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Multiscale hierarchical analysis of rock mass and its mechanical and hydraulic properties prediction

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ABSTRACT

Engineering geological and hydro-geological characteristics of foundation rock and surrounding rock mass are the main factors that affect the stability of underground engineering. This paper presents the concept of multiscale hierarchical digital rock mass models to describe the rock mass, including its structures in different scales and corresponding scale dependence. Four scales including regional scale, engineering scale, laboratory scale and microscale are determined, and the corresponding scale-dependent geological structures and their characterization methods are provided. Image analysis and processing method, geostatistics and Monte Carlo simulation technique are used to establish the multiscale hierarchical digital rock mass models, in which the main micro- and macro-structures of rock mass in different geological units and scales are reflected and connected. A computer code is developed for numerically analyzing the strength, fracture behavior and hydraulic conductivity of rock mass using the multiscale hierarchical digital models. Using the models and methods provided in this paper, the geological information of rock mass in different geological units and scales can be considered sufficiently, and the influence of downscale characteristics (such as meso-scale) on the upscale characteristics (such as engineering scale) can be calculated by considering the discrete geological structures in the downscale model as equivalent continuous media in the upscale model. Thus the mechanical and hydraulic properties of rock mass may be evaluated rationally and precisely. The multiscale hierarchical digital rock mass models and the corresponding methods proposed in this paper provide a unified and simple solution for determining the mechanical and hydraulic properties of rock mass in different scales.

1. Introduction

The rapid urbanization has posed a series of significant global challenges such as overpopulation, environmental pollution, tight supply of energy sources and global warming. We can take advantage of the natural benefits provided by underground space to meet current and future needs of the societies (Besner, 2016; Hunt et al., 2016; Kishii, 2016; Zhou and Zhao, 2016). In fact, underground space has been utilized for foundation and structures of roads and buildings, and storage of waste products, hazardous materials, energy resources and gas storage for a long time period. It helps to save land resources, promote metro development, and expand storage space. Geotechnical engineering safety is always one of the most important issues in all phases, including planning, design, construction and operation, of underground engineering (Aksoy and Onargan, 2006; Cauvin et al., 2009; Elmo and Stead, 2010; Dindarloo and Siami-Irdemoosa, 2015; Marcoulaki et al., 2016; Qian and Lin, 2016; Ghasemi et al., 2017). Many cases show that disasters occur due to neglecting or inadequately determining the engineering geological and hydro-geological conditions at engineering sites. For example, Fig. 1a shows the Hangzhou metro pit collapse in China on November 15, 2008, in which 21 workers were killed. Ground collapse occurred at a construction site of the Subway Line 10 in Beijing, China, on March 28, 2007, as shown in Fig. 1b. The collapsed section of the tunnel, about 11 m deep, covered an area of about 20 m^2. Six workers were buried in the accident. Fig. 1c shows the serious accident of water inrush and tunnel collapse that occurred in Shanghai Subway Line 4 on July 1, 2003, which caused a six-storey building to collapse, and the people in the other several

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(a) (b) (c)

Fig. 1. Disasters occurring in underground space development: (a) Hangzhou metro pit collapse, (b) Beijing metro collapse, and (c) collapse accident in Shanghai Subway Line 4.

buildings in the neighborhood had to evacuate. Besides the poor construction and management, unclear geological conditions are the main reasons causing these engineering disasters. Engineering geological and hydro-geological characteristics of foundation rock and surrounding rock mass are the main factors that affect the stability of underground engineering.

In rock mechanics and rock engineering, related parameters are often difficult to be determined (Cai et al., 2004). Laboratory testing can be an effective method, but it has some disadvantages. By contrast, only small rock samples, regardless of fractures and joints in the rock mass, can be investigated by laboratory testing. Obviously, the results obtained cannot show the true nature of the rocks. In addition, in situ tests to determine the engineering properties of rock mass are difficult to be implemented, and are time-consuming and expensive. Some empirical or semi-empirical methods (Hoek and Brown, 1997; Singh and Goel, 1999; Smith, 2004; Ramamurthy, 2004; Singh and Rao, 2005), such as RMR (Goel et al., 1995), RQD (Singh and Goel, 1999), Q-system (Barton, 2006), and Hoek-Brown strength criterion (Hoek and Brown, 1997), were provided to evaluate the engineering properties of rock mass and to classify the rock mass. These methods have been widely adopted in rock engineering, but they often do not identify all the mechanical and hydraulic parameters of rock mass. Moreover, these rock mass quality evaluation systems do not consider local geological characteristics and use the same rating ranges for every rock type, thus they cannot sufficiently present the engineering anisotropy of rocks. Based on these, numerical modeling becomes a necessary tool for estimating the engineering properties of rock mass (Holland and Lorig, 1997; Tang et al., 2002; Jing, 2003; Liu et al., 2008).

In this paper, the concept of multiscale hierarchical digital rock mass models is presented to describe the rock mass in different scales and its scale dependence. The multiscale hierarchical digital rock mass models are some computer models, in which the main structures of rock mass in different geological units and scales are reflected. The influence of downscale characteristics (such as mesoscale) on the upscale characteristics (such as engineering scale) can be calculated by considering the discrete geological structures in the downscale model as equivalent continuous media in the upscale model. Thus the mechanical and hydraulic properties of rock mass may be evaluated rationally and precisely. Moreover, computer codes have been developed for numerically analyzing the strength, fracture behavior and hydraulic conductivity of rock mass using the multiscale hierarchical digital rock mass models. By the models and methods provided in this paper, the geological information in different geological units and scales can be considered sufficiently, and the mechanical and hydraulic parameters of rock mass can be determined quantitatively. The results show that the effect of micro-defects on the deformation behavior and the effects of fracture geometry factors, such as dip angle, trace length, fracture spacing and width, on hydraulic conductivity of rock mass in engineering scale can be studied. The multiscale hierarchical digital rock mass models and the corresponding methods in this paper provide a unified and simple solution for determining the mechanical and hydraulic properties of rock mass in different scales.

2. Multiscale hierarchical digital rock mass models

Natural rock and rock mass are materials with hierarchical defect structures, such as micro-defects, micro-fracture, fractures, and faults (Liu et al., 2008, 2011). These hierarchical structures affect each other, controlling the mechanical and hydraulic behaviors of rock and rock mass (Warpinski and Teufel, 1987; Weng et al., 2011; Virgo et al., 2013; Behraftar et al., 2017; Chen et al., 2018). However, it is difficult to describe all the hierarchical structures in one model, thus the multiscale hierarchical digital rock mass models are presented to investigate the effect of these hierarchical structures on the engineering properties of rock mass. At each level of structural hierarchy, the material can be modeled as the constitution of a continuum and characteristic structures in this level for the purpose of analysis. In this paper, four scales are determined for analysis purpose, as shown in Fig. 2. In every scale, only one-level hierarchical structures exist, and the mechanical and hydraulic properties of rock mass in this scale are easily determined by the equivalent continuum method. The following sections describe the multiscale hierarchical digital rock mass models.

2.1. *Regional scale model*

Regional scale model, in which the engineering structures (e.g. dam and tunnel) and the regional geological body with topography are included, is presented for safety analysis of engineering structures. The distinct faults and rock layers, which are generally less and can be determined by geological investigation in regional scale, are classified as the first-level hierarchical structures. These structures should be considered in regional scale model, because they control the deformation characteristics and groundwater seepage in this scale. The first-level hierarchical structures divide the geological bodies in the whole region into many distinct independent bodies. These bodies are considered as equivalent continuum in this scale, as shown in Fig. 3, where an excavation process under a river is described.

2.2. *Engineering scale model*

In engineering scale, the distinct independent bodies divided by the first-level hierarchical structures are the main analysis objects. Though they have been considered as equivalent continuum in the regional scale, they are inhomogeneous and anisotropic in the engineering scale because a large number of fractures exist in them, as shown in Fig. 2b. These fractures are classified as the second-level

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