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Soil deformation induced by Double-O-Tube shield tunneling with rolling based on stochastic medium theory

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ABSTRACT

The prediction of soil deformation during tunneling is very difficult for Double-O-Tube (DOT) shield tunnel construction, especially for the shield rolling. According to the characteristics of DOT shield tunneling and rolling, a calculation model of soil deformation due to tunneling-induced ground loss was established. Based on the stochastic medium theory, the theoretical solutions of soil deformations considering the rolling of DOT shield machine were derived by polar coordinate transformation and multi-subdomain integral method. The predicted surface settlement from the proposed solution is better agreement with the observed data than those obtained by the two previous methods (namely the equivalent excavated-area method (EAM) and the simple superstition method (SM)). In addition, only ground surface settlement can be estimated under no rolling of DOT shield machine using the two previous methods, while this proposed solution owns great progress in solving the subsoil deformation and the influences of rolling. In order to further study the influence of DOT shield rolling angle on soil deformation under different engineering conditions, the parameter sensitivity analyses regarding the tunnel depth h, the ground loss parameter ε and the influence zone angle β_0 were extensionally discussed.

1. Introduction

Since the Double-O-Tube (DOT) shield tunneling method was first adopted in Hiroshima, Japan in 1989 (Moriya, 2000), DOT shield technology has been developing rapidly. According to the report summarized by Fang et al. (2012), up to 2010, 20 DOT shield tunnels have been successfully constructed, where 13 cases were in Japan, 6 cases in Shanghai, China and one in Taiwan. Compared with the single circular shield technology, DOT shield technology has obvious advantages in saving the underground space, maximizing the utilization of space, minimizing the impact on nearby structures and soils and improving the efficiency of construction (Gui and Chen, 2013; Fang et al., 2012; Shen et al., 2006, 2009, 2010; Hu et al., 2009; Chow, 2006). Moreover, DOT shield tunneling does not need the cross-passage between the left and right tunnels, avoiding the difficulties and potential risks associated with its construction (Shen et al., 2009; Chow, 2006. Therefore Simpson and Tatsuoka (2008) pointed out that the special-shaped shield technologies such as DOT shield would be an important direction for tunnel and underground space development.

It is unavoidable that an underground excavation will influence the surrounding soils and structures such as the pre-existing pile foundations and pipelines, which must lead to additional displacements and deformations, even to the damage and failure of lining structures (Xu et al., 2009). During shield tunnel construction, the soil deformations are mainly induced by (Sugimoto and Sramoon, 2002; Tang et al., 2010): (1) the ground loss due to the tail void; (2) the friction between the cutter head and soil; (3) the friction between the shield shell and soil; and (4) the thrust from the shield head. Meanwhile, the results studied by Tang et al. (2010) also demonstrated that the ground loss is the leading factor for soil deformation. Many approaches for predicting the soil deformation due to the ground loss induced by tunneling have been presented, such as empirical formulas (Peck, 1969; Attewell and Woodman, 1982; Mair et al., 1993), elastic strain method (Sagaseta, 1987; Verruijt and Booker, 1996; Loganathan and Poulos, 1998; Zeng et al., 2016), the Airy stress function-based method (Wood, 1975; Bobet, 2001; Park, 2004, 2005; Puzrin et al., 2012), the stochastic medium theory (Litwiniszyn, 1957; Yang et al., 2004; Yang and Wang, 2011) and numerical modelling methods (Finno et al.,

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Nomenclature

G_p	physical gap during tunneling
g	gap parameter
h	buried depth of tunnel center
i_0	surface settlement trough width parameter
i_z	settlement trough width parameter
k	soil-cutter resistance
R_1	radius of DOT shield shell
R_2	convergence radius of DOT shield tunnel
$\overline{R_2}$	radius of the lining segments
r, θ	local polar coordinates
t	half of the distance between centers of two tunnels
U	horizontal soil deformation due to ground loss
U_1, U_2, U_3, U_4	horizontal soil deformation induced by the subsoil excavation of area I, II, III and IV in Fig. 7, respectively
U^*_{3D}	3D elastoplastic deformation into the tunnel face
$u_e(x, z)$	horizontal soil deformation due to element excavation
W	soil settlement due to ground loss
W_1, W_2, W_3, W_4	soil settlement induced by the subsoil excavation of area I, II, III and IV in Fig. 7, respectively
$w_e(x, z)$	soil settlement due to element excavation
X_0, Z_0	origin coordinates of local polar coordinate system
x, z	global Cartesian coordinates
α	rolling angle of DOT shield
α_{max}	maximum rolling angle of DOT shield
β_0	influence zone angle of surface settlement
β_z	influence zone angle of soil settlement
Δ	thickness of tailpiece
δ_x	tunnel face soil intrusion
ε	ground loss parameter
ζ	clearance for erection of lining
η, ξ	local Cartesian coordinates
λ	workmanship factor
Ω	boundary of tunnel excavation
ω	boundary of tunnel convergence

1991; Swoboda and Abu-Krisha, 1999). However, these approaches are almost always aimed at predicting the soil deformation induced by the single circular tunnel construction.

Further, during the tunnel construction, the rolling of DOT shield machine is a prominent problem (e.g. Chow, 2006; Shen et al., 2006, 2009, 2010; Zeng et al., 2015), which will directly influence the distribution of ground loss and the soil deformation. For instance, according to the surface settlements observed by Gui and Chen (2013), which are from six cross-sections in the CA450A Contract of Taiwan Taoyuan International Airport Access (TIAA) Mass Rapid Transit (MRT) System Construction Project, the surface settlement curves in two cross-sections (section 1-1 and section 3-3) are obviously affected by the rolling of DOT shield machine. The surface settlement troughs are skewed to the axis of the left tunnel in section 1-1 and to the axis of right tunnel in section 3-3. The similar results were also observed by Ye et al. (2015) and Fang et al. (2012) during the construction of Lines M2, M6 and M8 of Shanghai Metro and Ariakekita Common Conduit in Japan. Currently the equivalent excavated-area method (EAM) and the simple superstition method (SM) regarding two single-circular tunneling were put forward by Fang et al. (2012) and Gui and Chen (2013), respectively. Using the two methods, only the surface settlement due to ground loss induced by DOT shield tunneling without rolling can be estimated (Fang et al., 2012; Gui and Chen, 2013). Meanwhile, taking account of the potential pre-existing piles or/and pipelines, etc., the subsoil deformation is also an important issue, but which cannot be calculated using the above two methods.

In this paper, according to the characteristics of DOT shield tunnel construction (especially for the rolling of the DOT shield machine during tunneling), a general convergent model of soil deformation around DOT shield tunnel is established, in which an arbitrary rolling angle of shield machine is involved. Based on the stochastic medium theory, utilizing the polar transformation, the theoretical relationship between the rolling angle as well as soil (ground surface and subsoil) deformation is then derived. The proposed solution is validated by comparing with the measured values in-situ and the calculated results by both SM and EAM. The surface deformations and the soil deformation fields with different DOT shield rolling angles are also analyzed. Moreover the influences of the shield rolling on soil deformation under different construction conditions are discussed.

2. DOT shield tunnel construction and rolling

Different from the single circular shield machine, the cross-section of DOT shield machine is composed of two incomplete circles, as illustrated in Fig. 1. During DOT shield tunnel construction, the soil is excavated by two cutter heads, each of which has four radial spokes. In order to avoid the contact and conflict between the left and right spokes, two cutter heads rotate synchronously at the same speed with a fixed phase angle.

In the advance of the DOT shield machine, the segments are erected by two independent erectors. As shown in Fig. 2, each ring of the tunnel lining is composed of eight curved segments (A), one large lower Y-shaped segment (B), one small upper Y-shaped segment (C) and one middle prop segment (D). These segments are connected with straight steel bolts. Chow (2006) introduced the procedure of erecting the segments in detail. The size of DOT shield tunnel is determined by the segmental lining, while the excavated area of soil depends on the dimension of the shield shell. The difference between the shield shell and the outside of the segmental lining must cause the tail void. For instance, the DOT shield machine used in the extension of Line M2 of Shanghai Metro has the outside dimensions of 6.52 m in diameter and 11.12 m in width. The inside and outside diameters of the segmental lining are 5.70 m and 6.30 m respectively. The segments are 300 mm in

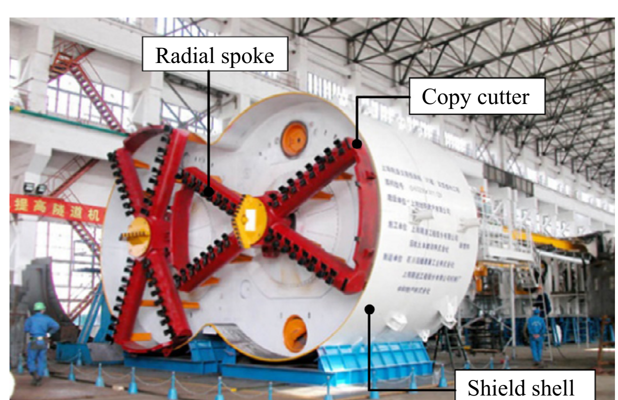

Fig. 1. DOT shield machine (after Ye et al., 2015).