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Ground and tunnel responses induced by partial leakage in saturated clay with anisotropic permeability

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ABSTRACT

Finite element analysis was conducted to study the ground and tunnel response to partial tunnel leakage coupled with anisotropic soil permeability, a novel and little-known approach that was developed from in-situ inspections of shield tunnel leakage in the Shanghai Metro system. The ground and tunnel settlements, which were caused by water leaking into the tunnel, significantly degraded both the serviceability and safety of the tunnel and its surroundings. In a typical analysis, such leakage is commonly assumed to be uniform along the tunnel circumference with a soil permeability that is isotropic. Numerical simulation results obtained in this paper indicated that partial tunnel leakage in only one side of the shield tunnel caused a greater pore pressure reduction at the tunnel spring line and a larger ground surface settlement than otherwise caused by uniform tunnel leakage with the same rate of water inflow. Indeed, observations showed that partial leakage in only one side of the shield tunnel caused remarkable lateral movements of the tunnel. Our analysis showed that coupling leakage boundary conditions with favorable soil permeability anisotropy could significantly decrease the maximum ground settlements induced by the leakage, which leads to an increase in the width of the surface settlement trough. Furthermore, the effect of soil permeability anisotropy on ground settlement was found more profound for cases involving partial tunnel leakage boundary conditions.

1. Introduction

Tunneling operations in low permeability saturated soils often result in very significant long-term ground movement and tunnel settlement (Yi et al, 1993; Shirlaw, 1995; Mair and Taylor, 1997; Mair, 2008; Cooper et al, 2002; Wongsaroj et al., 2007). For example, the accumulated long-term settlement of the shield tunnel in Shanghai, China reached 290 mm after 16 years of operation (from 1995 to 2011) (Shen et al., 2014). Similarly, O'Reilly et al. (1991) observed a continuous increase in the ground surface settlement during the first ten years of the Grimsby tunnel, which was constructed in clay. Shirlaw (1994) found that the post-construction ground surface settlement accounted for 30–90% of the total settlement for a tunnel built in clay. Harris (2002) also observed that the settlement and width of a ground surface settlement trough continuously increases throughout his five-year observation on the Jubilee Line Extension. Furthermore, the long-term ground movement was also found to cause tunnel squat, which led to an increase in the additional inner force of the tunnel lining (Mair, 2008; Zhang et al., 2012). Masset and Loew (2013) reported that the tunnel drainage induced ground surface settlement can be in the order of 10 cm and over several kilometers wide even in brittle crystalline rock.

Water leakage into the tunnel is a critical factor that affects the post-construction ground and shield tunnel settlement. In a low-permeability ground, the tunnel leakage introduces a long-term drainage boundary for the ground around the tunnel, which tends to decrease pore water pressure and increase the effective stress of the soil around the shield tunnel, causing ground and tunnel settlement (O'Reilly et al., 1991; Mair and Taylor, 1997; Shin et al., 2002; Shin, 2010; Asakura and Kojima, 2003; Wongsaroj et al., 2007; Mair, 2008; Zhang et al., 2012). The phenomenon of leakage-induced pore pressure reduction has been confirmed by Ward and Thomas (1965), Palmer and Belshaw (1980) and Wongsaroj et al. (2007) through field measurements.

The tunnel leakage-induced pore pressure reduction has been studied using both analytical and numerical solutions based on Darcy's law and the rule of mass conservation (Lei, 1999; El Tani, 2003; Kolymbas and Wagner, 2007; Park et al., 2008; Huangfu et al., 2010; Zhang et al., 2012). Moon and Jeong (2011) investigated the variation of water inflow rate into the tunnel as a highly pervious zone in the vicinity of tunnel using the image well method. Although analytical models are easy to use, the effect of permeability of tunnel lining on the leakage is generally not considered (O'Reilly, et al., 1991; Shin et al., 2002; Wongsaroj et al.,

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2007; Mair, 2008). In numerical simulations (O'Reilly et al., 1991; Li, 1999; Li and Berrones, 2002; Shin et al., 2002; Shin, 2010; Mair, 2008), the most common assumption is that the tunnel leakage is uniform along the tunnel circumference with an equivalent permeability. For a shield tunnel built in saturated clay, the surcharge and adjacent engineering activities may induce the opening and stagger of segmental joints and generate segmental cracks. Therefore, the leakage is often found at the locations such as the circumferential and longitudinal segmental joints, cracks and grouting holes, as shown in Fig. 1. Wongsaroj et al. (2007) found that use of the equivalent uniform permeability of the tunnel lining was inadequate to model the field measurements of pore pressure. Another commonly adopted assumption when undertaking numerical simulations is that the permeability of soil is isotropic, which may be inappropriate for alluvial deposits when their horizontal permeability is often considerably greater than the vertical. When the anisotropic soil permeability significantly affects the distribution of pore water pressures, the two existing assumptions of uniform tunnel leakage and isotropic soil permeability are inadequate for modeling the tunnel leakage-induced ground and tunnel responses.

Though long-term field monitoring via instrumentation is effective for investigating how partial tunnel leakage and soil permeability anisotropy affects the performance of tunnel and the surrounding ground, it is both expensive and time consuming. Consequently, there is a critical need to develop alternative methods for accurately determining leakage-induced settlement. Using a typical shield tunnel in Shanghai, China as an example, this paper attempts to use numerical modeling to investigate the response of ground and shield tunnel to partial tunnel leakage and anisotropic soil permeability.

The rest of this paper is organized as follows. We first present our numerical model with tunnel leakage boundary conditions learned from the on-site inspections of a typical shield tunnel in Shanghai, China. We next detail the parametric study of the effects of partial tunnel leakage and soil permeability anisotropy on tunnel leakage-induced ground and tunnel responses. Finally, we analyze the long-term response of the ground and shield tunnels to the partial tunnel leakage boundary conditions coupled with anisotropic soil permeability.

2. Method of analysis

The shield tunnels in Shanghai were constructed at depths between 9 and 15 m. These tunnels are surrounded by layers of soft clay with high compressibility, low strength and low permeability. The typical profile of these soils in the Shanghai area is shown in Fig. 2. It is noted that the tunneling process was not simulated in this paper. The ground and tunnel settlement, and the tunnel squat due to the tunneling were excluded. Thus, the ground and tunnel response presented in this paper are the increments induced specifically by the tunnel leakage. As the pore pressure change caused by the leakage is expected to reach the steady state over time, the leakage induced ground and tunnel settlement is likely to develop over a similar lengthy period.

Fig. 1. Leakage of the shield tunnel in low-permeability saturated soils in Shanghai.

2.1. Numerical model

The partial leakage of the shield tunnel was investigated using the ABAQUSTM software (Dassault Systèmes Simulia Corp., 2010) based on a typical shield tunnel in Shanghai. Fig. 3 shows one half of the finite element model mesh employed in this study. The model extended 400 m in width and 50 m in height and the tunnel was at a depth of 11 m from the ground surface to the tunnel center. The lateral displacement boundaries were fixed in the horizontal direction but allowed to move vertically, and the displacement boundary at the bottom were fixed in both horizontal and vertical directions. The lateral boundary was permeable, while the boundary at the bottom was impermeable. The boundary of the tunnel was determined by on-site inspection of shield tunnel leakage in Shanghai metro system and is discussed later in Section 2.2. The water pressure at the ground surface and the tunnel inner circumference are zero. This numerical model has been validated with the analytical solution proposed by Zhang et al. (2012). The obtained pore pressure from both methods matched well; suggesting that both methods are an adequate approximation.

2.2. Partial tunnel leakage boundary conditions based on inspection data

To obtain realistic boundary conditions for simulating leakage of water into the tunnel, two metro lines of shield tunnel built in Shanghai were inspected, and denoted as Line A and Line B, respectively. Each metro line is composed of twin shield tunnels, one up line and the other down line. While Line A has been in use for over a decade, Line B was in use only for a little over a year when the inspection was performed. Line A is approximately 60 km long with 72,554 rings and Line B is approximately 30 km long with 23,446 rings. The distributions of tunnel leakage locations are shown in Table 1 for both lines.

For the inspected shield tunnel, more than 89% of the water inflow occurs through the segmental joints (i.e., circumferential and longitudinal joints) for Line A. For Line B, more than 87% of the water inflow occurs through the segmental joints. Among all the leakage points, more than 70% and 60% of the tunnel leakage occur through the circumferential joints for Line A and Line B, respectively, as presented in Table 1. On the other hand, only 11% to 13% of the leakage occurs through the bolt and grouting holes. This is because the longitudinal stiffness of the shield tunnel is less than that of the tunnel ring, thus making the circumferential joints more prone to deformation than longitudinal joints, when the tunnel subsides. The tunnel leakage through circumferential joints is focused in this paper.

The updated distributions of leakage locations along the circumferential joint for both metro lines are shown in Fig. 4. More than half of the tunnel leakage occurs in the middle area of the circumferential joint with the central angle of 90° based on the on-site inspection (Tongji University, 2012). Thus, in the numerical model the leakage boundary condition is defined as permeable within this area and impermeable beyond, as shown in Fig. 5. The on-site inspection revealed also that the leakage may occur at both sides of the middle area or at one side of the middle area. Therefore, in our numerical study the tunnel leakages at one side and two sides of the middle area have both been investigated. The partial tunnel leakage at one side and two sides present the cases of non-symmetric and symmetric conditions, respectively.

The partial tunnel leakage at one side was specified at the left side in the numerical simulation. The variation of pore pressure and the ground settlement caused by partial tunnel leakage at the right side are assumed symmetrical about the tunnel center with those caused by partial tunnel leakage at the left side. The tunnel settlements are identical for the two cases. Furthermore, we also investigated the uniform tunnel leakage, which serves as a basis to examine the effects of the partial tunnel leakage; the leakage boundaries of which are summarized in Fig. 5.