Computers and Geotechnics 64 (2015) 132–145

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research Paper

Simplified procedure for finite element analysis of the longitudinal performance of shield tunnels considering spatial soil variability in longitudinal direction

Hongwei Huang [a], Wenping Gong [a,b], Sara Khoshnevisan [b], C. Hsein Juang [b,*], Dongming Zhang [a], Lei Wang [c]

[a] Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China
[b] Glenn Department of Civil Engineering, Clemson University, Clemson, SC 29634-0911, USA
[c] Parsons Brinkerhoff, 100 S Charles Street, Baltimore, MD 21201, USA

ARTICLE INFO

Article history:
Received 9 September 2014
Received in revised form 10 November 2014
Accepted 18 November 2014
Available online 8 December 2014

Keywords:
Longitudinal performance
Monte Carlo simulation
Random field
Shield tunnel
Spatial variation
Subgrade reaction coefficient

ABSTRACT

A simplified procedure based on finite element method (FEM) is developed in this paper for analyzing the longitudinal performance of shield tunnels considering the longitudinal variation of geotechnical parameters. Herein, the spatial variation of soil properties of the ground under the tunnel is explicitly considered. The validity of the FEM solution is verified by analytical solutions and model tests with various assumed scenarios. The random field theory is employed to model the spatial variation (in the longitudinal domain) of the subgrade reaction coefficient, which is a key soil parameter for FEM analysis of the longitudinal performance of shield tunnels. A hypothetical example is presented to demonstrate the capability of the simplified FEM procedure in analyzing the longitudinal performance of a shield tunnel with spatial soil variability. The results show that the overall settlement of the tunnel is mainly affected by the mean of soil properties, while the extent of the tunnel differential settlement is significantly affected by the variation and scale of fluctuation of soil properties.

1. Introduction

Since the first shield tunnel was completed in London 170 years ago, shield tunneling has gained greater popularity for its flexibility, cost electiveness and minimum impact on ground traffic and surface structures [18]. While the design methodology of shield tunnels evolves from empirical models to the mechanics-based models, the current practice of the design of the segmental lining is still based upon the analysis of critical tunnel cross sections, assuming a plane strain condition [2,17,18,32]. Furthermore, the selection of critical sections is quite subjective; it may be selected as the section with the deepest overburden, the shallowest overburden, or the lowest groundwater table; it may be selected as the section with large surcharge, eccentric loads, or unlevelled surface; or it may be selected at location where there is an adjacent tunnel at present or in the future [14]. However, for a shield tunnel that is hundreds or thousands of meters in length, the longitudinal variation of design parameters, which can be caused by the tunnel alignment, spatial variation of soil properties, and nearby underground construction (e.g., tunneling), is quite likely and should be considered in the design [1,14,17]. In particular, a more rational design of the shield tunnel should consider the longitudinal performance of the tunnel (referred to herein as the tunnel differential settlement, longitudinal rotation, longitudinal shear force and longitudinal bending moment) caused by the longitudinal variation of design parameters.

The longitudinal performance of a shield tunnel and its influence on the circumferential behavior (referred to herein as the structure safety and serviceability) of the segmental lining may be investigated using numerical models implemented in software such as ABAQUS, ANSYS, and PLAXIS. However, the design of a shield tunnel based on such numerical models is often computationally prohibitive in practice. A more feasible approach to analyze the tunnel longitudinal performance is to model the longitudinal structure of shield tunnels as a continuous elastic beam [27,28]. Then, the effect of longitudinal joints (referred to herein as the joints between segmental rings) on the flexural stiffness of the tunnel longitudinal structure is modeled through a reduction factor of tunnel longitudinal flexural stiffness [20]; and the soil–structure interaction between the tunnel longitudinal structure and the ground under the tunnel is simulated with Winkler model [31], Pasternak model [25], or Kerr model [15], while the overburden of the tunnel is represented with a pressure load

* Corresponding author.
E-mail address: hsein@clemson.edu (C.H. Juang).

http://dx.doi.org/10.1016/j.compgeo.2014.11.010
0266-352X/

and/or concentrated loads. Based on these assumptions, the analytical solution of tunnel longitudinal performance can readily be derived. Further, the effect of tunnel longitudinal performance on the circumferential behavior of the segmental lining may be analyzed by considering simultaneously the shearing effect [20] and the flattening effect [13].

Because of the inevitable length of shield tunnels, the effect of the spatial variation of soil properties on the tunnel longitudinal performance is often significant and must be explicitly considered. The spatial variation (in the longitudinal domain) of soil properties tends to complicate the numerical analysis and analytical solution of tunnel longitudinal performance. Therefore, the main goal of this paper is to derive a simplified procedure for FEM analysis of tunnel longitudinal performance that considers the longitudinal variation of tunnel design parameters such as the soil properties of the ground under the tunnel. Note that the spatial variation of the ground under the tunnel may refer to either the spatial variation of different types of ground under the tunnel or the spatial variation of soil properties within the same ground under the tunnel [9]. In this paper, our focus is placed on the latter, although the former is also analyzed to validate the FEM model that is derived in this paper.

This paper is organized as follows. First, a simplified procedure for FEM analysis of the tunnel longitudinal performance is developed. Second, the developed FEM procedure is verified with both analytical solutions and model tests. Third, the random field concept is introduced to simulate the spatial variation (in the longitudinal domain) of soil properties of the ground under the tunnel. Finally, a hypothetical illustrative example is presented to demonstrate how the tunnel longitudinal performance is affected by the spatial variation of soil properties of the ground under the tunnel.

2. Formulations of the simplified FEM procedure for tunnel longitudinal performance considering longitudinal variation of design parameters

In this section, a simplified procedure for FEM analysis of the tunnel longitudinal performance that considers the longitudinal variation of tunnel design parameters is derived. In which, the tunnel longitudinal structure is modeled with a continuous beam [27,28] and the effect of tunnel longitudinal joints is simulated with a reduction factor of tunnel longitudinal flexural stiffness [20]; the soil–structure interaction between the tunnel beam and the ground under the tunnel is modeled with Winkler elastic ground model [31], and the overburden of the tunnel is represented with the pressure load and/or concentrated loads. These are the conditions for formulating the FEM procedure herein, although other models (e.g., the more comprehensive beam-joint model instead of the continuous beam model) may be adopted. It should be noted that while the subject of beam on elastic (or elastoplastic) foundation, or the beam-soil spring model, is not new [11,16,29,34], the FEM solution presented in this paper is formulated specifically to consider the longitudinal variation of tunnel design parameters, the effect of which has never been studied.

2.1. Local stiffness matrix $[\boldsymbol{K}]^{\mathbf{e}}$ and local load vector $[\boldsymbol{F}]^{\mathbf{e}}$

For an elastic beam element on the Winkler elastic ground, the stiffness matrix of the element, denoted as $[\mathbf{K}]^{\mathbf{e}}$, can be determined with the stiffness matrices of both the elastic beam and the ground under the beam. The load vector of the element, denoted as $[\mathbf{F}]^{\mathbf{e}}$, consists of both the pressure load and the concentrated loads applied on the element. To derive the element stiffness matrix $[\mathbf{K}]^{\mathbf{e}}$ and load vector $[\mathbf{F}]^{\mathbf{e}}$ that can consider the longitudinal variation of soil properties of the ground under the tunnel and in the overburden of the tunnel in the FEM model of the tunnel longitudinal performance, the following assumptions are made: (1) both the pressure load (q) and the subgrade reaction coefficient (k) within an element, depicted in Fig. 1(a) and (b), respectively, can be approximated with the nodal values at both ends of the element using linear interpolation; and (2) tunnel settlement (w; referred to herein as the vertical deformation of tunnel structure) within an element can be modeled with the deformation pattern of a two-node Hermite element [22]. These assumptions are quite valid when the size of the element mesh in the FEM solution is relatively small.

Based upon the first assumption, the pressure load (q) and the subgrade reaction coefficient (k) within the element can be expressed as follows, respectively:

$$q(\xi) = q_1 + (q_2 - q_1)\xi \tag{1a}$$

$$k(\xi) = k_1 + (k_2 - k_1)\xi \tag{1b}$$

where q_1 and q_2 = the pressure loads at the left end (referred to Node 1 in Fig. 1) and the right end (referred to Node 2 in Fig. 1) of the element, respectively; k_1 and k_2 = the subgrade reaction coefficients at the left end and the right end of the element, respectively; and, ξ = a shape factor ranging from 0 to 1.0, which is used herein to represent the relative position within the element and estimated as:

$$\xi = \frac{x - x_1}{l} \quad (l = x_2 - x_1, x_1 \leqslant x \leqslant x_2) \tag{1c}$$

where l = the longitudinal length of the tunnel element of concern; x_1 and x_2 = the longitudinal coordinates of the left end and the right end of the element, respectively.

Based upon the second assumption, the settlement (w) within the element can be computed as follows:

$$w(\xi) = \sum_{i=1}^{2} H_i^{(0)}(\xi) w_i + \sum_{i=1}^{2} H_i^{(1)}(\xi)\theta_i = \sum_{i=1}^{4} N_i(\xi) a_i = [\boldsymbol{N}][\boldsymbol{a}]^{\mathbf{e}} \tag{2}$$

where w_1 and w_2 = the settlements at the left end and the right end of the element, respectively; θ_1 and θ_2 = the longitudinal rotations at the left end and the right end of the element, respectively; and, $[\boldsymbol{N}]$ and $[\boldsymbol{a}]^{\mathbf{e}}$ = the interpolation vector and the nodal deformation vector that are adopted within the two-node Hermite element, respectively. The terms $[\boldsymbol{N}]$ and $[\boldsymbol{a}]^{\mathbf{e}}$ are set up as [22]:

$$\begin{aligned}[\boldsymbol{N}] &= \begin{bmatrix} H_1^{(0)}(\xi) & H_1^{(1)}(\xi) & H_2^{(0)}(\xi) & H_2^{(1)}(\xi) \end{bmatrix} \\ &= \begin{bmatrix} 1 - 3\xi^2 + 2\xi^3 & (\xi - 2\xi^2 + \xi^3)l & 3\xi^2 - 2\xi^3 & (\xi^3 - \xi^2)l \end{bmatrix}\end{aligned} \tag{3a}$$

$$[\boldsymbol{a}]^{\mathbf{e}} = [\omega_1 \quad \theta_1 \quad \omega_2 \quad \theta_2]^{\mathrm{T}}, \quad \text{in which} \quad \theta_i = \left(\frac{dw}{dx}\right)_{x=x_i} \quad (i = 1 \text{ and } 2) \tag{3b}$$

As depicted in Fig. 1(c), the following sign conventions are adopted for the nodal deformation vector $[\boldsymbol{a}]^{\mathbf{e}}$: the settlement ($w$) is taken as positive when it moves downward and the longitudinal rotation (θ) is taken as positive when it yields a clockwise rotation. In general, the tunnel longitudinal structure may also be subject to the concentrated loads such as vertical load (P) and moment (M), as illustrated in Fig. 1(d). The vertical load (P) is regarded as positive when it yields a downward movement and the moment (M) is treated as positive when it yields a counterclockwise rotation.

Next, the energy concept is employed to derive the element equilibrium equation. The potential energy of the tunnel element shown in Fig. 1, denoted as Π_p, can be computed as follows: