Tunnelling and Underground Space Technology 70 (2017) 30–41

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Modified dynamic stress concentration factor for twin tunnels using a novel approach of FEM-scattering

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ARTICLE INFO

Keywords:
Monument
Near-field earthquakes
Twin tunnels
Wave scattering

ABSTRACT

The frequent failure of newly built tunnels under earthquake loading has led to a broader range of research into assessing the effect of seismic waves on tunnels. Numerous researchers have worked on twin tunnels and the effect of wave scattering due to vibration of harmonic waves to date. As for the near-field wave scattering and range of the recording of the acceleration of the ground during an earthquake. However, little research has been conducted on a comprehensive scale. This study attempted to examine the scattering in Si-o-seh Pol Bridge, a monument in Isfahan city, using the Hankel's function of the first and second kinds for near-field earthquakes (Northridge, Tabas and Kobe). All of scattering analysis were done through FESCAM code that designed and developed in MATLAB software as a toolbox by authors of this paper. The historic bridge of Si-o-seh Pol Bridge and its neighboring twin tunnels for subway were selected as a case study. The first kind of Hankel's function was considered as a supplementary parameter to the seismic analysis using finite element method procedure. The amount of dynamic scattering of twin tunnels subjected seismic loads considered as extra strain and stress around tunnels using Hankel's function results. The results between two cases with and without considering scattering waves of tunnels show that the mean horizontal displacement and the mean vertical displacement of Si-o-seh Pol Bridge can be increased about 28.8% and 30.11% respectively. The results of statistical analysis with Mann-Whitney test show that there is no significant difference between the seismic performance of Si-o-seh Pol Bridge with and without consideration of the scattering effect of the tunnels (P-Value = 0.6 > 0.05). However, the results of this study versus the past studies reflect the fact that horizontal and vertical displacements when involving the tunnel are 34.10% increase and −48.51% decline, respectively. This means that the twin tunnels are effective in displacement of the adjacent monument from the engineering perspective.

1. Introduction

Underground structures have been built and exploited more and more as a result of urban development. Tunnels are one of the most important lifeline systems. The frequent failure of newly built tunnels under earthquake loading has led to a broader range of research into assessing the effect of earthquake on tunnels. In this light, it is crucial to evaluate the effect of tunnels whether during excavation or actual operation and especially during an earthquake on the adjacent structures. This becomes even more important when considering the tremendous material and spiritual values of historic buildings (Amorosi and Boldini, 2009). In recent years, many historically important monuments have been damaged by sever earthquakes in Iran. There are about 40 cultural heritage properties which have sustained damages of various degrees in the earthquake-stricken area (Vosoughifar and Razmkhah, 2008; Vosoughifar and Davari, 2009). When earthquake wave hits an underground cavity like a tunnel, part of the wave redirects due to altered soil profile, while another part is emitted into the environment, which is called scattering (Liu et al., 2010). Pao and Mow (1973) examined the scattering of elastic waves around a cylinder in unlimited environment for the first time (Pao and MOW, 1973). Manolis (1980) studied on dynamic behavior of uncoated tunnels regarding the effect of wave scattering using the boundary element method. In Manolis and Beskos (1983) evaluated the shape of scattering of waves using the boundary limits (Manolis, 1980; Manolis and Beskos, 1983).

Scattering of *P* and *SV* waves in a heterogeneous environment at the Los Angeles basin was examined by Moeen-Varizi and Trifunac (1988). In 2002, a model for scattering of harmonic waves within a saturated pro-elastic environment was introduced based on the dimensionless frequency function through the Bessel Equations (Hasheminejad and Hosseini, 2002). In this study scattering of waves by a circular tunnel in an anisotropic elastic -porous media was evaluated. The proposed method involved both complex functions for the solid and fluid frameworks on the two-dimensional plane to solve the Biot Equations

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http://dx.doi.org/10.1016/j.tust.2017.07.006
Received 22 August 2015; Received in revised form 5 May 2017; Accepted 10 July 2017

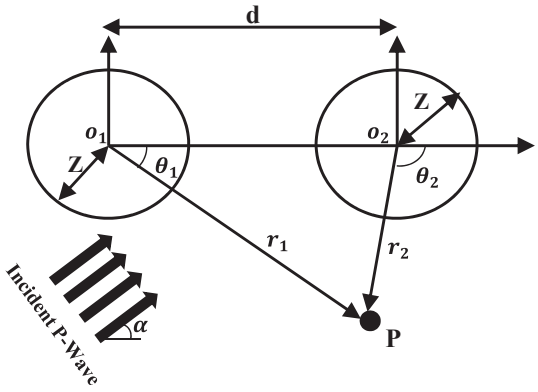

Fig. 1. Twin tunnels and effective parameters on wave scattering.

Table 1
Specifications of scaled near-field accelerograms.

Earthquakes	Year	Station	Magnitude	PGA (g)	R_{rup} (km)
Northridge	1994	Anacapa Island	6.69	1.2919	20.72
Tabas	1978	Dayhook 9102	7.35	0.4301	19.41
Kobe	1995	Nishi Akashi	6.9	0.9340	7.08

Table 2
Frequency domain data of selected earthquakes.

Frequency	Fourier amplitude (Northridge)	Fourier amplitude (Tabas)	Fourier amplitude (Kobe)
0.1	0.234	0.030	0.028
1	0.129	0.038	0.12
10	0.014	0.073	0.029

Table 3
Maximum frequency of selected earthquakes.

Earthquake	$Frequency_{(PeakAcceleration)}$	Fourier amplitude
Northridge	3.394	0.276
Tabas	6.714	0.810
Kobe	7.251	0.095

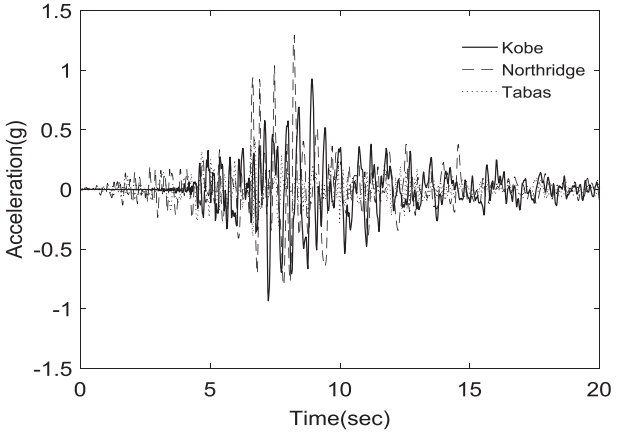

Fig. 2. Time history of acceleration for three near-field earthquakes (Northridge, Tabas and Kobe).

(Gatmiri and Eslami, 2007, 2008; Jiang et al., 2009). The effects of harmonic plane waves on twin tunnel of unlimited length in a saturated pro-elastic environment were investigated with considering on the type of materials, wave frequency, drainage conditions and proximity (Hasheminejad and Avazmohammadi, 2007, 2008(. Helmholtz

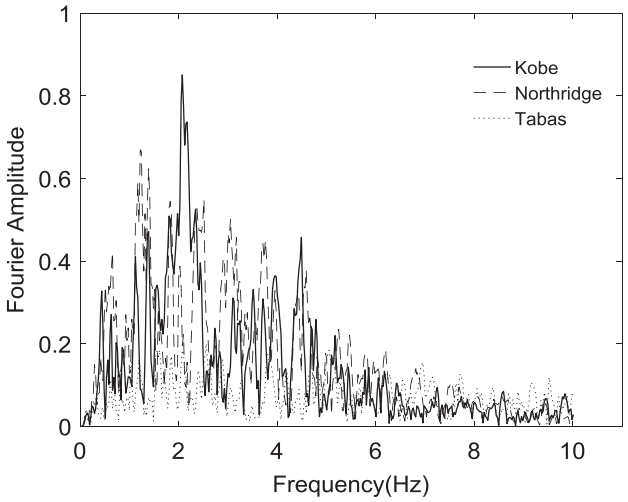

Fig. 3. Fourier spectrum for the three near-field earthquakes (Northridge, Tabas and Kobe).

equation has been used to estimate the stresses and displacements based on a complex variable function in a circular tunnel & twin tunnels (Liu and Wang, 2012; Liu et al., 2014).

Some of researchers evaluated the effect of stress concentration caused by the scattering of seismic waves and the tunnel lining in recent years. These researchers analyzed the effect of wave number and spacing of cavities on the dynamic stress distribution (Liu and Wang, 2012; Yi et al., 2014; Zhou et al., 2014). The theory of complex variables on the plane and the visual method were used to propose an analytic solution for the longitudinal (P-wave), shear (SV-wave) and Rayleigh harmonic wave scattering inside a shallow circular tunnel in semi-elastic media. It was shown when the wave emitted perpendicular to the cylinder axis, the polarization of the dispersed wave remained unchanged. The scatter wave emitted in this scheme was the same as the input wave. Moreover, when the wave is emitted along the neutral axis (i.e. diagonal angle to the axis of the cylinder), the scattered wave was non-polar, where the spatial distribution was three-dimensional (Lee, 2015; Liu et al., 2013).

As mentioned above, many researchers have studied the seismic behavior of monument and historic structures without considering the effect of scattering such as subway tunneles. The most important researches in this field were done without considering scattering waves (Afifipour et al., 2011; Azadi and Zahedi, 2011; Sevim et al., 2011; Russo, 2013; Didem Aktas and Turer, 2015). Previous researches have not been considered the scattering of actual seismic waves. Other researchers have studied the other kind of seismic loads like vibration of train movement and serious problems in buildings that are in close proximity to subway systems. Some different methods such as the power spectral density (PSD) model of the displacement in the soil and the thin-layer (TLM) model in arbitrarily layered half-spaces were suggested to consider some parts of scattering waves (Hussein et al., 2015; Jones and Hunt, 2012). The limits of empirical prediction of scattered waves may be clarified by numerical simulations. In order to overcome the limitations of numerical and empirical methods, a hybrid or semi-empirical method can be useful (Lombaert et al., 2014).

In this paper the effect of seismic wave scattering in displacement of twin tunnels and specially focused on their side effect on a monument which are settled adjacent the tunnels was evaluated. In this way, the displacement of monument in possible earthquake condition with and without considering the scattering was compared. In first step, two different models of the study domain with and without tunnels were analyzed in a proper and strong finite element program such as ABAQUS. Then the FEM numerical analysis was conducted to calculate dynamic stress concentration factor for comparing with other results in this step the first kind of Hankel's function was used to analyze the