Tunnelling and Underground Space Technology 46 (2015) 116–124

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

3-D shell analysis of structure in portal section of mountain tunnel under seismic SH wave action

Lianjin Tao [a,b], Sen Hou [a,*], Xu Zhao [a], Wenge Qiu [c], Tianbin Li [d], Chunxiao Liu [a], Ke Wang [a]

[a] Key Laboratory of Urban Security and Disaster Engineering of Ministry of Education, Beijing University of Technology, Beijing 100124, China
[b] Beijing City Traffic Collaborative Innovation Center, Beijing University of Technology, Beijing 100124, China
[c] Key Laboratory of Transportation Tunnel Engineering, Ministry of Education, School of Civil Engineering, Southwest Jiaotong University, Chengdu, SiChuan, China
[d] State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Dongsan Rd. 1, Chenghua District, Chengdu City, China

ARTICLE INFO

Article history:
Received 1 January 2014
Received in revised form 26 August 2014
Accepted 17 November 2014

Keywords:
Mountain tunnel
Shell theory
Single free face slope
Strain
Theory of elastic wave

ABSTRACT

Tunnel portals are often located in rather weak rock. Also the ground surface of tunnel portal section is often inclined to form slopes. These characteristics in engineering geology make this section easy to be damaged during earthquakes both in slope and in structures. A model with single free surface slope is built to analyze the dynamic response of portal section of a mountain tunnel. First, the theory of elastic wave propagation is used to deduce the solution of free field ground motion on the axis of tunnel under incident SH wave without considering the existence of the tunnel. Then, the ground motions are putting on tunnel structure, where the 3-D elastic shell theory is employed in order to provide strains of the structure. The analytical solutions of the model are verified by the results of shaking table test. In this way, the analytical solutions do not only consider the amplitude-time–frequency effects, but also derives analytical expressions of axial, hoop and shear strain distribution on tunnel cross-sections. These results could be references for seismic design of tunnel portal section in mountain tunnels and have positive effects on reasonable understandings of the seismic response characteristics in this section.

1. Introduction

Tunnel portals are likely to be damaged by earthquake because they often locate in rather weak ground where earthquake motion is amplified and the ground deforms to a large extent. The damage to tunnel portal sections includes the cracks in portal part structure and lining (Genis, 2010). There are numerous reports on the damage to tunnel portals caused by earthquakes. Chi-Chi earthquake (Wang et al., 2002; Uenishi et al., 1999), Düzce earthquake (1999) and Wenchuan earthquake (Chen et al., 2012; Li, 2012) cause extensive failures in portal section of mountain tunnel, reviving the interest in the associated analysis and design methods.

Three methods are mainly used for the seismic study of underground structures: model tests, theoretical analysis and numerical analysis. By limitation of monitoring method, sometimes data are not enough in model test. Further, it takes much cost. Numerical analysis is aimed at case-specific analyses and complex problem. Nevertheless, theoretical analysis can enrich and replenish effectively to model test, which is essential in exploring physical nature of the problem, and also can be used for checking the accuracy of numerical methods.

The seismic study of underground structure in theoretical analysis way has increased considerably in the past three decades. The analytical solutions are divided into fluctuation method based on wave equation and interaction method based on motion equation. Free field deformation approach is a simper type of fluctuation method, which is widely used in current design guidelines, and can provide a first-order estimate of the anticipated deformation of the structure (Hashash et al., 2001). The method is based on the theory of wave propagation in homogeneous, isotropic, elastic media, which ignore the interaction between the structure and soil (Newmark, 1968).

In order to provide design seismic strains and stresses of underground structure due to body and surface waves through the previous method, Newmark (1968) and Kuesel (1969) calculated ground strains due to a wave propagating at a given angle of incidence in a medium. St John and Zahrah (1987) used Newmark's approach to develop solutions for these strain components due to *P*-waves, *S*-waves and *R*-waves. Furthermore, axial, hoop and shear strains are presented through 3-D shell theory, regarding long cylindrical underground structures subjected to seismic shear (*S*) and Rayleigh wave excitation (Kouretzis et al., 2006, 2011). Some other analytical solutions simulate soil-structure interaction effects, by employing the beam-on-elastic foundation approach or modeling the underground structure as a cylindrical shell

* Corresponding author. Tel.: +86 18101358903.
E-mail address: airforcehou@gmail.com (S. Hou).

http://dx.doi.org/10.1016/j.tust.2014.11.001
0886-7798/

embedded in an elastic half-space, and account for slippage at the soil-structure interface (Wong et al., 1986; Luco and de Barros, 1994).

The presented researches mainly calculate structure strains in half-space and infinite space. To the authors' knowledge, no studies have discussed on seismic response of structures embedded in inclined plane based on free field deformation approach.

However, dynamic response of lining at the tunnel portal section is mainly affected by slope. Different angle of slope will cause different extent, types and directions of reflected wave. The waves are superimposed in the vicinity of slope forming a complex wave field (Shi et al., 2008). Mechanics characteristics of lining under complex wave field caused by slope reflection are not well studied. Single free face slope is built to model entrance section of a mountain tunnel. The theory of elastic wave propagation is used to deduce the solution of free field ground motion on the axis of tunnel under incident SH wave, while ignoring the existence of tunnel structure. Then the 3-D elastic shell theory is employed in order to provide strains by the ground motion. Due to the relative complexity of the mathematics, the resulting relations are verified against results from shaking table test.

2. Theoretical derivation

2.1. Basic assumptions

The derivation is based on following assumptions:

(1) Ignoring the impact of presence of tunnel on dynamic response of ground.
(2) Ignoring interaction between tunnel and rock.
(3) Simplifying tunnel portal section as single free face slope, while the grading angle of slope is less than 45°.
(4) In many cases, severely-weathered, broken and loose rock mass are distributed in portal section of tunnel. This kind of rocks would be classified into class V according to the BQ system in China Code for Design of Road Tunnels (JTG D70-2004), which matches to RMR < 20 in the RMR system of Bieniawski. The property and parameters of the rock is similar to soil. Therefore, the rock and tunnel material are considered as homogeneous isotropic linear elastic.

2.2. Analytical expressions of displacement field at tunnel axis for single free surface slope

The model of SH wave propagation in single free surface slope is presented in Fig. 1. According to the principle of wave propagation, SH wave vertically propagate from bedrock, spreading along O_1B, and reaching point B, resulting in reflected SH wave on the slope surface. As shown in Fig. 2, the reflected SH wave reaches the point A of tunnel along BA, and superimpose on incoming SH wave propagating along O_2A at point A.

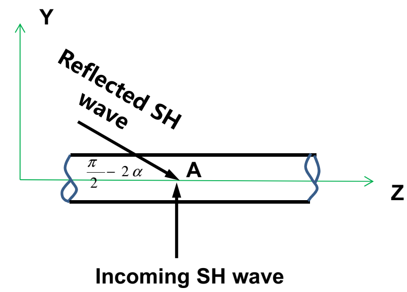

Fig. 2. Wave superposition at point A.

The seismic excitation can be modeled as a train of harmonic waves with plane front. For harmonic plane SH waves propagating in *Y* direction from bedrock, the displacement field is described as (Lin, 1990)

$$u_x = A_{\max} \sin\left[\frac{2\pi}{L}(y - C_s t)\right] \tag{1}$$

where $A_{\max}$ is the peak particle displacement of the seismic motion, L is the wavelength, C_s is the shear wave propagation velocity. For reflected wave under free boundary condition, ground motion can be described as

$$u_x = A_{\max} \sin\left[\frac{2\pi}{L}(z' - C_s t')\right] \tag{2}$$

where $t' = t - t_0$, t_0 is the time of incident wave propagating from D to A. In Fig. 1, the original point of Cartesian coordinate can be set at point C, then the coordinates of point A is (0, z), so delay time of reflected wave is

$$t_0 = \frac{z \sin 2\alpha}{C_s} \tag{3}$$

As initially introduced by Kuesel (1969), reflected SH wave at an angle $\frac{\pi}{2} - 2\alpha$ with tunnel axis is equivalent to the following waves:

(1) An SH wave propagating along the tunnel axis, with a wavelength of $L/\cos\left(\frac{\pi}{2} - 2\alpha\right)$, a propagation velocity of $C_s/\cos\left(\frac{\pi}{2} - 2\alpha\right)$, and a maximum amplitude of $A_{\max}$.
(2) An SH wave propagating transversely to the tunnel axis, with a wavelength of $L/\sin\left(\frac{\pi}{2} - 2\alpha\right)$, a propagation velocity of $C_s/\sin\left(\frac{\pi}{2} - 2\alpha\right)$, and a maximum amplitude of $A_{\max}$.

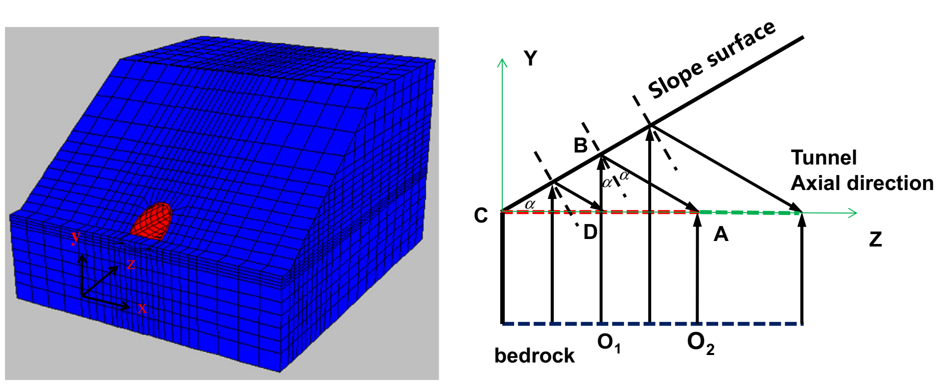

Fig. 1. Model of SH wave propagation in single free surface slope.