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Predicting the grouting effect on leakage-induced tunnels and ground response in saturated soils

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ABSTRACT

This paper suggests a new set of analytical solutions for predicting the effect of grouting on ground and shield tunnel behaviour as a consequence of steady water inflow into a tunnel in saturated clay. These solutions allow the effects of the tunnel lining and grouting material to be considered on the basis of their relative permeability to the surrounding soil. Moreover, the equivalent permeability of the tunnel lining can be derived based on the water inflow rate, which is commonly assumed to be proportional to the soil permeability in a typical analysis. A comparison of the results of analytical and numerical simulations indicates that the solutions are sufficiently accurate for tunnel applications. The effect of grouting material on the tunnel-leakage-induced seepage field, ground and tunnel settlements, internal forces and tunnel convergence of the shield tunnel are examined with the verified solutions. Based on the analytical results, the effect of grouting material on the tunnel leakage appears to depend on the permeability of the tunnel lining. Thus, a dimensionless parameter RP_{slg} integrating the permeability and geometry of the tunnel lining and grouting material is proposed to quantitatively describe the effect of the grouting material on tunnel leakage. Using RP_{slg}, the effect of the grouting material on tunnel leakage can be easily derived. Indeed, the analytical results show that tunnel leakage produces significant ground and tunnel settlement. The grouting can clearly reduce the effect of tunnel leakage on tunnel and ground settlement when the relative permeability of the grouting material and soil k_g/k_s is less than 0.01. Moreover, the increase in the tunnel-leakage-induced bending moment and the decrease in hoop thrust are generally small but this may increase the permeability of the tunnel joints. The leakage-induced tunnel convergence is small and is therefore unlikely to degrade the serviceability or safety of a tunnel.

1. Introduction

The construction of tunnels in soft soils has become increasingly common in recent decades. The lining of a shield-driven tunnel is assembled by bolting together prefabricated concrete segments. The joints are very likely to open and to shear between segments when subjected to thrust jacking forces in the process of shield tunnelling and permanent earth and pore pressure. Meanwhile, concrete cracks may be generated. Furthermore, the tunnel segments usually contain preformed holes for synchronous grouting during tunnelling. For simplicity, for the abovementioned opening and shearing of segmental joints, the cracks and grouting holes are referred to as tunnel defects in this study. When a tunnel is built in saturated soils, ground water may flow into the tunnel through these tunnel defects, as shown in Fig. 1 for a tunnel in Shanghai, where shield tunnels are embedded in saturated clays.

In low-permeable clay, tunnel leakage will result in a continuous decrease in pore pressure around the tunnel and thereby induce ground and tunnel settlement. This leakage-induced tunnel settlement will deteriorate tunnel defects and threaten the safety of tunnel operation. To control tunnel leakage in practice, grouting is widely used as a water barrier. Indeed, grouting is always used to backfill the physical annular gap between the ground and tunnel lining, caused by shield machine driving, to reduce tunnelling-induced ground settlement during tunnelling, as illustrated in Fig. 2 (Youn and Breitenbücher, 2014); thus, the annular gap grouting material is also considered the primary water barrier for segmental tunnels. However, how to predict the effect of annular gap grouting material on leakage-induced ground and tunnel

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Nomenclature

r_0	internal radius of the tunnel lining
R	external radius of the tunnel lining
r_g	external radius of the grouting material
h	tunnel depth from the tunnel centre to the ground surface
k_s	permeability of soil
k_g	permeability of the grouting material
k_l	permeability of the tunnel lining
H	hydraulic head
p	pore pressure
y	elevation hydraulic head
γ_w	unit weight of water
H_1	hydraulic head of the ground water table
H_{rg}	hydraulic head at the interface of the grouting material and soil mass
H_R	hydraulic head at the interface of the grouting material and tunnel lining
α_s	radius in the transformed ξ–η plane
ξ	in the mapping coordinates related to x in Cartesian coordinates
η	in the mapping coordinates related to y in Cartesian coordinates
C_1, C_2, C_3, C_4	constants determined by the hydraulic boundary condition
ρ	seepage radius in soil
ρ_g	seepage radius in the grout
Q_s	water inflow rate into grouting material from soil mass
Q_g	water inflow rate into tunnel lining from the grouting material
Q_l	water inflow rate into the tunnel from the tunnel lining
p_{min}	minimum pore pressure
p_{max}	maximum pore pressure
a	relative permeability between the grouting material and tunnel lining
c	relative permeability between the soil mass and grouting material
b	parameter related to the geometries of the tunnel lining and grouting material, $b = \ln(R/r_0)/\ln(r_g/R)$
d	parameter related to the geometries of the tunnel lining and grouting material, $d = -\ln(r_g/R)/\ln\alpha_s$
q	vertical effective earth pressure
p_1	lateral earth pressure at the depth of the tunnel crown
p_r	reaction pressure at the bottom of the lining
g	weight of the tunnel lining
p_k	soil resistance
M	bending moment of tunnel lining
N	hoop thrust of tunnel lining
Q	shearing force of tunnel lining
η	bending rigidity reduction coefficient
E_1	Young's modulus of the continuous tunnel ring
E_c	Young's modulus of segment concrete
Δp	change of pore pressure
RP_{slg}	proposed parameter to consider the coupled effect of k_g/k_s and k_l/k_s
D	tunnel's external diameter
κ	normalized hoop thrust of the tunnel lining
λ	normalized bending moment of the tunnel lining
f_{ck}	axial compressive strength of segment concrete
w	width of the tunnel ring
t	thickness of the tunnel segment
ΔD	increase in the tunnel's horizontal diameter
ε_x, ε_y, ε_z	soil strain caused by tunnel leakage
ε_v	soil volume strain
σ_x', σ_y', σ_z'	effective stress
s_y	ground settlement
E	elastic modulus of the soil
v	Poisson's ratio
K_0	lateral earth pressure coefficient at rest
ϕ'	effective internal frictional angle of the soil
K	bulk modulus

response is still not well understood even though it has been widely adopted in tunnel engineering practice.

Monitoring long-term pore pressure is very helpful in capturing the effect of grouting material on tunnel leakage, and this is important for maintaining existing tunnels. However, field observations of tunnel-leakage-induced pore pressure changes are very limited because of the tremendous cost of long-term monitoring. To determine the effect of grouting material on tunnel-leakage-induced ground and tunnel response, the effect of grouting material on leakage-induced pore pressure must first be predicted. However, because of the complexity of tunnel leakage in saturated clay, grouting material has long been excluded from studies of pore pressure changes caused by tunnel leakage. Many researchers have studied tunnel-leakage-induced ground and tunnel response using numerical solutions without considering the effect of grouting material (O'Reilly et al., 1991; Shin et al., 2002; Wongsaroj, 2005; Zhang et al., 2005; Wongsaroj et al., 2007; Mair, 2008). Moreover, as an important supplement to numerical simulation, analytical solutions are also valuable for predicting tunnel-leakage-induced ground and tunnel response because they are simple to use and have a clear physical meaning (Lei, 1999; El Tani, 2003; Kolymbas and Wagner, 2007; Park et al., 2008; Huangfu et al., 2010; Zhang et al., 2012). Notably, these analytical solutions are very useful for predicting different tunnel leakage problems. The common assumption behind these solutions is that the effect of grouting material is negligible.

This paper presents a new set of analytical solutions for predicting the effect of grouting material on leakage-induced ground and tunnel response. The novel feature of these solutions is that the effects of tunnel lining and grouting material have been rigorously considered. This paper is organized as follows. First, an analytical solution for predicting the pore pressure around a tunnel considering a tunnel lining and grouting material is developed. An analytical solution for leakage-induced ground and tunnel settlements and tunnel behaviour in terms of hoop thrust, bending moment and convergence is then derived by considering the effect of grouting material. The analytical solution is validated using the numerical solution because of limited field observations. The effect of grouting material on ground and tunnel response is then clarified by a parametric study. Finally, a shield tunnel in Shanghai is examined as a case study.

2. Analytical solution for tunnel-leakage-induced ground and tunnel response considering the effect of grouting

2.1. Analytical model

Fig. 3 shows the seepage model for a shield tunnel constructed in saturated clay with grouting and a tunnel lining. The analytical solution was derived based on the assumption that the tunnel leakage is in a state of steady flow although it can take decades