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Theoretical model of the equivalent elastic modulus of a cobblestone–soil matrix for TBM tunneling ☆

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ABSTRACT

Cobblestone–soil mixed ground is a composite comprising cobblestones surrounded by soil. It is typical mixed-face ground encountered during tunnel boring machine (TBM) tunneling, and it may result in cutter wear, jamming of the roller cutterhead, poor TBM performance and cost overruns. The present paper investigates the deformation problem of cobblestone–soil mixed-face ground during TBM excavation. The ground under study is composed of two components (soil matrix and cobblestones) usually firmly bonded together at the interface, and can be regarded as a continuum. Previous studies have proposed many theoretical models for a composite material with two components. Representative models include the parallel model, series model, and effective medium theory model. Nonetheless, these models are limited by their assumptions and preconditions. In the present study, under an assumption of uniform strain, analytical solutions were derived for the equivalent elastic modulus while the cobblestone is assumed to be perfectly spherical or ellipsoidal. Triaxial compression tests were carried out to validate the analytical solutions. The equivalent elastic modulus derived from the triaxial experiments and theoretical models matched rather closely. The analytical solutions are helpful in clarifying the deformation of such ground and enhancing TBM performance.

1. Introduction

With the development of underground construction technology, tunnels have become essential infrastructure for transportation, road systems, sewerage, electricity cables, communication cables and subway systems (Katebi et al., 2015). In past decades, mechanized tunneling has developed rapidly. Excavation using a tunneling boring machine (TBM) is regarded as a potentially fast method of excavating and supporting a tunnel (Zhao, 2007). TBM technology has been improved in recent years and nowadays TBMs are popular in mining and civil engineering works (Balci and Tumac, 2012). Currently, the TBM can adapt to a variety of geological conditions from hard rock to soft soil. A mature theoretical foundation and engineering experiences are available for hard rock and soft soil strata (Farrokh et al., 2012). Although the TBM is becoming more versatile and capable of boring through varying geological conditions, the geological conditions strongly affect the efficiency and overall performance of the TBM (Delisio et al., 2013; Zhao et al., 2007). Especially for mixed-face ground, the use of the TBM is still in an exploratory stage.

Cobblestone–soil mixed ground is a composite comprising cobblestones and soil. It is typical mixed-face ground that presents an outstanding problem to TBM tunneling (Steingrimsson et al., 2002) in terms of ground settlement, low TBM performance and cost overrun (Blindheim et al., 2002). For TBM tunneling, mixed-face ground can be defined as ground in which there is the simultaneous occurrence of multiple geological formations, and the TBM performance for multiple formations is greatly different from that for any single type of ground. Driving a tunnel boring machine (TBM) in mixed-face ground is one of the most difficult tasks in mechanized tunneling (Tóth et al., 2013). Fig. 1 shows typical sandy pebble ground found along Line 1 of the Chengdu Metro (CDM) in China. The ground is mainly a mixture of granite, diorite and quartzite pebbles and sandy soil. Many problems were encountered during TBM tunneling when constructing the CDM, including extremely high cutter damage and wear, ground loss, long downtimes and a low penetration rate. The TBM performance was thus poor, and, to a certain extent, could be attributed to a lack of knowledge about the mixed ground.

The main problems encountered during TBM tunneling in such ground are (1) irregular ground settlement, (2) a complex stress

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Fig. 1. Cores recovered from tunnels of Line 1 of the CDM.

distribution and difficulties in deformation control, and (3) an unclear rock breakage mechanism and lack of theoretical guidance on the stress analysis for cutters. A proper cobblestone–soil constitutive model will help solve these problems.

The mechanical properties of a cobblestone–soil mixture and continuous media are distinct. The force transfer in a cobblestone–soil mixture is mainly decided by the cobblestones. When a TBM excavates in a cobblestone–soil mixture, cobblestones begin to rotate with the cutterhead, leading to point-to-point contact between adjacent cobblestones, and the transfer of stress. The soil between cobblestones plays a larger role only when it is subjected to large tensile forces. This special force transfer process is called the skeleton effect. In other words, to some extent, the strength of the cobblestone–soil mixture is decided by the structural characteristics of the skeleton. However, as most cobblestones are approximately ellipsoidal, instead of spherical, the direction of the long axis changes with the rotation of cobblestones during excavation. At this time, the skeleton completely changes and large deformation occurs on a macro-scale. This leads to greater challenges in establishing a constitutive model for such a mixture. Therefore, studies on the equivalent physical properties of a mixed material not only are beneficial to the analysis of the material properties but also can help clarify the mechanism of TBM excavation in such material. Nowadays, theories on hard rock and soft soil are relatively mature and a large number of constitutive models have been proposed in the continuous-medium framework, which can be applied to analyze stress and strain behaviors. A great amount of research has been conducted on the design of TBM machinery and the prediction of TBM performance in hard rock and soft ground (Guo et al., 2005). However, little attention has been paid to mixed-face ground, especially the cobblestone–soil mixture. The representative volume element (RVE) has been proposed for the study of the mechanical properties of two-phase materials (Hashin and Shtrikman, 1963; Thorpe and Sen, 1985). Although the existing theoretical models can predict physical properties of a mixed material with two components (MMTC), most were established on the assumption of a simple geometric shape and ideal state. Hence, these models have limited applications, especially for mixed materials with complicated structure.

The present paper investigates the equivalent elastic modulus of mixed material. The mixed material here comprises cobblestones and soil, and can be regarded as a continuum since the two materials are usually firmly bonded together at the interface (Hashin, 1983).

2. Existing methods for determining the equivalent elastic modulus of mixed material

Since the first study on the equivalent elastic modulus published by Einstein in 1906, many studies have investigated various mechanical properties of mixed material (Hashin and Shtrikman, 1963). Nevertheless, the analysis and prediction of the behaviors of mixed materials are generally more intricate. The components of the mixture interact with each other and the properties at the interface differ from those of any component (Bishop et al., 2006; Lee and Pyo, 2008). The overall behaviors or macroscopic properties of mixed material are not identical to those of any single component, but are rather the collective properties of all components forming the mixture (Feng and Liu, 2008). The concept of equivalent physical properties has become widely accepted (Bonnet, 2007; Masson et al., 2000), where the equivalent properties can be thought of as the properties of a hypothetical material that yields the same response for given conditions. Only pure physical properties are considered for equivalent physical properties (Liu and Chen, 2003). Many theoretical or analytical models of equivalent physical properties have been proposed over the last century, most of which focus on the microstructure (Feng and Liu, 2006). For an MMTC, theoretical approaches include the use of basic models, combined models, and network models. Representative models are the parallel model, series model, and effective medium theory (EMT) model (Wang and Pan, 2008).

2.1. Parallel and series models

The parallel and series models are the simplest theoretical models for an MMTC, and are often used as benchmarks for the validation of new models. They often offer the upper and lower bounds of MMTC properties (Wong and Bollampally, 1999). The models are based on the assumption of a uniform and isotropic medium (Paul, 1959).

For the equivalent elastic modulus of an MMTC, let E, K, G, ν and f denote the elastic modulus, the bulk modulus, the shear modulus, Poisson's ratio, and the area or volume fraction of the inclusions, respectively. Subscripts 1 and 2 stand for the matrix and inclusion, respectively. Apparently, the conditions

$$E = E_1, \quad \text{when } f = 0, \tag{1}$$

$$E = E_2, \quad \text{when } f = 1, \tag{2}$$

are satisfied in any case.

The simplest linear relationship satisfying these conditions can be obtained under the assumption that each component contributes to the MMTC in proportion to its own strength and fraction; i.e.,

$$E = E_1(1-f) + E_2 f. \tag{3}$$

Eq. (3) is commonly called the parallel model, and in fact provides an upper bound of the elastic modulus E if both materials are assumed to have the same Poisson's ratio.

If $1/E$ complies with Eqs. (1) and (2), another simple relationship can be derived by a linear interpolation between the extreme values:

$$\frac{1}{E} = \frac{1}{E_1}(1-f) + \frac{1}{E_2}f. \tag{4}$$

Eq. (4) was proposed by MacDonald and Ransley (Vekinis et al., 1997) for different types of ground as a lower bound and is referred to as the series model in general.