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# Dynamic response and long-term settlement of a metro tunnel in saturated clay due to moving train load

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**Abstract**

The purpose of this study is to investigate the train-induced settlement of a metro tunnel in saturated clay through the soil-water full coupling dynamic finite element method (FEM). The train vibration load is first evaluated using the rail-fastener-tunnel-subgrade model and then applied to the track bed to simulate the movement of metro train in the 3D model. Cyclic Mobility Model introduced in the numerical analysis to simulate the mechanical behavior of saturated soft clay. Three cases of numerical analyses are conducted to study the train-induced vibration in saturated clay, e.g., dynamic responses on the ground surface and excess pore water pressure (EPWP) around the tunnel. The calculations are conducted using the finite element program DBLEAVES. Particular attention is paid to the response difference between the soil-water coupling analysis and the single-phase analysis with a 3D model, and the difference between a 2D and 3D soil-water coupling analysis. It was found that the dynamic responses from the coupling analysis and single-phase analysis differed significantly. The presence of underground water may greatly weaken the ground vibration and decrease the accumulation rate of ground settlement. The ground surface acceleration, displacement and accumulated EPWP evaluated from a 2D analysis are far larger than those from a 3D analysis. Train vibration in trial operation was simulated by 2D and 3D models to verify the feasibility of the numerical method proposed in this paper in evaluating train-induced settlement. Finally, the long-term tunnel settlement in normal operation was predicted by the 2D model, and it was concluded that the final settlement of a metro tunnel in saturated clay due to repeated train vibration may reach 80 mm.



*Keywords:* Train-induced vibration; Soil-water coupling dynamic analysis; Cyclic Mobility model; Saturated clay; Excess pore water pressure; Train-induced settlement

## 1. Introduction

In recent years, to alleviate the traffic pressure from rapid urbanization and growing population, mass rapid rail transit systems are being constructed in metropolitan areas all over the world. While mass rapid rail transit brings great conveniences to people's daily life, its operation may also induce environmental vibration. For metro lines passing through the downtown, the ground vibration has sometimes reached a level that can hardly be tolerated by neighboring residents (Yang et al., 2007a,b). Besides train-induced environmental vibration or noise, long-term settlement due to train load is another big problem for

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metro tunnels built in soft clayey soils (Ng et al., 2013; Shen et al., 2014). Although the dynamic settlement is trivial for each train vibration, the accumulation of permanent deformation and EPWP does occur in saturated soft clay. As a result, ground vibration and the resultant tunnel settlement are two matters of concern when studying the influence of train vibration on the metro tunnels.

Voluminous research has been published regarding train-induced vibration from underground tunnels. These researches can be divided into three categories in terms of their research methods, namely an analytical approach, field measurements and numerical methods. Metrikine and Vrouwenvelder (2000) theoretically investigated the surface vibration of a 2D tunnel-soil model by assuming the tunnel as Euler-Bernoulli beam, above and below the beam are viscoelastic soil layers; Forrest and Hunt (2006a,b) proposed a 3D Pipe in Pipe model to study ground vibration assuming the tunnel as a thin cylinder shell deeply buried in the full space. Some researchers (Lu and Jeng, 2006; Zeng et al., 2014, 2015; Yuan et al., 2015, 2016) developed an analytical solution of saturated ground based on Biot's elastodynamic theory (Biot, 1956, 1962). Although the analytical approach can predict the dynamic response of tunnel at specific cases, it is usually viable for relatively simple cases, and the plastic deformation of the soil cannot be considered. In addition, the analytical solutions are generally too complex, with numerical transform techniques required to obtain the final outcome. Field measurements (Pan et al., 1995; Gupta et al., 2008; Tang et al., 2008) can derive reliable ground vibration level, but are only feasible for constructed projects. Parametric studies are not suited to all cases, so field measurements are only valid case by case. As for numerical analysis, different numerical methods are available, such as finite element method (FEM), boundary element method (BEM) and infinite element method, etc. Numerical methods are able to consider the nonlinear behaviors of soils, patterns of train load as well as performing parametric study in analyzing train-induced ground response. Many works have been done to investigate train-induced vibration (Gardien and Stuit, 2003; Andersen and Jones, 2006; Degrande et al., 2006; Gupta et al., 2007; Yang and Huang, 2008; Ma et al., 2016). However, these researches treat the ground as single-phase elastic or viscoelastic medium, rather than a coupling soil-water system, as is commonly found in real saturated ground. Researchers have confirmed that the presence of water in soil can significantly influence the wave propagation induced by moving train load (Lu and Jeng, 2006; Zeng et al., 2014; Yuan et al., 2016). Moreover, Cai et al. (2009) and Sun et al. (2007) found that once the speed of moving load exceeds 0.6 times of the shear velocity of saturated soil, the response of saturated soil becomes different from that in single-phase soil. Furthermore, the response difference between two dimensional (2D) and three dimensional (3D) numerical analyses are not very clear for saturated clay. In practice, a 2D model is still preferred to perform dynamic FE analysis even it is true that a 3D model is more reasonable to simulate the train movement. The major shortcoming of 3D dynamic simulation is that it is too time-consuming and storage-demanding, and considered to be unrealistic and overall impossible for long-term vibration. Therefore, the common practice is to approximate the 3D results by a 2D model. Some researchers (Andersen and Jones, 2006; Real et al., 2012; Xu et al., 2015) made attempts to compare the response difference between 2D and 3D models, and concluded that 3D model was more accurate for absolute prediction of train-induced vibration while the 2D model was just feasible in a qualitative manner. However, these conclusions were made from the numerical results of single-phase analysis. As for saturated soft clay, however, it remains unclear and needs further investigation. Accordingly, the 2D and 3D dynamic responses of saturated soft clay are compared in the paper. In addition, previous studies rarely considered the plastic deformation of soil induced by train vibration load. However, for the soft clay ground, it generally demonstrates evident nonlinear characteristics in the soil-tunnel interaction (Lee et al., 1999; Zhang et al., 2017), therefore, the surrounding soft clay can be easily disturbed by the frequent train vibration in the metro tunnel, which induces long-term settlement and accumulation of EPWP (Shen et al., 2014; Tang et al., 2008). In recent years, traffic load induced settlement has attracted geotechnical engineers' attention (Zhou et al., 2000; Chai and Miura, 2002; Bian et al., 2010; Jiang et al., 2013), the elastoplastic behavior of saturated soft clay should not be neglected, especially in analyzing the long-term effect of train vibration. However, due to the lack of accurate dynamic constitutive models for soft clay, most researchers turn to empirical methods (Monisimith et al., 1975; Li and Selig, 1998; Chai and Miura, 2002) to predict train-induced settlement rather than numerical methods. Empirical methods enable the use of explicit expressions about cumulative plastic strain or cumulative EPWP, the total settlement can be easily estimated by calculating settlements from cumulative plastic deformation and EPWP dissipation. Nevertheless, they are unable to reflect the soil-water interaction in saturated soil, and the empirical expressions usually involve too many parameters, some of which have unclear physical meanings.

Considering the shortcomings of the existing studies in analyzing train-induced response and settlement, a soil-water coupling dynamic FE analysis is performed in the present paper. An advanced elastoplastic model called Cyclic Mobility model is adopted to describe the mechanical behaviors of saturated soils. Meanwhile, a full soil-water coupling scheme is established based on Biot's theory. Therefore, the cumulative plastic deformation and EPWP under dynamic load can be determined simultaneously. In the present study, Cyclic Mobility Model and soil-water coupled scheme have been integrated into FE code called DBLEAVES (Ye et al., 2007), whose feasibility has been verified by many applications in the geotechnical engineering (Xia et al., 2010; Bao et al., 2012a,b; Gu et al.,