Tunnelling and Underground Space Technology 72 (2018) 218–227

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Internal force of a tunnel lining induced by seismic Rayleigh wave

Zhang Yun-liang*, Bai Shao-guo, Borjigin Mang-lai

Faculty of Infrastructure Engineering, Dalian University of Technology, Dalian 116024, Liaoning Province, China

ARTICLE INFO

Keywords:
Rayleigh wave
Tunnel
Internal force
Earthquake

ABSTRACT

In preliminary seismic analysis and design of a tunnel lining, compared to the frequently-assumed incident S-wave, analytical solutions to internal forces (axial force or thrust, bending moment and shear force) induced by incident R- (Rayleigh) wave are relatively few. Furthermore, in existing solutions the ground-structure interactions, temporal and spatial seismic response variations are not considered simultaneously. In this paper new closed-form solutions to internal forces induced by R-wave were derived for a tunnel lining. Comparison between the proposed solutions and the ones given in literature were made through a typical problem. It shows that: if R-wave propagates along the axis of a tunnel, the longitudinal axial force, bending moment and shear force on a cross section can reach their respective maxima. The maximum resultant normal stress given by literature may be over-predicted; if R-wave propagates perpendicularly to the tunnel's axis, the circumferential thrust, bending moment and shear force on a longitudinal section can also reach their respective maxima with the maximum thrust being much higher than that due to S-wave; the P-wave component of R-wave is predominant.

1. Introduction

It is known that the ground motion induced by a seismic surface R-(Rayleigh) wave is quite different from that induced by the frequently-assumed body S-wave. The R-wave generally occurs and develops near the free surface of a homogeneous, isotropic, semi-infinite medium and in some layered sedimentary deposits or basins, valleys or near slopes (Power et al., 2006; Roberto, 2009). If associated with strong earthquake, the R-wave motion may cause much higher strains/stresses or internal forces in an underground structure and could be more damaging than S-wave (Wang, 1993; Power et al., 2006; Kouretzis et al., 2011). In seismic analysis and design of underground structures researches on R-wave effects are relatively few and have gradually received attentions.

There are three basic ways, i.e., numerical simulation, experimental study and theoretical analysis, to investigate pseudo-static or dynamic seismic responses of an underground structure under R-wave (Newmark, 1968; Kuesel, 1969; Yeh, 1974; St. John and Zahrah, 1987; Liu and Li, 2006; Power et al., 2006; Sanchez-Merino et al., 2009; Kouretzis et al., 2011, 2012; Wu et al., 2015; Chen et al., 2016; Tremblay et al., 2017). About the numerical simulation and experimental study, they are not the emphasis of this paper. As to the theoretical analysis, closed-form solutions to the internal forces including axial force or thrust, bending moment and shear force of an underground structure due to R-wave were reported representatively by St. John and Zahrah (1987). However, the existing analytical procedures take no into account the temporal and spatial variations of seismic responses when performing the superposition of compression and shear components of R-wave (Kuesel, 1969; Yeh, 1974; St. John and Zahrah, 1987). In fact seismic responses of an underground structure are functions of time and space coordinates during an earthquake and when they are estimated, this kind of characteristics shall be noticed. Otherwise it may lead to incorrect results.

Based on thin shell theory Kouretzis et al (2011, 2012) recently derived a set of expressions of strains for buried pipelines and thin-walled tunnels due to propagation of R-wave considering the temporal and spatial variation of strains. But in his work the ground-structure interactions are ignored. If the stiffness of an underground structure is higher or lower than that of the surrounding ground, the ground-structure interactions may lead to under- or over-predictions of seismic responses (Wang, 1993; Penzien and Wu, 1998; Penzien, 2000; Hashash et al., 2001, 2005; Bobet, 2003, 2010; Power et al., 2006; Park et al., 2009). The ground-structure interactions are often considered in the case of incident S-wave (St. John and Zahrah, 1987; Wang, 1993; Penzien and Wu, 1998; Penzien, 2000; Hashash et al., 2001, 2005; Bobet, 2003, 2010; Power et al., 2006; Park et al., 2009) but with the temporal and spatial variations of seismic responses not being reflected.

In summary, in derivation of the closed-form internal forces and in estimation of the corresponding maxima for an underground structure under R-wave, the aforementioned ground-structure interactions as

* Corresponding author.
E-mail addresses: zhang-yunliang@dlut.edu.cn (Y.-l. Zhang), baishao1988@126.com (S.-g. Bai), manglai@mail.dlut.edu.cn (M.-l. Borjigin).

https://doi.org/10.1016/j.tust.2017.11.014
Received 26 January 2016; Received in revised form 28 October 2017; Accepted 1 November 2017
Available online 24 November 2017

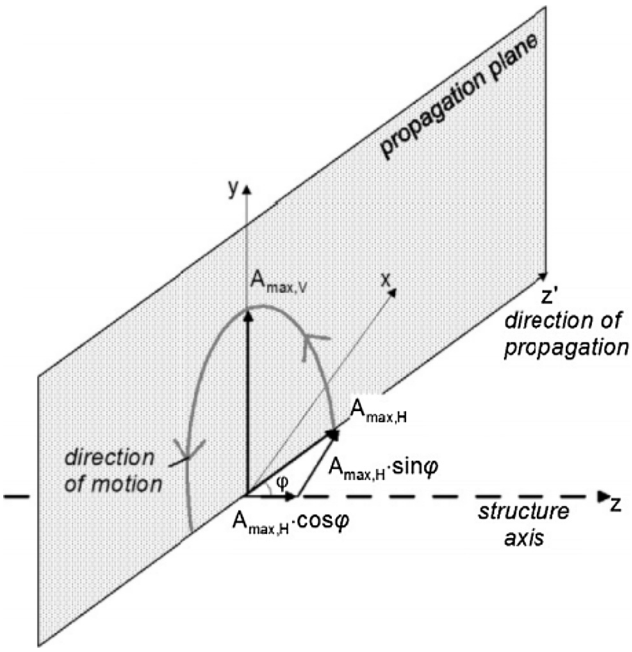

Fig. 1. Propagation of a surface R-wave at an arbitrary angle φ with the axis of an underground structure (From Kouretzis et al., 2011).

well as temporal and spatial variations shall both be considered. However, no literature has been found to present the related expressions.

In this paper, firstly according to the concept of apparent wave and some assumptions, decomposition of a surface R-wave into several component waves was performed. Then analytical expressions of the longitudinal internal forces on a cross section and the circumferential internal forces on a longitudinal section of a shallow circular tunnel lining caused by R-wave were derived in detail with ground-structure interactions as well as temporal and spatial variations being considered simultaneously. A typical tunnel problem was shown to compare results calculated by the proposed solutions and the ones by solutions from the representative literature. Lastly some conclusions and suggestions were given.

2. Decomposition of R-wave

A surface R-wave is here assumed to be harmonic and propagates horizontally along an arbitrary z'-axis in the elastic half-space with a plane front at an angle φ with a tunnel's axis, z, as shown in Fig. 1. The induced displacement motion in the half-space can be decomposed into a horizontal, compression (P) component, denoted by $U_{z'}$, and a vertical, shear (SV) component, denoted by U_y, respectively. According to Roberto, 2009, the two components are derived and have the following form:

$$\begin{cases} U_{z'} = \Lambda K_R \left[\exp\left(-\frac{\sqrt{\eta^2-\varsigma^2}}{\eta} K_R y\right) \right. & \sin\left[\frac{2\pi}{L}(z'-C_R t)\right] \\ \left. \quad -\left(1-\frac{1}{2\eta^2}\right) \exp\left(-\frac{\sqrt{\eta^2-1}}{\eta} K_R y\right) \right] & \\ U_y = \Lambda K_R \left[\frac{2\eta\sqrt{\eta^2-\varsigma^2}}{2\eta-1} \exp\left(-\frac{\sqrt{\eta^2-1}}{\eta} K_R y\right) \right. & \cos\left[\frac{2\pi}{L}(z'-C_R t)\right] \\ \left. \quad -\frac{\sqrt{\eta^2-\varsigma^2}}{\eta} \exp\left(-\frac{\sqrt{\eta^2-\varsigma^2}}{\eta} K_R y\right) \right] & \end{cases}$$

$$\eta = \frac{C_{SV}}{C_R}, \quad \varsigma = \frac{C_{SV}}{C_P}$$

$$C_P = \sqrt{\frac{2-2\nu_m}{1-2\nu_m}} C_{SV}, \quad C_R = \frac{0.87+1.12\nu_m}{1+\nu_m} C_{SV} \tag{1}$$

where Λ denotes a constant to be determined by initial conditions; K_R, C_R, L represent R-wave number, propagation velocity and wave length of the medium, respectively; C_P and C_{SV}, propagation velocity of P- and SV-wave, respectively; ν_m, the Poisson's ratio of the medium; y, the vertical coordinate with positive direction being upward.

Near the free ground surface ($y \approx 0$), let $A_{max,H}$ and $A_{max,V}$ denote the medium's maximum horizontal and vertical displacement amplitudes, respectively. Then the first two expressions of Eq. (1) can be simplified as

$$\begin{cases} U_{z'} = A_{max,H} \sin\left[\frac{2\pi}{L}(z'-C_R t)\right] \\ U_y = A_{max,V} \cos\left[\frac{2\pi}{L}(z'-C_R t)\right] \end{cases} \quad \text{where} \quad \frac{A_{max,V}}{A_{max,H}} = \frac{2\eta\sqrt{\eta^2-\varsigma^2}}{2\eta^2-1} \tag{2}$$

According to concept of apparent waves, the propagation of SV component at an angle φ relative to the tunnel's z-axis is equivalent to the following apparent waves (Kouretzis et al., 2011):

(a) An apparent SV-wave, denoted here by SV1, propagating along the tunnel's z-axis, as shown in Fig. 1, with wavelength $L/\cos\varphi$, propagation velocity $C_R/\cos\varphi$ and amplitude $A_{max.V}$. The displacement, denoted by $U_{y,SV1}$, induced by the apparent wave SV1, can be expressed in the following form:

$$U_{y,SV1} = A_{max,V} \cos\left[\frac{2\pi}{\frac{L}{\cos\varphi}}\left(z-\frac{C_R}{\cos\varphi}t\right)\right] = A_{max,V} \cos\left[\frac{2\pi}{L}(z\cos\varphi - C_R t)\right] \tag{3}$$

(b) An apparent SV-wave, denoted here by SV2, propagating perpendicularly to the tunnel's z-axis, i.e., along the x-axis, with wavelength $L/\sin\varphi$, propagation velocity $C_R/\sin\varphi$ and amplitude $A_{max.V}$. The displacement, denoted by $U_{y,SV2}$, induced by SV2 has the form:

$$U_{y,SV2} = A_{max,V} \cos\left[\frac{2\pi}{\frac{L}{\sin\varphi}}\left(z-\frac{C_R}{\sin\varphi}t\right)\right] = A_{max,V} \cos\left[\frac{2\pi}{L}(z\sin\varphi - C_R t)\right] \tag{4}$$

Similar to the decomposition of SV component, the propagation of P component at an angle φ relative to the tunnel's z-axis is equivalent to the following apparent waves (see Fig.1):

(c) An apparent SH-wave, denoted here by SH1, propagating along the tunnel's z-axis, with wavelength $L/\cos\varphi$, propagation velocity $C_R/\cos\varphi$ and amplitude $A_{max.H}\sin\varphi$. The displacement $U_{x,SH1}$ induced by SH1 can be written as:

$$\begin{aligned} U_{x,SH1} &= A_{max,H} \sin\varphi \sin\left[\frac{2\pi}{\frac{L}{\cos\varphi}}\left(z-\frac{C_R}{\cos\varphi}t\right)\right] \\ &= A_{max,H} \sin\varphi \sin\left[\frac{2\pi}{L}(z\cos\varphi - C_R t)\right] \end{aligned} \tag{5}$$

(d) An apparent P-wave, denoted here by P1, propagating along the x-axis, with wavelength $L/\sin\varphi$, propagation velocity $C_R/\sin\varphi$ and amplitude $A_{max.H}\sin\varphi$. The displacement $U_{x,P1}$ induced by P1 can be written as:

$$\begin{aligned} U_{x,P1} &= A_{max,H} \sin\varphi \sin\left[\frac{2\pi}{\frac{L}{\sin\varphi}}\left(x-\frac{C_R}{\sin\varphi}t\right)\right] \\ &= A_{max,H} \sin\varphi \sin\left[\frac{2\pi}{L}(x\sin\varphi - C_R t)\right] \end{aligned} \tag{6}$$

(e) An apparent P-wave, denoted here by P2, propagating along the tunnel's z-axis, with wavelength $L/\cos\varphi$, propagation velocity $C_R/$