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Research Paper

Three-dimensional multilayer cylindrical tunnel model for calculating train-induced dynamic stress in saturated soils

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ABSTRACT

This study proposes an improved tunnel model for evaluating train-induced dynamic stress in saturated soils, which can consider multiple moving loads, grouting layer and pore-water pressure. Using Shanghai Metro's actual parameters for train speed, tunnel, grouting layer and soils, the analysis of the spatial distribution of dynamic stress for soils and stress state of various locations under moving train loads shows that neglecting effects such as pore-water pressure can lead to underestimating dynamic normal stress and overestimating dynamic shear stress in the soils below tunnel. This model can be further extended to investigate principal stress axes rotations and tunnel settlement.

1. Introduction

The current development of Chinese metro systems has entered a stage of large-scale construction and operation. Due to years of service, considerable tunnel settlement has occurred in metro systems constructed in soft soil areas such as Shanghai. Fig. 1 shows an example of the observed long-term settlement of the Shanghai Metro Line No. 1. Excessive tunnel settlement now impedes operation and is leading to increased maintenance costs [1–5]. Traffic loading is one of the primary causes of the long-term tunnel settlement [6,7]; for instance, the Shanghai Metro Line 1 only experienced 2–6 mm of settlement within 27 months after construction (when the line was not in service), but approximately 60 mm of settlement was observed after eight months of service. The train-load-induced settlement triggers soil stress and pore-water pressure change. Thus, studying the dynamic responses of tunnel foundations is fundamental to tunnel settlement assessment.

Several tunnel models have been established to simulate the dynamic responses of a tunnel-soil system. There are four typical modeling methods: an embedded Euler beam, a Pipe-in-Pipe (PiP) model, a periodic finite element-boundary element method, and a finite/infinite element approach. Metrikine et al., Haak and Yuan et al. modeled tunnels as embedded Euler beams to study the ground vibrations resulting from a moving train inside a tunnel [8–10]. Forrest and Hunt developed a three-dimensional analytical model (i.e., PiP model) for a deep underground railway tunnel with a circular cross-section. The tunnel lining was conceptualized as a thin cylindrical shell surrounded by soils with infinite radial extent [11]. The PiP model was further improved by Hunt and Hussein, who incorporated a floating slab track of the metro tunnel [12,13]. The PiP model is computationally efficient but it is limited to a tunnel with a circular cross-section. Degrande et al. proposed a periodic finite element-boundary element (FE–BE) method to analyze ground-borne vibrations from underground railway traffic [14]. Gupta et al. compared the periodic finite element-boundary element model with the PiP model; the PiP model was validated by the coupled FE–BE model for a tunnel embedded in full space [15]. Yang and Hung proposed a 2.5-dimensional finite/infinite element approach to analyze the wave propagation problems caused by underground moving trains [16]. Numerical models such as coupled FE–BE models can account for different forms of tunnel cross-sections (e.g., rectangular tunnel) but they require significant computational effort. The aforementioned research work primarily focused on the soil displacement generated by the underground railways.

Several investigators have examined the soil stress induced by train movements. Wang and Chen calculated the train-induced dynamic stress in soils and analyzed the stress state variation and principal stress axes rotations generated by ground railways [17,18]. Gong et al. used the finite element method to assess the influence range of train-load-induced stress of ground surrounding a shield tunnel [19]. There is little research on modeling the grouting layer in shield tunnels. It should be noted that previous

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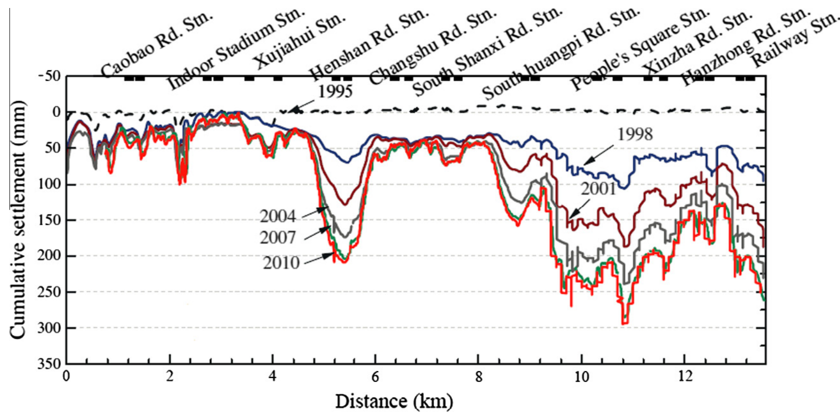

Fig. 1. Observed long-term settlement of the Shanghai Metro Line No. 1 (adapted from [1]).

research simply treated soils as single-phase elastic or visco-elastic media. However, pore-water pressure is an important factor that should be considered in any modeling that analyzes train-induced dynamic stress in saturated soil. One study reported on the dynamic response of a shield tunnel surrounded by saturated porous medium under harmonic load in lieu of an actual train load [20]. Based on a field test, the train-load-induced stress and pore-water pressure of the ground at the side of a tunnel of Shanghai Metro Line No. 2 were monitored [21]; due to the limited test conditions, monitoring data on the dynamic stress and pore-water pressure values beneath the tunnel were unavailable. Therefore, research is necessary to understand the train-load-induced stress of saturated ground beneath a tunnel to contribute to tunnel settlement assessment.

This study develops a new tunnel model by extending the PiP model to evaluate the vibration induced by a metro train in a shield tunnel buried in saturated soils. Compared with the standard PiP model, the newly developed model offers several contributions. (1) It is important to understand the effect of the grouting layer on the dynamic response. The PiP model treats a tunnel lining without a grouting layer as a single shell, whereas the improved model simulates a tunnel lining with a grouting layer by using double cylindrical shell and simulates the surrounding saturated soils of the tunnel by using a porous medium. (2) The PiP model considers the soil as a single-phase medium, whereas the improved model uses Biot's saturated porous medium to simulate the soil and improves the foundation component of the existing model. This advantage is important when studying the dynamic interaction between the saturated soils and the tunnel and when obtaining the excess pore-water pressure. (3) The determination of dynamic stress in the soils is a prerequisite to analyzing the train-load-induced soil stress state variation, the principal stress axes rotation of the soils and the train-load-induced cumulative settlement evaluation. The PiP model uses a harmonic at a fixed location, whereas the improved model simplifies the metro train load as a series of moving wheel loads P at a constant speed v. Based on this improved model, the train-load-induced stress in the soils surrounding the tunnel can be calculated and analyzed. It is shown that this improved model can rationally evaluate the dynamic stress and stress state of the soil element induced by moving metro train loads.

2. Governing equations of the shell-cylinder model

2.1. Double cylindrical shell equations

During the shield tunneling process, a gap forms between the excavation of the cave walls and the tunnel lining that is called the shield tail gap. To reduce the stress release and stratum deformation due to the shield tail clearance, a grouting technique is often utilized to fill the construction clearance, as shown in Fig. 2. After the grouting slurry coagulates, a ring grouting layer is formed around the tunnel lining [22].

In one PiP model [11], a three-dimensional tunnel model was developed by using Flügge equations of motion for a thin cylindrical shell made of linear elastic, homogeneous and isotropic material. This previous study focused on a general tunnel in which the tunnel lining was considered as one shell. The present study focuses on a shield tunnel that involves grouting. To take the grouting layer of the shield tunnel into account, the tunnel lining and the grouting layer is modeled as a double thin cylindrical shell with infinite longitudinal length. The material of the double cylindrical shell is linear, elastic, homogeneous and isotropic. Fig. 3 shows the double shell and its cylindrical-coordinate system.

The Flügge equations of motion for a double cylindrical shell in terms of equilibrium relationships are given as follows:

Equilibrium in the longitudinal direction x gives

$$R^2\,A_{s1}\frac{\partial^2 u}{\partial x^2}+\frac{1}{2}(A_{s1}-A_{s1v})\frac{\partial^2 u}{\partial\theta^2}+R\frac{1}{2}(A_{s1}+A_{s1v})\frac{\partial^2 v}{\partial x\partial\theta}-A_{s1v}R\times\frac{\partial w}{\partial x}+\kappa\frac{1}{2}(1-\eta)\frac{\partial^2 u}{\partial\theta^2}+\kappa\left[R^3\frac{\partial^3 w}{\partial x^3}-\frac{R}{2}(1-\eta)\frac{\partial^3 w}{\partial x\partial\theta^2}\right]=m_sR^2\frac{\partial^2 u}{\partial t^2}-R^2q_x, \quad (1)$$

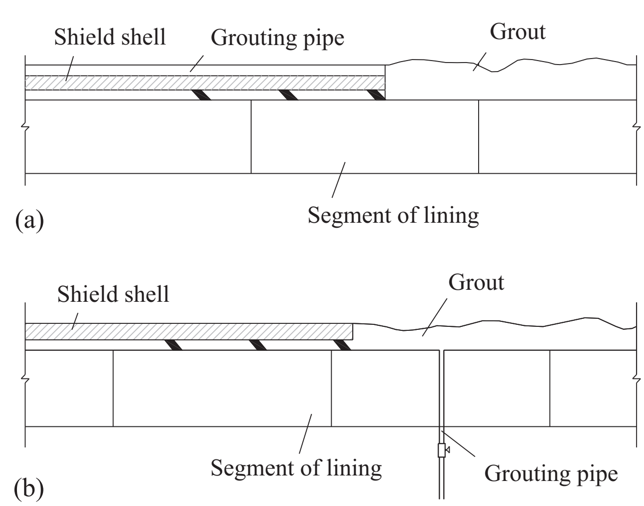

Fig. 2. Diagram of grouting in shield tunneling (adapted from [22]): (a) grouting at the tail; (b) grouting at the segment.