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Theoretical prediction of ground movements induced by tunnelling in multi-layered soils

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ABSTRACT

The theoretical predictions of ground movements induced by tunnelling are usually based on the assumptions that the ground is homogeneous. Actually, layered formations with different soil properties are usually encountered in situ and effects of soil stratification should be taken into account. This paper presents the displacement controlled boundary integral method aimed specially at investigating the effect of soil stratification on the tunnelling-induced ground movements. The modified elastic layered half-space model is combined with the method to consider the soil non-homogeneous characters, whereas the Kelvin and Mindlin solution based on homogeneous materials are employed previously. The applicability of the proposed method is verified with other available published results as well as the displacement controlled finite element analysis. Surface settlements and lateral displacements induced by tunnelling on the layered soil condition are compared with those based on the homogeneous soil. The results discussed in this paper show that the soil stratification, neglected in previous solutions, have a significant influence on the tunnelling-induced ground movements in multi-layered soils.

1. Introduction

Increasing pressure on land use within urban areas has lead to escalation in the number of tunnelling projects for public services and transportations purposes world-wide. However, complex tunnelling process will inevitably result in ground movements, and as a result tunnel constructions may cause damage to the adjacent existing building and public facilities. Therefore one of the important issues of tunnelling in urban areas is the estimation of the potential tunnelling-induced ground movements, so that the possible damage level of adjacent structures can be assessed.

Some attempts have been made to develop the related researches about tunnelling-induced ground movements. Methods for solving the problem may be classified into three categories: empirical methods, numerical methods, and analytical methods. Empirical methods such as the Gaussian distribution curve proposed by Peck (1969) are based on field observations and intuitive deductions, thus slack in theory and ambiguous in range of applicability. Numerical simulation, such as finite element analysis, is commonly used to predict ground movements due to tunnelling. The numerical simulation method can consider the nonlinear interaction between the tunnel and its surrounding soils, the soil elastoplastic behavior, and the complexity of construction operations. However, the substantial computation performance and the professional software are required. Particularly, it usually takes a very long time to obtain the logical numerical results of the problem (Kitiyodom et al., 2005).

In addition, analytical methods are the preferred approach to analyze the ground movements induced by tunnelling. Four main categories exist for the analytical methods, namely: the virtual image technique (Sagaseta, 1987; Verruijt and Booker, 1996; Loganathan and Poulos, 1998), the complex variable method (Verruijt, 1997, 1998), the general series form stress function in polar coordinate (Bobet, 2001; Chou and Bobet, 2002; Park, 2004, 2005), and the stochastic medium theory (Yang et al., 2004). The displacement controlled pattern is imposed in the above-mentioned methods with the assumption of a uniform radial or oval-shaped soil deformation around the tunnel opening. In general, analytical methods are based on the elastic homogeneous soil, and they are obtained through explicit theoretical deduction. However, there has been little attention given to the development of movements in ground made up of more than one soil layer.

The geology of many urban environments throughout the world consists of multi-layered soils with different material properties. Furthermore, underground structures are founded at various depths within the soil mass. There are above ten tunnel lines in Shanghai, and several different layered formations, including brown clay, loamy silty clay, gray silty clay, sap green silty clay,

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and grass yellow sandy silt, have encountered. Multi-layered formations have also encountered during tunnelling in most of other cities in China. Actually, Model tests have been performed in order to study the ground deformation due to tunnelling in layered soils (Lin, 1996, and Chu et al., 2007). The experimental results show that the soil non-homogeneity has significant effects on the ground deformation induced by tunnelling. Therefore, it is desirable to develop an analytical or semi-analytical method of predicting tunnelling-induced ground movements in multi-layered formations instead of homogenous material, so that the analyzed results would reflect actual situations during tunnelling.

In order to consider effects of soil stratification on the ground movements due to tunnelling, it is preferred approach to simulate the layered characters by analytical solutions for the elastic layered half-space model in highway engineering. From an historical perspective, the theoretical analysis of the elastic layered half-space model was initially based on integral transformation methods. Starting from the basic equation of elasticity and writing the boundary conditions at the interface between the connected layers, analytical expressions for the Fourier or Hankel transformation of displacements and stresses can be obtained for a prescribed distribution of the surface stresses. The theoretical basis of this approach can be found by Burmister (1945), who developed an elasticity theory for axisymmetric contacts and obtained solutions for the two-layered and three-layered airport pavement. Since these classical studies, analyses of multi-layered material regions subjected to axisymmetric loads have been extensively carried out in the cylindrical coordinate (Wang and Fang, 1999; Zeng and Liang, 2002; Han, 2006; Alkasawneh et al., 2007). In addition, few theoretical studies have conducted to overcome asymmetric contacts problems in the cylindrical coordinate (Ai et al., 2002; Fukahata and Matsu'ura, 2005). According to asymmetric problems, the field variables and asymmetric loads must firstly be expressed in terms of the Fourier series expansion. It is convenient to adopt the cylindrical coordinate to solve elastic layered material problems, since the basic equations can be easily converted into the state space equations by Hankel transformation. However, the above-mentioned methods have some disadvantages, including complicated derivation process and formula, slow convergence and even not convergence of the trigonometric series. Furthermore, most of the aforementioned researches are focus on the solutions subjected to external loads located on the surface ground. Little researches give attentions to consider the condition with internal loads in the layered medium. For most of the geotechnical situations, however, arbitrary construction loads are usually encountered extensively. Therefore, it is necessary to solve the problem about arbitrary loads in the layered half-space medium.

The Kelvin solution for infinite homogeneous medium or the Mindlin solution for semi-infinite homogeneous medium is applied to solve the problem about non-homogeneous body by the traditional boundary integral method. It should be noted that the boundary integral and element discretization must be conducted along each interface between any two connected layers. The computation scale of the traditional method is large, and it commonly takes a very long time to obtain the final results. Therefore, the main advantage of the boundary integral method (i.e., discretization of the problem on boundaries only) may be lost if one approaches the problem by the traditional method. Thus remarkably little attention has been paid to the development of tunnelling-induced ground movements in multi-layered soils by the traditional boundary integral method.

In order to avoid complicated integral for all of the interfaces and reflect soil stratification for the semi-infinite medium, the displacement controlled boundary integral method is presented for the analysis of tunnelling-induced ground movements in multi-layered soils. The modified elastic layered half-space model is combined with the method to consider the soil non-homogeneous characters, whereas the Kelvin and Mindlin solution based on homogeneous materials are employed previously. Since the foundation model is built in the Cartesian coordinate, it is very easily to solve asymmetric problems and consider the condition with internal loads in multi-layered soils. Furthermore, the oval-shaped ground deformation pattern is imposed as the boundary condition at the tunnel opening to consider real non-uniform ground deformation pattern induced by tunnelling. In particular, the low-order constant elements in the boundary discrete equations are replaced by the high-order isoparametric elements for the high calculation accuracy.

2. Method of analysis

2.1. Modified elastic layered half-space model subjected to arbitrary loads in a Cartesian coordinate system

The fundamental solution from the modified elastic layered half-space model represents the elastostatic field in a layered half-space subjected to arbitrary loads in a Cartesian coordinate system. The elastic layered half-space consists of n parallel, elastic isotropic layers lying on the homogeneous elastic half space, where n is an integer and satisfies $n \geqslant 1$. By referring to Fig. 1, the ith layer occupies a finite layer region $h_{i-1} \leqslant z \leqslant h_i$ of thickness Δh_i ($\Delta h_i = h_i - h_{i-1}$), Young's modulus E_i and Poisson's ratio μ_i, where $i = 1, 2, 3, \ldots,$ or n, and h_0 is defined by the value of zero. The boundary surface $z = 0$ of the layered soils is considered as traction free. The interface between any two connected layers is assumed to be perfectly bonded, where the stresses and the displacements are completely continuous. Without loss of generality, it is assumed that the arbitrary load is concentrated at a point (x_0, y_0, h_{m1}) in the mth layer (assuming the load surface is considered as an artificial interface). The arbitrary load can be decomposed into the three components $P(x_0, y_0, h_{m1})$, $R(x_0, y_0, h_{m1})$, and $Q(x_0, y_0, h_{m1})$ along the x, y, z direction, respectively.

2.1.1. Transfer matrix for a single layered soil

Using the elasticity equations of static equilibrium and the relations between stresses and displacements, a set of partial differential equations is obtained as follows:

$$\frac{\partial}{\partial z}[E(x,y,z)] = A(x,y)E(x,y,z) \tag{1}$$

where $E(x,y,z)$ is the state variable vector in the physical domain, i.e.,

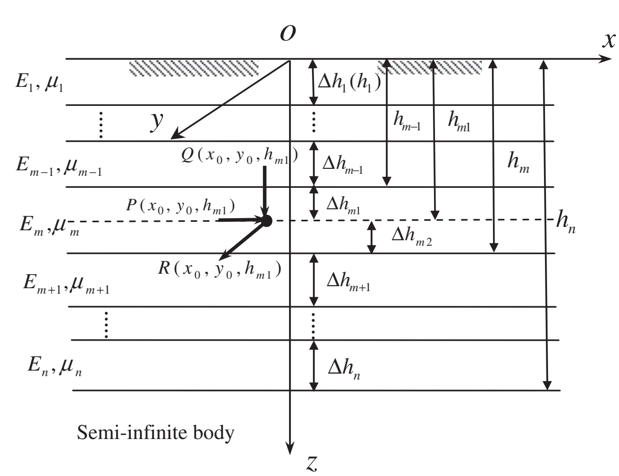

Fig. 1. Modified elastic layered half-space model.