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Analysis of shearing effect on tunnel induced by load transfer along longitudinal direction

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Abstract

In order to analyze the behavior of load transfer mechanism of shield-constructed tunnel in longitudinal direction, tunnel is modeled as the cylindrical shell within elastic foundation (CSEF). By applying the theory of elastic cylindrical shell (ECS) with considering shear deformation and assumed displacement functions of trigonometric series, the distribution of stress and deformation in tunnel lining is obtained. In the solution, the stiffness of tunnel lining is decomposed into two components of circumferential and radial stiffness. The effects of both components on the behavior of deformation and internal forces of tunnel lining are discussed in details. By using the proposed solution, more reasonable results on the behavior of tunnel lining are obtained, e.g bending moment in tunnel cross section becomes smaller with the increase of the circumferential shear stiffness. The analytical results are verified by the results of 3D FEM analysis and field measured data. In accordance with the proposed analytical method, the tunnel lining in soft ground should be designed via considering the following aspects: (i) three dimensional effect of tunnel lining; (ii) relatively weaker shear stiffness in radial direction, and (iii) increase the circumferential shear resistance between rings.

Keywords: Shield tunnel; Longitudinal shear transfer (LST); Cylindrical shell on elastic foundation; Trigonometric function

1. Introduction

In most design codes, tunnel is designed by only considering the lateral deformation. However, in urban area, there exist many underground infrastructures, e.g. the metro tunnels, tunnels may across one another. Consequently, the behavior of deformation and load bearing of shield-constructed tunnel in soft ground is not only laterally in cross section but also longitudinally. For this reason, Liao et al. (2005a) presented a one-dimensional (1D) solution to analyze the mechanism of longitudinal shear transfer (LST) along tunnel. In fact, tunnel generally behaves three dimensionally (3D), i.e. the tunnel lining bends both in radial and longitudinal directions. Therefore, more sophisticated method is required to reveal the load-bearing mechanism both in radial direction and in longitudinal direction.

In order to analyze this 3D behavior of tunnel, tunnel lining is modeled as a 3D cylindrical shell. The analytical solutions for elastic cylindrical shells with the mid-thick plates have become the great interests to engineers and researchers. By considering some boundary conditions, i.e. shear deformation conditions, some significant solutions were obtained in the previous century (Flügge, 1966; Naghdi, 1963; Seide, 1975; Wu and Xu, 1989). Flügge's shell theory (Flügge, 1966) is the basic and the most precise solution among all of the cylindrical shell theories. However, the basic equations of Flügge solution are quite complicated, which limits its application. Donnell's (1976) plate theory gave more simple and effective result through simplifying the assumptions on the physical, geometric, and equilibrium

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equations, which are the famous Donnell type equations. The disadvantage of the Donnell's method is that it is only suitable to short cylindrical shell and generates big errors for long cylindrical shell under concentrated loads (Qu et al., 2000; Wu and Xu, 1989).

According to the plate theory, the cross section of tunnel will resist additional bending moment with the occurrence of longitudinal deformation. Wu and Xu (1989) modified Flügge's theory via considering both radial and tangential shear deformation. Their solution is comparatively simple and can be applied to any length of shell. However, Wu and Xu's solution cannot analyze the tunnel and/or pipeline within elastic foundation. This is because in Flügge's theory, only fixed point support (no deformation) condition was considered. In engineering practice, the foundation of long tunnel can deform. The objective of this paper is to give a solution for the bending and longitudinal shear effect of tunnel within elastic foundation. In the analysis, tunnel was modeled as a cylindrical shell within elastic foundation (CSEF). Then, Wu and Xu's method was employed to analyze the problem of CSEF. For simplicity, the functions of trigonometric series are employed to solve the CSEF problem and the mechanism of longitudinal shear transfer (LST) is discussed. Finally, theoretical solution is verified by 3D FEM analysis and field measured data.

2. Theoretical solution for CSEF

2.1. Equilibrium equations

Fig. 1 illustrates a cylindrical shell of tunnel (Wu and Xu, 1989). The length of shell is L and the curve coordinates are ρ and ϕ, which are expressed as:

$$\rho = z/a, \quad \phi = s/a$$

where a is the radius of tunnel, and z and s are axial and circumferential coordinates, respectively.

If the body force (in this study it is self-weight) is not considered, the equilibriums can be expressed as follows:

$$\begin{aligned} &\frac{\partial T_1}{\partial \rho} + \frac{\partial T_{21}}{\partial \varphi} + ak(u - u_d) = 0 \\ &\frac{\partial N_1}{\partial \rho} + \frac{\partial N_2}{\partial \varphi} - T_2 + ak(w - w_d) = 0 \\ &\frac{\partial T_{12}}{\partial \rho} + \frac{\partial T_2}{\partial \varphi} + N_2 + ak(v - v_d) = 0 \end{aligned} \tag{1}$$

where k is the coefficient of foundation reaction; u, v, and w are the axial, tangential, and radial displacement of tunnel lining, respectively; u_d, v_d, and w_d are the axial, tangential, and radial displacement of foundation; T_1 is normal inner force of shell plate longitudinally, and T_2 = normal inner force of shell plate circumferentially, T_{12} and T_{21} = shear force in plane of plate, N_1 and N_2 are the shear force of shell plate radially. At the same time, there exist the following relationships:

$$\frac{\partial M_{12}}{\partial \rho} + \frac{\partial M_2}{\partial \varphi} - aN_2 = 0 \tag{2a}$$

$$\frac{\partial M_1}{\partial \rho} + \frac{\partial M_{21}}{\partial \varphi} - aN_1 = 0 \tag{2b}$$

$$\begin{aligned} T_{12} &= T_{12} \\ M_{21} &= M_{12} \end{aligned} \tag{2c}$$

where M_1 and M_2 are the moment of plate, M_{12} and M_{21} are moment of torsion in plate.

2.2. Geometric relationships

According to the theory of mid-thick plate, if the shear deformation of mid plane is not considered, the geometric relationships can be expressed as the following formulae (Wu and Xu, 1989; Jing, 1989):

The strain components are as follows:

$$\varepsilon_1 = \frac{1}{a}\frac{\partial u}{\partial \rho}, \quad \varepsilon_2 = \frac{1}{a}\left(\frac{\partial v}{\partial \varphi} + w\right), \quad \gamma = \frac{1}{a}\left(\frac{\partial v}{\partial \rho} + \frac{\partial u}{\partial \varphi}\right)$$

The curvature components are as follows:

$$\begin{aligned} k_1 &= -\frac{1}{a^2}\frac{\partial^2 w}{\partial \rho^2} \\ k_2 &= -\frac{1}{a^2}\frac{\partial}{\partial \varphi}\left(\frac{\partial w}{\partial \varphi} - v\right) \\ k_{12} &= -\frac{1}{a^2}\frac{\partial}{\partial \rho}\left(\frac{\partial w}{\partial \varphi} - v\right) \end{aligned}$$

2.3. Physical equations and internal forces

Substituting the above geometry relationship into Love equations (Qu et al., 2000), the internal force components of tunnel lining are obtained:

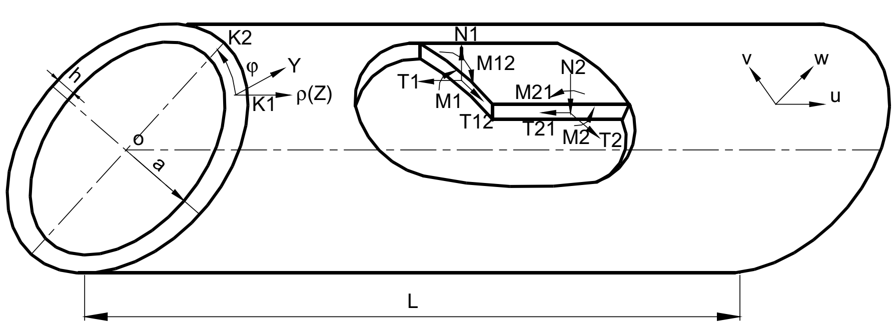

Fig. 1. Coordinate system and components of internal forces (Wu and Xu, 1989).