Tunnelling and Underground Space Technology 77 (2018) 103–114

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Analytical solution for longitudinal seismic response of tunnel liners with sharp stiffness transition

Haitao Yu[a,b,c,*], Zhengwei Zhang[d], Juntao Chen[d], Antonio Bobet[e,f], Mi Zhao[g], Yong Yuan[h]

[a] Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai 200092, China
[b] Key Laboratory of Soft Soils and Geoenvironmental Engineering of Ministry of Education, Zhejiang University, Hangzhou 310058, China
[c] Shanghai Municipal Engineering Design Institute (Group) Company Limited, Shanghai 200092, China
[d] Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China
[e] High-End Foreign Expert, Tongji University, Shanghai 200092, China
[f] Lyles School of Civil Engineering, Purdue University, West Lafayette, IN 47907, USA
[g] Key Laboratory of Urban Security and Disaster Engineering of Ministry of Education, Beijing University of Technology, Beijing 100124, China
[h] State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China

ARTICLE INFO

Keywords:
Tunnel
Stiffness transition
Seismic response
Analytical solution
Parametric analyses

ABSTRACT

Sharp transitions in structure stiffness and/or ground properties have a significant influence on the seismic response of tunnels. These issues are not well understood yet, or at least not well considered during design. An analytical solution is derived to investigate the seismic response of long tunnels, built in non-homogeneous ground, subjected to sinusoidal shear motions. It is assumed that the tunnel is excavated in two different soil deposits that have a sharp contact, and there is a transition zone through the contact. It is also assumed that the tunnels can be represented as beams on an elastic medium. Continuity at the contact between the different contact sections of the tunnel is imposed to solve the governing equations of equilibrium. In addition, wave passage effects along the tunnel are considered by including a phase angle in the far-field displacements. Explicit formulations are obtained for tunnel deflection, bending moments and shear forces. The solution is verified by providing comparisons between its results and those from the Finite Element program ABAQUS. A parametric analysis is presented where the effects of the stiffness of the structure, the shear velocity of the soil and the length of the transition zone are investigated.

1. Introduction

Due to the fast growth of urban construction, particularly in big cities, available urban space is becoming extremely limited and costly, and so the construction of underground structures is developing rapidly. As one of the most important infrastructure elements in traffic systems, tunnels may encounter sharp transitions along their length either due to changes of cross section, changes of support and/or changes of ground properties. For instance, a hybrid tunneling method was expected to be employed for potential construction of a railway tunnel crossing the Rion-Antirrion Straits in Greece, which was composed of a central immersed tunnel and two bored tunnels on the two sides (Anastasopoulos et al., 2007). The Xiamen Subway Line 3 in China has to pass through rock, fully weathered strata and strongly weathered strata. While construction through these transitions does not offer any particular difficulty, their seismic response may pose some challenges. Indeed, seismic investigations (Zhao et al., 2012; Yu et al., 2016b) showed that tunnels with a sharp change of their structure stiffness or that pass through different ground layers may suffer severe damage during earthquakes in the form of segment dislocation, water leakage, bolt shear failure, etc. Shaking table tests (Zhang et al., 2017; Yuan et al., 2016; Yu et al., 2018a,b) have shown that strains and internal forces both increase significantly in tunnel sections with a sharp contrast of cross-section stiffness or ground properties. Clearly, the seismic design of transitional cross-sections should be investigated.

Previous studies on the seismic response of tunnels generally rely on numerical approaches such as the Finite Difference Method, the Finite Element Method and the Boundary Element Method (Yu et al., 2016a), while other numerical methods are currently being developed and successfully used (Stamos and Beskos, 1995, 1996; Wang et al., 2003; Park et al., 2009; Yu et al., 2013a, 2013b; Zhou et al., 2013; Li and Song, 2015). Although all these methods may be used to study the seismic response of tunnel structures with sharp transitions of the structure's stiffness and/or ground properties, inclusion of these details

* Corresponding author at: Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China.
E-mail address: yuhaitao@tongji.edu.cn (H. Yu).

https://doi.org/10.1016/j.tust.2018.04.001
Received 6 December 2017; Received in revised form 7 March 2018; Accepted 1 April 2018
Available online 06 April 2018

Nomenclature

I	moment of inertia of the tunnel cross section
E	Young's modulus of elasticity
EI_1	stiffness of the Tunnel 1
EI_2	stiffness of the Tunnel 2
EI_3	stiffness of the Tunnel 3
K_h	foundation modulus
u_g	transverse displacement of the free field
x	coordinate in x axis
u_{max1}	peak free field transverse displacement in Soil A
u_{max2}	peak free field transverse displacement in Soil B
λ	wavelength
α_0	displacement phase angle
u_t	displacement of the tunnel
u_t'	rotation of the tunnel
P	pressure between the liner and the surrounding soil
ρ	soil density
V_s	soil shear velocity
ν	Poisson's ratio of the soil
d	diameter of a circular tunnel or height of a rectangular tunnel
M	bending moment
Q	shear force

tends to increase the complexity of the discretization, computation and analysis. It can be argued that they can be far too complex to be adopted in practice. Computational efficiency however could be improved if simplified models and analytical solutions were available. Two approaches have been widely used to study the longitudinal seismic response of tunnel structures (Hashash et al., 2001), namely the free field deformation approach and the soil-structure interaction approach. In the first approach, the free field deformation of the ground without the tunnel is obtained and the ground deformations at the location of the tunnel are imposed to the structure. However, the free field deformation approach may overestimate or underestimate the seismic deformations of tunnels (Hashash et al., 2001; Zhou et al., 2002; Bobet, 2003; Huo et al., 2006). The soil-structure interaction approach includes the interplay that exists between structure and surrounding ground. An estimate of the longitudinal deformations of the tunnel, which is the focus of this paper, can be obtained using wave propagation theory in an infinite, homogeneous, isotropic, elastic medium, while approximating the tunnel as an elastic beam on an elastic foundation (St. John and Zahrah, 1987). In addition, the seismic input motion is assumed as an incident sinusoidal wave with a wavelength λ and amplitude A. This approach is similar to that used by St. John and Zahrah (1987), who used a Winkler-type model to develop closed-form expressions for the maximum axial forces, shear forces and bending moments on the tunnel cross section when subjected to P-, S- and Rayleigh waves. The approach proposed, while limited due to the assumptions made, e.g. elastic ground and tunnel as a beam, can provide a first estimate of the response of the tunnel to waves traveling along the axis of the tunnel. The method relies on the assumption that the ground is homogeneous; that is, there are no changes of ground properties along the tunnel.

The paper presents a new analytical solution for the pseudo-static response of tunnel liners with transitional sections, either due to a change of stiffness of the tunnel support or to the ground properties. That is, there are two homogeneous zones in the problem, one on each side of the (sharp) contact, and a transition zone (Fig. 1). The solution is reached based on the following assumptions: the tunnel is divided into two semi-infinite tunnels, one for each homogeneous zone, and a finite tunnel for the transition between the two homogeneous zones; each zone has a uniform stiffness; a sinusoidal shear motion propagates along the tunnel axis; and the wave passage effect can be considered by employing a displacement phase angle.

The following sections include the new analytical solution, verification of the solution by comparing its predictions with those of a Finite Element Method, and a parametric analysis to investigate the effect of the most important variables, as identified in the analytical solution.

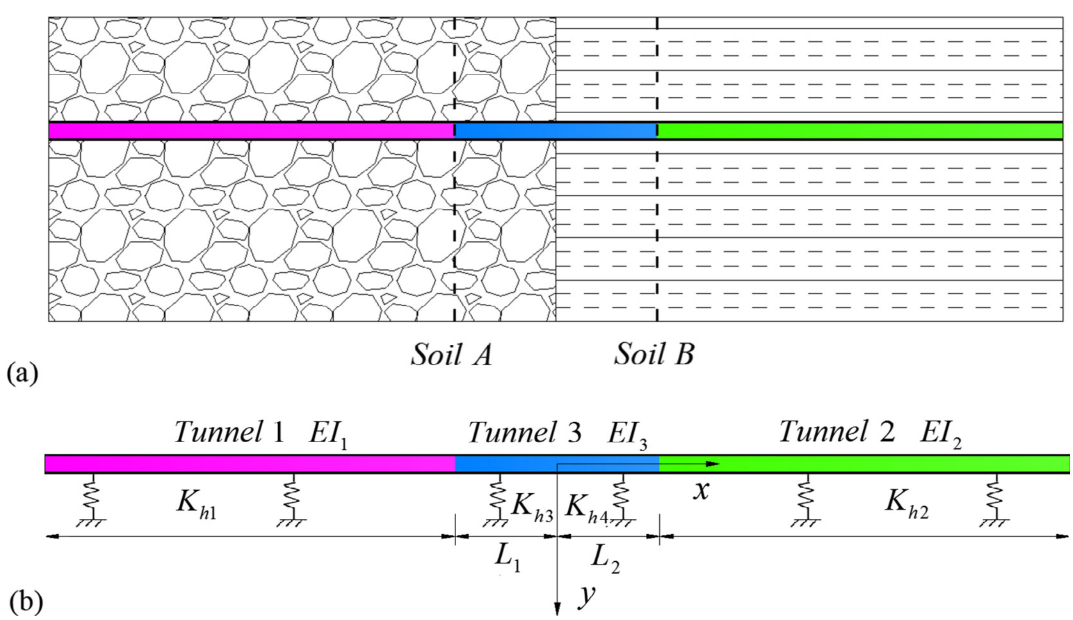

Fig. 1. Long lined tunnel with a sharp transition of liner and/or ground properties: (a) longitudinal profile of the tunnel; and (b) Winkler beam model.