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Numerical simulation of shaking table test on utility tunnel under non-uniform earthquake excitation

Jun Chen [a,b], Luzhen Jiang [c], Jie Li [b,*], Xiaojun Shi [b]

[a] Institute for Advanced Study in Civil Engineering, Tongji University, PR China
[b] State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, PR China
[c] School of Civil Engineering, Hebei University of Science and Technology, Shi Jiazhuang, PR China

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ABSTRACT

This paper studies numerical simulation of shaking table test on utility tunnel model subjected to non-uniform earthquake excitation. The experimental work is first introduced with focuses on experimental strategy, structural model and soil, instrumentation and test cases. Followed are numerical modeling details of the shaking table tests, including modeling of shear box, soil–structure interaction and initial stress equilibrium. Numerical results are presented and compared with experimental records in terms of boundary effect of the shear box, soil and structure model acceleration response, soil displacement and structural strain responses. It is found that the utility tunnel has a bending deformation and its acceleration response is larger than the surrounding soil for high shaking intensity. The proposed numerical model is found to be satisfactory in predicting many details of the experimental results. The modeling methodology suggested in this paper is reasonable for representing the shaking table test and it can be used for further analysis.

1. Introduction

A utility tunnel is a kind of underground structure that accommodates various utilities as water, sewerage, gas, electrical power, telephone and heat supply, and also provides enough head-room to allow maintenance personnel to walk through and to perform maintenance tasks. The utility tunnels are linear and cut-and-cover structures whose cross sections are typically smaller than the traffic tunnel and larger than buried underground pipelines. The adoption of utility tunnel for construction and maintenance of underground utility pipelines has many advantages against the traditional digging-up manner, such as exempting streets from frequency traffic-blocking and providing easy access for maintenance and improvement. Therefore, utility tunnels have been widely constructed throughout the world after it first appeared in Paris in 1851.

The safety and reliability of utility tunnels is of great importance for modern city since they contain pipelines of city's lifeline system. Experiences from major earthquakes have shown that cut-and-cover tunnels are more vulnerable to earthquake damage than circular bored tunnels (Hashash and Hook, 2001). In 1995 Hyogoken–Nambu earthquake, for instance, different types of damages, such as longitudinal and transverse cracks, spalling of concrete and movement of tunnel joints, were observed on almost all the utility tunnels in the adjacent areas affected by the earthquake (JSCE, 1999; PWRI, 2001). Observations from major earthquake events have pointed out several reasons for causing severe damage to underground structures: slop instability, soil liquefaction, fault displacement and earthquake wave propagation (Hashash and Hook, 2001). On the other hand, shaking table tests have been carried out by many researchers to investigate the performance of underground structure and to check current design/analysis methods. Ohtomo et al. (1973) conducted shaking table tests on 1:250 submerged tunnels model. Silicone rubber and gelatin gel material were used in the experiment for the tunnel model and the soil. The dimension of the soil container is 2.2 m by 1.0 m. Ohtomo et al. (2001, 2003) carried out shaking table experiments on a large tunnel model (3.0 m × 1.75 m × 0.97 m, scale ratio 1/3–1/4) to learn the soil–structure-interaction (SSI) based on the assumption of two-dimensional plane strain problem. A small sampling of some recent similar experimental research works includes Yang et al. (2003), Prasad et al. (2004), Huang et al. (2006), Shi et al. (2007, 2009), and Luzhen et al. (2010). All these research works have expanded our knowledge on performance of underground structures under earthquake attack.

All the above mentioned experiments were performed on single shake table. Therefore only uniform earthquake excitation was simulated in the test. The spatial distribution of ground motion is

* Corresponding author at: State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, PR China. Tel.: +86 21 6598 3526; fax: +86 21 6598 6345.

E-mail addresses: cejchen@tongji.edu.cn (J. Chen), jiangluzhen@163.com (L. Jiang), lijie@tongji.edu.cn (J. Li), sxj149@163.com (X. Shi).

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Fig. 1. Photo of the prototype utility tunnel.

Fig. 2. 1:8 Scaled test model.

Table 1
Material parameter of soil and structure.

	Density (kg/m^3)	Elastic modulus (Mpa)	Poisson's ratio	Inner friction angle (°)	Cohesion (kPa)	Dilation angle (°)
Soil	1800	16.5	0.4	27.9	24.4	0
Structure	2400	33,000	0.20	–	–	–

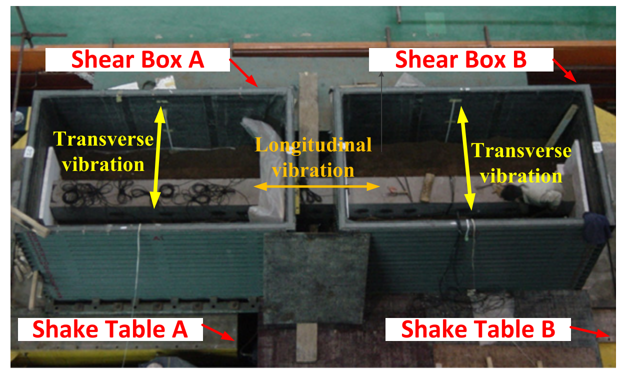

Fig. 3. Installation of the utility model on the shake tables.

considered as one of the main factors for causing damage to shallow buried tunnels (Hashash and Hook, 2001; Chouw and Hao, 2005, 2008). However, shaking table test on tunnel model using non-uniform earthquake excitation is very rare. The following two reasons are identified: (1) lack of test facility in the past; (2) with current available test facility as shaking tables array, it is still not an easy task to simulate the continuously changing earthquake wave acted along the tunnel. Consequently, few experimental results or numerical simulations were available in literature on performance of utility tunnel under non-uniform earthquake wave excitation. In view of this, we had designed and conducted a series of shaking table tests on a scaled utility tunnel model. Technical details of the test including test facility, experimental setup, soil and structural model, design and fabrication of the soil container and simulations of non-uniform earthquake excitation have already been presented in Chen et al. (2010). In this paper we further establish finite element model of the whole box–soil–tunnel system in order to simulate the shaking table test. The experimental results are used as a basis for verifying the numerical model. After a brief introduction of the shaking table test, numerical modeling details are presented and the numerical results as structural and model acceleration responses, structural strain responses and soil pressure are calculated and compared with the experimental records.

2. Overview of the shaking table tests

Main features of the shaking table test are outlined in this section for completeness and comparison purpose. In the test, a structural model was built after an existing utility tunnel with the geometrical scale of 1:8 (see Figs. 1 and 2). Unsaturated clay soil was adopted and placed in two soil containers which were in turn fixed on two shake tables (Fig. 3). Material properties of the tunnel model and the model ground were tested before the shaking table experiments, and the results are summarized in Table 1. The non-uniform earthquake was simulated in the experiment by applying two different input waves to two different shake tables, namely Tables A and B as demonstrated in Fig. 3. As can be seen from Fig. 3, two shear boxes were used in the test. The two boxes were of identical dimensions and each comprised sixteen steel frames that were stacked on each other. Each frame was made of rectangular