[21–23] Among them, the simulated annealing reconstruction method appears to be the most attracting method for its capability to introduce any number and arbitrary type of control function. Torquato[22,23] formulated a procedure to reconstruct the disordered heterogeneous material based on simulated annealing algorithm. Kröner[24,25] and Beran[26] also proposed a theoretical model with the N-point statistical functions to illustrate the effects of the volume fraction and the number of the phase in the multiple-phase model. Manwart and Hilfer[27] proposed a novel method to reconstruct random media based on Monte Carlo methods. Jiao and Stillinger[28,29] introduced a novel heterogeneous-media reconstruction algorithm called "lattice-point", and proposed a theoretical method to reconstruct the heterogeneous materials based on two-point correlation functions.

Although quite a few works for the simulated annealing reconstruction have been done by the predecessors, reconstructing the porous rocks from its disordered state is still supposed to be a challenging task. Moreover, it naturally needs to consider seriously how to actually reflect the intrinsic characteristics of rocks in the reconstruction model for prediction purpose. Specifically, the challenge is just to identify the characteristic descriptors that are necessary and appropriate for reconstructing different classes of porous materials with different microstructures. However, compared with other reconstruction methods, the simulated annealing reconstruction method is only required to concentrate on the ability of the control function to describe the configuration of the real pore structures. Besides the challenge of the identification ability, the other challenge is the continuous requirement for the improvement of the computational ability with increasing the control functions. Especially for the rock materials, the multi-scale feature in engineering problems demands more computational resources.

Therefore, in this paper, a hierarchical-fractal annealing reconstruction algorithm is proposed to more quickly and more efficiently reconstruct sandstone with more accurate characteristics. Firstly, for the delay in the computation caused by the introduction of the additional control function, we improved the system updating mode to avoid wasting time on the unnecessary and unsuccessful position exchange or phase transition. Secondly, considering the multiple-scale features of the rock engineering problem, a hierarchical simulated annealing algorithm is developed, which is previously proved to have a great of benefit in the computational efficiency.[30] Thirdly, to better characterize the irregularity and roughness of the pore structures in rocks, a time-dependent fractal control function is introduced. Fourthly, to verify the proposed reconstruction algorithm, an independently developed industrial micro-computed tomograph (CT) device is used to generate high-resolution X-ray computed tomograph (CT) images from Xingluokeng sandstone samples. Finally, to obtain the necessary mechanical parameters for simulation and the necessary results for comparison, a series of triaxial compression experiments are performed on Xingluokeng sandstone samples by the multifunction triaxial rock testing system. The simulation results have a good agreement with the experimental data, which indicates that the proposed method has a strong ability to predict the macroscopic behaviors of rocks with a limited number of X-ray CT images and a few triaxial compression experiments.

2. X-ray micro-CT scanning and experimental testing

2.1. X-ray micro-CT scanning

X-ray micro-CT has been widely employed to nondestructively detect the inherent microcracks of the engineering structure. Moreover, it can also be used to measure the internal microstructures of porous rocks so as to investigate the influence of the microstructures on the mechanical behaviors. The model number of the X-ray micro-CT scanner employed in this paper is CD-90BX, and this X-ray micro-CT scanner is independently developed and manufactured by the Industrial CT Nondestructive Examination Engineering Research Center of Ministry of Education, Chongqing University, China. The parameters of this prototype are listed as follows: The X-ray tube voltage is 20–100 kV, the spatial resolution is 3–5 μm, the diameter of the detection workpiece is 5–90 mm, the surface leakage dose rate is 0.5 μSv/h, the size and the weight of the X-ray micro-CT instrument are 2060 mm × 900 mm × 1900 mm and 2 t, respectively. The operating principles of this micro-CT scanner can simply be summarized in Fig. 1. The whole system mainly consists of four parts which are X-ray source, sample stage, flat panel detector and computer processing system. The energy beam is emitted by the X-ray source to penetrate the sample, then the 2D reconstruction image is obtained by the attenuation of the energy beam. The quality and completeness of the reconstruction image can be improved by the sample stage, which is used to rotate and translate the sample stage. The attenuation degree of the energy beam is measured by the flat panel detector, and the received signal is enlarged and converted to digital data which will be sent to the computer to reconstruct the image. The whole scanning process is controlled by the computer processing system, which is also in charge of parameter adjustment, image reconstruction and visualization.

The working process of X-ray micro-CT device can be generally divided into two part, the first part is the mechanical scanning process,