Tunnelling and Underground Space Technology 77 (2018) 216–226

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Seismic response of shield tunnel subjected to spatially varying earthquake ground motions

Yu Miao[a], Erlei Yao[a], Bin Ruan[a,*], Haiyang Zhuang[b]

[a] School of Civil Engineering and Mechanics, Huazhong University of Science and Technology, Wuhan 430074, PR China
[b] Institute of Geotechnical Engineering, Nanjing Tech University, Nanjing 210009, PR China

ARTICLE INFO

Keywords:
Generalized response displacement method
Multi-support excitation
Spatially varying ground motions
Seismic behaviors
Identical support excitation

ABSTRACT

The subway shield tunnel of Sanyang Road in Wuhan, China, is a Yangtze River-crossing tunnel project with a mega diameter of 15.7 m, which crosses several soil layers with sharply different properties. To investigate the seismic characteristics of this special subway tunnel under spatially varying earthquake ground motions (SVEGMs) with high efficiency, the concept of response displacement method was utilized and realized with a refined free-field model and a simplified soil-tunnel model. Two sets of borehole accelerograms, denoting near-field and far-field ground motions, respectively, were selected and taken as the reference to generate fully non-stationary SVEGMs. A lot of responses along the longitudinal direction under multi-support excitation (MSE), including intersegment opening width, inner forces, and acceleration, were observed and compared with those under identical support excitation (ISE). The comparative results showed that the responses of subway shield tunnel under MSE are generally higher than those under ISE. The longitudinal distributions of intersegment opening width and bending moment response of lining are dominantly affected by the site conditions. Excitation methods, spectral characteristic and PGA of input earthquake can also have effect on the longitudinal distribution of tunnel response. The results can contribute to revealing the difference between seismic response characteristics of shield tunnel under MSE and those under ISE and predicting the underlying location of seepage or severe damage of shield tunnel. The analysis procedure established in this paper possesses highly potential for application to the aseismic design of practical shield tunnel project.

1. Introduction

Due to the severe damage of tunnels occurred in Kobe (1995), Chi-Chi (1999), Koceali (1999) and Wenchuan (2008) earthquakes, the importance of seismic analysis of tunnel has drawn more and more attention. A series of investigations have been performed by a number of researchers for evaluating the seismic behaviors of tunnels during the past decades. Hashash et al. (1998) conducted three-dimensional (3D) analyses of the dynamic response of the immersed tubes in the San Francisco Bay Area. It has been concluded that the arrival time delay of the ground motion has a significant influence on the axial deformation of tunnel. Lee and Trifunace (1979) studied the response of underground circular tunnel subjected to incident SH-waves and obtained an analytical solution. Park et al. (2009) developed a longitude displacement profile-based method for simulating the tunnel response under SVEGM and performed a series of pseudo-static 3D finite element analyses. It has been found that the SVEGM causes longitudinal bending of the tunnel and can induce substantial axial stress on the tunnel. Chen et al. (2012) investigated the influence of the depth of a tunnel on its seismic damage based on a dynamical finite element analysis method. Bao et al. (2017) clarified sufficiently the seismic behavior and floatation mechanism of the large metro tunnel structure in liquefied soil deposits by using an effective stress-based soil-water fully coupling finite element-finite difference method. Tsinidis (2017) carried out a numerical parametric study on diverse soil-rectangular tunnel systems to shed light on critical response characteristics of rectangular tunnels subjected to transversal ground shaking. Shahrour et al. (2010) conducted an elastoplastic finite element analysis of the seismic response of tunnels constructed in soft soils and the results showed that the plastic deformations induce an important reduction in the seismic-induced bending moment in the tunnel, while the soil dilatancy moderately affects the bending moment in the liner. Amorosi and Boldini (2009) compared the results of a set of analyses aimed at studying the seismic transversal response of a shallow tunnel and proposed that adopting more advanced constitutive models for both soil and tunnel lining, capable of reproducing more realistically their behavior under dynamic conditions, is needed. Chen et al. (2017) conducted a time history analysis to explore the influence of SVEGM on seismic responses of the

* Corresponding author.
E-mail address: ruanbin666@hust.edu.cn (B. Ruan).

https://doi.org/10.1016/j.tust.2018.04.006
Received 28 November 2017; Received in revised form 1 March 2018; Accepted 6 April 2018

long immersed tunnel. Results showed that SVEGM enlarges seismic responses of the immersed tunnel significantly and considering wave passage effect and incoherence effect simultaneously makes the seismic responses increase more sharply than considering the latter only. Yan et al. (2016), Yuan et al. (2016) and Yu et al. (2016, 2017) conducted a series of shaking table tests on long immersed tunnels subjected to non-uniform seismic loadings. The results indicated that tunnel responses under non-uniform earthquake excitation are much higher than those under uniform earthquake excitation and the effect of spatial distribution of earthquake excitation should be considered in the design of immersed tunnels.

Subway tunnel is an extremely long structure occupying large space. The SVEGMs have a significant effect on the response of long structures (Zerva, 2009), because of which commentaries and provisions on seismic analysis of spatially extended structures are specified in many design standards (CEN, 2004; CEN, 2005; Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2010; Ministry of Transport of the People's Republic of China, 2008). Therefore, the aseismic design of subway tunnel should account for the effects of ground motion spatial variability. Spatial variation of ground motions results from: (i) wave passage effects, which is the difference in arrival times of the seismic waves at different stations; (ii) incoherence effects due to wave scattering or extended source effects; and (iii) local site effects. A lot of contributions have been devoted to the aseismic analyses of large-scale structures subjected to SVEGM, such as bridges (Lou and Zerva, 2005; Dumanogluid and Soyluk, 2003; Apaydin et al., 2016; Zhang et al., 2013; Liang et al., 2017) and pipelines (Soliman and Datta, 1996; Zerva, 1993). However, studies about the influence of SVEGM on the response of subway tunnel are still lacking.

Usually, the ISE of earthquake was utilized to study the seismic response of large-scale subway tunnels and the spatial variance of earthquake motions was neglected. To investigate the influence of SVEGM on the response characteristics of subway shield tunnel, a series of seismic analyses of shield tunnel under MSE and ISE of earthquake were conducted through a case study in ABAQUS and the results were compared. Besides, the previous numerical methods for 3D large-scale underground structures are time-consuming and may cost a great deal of computing resources. Therefore, the concept of response displacement method (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2014) was adopted and realized to proceed with the study. This method is named generalized response displacement method (GRDM) and can facilitate the simulation with higher efficiency and be more applicable to numerical analysis of large-scale underground structures. Moreover, the effect of excitation methods, spectral content and intensity of input motion as well as site conditions on the response characteristics of shield tunnel was also studied. The results can help to predict the underlying location of seepage or severe damage of shield tunnel under earthquake and thus the analysis procedure established in this paper possesses highly potential for application to practical shield tunnel project. The methodology for the problem, including ground motion selection, simulation of SVEGMs and the time-history analysis method we used, is presented in Section 2. In Section 3, the setup of a numerical model is presented as well as some information about the reference engineering. Subsequently, Section 4 offers the dynamic responses of tunnels under MSE and ISE. Finally, concluding remarks are given in Section 5.

2. Methodology

2.1. Ground motion selection

According to certain criteria, the input motions on bed rock were selected based on the records from Kiban-Kyoshin Network (KiK-Net) in Japan. The KiK-Net consists of more than 600 vertical arrays with an uphole/downhole pair of strong motion seismometers. These arrays were built by the National Research Institute for Earth Science and Disaster Resilience in Japan (NIED) after 1995 Kobe earthquake. More than a million accelerograms recorded between 2009 January and 2014 June by all 697 KiK-Net sites during 5007 earthquakes events were collected and then a ground motion data base was constructed. The accelerograms encompassed an ample range of peak ground acceleration (PGA) (from 0.1 to more than 1000 Gal), of epicentral distances (from 1 km to more than 1000 km), of moment magnitudes (from 2 to 9), and of borehole depths (from 100 m to more than 3000 m). Based on this data base the selection was carried out.

We utilized three conditions to conduct the selection: (i) borehole depth ≥ 100 m; (ii). PGA ≥ 100 Gal; (iii). Magnitude = 6.5–7.5 M. We selected the ground motions through two steps: Firstly, we picked a total of 59 horizontal borehole accelerograms according to the conditions above mentioned. Secondly, these accelerograms are assigned into two groups by epicentral distance: 0–60 km and 120–180 km. There are 21 accelerograms with epicentral distance from 0 to 60 km and 7 accelerograms with epicentral distance from 120 to 180 km. Then, we calculated the Fourier spectrum of every ground motion and the averaged one for each group, and selected the accelerogram which has the smallest difference with the average Fourier spectrum as the horizontal input ground motion. Make sure the selected accelerogram is the most representative in this group.

2.2. Simulation of ground motions

Hao et al. (1989) proposed a method for generating spatially correlated ground motions in the process of which only the correlation between present ground motion and previous ones was considered and the Cholesky decomposition of power spectral density function (PSDF) matrix was used correspondingly. Qu and Wang (1998) and Qu and Wang (1998) extended Hao's method by taking the correlation between present ground motion and all the other ones into account. According to Qu's method, 1D-nV (one-dimensional, n-variate) stochastic process can be expressed as:

$$x_j(t) = \sum_{m=1}^{n}\sum_{k=0}^{N-1} a_{jm}(\omega_k)\cos[\omega_k t + \theta_{jm}(\omega_k) + \varphi_{mk}] \quad (1)$$

where N is the number of frequency interval. ω_k is the kth value of ω. φ_{mk} are random phase angles uniformly distributed between 0 and 2π. And

$$a_{jm} = 2\sqrt{\Delta\omega}\ |u_{jm}(i\omega_k)| \quad (2)$$

$$\theta_{jm} = \arctan\frac{\mathrm{Im}[u_{jm}(i\omega_k)]}{\mathrm{Re}[u_{jm}(i\omega_k)]} \quad (3)$$

with Im and Re denoting the imaginary and the real part of a complex number, respectively.$\Delta\omega$ is frequency bandwidth. u_{jm} are the elements of the lower matrix obtained by using Cholesky decomposition of PSDF matrix. $i = \sqrt{-1}$.

In the present study, the square root decomposition proposed by Wu et al. (2011) and Wu et al. (2018) was used to decompose the PSDF matrix. To incorporate full non-stationarity similar to the reference accelerogram, the reference earthquake time history was divided into a few of segments each having a unique, but stationary, PSDF (Rodolfo Saragoni and Hart, 1974). Note that the number of segments is arbitrary, but in the present research three segments are used. For each segment, the target PSDF was estimated using periodogram method and used in conjunction with coherency model to establish cross-PSDF matrix. Herein, the Sobczyk model which is applicable to describe the coherency loss at the base rock was used as shown in Eq. (4).

$$\begin{aligned}\gamma_{jm}(i\omega) &= |\gamma_{jm}(i\omega)|\ \exp(-i\omega d_{jm}\cos(\alpha)/V_{app}) \\ &= \exp(-\beta\omega d_{jm}^2/V_{app})\cdot\exp(-i\omega d_{jm}\cos(\alpha)/V_{app})\end{aligned} \quad (4)$$

The phase difference spectrum was simulated for each segment according to the distribution of that of the counterpart in the original