Ocean Engineering 75 (2014) 64–70

Contents lists available at ScienceDirect

Ocean Engineering

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

Seismic response of fluid–structure interaction of undersea tunnel during bidirectional earthquake

Xuansheng Cheng[a,b,c,*], Weiwei Xu[a], Caiquan Yue[a], Xiuli Du[b], Charles H. Dowding[c]

[a] School of Civil Engineering, Lanzhou University of Technology, Lanzhou 730050, PR China
[b] Key Laboratory of Urban Security and Disaster Engineering of Education, Beijing University of Technology, Beijing 100124, PR China
[c] Department of Civil and Environmental Engineering, Northwestern University, Evanston 60208, USA

ARTICLE INFO

Article history:
Received 25 July 2013
Accepted 9 November 2013
Available online 26 November 2013

Keywords:
Undersea tunnel
Bidirectional earthquake
Seepage
Fluid–structure interaction
Seismic response

ABSTRACT

In this study, the seismic response of the fluid–structure interaction (FSI) of an undersea tunnel in a broken fault zone during a bidirectional earthquake is examined. An undersea tunnel FSI model that accounts for the effects of the viscoelastic artificial boundary, seepage, and dynamic liquid pressure, and considers the rock mass as a saturated porous medium, is created through finite element analysis software ADINA. The seismic response of the undersea tunnel is determined by considering both horizontal and vertical ground motion and analyzing the time history curve of the displacement, acceleration, and principal stress of the lining key point. Numerical results show that (1) the maximum displacement, acceleration, and tensile stress of the lining structure are all present in the vault area; (2) the time history curves of the displacement, acceleration, and principal stress of the key points follow a similar variation law; (3) the vertical displacement of the lining structure is greater than its horizontal displacement; and (4) tensile areas generally appear in the vault and inverted arch, but the hance is in the compression state.

1. Introduction

The rapid development of economy and engineering technology has drawn attention to the development of underground spaces. Underground structures, such as subways, cross-river tunnels, and undersea tunnels, have gradually increased. In particular, undersea tunnels facilitate travel and promote regional economic development because they can link various islands and lands. Thus, an increasing number of countries pay attention to undersea tunnels.

The seismic resistance of underground structures has increasingly received attention since the Kobe earthquake in 1995. The seismic performance of underground structures can be examined in three ways (Liu and Li, 2006): prototype observation, model test, and numerical simulation. Many scholars have extensively studied the seismic response of underground structures, such as onshore tunnels, through the analytical and numerical methods, but research on the seismic resistance of underwater tunnels seriously lags behind. Liu et al. (2011a,b) analyzed the earthquake response of a large-diameter channel tunnel at high seismic intensity as well as its influence factors using FLAC3D. Zhu and Zhou (1992) studied the response analysis of a channel tunnel at the bottom of a given ground motion according to a finite element model and the solution of the time-domain system. Geng et al. (2007) proposed a seismic design for an underwater shield tunnel (which has a large cross section, high water head, and a complex structure) based on structure features along the cross section and longitudinal direction. Yang et al. (2001) introduced a calculation model for tunnel analysis based on Tokyo Bay tunnel analysis and analyzed the seismic response of the Huangpu River crossing tunnel. Gao et al. (2012) studied the dynamic characteristics and failure mechanism of a river-crossing tunnel using the 3D dynamic finite difference method. Liu et al. (2007) analyzed the dynamic response of a river-crossing shield tunnel under seismic load through 2D dynamic finite element simulation. Han et al. (1999) and Han and Tang (1999) proposed two methods for seismic analysis and design, namely, the time history response and traveling wave methods, according to their examination of the sinking tube tunnel of the Pearl River. Tang and Gong (2007) studied the seismic response of a river-crossing shield tunnel in a soft soil layer through the dynamic calculation model of equivalent linearization based on the dynamic analysis of effective stress. Deng (2006) investigated the seismic response of the lining of the Yangtze River tunnel by developing its 3D model. Li et al. (2010) analyzed the seismic response of an underwater highway tunnel under bidirectional seismic loads using FLAC3D. Okamoto and Tamura (1973) discussed the numerical simulation results of the earthquake response of an underwater tunnel. Taylor et al. (2005) studied the seismic response characteristics of an immersed tube tunnel (i.e., the George Massey Tunnel) according to seismic intensity. Anastasopoulos et al. (2008) examined the nonlinear dynamic response of an immersed tube

* Corresponding author at: School of Civil Engineering, Lanzhou University of Technology, Lanzhou 730050, PR China. Tel.: +86 931 2976063.
E-mail address: chengxuansheng@gmail.com (X. Cheng).

0029-8018/$ - see front matter
http://dx.doi.org/10.1016/j.oceaneng.2013.11.017

tunnel during a strong earthquake. Pilato et al. (2008) investigated the dynamic response of underwater suspended tunnels under seismic action by numerical simulation.

These studies have extensively analyzed the seismic response of underwater tunnels; however, they have the following limitations. (1) These analyses have heavily focused on cross-river tunnels and saturated soft soil foundations. (2) The underwater shield tunnels examined had little cover soil. (3) The mass surrounding the tunnels was mostly saturated moderately or slightly weathered fractured rock. (4) The influence of dynamic water pressure was disregarded. Analyses of the seismic response of undersea tunnels during a bidirectional earthquake reveal high dynamic water pressure on dynamic characteristics when seepage is considered (Chen and Zhang, 2012; Peng et al., 2008). Undersea tunnels have high pore water pressure, which can change effective stress and the mechanical effect of the rock mass. Thus, the seepage effect on dynamic characteristics of undersea tunnels should be accounted for. This study defines the mass surrounding the tunnel as a saturated porous medium and considers the viscoelastic artificial boundary, seepage, and influence of the dynamic water pressure. A fluid–structure interaction (FSI) model of an undersea tunnel is created through finite element analysis software ADINA. With horizontal and vertical earthquake ground motion considered, the seismic response of the undersea tunnel during a bidirectional earthquake is determined by analyzing the time history curve of the displacement, acceleration, and principal stress of the lining structure key point. The results of this analysis provide a reference for the anti-seismic design and construction of undersea tunnels.

2. FSI dynamic analysis

2.1. Dynamic analysis equation

Biot's dynamic consolidation theory (Xie and Zou, 2002) holds that, with the compressibility of the pore fluid disregarded, the equation for saturated pore fluid continuity is as follows:

$$\frac{\partial \varepsilon_{ii}}{\partial t}+\frac{1}{\gamma_f}\nabla^T(-\boldsymbol{K}(\nabla P))=0, \tag{1}$$

where ∇ is the Laplace operator, $\boldsymbol{K}$ is the permeability coefficient matrix of the rock or soil mass, ε_{ii} is the volume strain of the rock or soil skeleton, P is the pore water pressure, t is the consolidation time, and γ_f is the unit weight of the pore fluid.

When the pore fluid relative to the acceleration effect of the rock or soil mass skeleton and the geotechnical compressibility are ignored, the dynamic equilibrium equation of the saturated rock or soil mass is as follows:

$$\sigma'_{ij,j}+p_{,j}\delta_{ij}+\rho b_i=\rho\ddot{u}_i \quad (i,j=1,2,3), \tag{2}$$

Where $\sigma'_{ij,j}$ is the effective stress, δ_{ij} is the Kronecker sign, ρ is the density of the rock mass or soil mass, b_i is the volume force acceleration, $p_{,j}$ is the pore water pressure, and $\ddot{u}_i$ is the acceleration of the rock or soil mass skeleton.

Elastic dynamics theory suggests that the dynamic control equation of the lining structure of a subsea tunnel is as follows:

$$\sigma_{pij,j}+\rho_p b_{pi}=\rho_p\ddot{u}_{pi} \quad (i,j=1,2,3), \tag{3}$$

where σ_{pij} is the lining structure's internal stress, ρ_p is its mass density, b_{pi} is its volume force acceleration, and $\ddot{u}_{pi}$ is its acceleration.

2.2. Dynamic finite element equation and numerical solution of saturated rock or soil mass and lining structure of subsea tunnel

2.2.1. FSI dynamic finite element equation of saturated rock or soil mass

The Galerkin method (Wang and Dong, 2003) is used in the analysis. Finite element discretization of Eqs. (1) and (2) yields the FSI dynamic finite element equation of saturated rock or soil mass:

$$\begin{bmatrix} {}^{t+\Delta t}\boldsymbol{M} & 0 \\ 0 & 0 \end{bmatrix}\begin{Bmatrix} {}^{t+\Delta t}\ddot{\boldsymbol{U}} \\ {}^{t+\Delta t}\ddot{\boldsymbol{p}}_f \end{Bmatrix}+\begin{bmatrix} {}^{t+\Delta t}\boldsymbol{C} & 0 \\ {}^{t+\Delta t}\boldsymbol{K}^T_{up_f} & 0 \end{bmatrix}\begin{Bmatrix} {}^{t+\Delta t}\dot{\boldsymbol{U}} \\ {}^{t+\Delta t}\dot{\boldsymbol{p}}_f \end{Bmatrix}+\begin{bmatrix} {}^{t+\Delta t}\boldsymbol{K}_{uu} & {}^{t+\Delta t}\boldsymbol{K}_{up_f} \\ 0 & -{}^{t+\Delta t}\boldsymbol{K}_{p_fp_f} \end{bmatrix}\begin{Bmatrix} {}^{t+\Delta t}\boldsymbol{U} \\ {}^{t+\Delta t}\boldsymbol{p}_f \end{Bmatrix}=\begin{Bmatrix} {}^{t+\Delta t}\boldsymbol{R}_u \\ {}^{t+\Delta t}\boldsymbol{R}_{p_f} \end{Bmatrix}, \tag{4}$$

where

$${}^{t+\Delta t}\boldsymbol{K}_{uu}=\sum_m\int_{{}^{t+\Delta t}v_{(m)}}{}^{t+\Delta t}\boldsymbol{B}_u^{(m)^T}\cdot{}^{t+\Delta t}\boldsymbol{D}^{(m)}\cdot{}^{t+\Delta t}\boldsymbol{B}_u^{(m)}\cdot d^{t+\Delta t}v^{(m)}, \tag{5a}$$

$${}^{t+\Delta t}\boldsymbol{K}_{up_f}=\sum_m\int_{{}^{t+\Delta t}v_{(m)}}{}^{t+\Delta t}\boldsymbol{B}_u^{(m)^T}\cdot\boldsymbol{I}^{(m)}\cdot{}^{t+\Delta t}\boldsymbol{H}_{p_f}^{(m)}\cdot d^{t+\Delta t}v^{(m)}, \tag{5b}$$

$${}^{t+\Delta t}\boldsymbol{K}_{p_fp_f}=\frac{1}{\gamma_f}\sum_m\int_{{}^{t+\Delta t}v_{(m)}}{}^{t+\Delta t}\boldsymbol{B}_{p_f}^{(m)^T}\cdot{}^{t+\Delta t}\boldsymbol{K}_{(m)}\cdot{}^{t+\Delta t}\boldsymbol{B}_{p_f}^{(m)}\cdot d^{t+\Delta t}v^{(m)}, \tag{5c}$$

$${}^{t+\Delta t}\boldsymbol{R}_{p_f}=\sum_m\int_{{}^{t+\Delta t}s_q^{(m)}}({}^{t+\Delta t}\boldsymbol{H}_{p_f}^{{}^{t+\Delta t}s_q^{(m)}(m)})^T\cdot{}^{t+\Delta t}\boldsymbol{q}^{(m)}\cdot d^{t+\Delta t}s_q^{(m)}, \tag{5d}$$

$${}^{t+\Delta t}\boldsymbol{R}_u=\sum_m\int_{{}^{t+\Delta t}v_{(m)}}{}^{t+\Delta t}\boldsymbol{H}_u^{(m)^T}\cdot{}^{t+\Delta t}\boldsymbol{f}_{(m)}\cdot d^{t+\Delta t}v^{(m)}+\sum_m\int_{{}^{t+\Delta t}s_f^{(m)}}({}^{t+\Delta t}\boldsymbol{H}_u^{{}^{t+\Delta t}s_f^{(m)}(m))^T}\cdot{}^{t+\Delta t}\boldsymbol{f}_{(m)}\cdot d^{t+\Delta t}s_f^{(m)}, \tag{5e}$$

where $\boldsymbol{U}$ and $\boldsymbol{P}_f$ are the geotechnical nodal displacement and pore water pressure vectors, respectively; $\boldsymbol{M}$ and $\boldsymbol{C}$ are the rock or soil mass and damping matrices, respectively; $\boldsymbol{D}$ is the geotechnical flexibility coefficient matrix; $\boldsymbol{f}$ and $\boldsymbol{q}$ are the load vectors; $\boldsymbol{B}_u$ and $\boldsymbol{B}_{pf}$ are the nodal displacement and pore water pressure, respectively, of the rock/soil mass geometry gradient matrix; $\boldsymbol{H}_u$ and $\boldsymbol{H}_{pf}$ are the interpolation function matrices of the nodal displacement and pore water pressure, respectively, of the rock or soil mass; $\boldsymbol{I}$ is the unit matrix; m is the number of the micro element; s_q is the area of the soil micro element and s_f is the area of he fluid micro element.

2.2.2. Dynamic finite element equation of tunnel lining structure

The Galerkin method is also used in this analysis. Finite element discretization of Eq. (3) yields the dynamic finite element equation of the tunnel lining structure:

$${}^{t+\Delta t}\boldsymbol{M}_p\cdot{}^{t+\Delta t}\ddot{\boldsymbol{U}}_p+{}^{t+\Delta t}\boldsymbol{C}_p\cdot{}^{t+\Delta t}\dot{\boldsymbol{U}}_p+{}^{t+\Delta t}\boldsymbol{K}_{uup}\cdot{}^{t+\Delta t}\boldsymbol{U}_p={}^{t+\Delta t}\boldsymbol{R}_{up}, \tag{6}$$

where

$${}^{t+\Delta t}\boldsymbol{K}_{uup}=\sum_m\int_{{}^{t+\Delta t}v_p^{(m)}}{}^{t+\Delta t}\boldsymbol{B}_{up}^{(m)^T}\cdot{}^{t+\Delta t}\boldsymbol{D}_p^{(m)}\cdot{}^{t+\Delta t}\boldsymbol{B}_{up}^{(m)}\cdot d^{t+\Delta t}v_p^{(m)}, \tag{7a}$$

$${}^{t+\Delta t}\boldsymbol{R}_{up}=\sum_m\int_{{}^{t+\Delta t}v_p^{(m)}}{}^{t+\Delta t}\boldsymbol{H}_{up}^{(m)^T}\cdot{}^{t+\Delta t}\boldsymbol{f}_p^{(m)}\cdot d^{t+\Delta t}v_p^{(m)}+\sum_m\int_{{}^{t+\Delta t}s_{f_p}^{(m)}}({}^{t+\Delta t}\boldsymbol{H}_{up}^{{}^{t+\Delta t}s_{f_p}^{(m)}(m)})^T\cdot{}^{t+\Delta t}\boldsymbol{f}_p^{(m)}\cdot d^{t+\Delta t}s_{f_p}^{(m)}, \tag{7b}$$