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A multi-scale analysis method for the simulation of tunnel excavation in sandy cobble stratum

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ABSTRACT

Sandy cobble stratum is a kind of heterogeneous geological body. A further study on the safety of wall rocks and underground structure demands developing suitable analysis method to simulate tunnel excavation in such a formation. Macro-scale simulations assume the sandy cobble soil to be homogeneous in numerical models. They get more efficient computing, but have difficulties in capturing enough information about the meso-scopic fields needed. Meso-scale simulations explicitly represent the individual components of the heterogeneous internal material structure in numerical models, e.g. the shape and the spatial distribution of rocks. They achieve high accuracy, but large computational cost would be needed. To reduce the numerical effort with the precision guaranteed, a multi-scale analysis method for simulating tunnel excavation in sandy cobble strata is proposed. In this method, the numerical model is divided into two regions, involving the meso-scale region and macro-scale region. The meso-scale region is a critical sub-domain disturbed by tunnel excavation, in it, the rocks and soil are considered as separate constituents. In the macro domain, the sand gravel soil was regarded as homogeneous materials whose effective material parameters were determined using an equivalent homogenization method. Three critical issues in the multi-scale method are explored, including: (i) the determination of meso domain and macro domain, (ii) the determination of rock maximum size that can be homogenized in the meso domain and iii) the determination of effective material parameters of soil-rock mixture during the equivalent process. By comparing with simulation results predicted by macro-scale and meso-scale simulation methods, the validation of the proposed multi-scale simulation method was carried out. The result indicates that the proposed multi-scale analysis method has a high efficiency without loosening accuracy on the simulation of tunnel excavation in sandy cobble stratum.

1. Introduction

Nowadays, demands for underground transportation has grown considerably, which inevitably needs to carry out construction in complex geological conditions. Sandy cobble stratum, which composed of heterogeneous soil-rock mixture (SRM) (Lindquist, 1994; Medley, 1994; Medley and Wakabayashi, 2004), is one of the most common complicated engineering geological body. When tunneling in this formation, the performance of ground and lining structure will differ from that in homogeneous layer (Zhang et al., 2018). Since the frequent occurrence of engineering accidents happened in sandy cobble stratum, it is of great importance to develop the specific analysis method and modelling theory on tunneling in this formation.

Generally, the explorations on tunnel excavation in sandy cobble formation mainly through field observations, physical model tests and numerical simulations. Site measurements and projects dates are good ways for providing valuable and reliable sources of information (McCabe et al., 2012; Fargnoli et al., 2013, 2015; Zhang et al., 2013; Mooney et al., 2016), however, only few monitoring data is available in the actual projects (Chen and Chen, 2007). Model tests could give reasonable results (Fan and Zhang, 2013; He et al., 2015), but the development of physical model test is quite complex and time-consuming. Exactly due to this, limited indications have been provided to obtain empirical solutions for deformation and stress in sandy cobble stratum. In light of this, it would be extremely useful to investigate the tunnel excavation using numerical methods.

In the numerical investigations, macro-scale simulations are often used to simulate tunnel excavation in sandy cobble strata, in which the sandy cobble soil was assumed to be homogeneous material. In the efforts of Migliazza et al. (2009); Zhou et al. (2009); Zhang et al.

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(2013); Fargnoli et al. (2015); Su (2015); Mooney et al. (2016), macroscopic homogeneous numerical models were employed to investigate the ground deformation during tunneling. Adopting macroscopic finite element models of tunnel excavation, Małkowski (2015) and Xiao et al. (2016) analyzed the plastic zone variations affected by physical model selection or different excavation scheme, respectively. Yen and Shou (2015); Shou et al. (2010) and Katebi et al. (2015) carried out macro-scale simulations to evaluate tunnel lining loads or jacking force. In their simulations, the sandy cobble soil was represented in a homogenized way using effective material properties, and the equivalent material parameters were mainly obtained from laboratory experiments (Migliazza et al., 2009; Zhang et al., 2013; Xiao et al., 2016; Zhang et al., 2016), field experiments (Katebi et al., 2015) and engineering analogue (Małkowski, 2015; Fargnoli et al., 2015). However, since the particle size in sandy cobble strata ranging from millimeter to meter, the specimen always hardly cover all the particles, a significantly error will be presented in the effective material properties. On the other hand, the internal structure of material indicates the sandy cobble soil is not a homogenous material in nature. Therefore, though macro-scale simulations achieve a high efficiency, they have difficulties in capturing enough information about the mesoscopic fields needed.

Recently, meso-scale simulations have been employed to explore the tunnel excavation in sandy cobble formation. On the meso-scale, the sandy cobble strata can be regarded as a composite material formation composed by fine-grained soils and large-sized hard rocks, with or without jointing between them (Zhang et al., 2018). The individual components of the heterogeneous internal material structure, e.g. the shape and the spatial distribution of the rocks are represented explicitly in the model (Xu et al., 2008; Xu et al., 2015; Chen et al., 2018). For each individual component, i.e. soil matrix and rock, there are considerable difference in their mechanical properties, such as elastic modulus, shear strength, friction angle and cohesion. Zhang et al. (2018) developed a mesoscopic numerical model of sandy cobble stratum and demonstrated its application in tunneling. The computational result showed the merits of modelling the heterogeneity of sandy cobble soil in better modelling the macro-mechanical behavior, compared with the macro-scale model. Meso-scale simulations require the discretization of the internal material structure, so they have a high accuracy. However, compared with macro-scale simulations, the numerical effort and the memory demand increase dramatically (Unger and Eckardt, 2011) for meso-scale simulations. Therefore, meso-scale simulations are always limited to small specimens. On the other hand, treating sandy cobble soil as a series of particles, some researchers also carried out discrete element simulations on tunnel excavation (He et al., 2012; He et al., 2013; Shi et al., 2013; Jiang et al., 2015). However, owing to the complex contact algorithm and parameter calibration between particles, the application of discrete element simulation is also limited to small size models.

Multi-scale method provides a strategy to handle the evolution of deformation at the larger scales while retaining important small-scale details. In this method, the descriptions of material behavior are described on different length scales. On the macro-scale, sandy cobble soil is considered as homogeneous material whereas on the meso-scale the heterogeneous internal material structure is explicitly resolved. Considering the material heterogeneity, two main concepts of multi-scale method can be distinguished (Unger and Eckardt, 2011). The first category is the hierarchical multi-scale approach (Andrade et al., 2011; Ghassan et al., 2016; Argilagaa et al., 2017). In this approach, the entire model is discretized on the macro-scale, and the constitutive relationship on the maco-scale is derived from the structural response of a representative material sample modeled on the meso-scale. The second category, followed in this work, is the concurrent multi-scale approach (Cai et al., 2007; Dang and Meguid, 2013). In this method, the model is subdivided into sub-domains and the heterogeneous internal material structure is only explicitly represented in the critical sub-domain. Great progress has been made in the multi-scale technique on analysis of composite material (Raghavan and Ghosh, 2004; Talreja, 2006; Timofte, 2013) and concrete structure (Tao and Nie, 2016), which provides significant reference for developing a multi-scale method to simulate tunnel excavation.

The aim of the present study is to develop a multi-scale method for the simulation of tunnel excavation in sandy cobble strata. Taking the heterogeneity into account, the sand gravel soil was treated as a two-phase composite material within a relatively small area of great concern, while it was considered as homogeneous material in other regions. By comparing with the meso-scale and macro-scale analysis simulations, the multi-scale analysis method is verified to be more effective in predicting deformation and stress performance. It provides a new way in the simulation of tunnel excavation in heterogeneous formation.

After the Introduction, the paper is organized as follows. In Section 2, a homogenization method for studying macro-mechanical properties of SRM is illustrated briefly, which will be employed in determining effective material parameters in the following. Section 3 presents a multi-scale method for the simulation tunnel excavation in sandy cobble strata, and four key issues of the method are discussed. On the basis of the proposed method, a multi-scale computational model of tunnel excavation is established in detail, as shown in Section 4. Then, by analyzing the simulation results of meso-scale, macro-scale and multi-scale models, the accuracy and efficiency of the proposed method is verified in Section 5. Finally, Section 6 presents some conclusions.

2. Homogenization for the mechanical properties of SRM

Sandy cobble soil is a typical SRM, which composed of soil matrix and rocks. The individual material constituents and their mutual interactions have a significant effect on the mechanical and deformation performance of SRM on the macro-scale. Due to the wide range of rock size, it becomes more difficult to obtain the equivalent material properties of SRM.

Recently, a meso-scopic equivalent method for studying macro-mechanical properties of SRM has been developed by the authors (Du et al., 2017). This method has been demonstrated to have acceptable accuracy and high efficiency. Fig. 1(a) shows a typical random distribution structure of SRM, which contains soil matrix and rock blocks sized by $D_0 \le D \le D_j$. Similar with that in Xu et al. (2008); Shi et al. (2013); Wang et al. (2015) work, the interfacial transition zone between the rock blocks and soil matrix was not considered herein. The basic idea of the multi-step equivalent analysis method can be illustrated as follows.

(1) Firstly, the smaller rock blocks with a diameter interval $D_0 \le D \le D_1$ are put into soil matrix randomly, and the representative samples are established to form a homogenous equivalent matrix M_{E1}, as depicted in Fig. 1(b);
(2) The rock blocks with a diameter interval $D_1 < D \le D_2$ are then put into the equivalent matrix M_{E1}, and the specimens based on the newly SRM are developed to obtain the homogenous equivalent matrix M_{E2}, as shown in Fig. 1(c);
(3) Similarly, the newly homogenous equivalent matrix M_{Ej} is generated by putting rock blocks with the diameter interval $D_i < D \le D_j$ into the equivalent matrix M_{Ei}, as can be seen from Fig. 1(d);
(4) Finally, the rocks with a diameter $D > D_j$ are integrated into homogenous equivalent matrix M_{Ej}, and the macroscopic mechanical properties of SRM can be obtained.

It is to be noted that the equivalent method has two key issues, namely, the determinations of key rock diameter in the random distribution model and the homogenization technique. According to the Standard for soil test method of China (GB/T 50123) (2007), when the diameter of representative sample smaller than 100 mm, the allowable maximum particle size can take 1/10 of sample diameter. If the diameter of representative sample larger than 100 mm, the allowable