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Undrained analysis of ground reaction curves for deep tunnels in saturated ground considering the effect of ground reinforcement

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ABSTRACT

This paper investigated the undrained responses for deep circular tunnels with reinforcement in saturated ground analytically. An idealized model of an axisymmetric tunnel with an initial hydrostatic stress field was proposed. Plane-strain analysis was performed to obtain the ground reaction curves by gradually decreasing the internal support pressure from the initial stress to zero after tunnel excavation. The reinforced ground by full-face grouting was assumed as an equivalent circular region to consider the reinforcement effect. Both of the natural ground and the reinforced ground were assumed as the elastic-perfectly plastic materials satisfying the Mohr-Coulomb yield criterion. The proposed model was used to estimate the efficiency of the reinforcement parameters for a deep underwater tunnel. The analytical results were validated by the numerical results. Results show that as the decrease of internal support pressure, the plastic zone may firstly appear not only in the reinforced ground or in the natural ground, but also appear in the two zones simultaneously. Six forms of different plastic zone distributions were categorized. The ground reaction curve for each form was analyzed and 8 critical support pressures were obtained in the unified theoretical framework for the specific boundary conditions. The present model has advantages in undrained analysis of ground reaction curves for deep tunnels in saturated ground considering the effects of ground reinforcement compared with the classical model.

1. Introduction

The convergence-confinement method (CCM) can consider the tunnel-support interaction effectively. It thus has been used in the preliminary design of lining structures widely (Cui et al., 2017). The CCM is represented by two independent curves, i.e., the ground reaction curve (GRC) and the support reaction curve. After tunnel excavation, the GRC can be characterized by gradually decrease of the internal support pressure from the initial stress to zero. Derivation of an appropriate GRC is important in the application of the CCM.

Brown et al. (1983) proposed a closed-form solution to obtain the GRC by considering the ground to be an elastic plastic material. Stille et al. (1989), Carranza-Torres and Fairhurst (1999, 2000), Wang (1996), Oreste (2003), Sharan (2005) and González-Nicieza et al. (2008) studied the GRCs by assuming different behaviors of the ground. Fang et al. (2013), Heidari and Tonon (2015) performed analysis of GRCs considering the effect of ground reinforcement. However, all of the aforementioned studies were conducted in a particular condition without water in the ground, which were different from a saturated condition.

The underground water has significant influence on the GRCs for tunnels beneath the water table (Shin et al., 2011; Ma et al., 2017). The lining structure of underwater tunnels should be designed to resist the combined pressure from both of the ground and the groundwater (Bu et al., 2017; Zhang et al., 2017; Li et al., 2013a,b; Bobet, 2003; Nam and Bobet, 2006; Lee and Nam, 2001). High pore-water pressure reduces the effective strength of the surrounding rock, thereby deteriorates the arching effect and the stratum stability. Bobet (2003, 2010) and Nam and Bobet (2006) derived the complete analytical solution of displacements and stresses for tunnels affected by the pore-water pressure. These studies considered different ground conditions of dry or saturated ground, shallow or deep tunnel, with or without air pressure. However, these studies were restricted to situations where the tunnel displacements were small with both of the ground and the support behave elastically.

The effects of ground water on the GRC for deep tunnels in saturated ground were investigated by proposing a series of simplified analytical solutions of GRC (Bobet and Yu, 2016; Shin et al., 2011; Bobet, 2010; Schweiger et al., 1991; Arjnoi et al., 2009). Generally, static analysis of deep tunnels in the saturated ground could be simplified as two

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Notation

r_i	tunnel radius
r_g	radius of grouting circle
S_0	initial total stress
S_0'	initial effective stress
P_0	initial pore water pressure
r_0	far field boundary radius
R_1	plastic zone radius inside the reinforced zone
R_2	plastic zone radius inside the natural zone
$r(\theta)$	radial (tangential) direction
σ_r	total radial stress
σ_θ	total tangential stress
ε_r	radial strain
ε_θ	tangential strain
u_r	radial displacement
B	integration constant
σ_r'	effective radial stress
σ_θ'	effective tangential stress
t_g	thickness of the reinforced zone
E	elastic modulus of the natural ground
μ	Poisson's ratio of the natural ground
G	shear modulus of the natural ground
q	internal support pressure
q_{12}^*	critical support pressure for Forms I and II
q_{13}^*	critical support pressure for Forms I and III
q_{14}^*	critical support pressure for Forms I and IV
q_{24}^*	critical support pressure for Forms II and IV
q_{25}^*	critical support pressure for Forms II and V
q_{34}^*	critical support pressure for Forms III and IV
q_{46}^*	critical support pressure for Forms IV and VI
q_{56}^*	critical support pressure for Forms V and VI
c'	effective cohesion of the natural ground
φ'	effective internal friction angle of the natural ground
c_g'	effective cohesion of the reinforced ground
φ_g'	effective internal friction angle of the reinforced ground
C_u^0	purely cohesive shear strength of the natural ground
C_u^g	purely cohesive shear strength of the reinforced ground
S_g	total mean stress in the reinforced ground
P_g	pore water pressure in the reinforced ground
$\tau_{\max}$	maximum shear stress
E_g	elastic modulus of the reinforced ground
μ_g	Poisson's ratio of the reinforced ground
G_g	shear modulus of the reinforced ground

idealized conditions, named as the short-term condition and the long-term condition. The short-term condition could be applied to characterize the undrained behavior of the clay ground. When the permeability of the ground was small, the tunnel excavation and the support installation were completed promptly before the dissipation of the excess pore water pressure. When time after construction was sufficiently long, the excess pore pressure dissipated, referred as long-term condition, which was characterized by a steady-state seepage.

Ground reinforcement by full-face grouting was widely adopted to reduce the wall displacement and the inflow into the tunnels (Fig. 1). An equivalent circular region for the reinforcement effect were adopted to investigate the effect of grouting (Peila and Oreste, 1995; Osgoui and Oreste, 2010; Bobet and Einstein, 2011). Shin et al. (2011) performed the theoretical analyses on the GRC with the ground reinforced by grouting. Considered the seepage forces in a steady state flow condition. However, these studies assumed that the plastic zone appeared only in the reinforced ground around the tunnel. In practical engineering, as the decrease of the internal support pressure, the plastic zone may appear in the reinforced ground or the natural ground, or in the two zones simultaneously (Fang et al., 2013).

In this study, an analysis of GRC in a short term condition for deep tunnels in saturated ground considering the effect of ground reinforcement was carried out. The plane solutions of the stress and displacement distributions were obtained for the deep circular tunnels in an isotropic saturated ground with reinforcement. Both of the numerical analysis and a classical model verified the proposed analytical model.

2. GRC derivation

2.1. Analytical model

This study aims to derive the GRCs of deep tunnels in the saturated ground considering the effect of ground reinforcement in the short term condition. The undrained analysis of the tunnel-support interaction is herein performed in an infinite field, as showed in Fig. 2. The GRC can be characterized by decreasing the internal support pressure q from the initial total stress S_0 to zero ($S_0 = S_0' + P_0$, where S_0' and P_0, are the

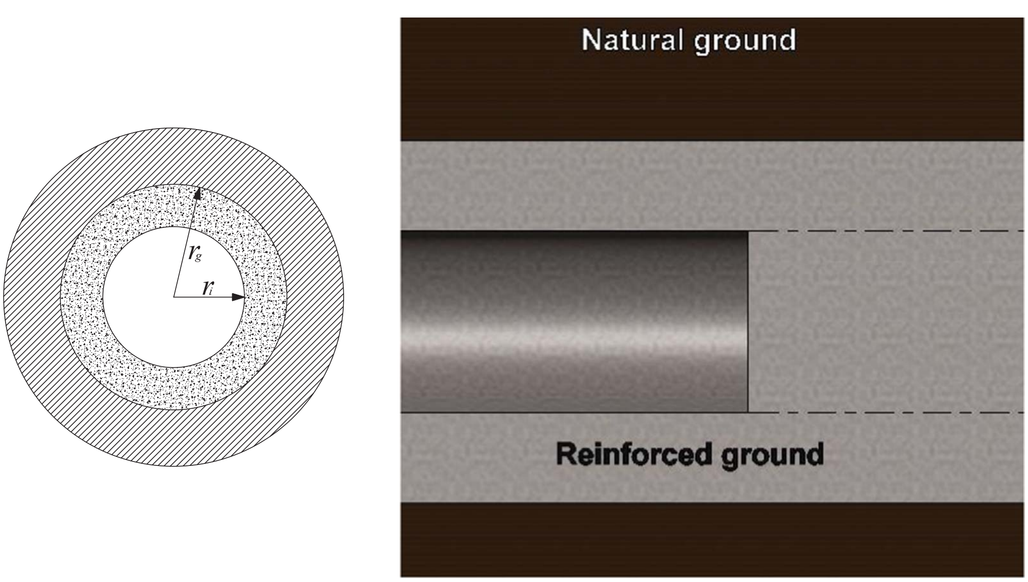

Fig. 1. Full face grouting for a deep tunnel.