Numerical study on effectiveness of continuum model box used in shaking table test under non-uniform excitation

† Zhiyi Chen[1], *Sunbin Liang[1]

[1]Department of Geotechnical Engineering, Tongji University, China.

*Presenting author: 550507206@qq.com

† Corresponding author: zhiyichen@tongji.edu.cn

Abstract

Unlike superstructure, it is necessary to bury underground structure model into model soil carried by a continuum model box, when conducting shaking table test under non-uniform excitation. The problem, how to transmit dynamic effectively between different shaking tables is need to be solved firstly. The present paper is devoted to study the effectiveness of continuum model box using when conducting non-uniform excitation shaking table test. A full-scale 3D entity finite element model of soil and model boxes is simulated. In order to avoid the randomness of calculation result, three conventional coherency models are adopted to synthetize non-uniform ground motions respectively. In order to evaluate the effectiveness of continuum model box, the calculation results, including time history and frequency spectrum of soil acceleration responses, are contrasted with those of 2D free field analysis. The calculation results show that the distribution of peak acceleration response of soil cased in the continuum model box is almost the same as that of 2D free field analysis. The Fourier Amplitudes of the surface acceleration responses of soil state that the frequency spectrum components of soil acceleration response have little difference between 3D dynamic analysis and 2D free field analysis. Thus, it is rational to adopt continuum model box with rigid connection to conduct shaking table test of underground structure under non-uniform excitation.

Keywords: Effectiveness; Continuum model box; Shaking table test; Non-uniform excitation.

1. Introduction

Observations from earthquake strong-motion arrays show notable differences among the records of ground motions at different locations within the dimensions of typical extended structures [1]. That is called spatially varying ground motions, which is caused by the wave passage effect, the incoherence effect and the site-response effect [2]. Unlike the small-scale structure, it is necessary to conduct non-uniform excitation analysis for extended structures, such as tunnels, bridges and pipelines, since spatially varying ground motions may have significant influence on seismic response.

In the last few decades, researches on seismic responses of tunnel induced by non-uniform excitations are mainly limited to numerical analysis. Hashash et al. [3] and Anastasopoulos et al. [4] performed 3-D dynamic analysis to study seismic responses of the San Francisco bay tunnel and Greece Rion-Antirrion strait tunnel under spatially varying ground motions, respectively. A consistent conclusion stated that spatially varying ground motions increased the seismic responses of the immersed tunnels significantly. Park et al. [5] conducted pseudo-static 3-D finite element analysis to investigate seismic responses of a tunnel under non-uniform excitations. Yu et al. [6] proposed a multi-scale method to simulate a water delivery tunnel constructed by shield method and studied the influence of wave passage effect on seismic responses. Li and Song [7] developed a 3-D finite element model in time domain to provide feasible computational modeling technique for the tunnels under asynchronous excitations. However, few experimental investigations are conducted to study the seismic responses of tunnels under non-uniform excitations.

Experimental method plays an important role in geotechnical engineering researches. It provided a realistic way to test and verify the results derived from theoretical analyses, and potentially to identify novel phenomena that are inaccessible by theoretical analysis alone. In recent years, centrifuge and shaking table tests are conducted to study the seismic performance and reveal failure mechanism of underground structure [8]-[10]. Since centrifuge test can reproduce the in situ stress state of soil, it is commonly believed that the is an attractive way to study seismic performance of underground structure [11]. However, shaking table test is precise in seismic loading, control and observation [12]. Moreover, shaking table array provides a feasible way to study the dynamic response of the extended underground structure, like tunnel, under non-uniform excitations. Unlike superstructure, it is necessary to bury underground structure model into model soil carried by a continuum model box, when conducting shaking table test under non-uniform excitation. Extremely limited shaking table test of underground structure under non-uniform excitations has been conducted. Chen et al. [13] performed a shaking table test of utility tunnel to study the effect of non-uniform earthquake wave excitations. However, two separating model boxes were adopted, and it ignored the continuum of soil. It is believed that this ignorance affects the evaluations of seismic performance since the deformation of the surrounding soil rather than structural dynamic characteristic is the control factor of response of underground structure. Thus, in order to represent the reality of dynamic response of line-like underground structure as far as possible, some efforts should devoted to develop a continuum model box before conducting non-uniform shaking table tests. Therefore, the problem, verifying the effectiveness of continuum model box connecting different shaking tables, is need to be solved.

Aiming this goal, a full-scale 3D entity finite element model of soil and model box is simulated to verify the effectiveness of continuum model box in this paper. To avoid the randomness of calculation results, three conventional coherency models are adopted to synthetize non-uniform ground motions as input excitations, respectively. The conclusions of the presented paper could be valuable to the non-uniform excitation shaking table test of underground structure.

2. Numerical modeling of shaking table tests

The prototype shake table array is consisting of two Quanser Company shake tables, named Shake Table Π, at the Structural Engineering Laboratory in Tongji University. As shown in Fig.1, the dimension of each table stage is 46cm × 46cm in plane. The maximum acceleration is 2.5g with the maximum payload 7.5kg. The frequency of the input ground motion covers the range 0.1–20 Hz. Finite element model of the soil-continuum box system is established in this section based on the prototype shake table array.

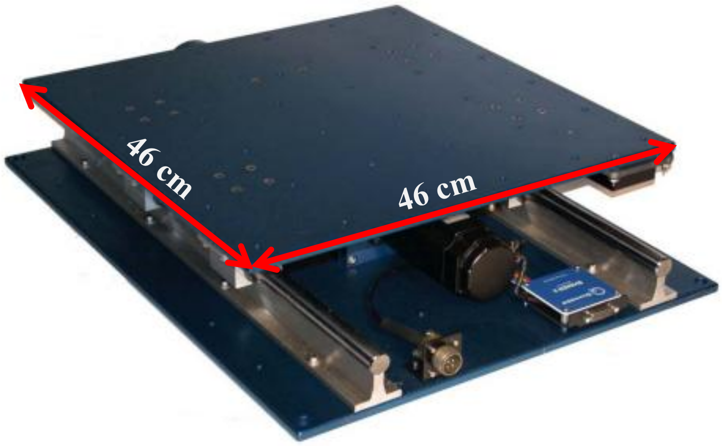

Fig. 1. Prototype of Shake Table Π

In the presented paper, dynamic time-history analyses are carried out using the general-purpose commercial ABAQUS software [14]. Element C3D8R is adopted to simulate model soil, and the soil density, elastic modulus and Possion's ratio are set as 700kg/m^3, 4.89MPa and 0.35, respectively. Mohr-Coulomb model and Rayleigh damping are used to take the plasticity and nonlinear dynamical characteristics into account. The detailed information of soil is listed in Table 1.

Table 1. Properties of the soil

Description	Parameter	Value
Density	ρ(kg/m^3)	700
Elastic modulus	E(MPa)	2000
Possion's ratio	υ	0.35
Friction angle	φ(°)	33
Cohesion	c(kPa)	10.6
Rayleigh damping	α	0.288043
	β	0.045054

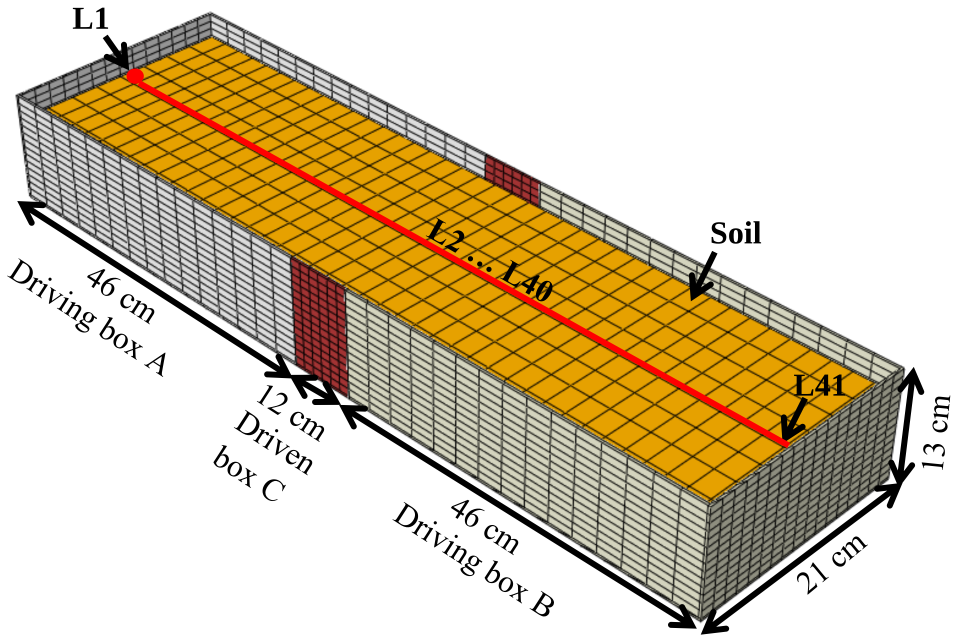

Fig. 2. 3D finite element model of the whole soil-continuum box system

Fig. 2 illustrates the finite element model of the whole soil-continuum box system. There are two driving model box, consisting of driving box A and box B that are fixed on two shaking tables and a driven model box. The model box will be fabricated by organic glass in the future physical shaking table test, which is a homogeneous material with a stable mechanical property. Element C3D8R is also employed to simulate model box. The density, elastic modulus and Possion's ratio of model box are set as 1120kg/m^3, 3150MPa and 0.3, respectively. As shown in Fig. 2, the whole continuum box is with the length of 104cm, consisting of two driving model box (box A and B) are both with the length of 46cm and a driven model box (box C) is with the length of 12cm. Since the materials of driving and driven boxes are the same, the model box with the length of 104cm is established as one whole. The transverse dimension of the model box is 21cm (width) × 13 cm (height). The thickness of model box is 3mm. Due to capability limitation of the prototype shaking table, the height of soil cased in the model box, which is denoted as *H*, is set as 9cm. The surface interaction of the soil and the sidewalls of the model box are all set as Finite Slip with the friction and the slip tolerance factors of 0.2 and 0.005, respectively. Tie Constraint is adopted to simulate the surface interaction of the soil and the bottom of the model box.

3 Analysis process and calculation cases

3.1 Analysis process

To verify the effectiveness of continuum model box used in shaking table test under non-uniform excitation, the following analysis process is used.

1. As stated above, a full-scale 3D entity finite element model of soil and model boxes is established. Three conventional coherency models are adopted to synthetize non-uniform ground motions as input excitations to avoid the randomness of calculation results.
2. In order to evaluate the validity of the above-mentioned 3D dynamic analysis, 2D free field analysis, as a reference standard, is performed under three different non-uniform excitations. The finite element model of 2D free field analysis is depicted in Fig. 3. There are three parts of the free field with the length of 46, 12 and 46cm, which are corresponding to the soil cased in boxes A, B and C in 3D dynamic analysis. The infinite element is adopted in two sides of the free field model to consider the boundary effect. Element CPE4R is used to simulate the soil with density, elastic modulus and Possion's ratio of 700kg/m^3, 4.89MPa and 0.35, respectively. Same as 3D dynamic analysis, Mohr-Coulomb model and Rayleigh damping are used to consider the plasticity and nonlinear dynamical characteristics. As shown in Table 1, the soil characteristics are the same as 3D dynamic analysis.
3. After the aforementioned two steps, the soil acceleration responses in longitudinal direction, which emphasize the peak values and the Fourier Spectrum, of 3D dynamic analysis and 2D free field analysis are compared to each other. There are some conclusions drawn from the calculation results.

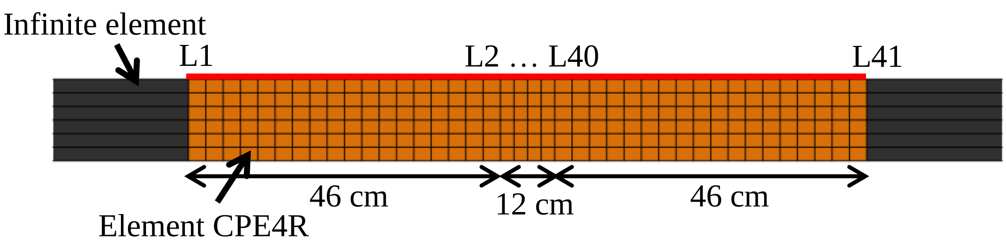

Fig. 3. 2D finite element model of free field analysis

3.2 Calculation cases

In the presented paper, the effectiveness of continuum model box is studied by full-scale 3D dynamic analysis. 2D free field analysis is conducted as a reference standard. In order to avoid the randomness of calculation results, three conventional coherency models are used to synthetize non-uniform ground motions as input excitations, respectively. The selected coherency models are described as following.

1) Hindy and Novak coherency model: When conducting a stochastic analysis of the pipeline, Hindy and Novak [15] firstly introduced the coherency model into earthquake engineering to describe the spatial variation of the ground motion. Based on wind engineering, the expression is relatively simple with only two parameters, that is:

$$|\gamma(\omega,d)| = exp\left(-\alpha(\omega d)^{\beta}\right) \tag{1}$$

Where, ω and d are the angular frequency and distance respectively; and the model parameters are $\alpha=3.007\times10^{-4}$, $\beta=0.9$. H-N model is depicted in Fig. 4(a).

2) Harichandran and Vanmarcke coherency model: Basing on the study of four events recorded by SMART-1 array in Taiwan, Harichandran and Vanmarcke [16] proposed an empirical coherency model, which has been widely applied. The expression of this coherency model is shown as follows:

$$\left|\gamma(\omega,d)\right| = A\exp\left[-\frac{2d}{\alpha\theta(\omega)}(1-A+\alpha A)\right]+(1-A)\exp\left[-\frac{2d}{\theta(\omega)}(1-A+\alpha A)\right] \tag{2}$$

Where, $\theta(\omega)=k[1+(\omega+\omega_o)^b]^{-0.5}$; basing on Event 20 recorded by the SMART-1 array, the model parameters are $A=0.636$, $\alpha=0.0186$, $k=31{,}200$ m, $\omega_o=9.49$ rad/s, $b=2.95$ [17]. H-V model is shown in Fig. 4(b).

3) Qu-Wang-Wang coherency model: From the standpoint of coherency model in engineering application, Qu et al. [18] referenced to the method of determining the design response spectrum in seismic code, averaged the collected coherence value of the empirical coherency model for several earthquakes, and proposed a coherency model. It is beneficial for practical application to put forward a mean coherency model referencing the determination of design response spectrum. The function is shown as:

$$\left|\gamma(\omega,d)\right| = \exp\left[-a(\omega)d^{b(\omega)}\right] \tag{3}$$

Where, $a(\omega)=a_1\omega^2+a_2$; $b(\omega)=b_1\omega+b_2$; the parameters are $a_1=0.00001678$, $a_2=0.001219$, $b_1=-0.0055$ and $b_2=0.7674$. Q-W-W model is depicted in Fig. 4(c).

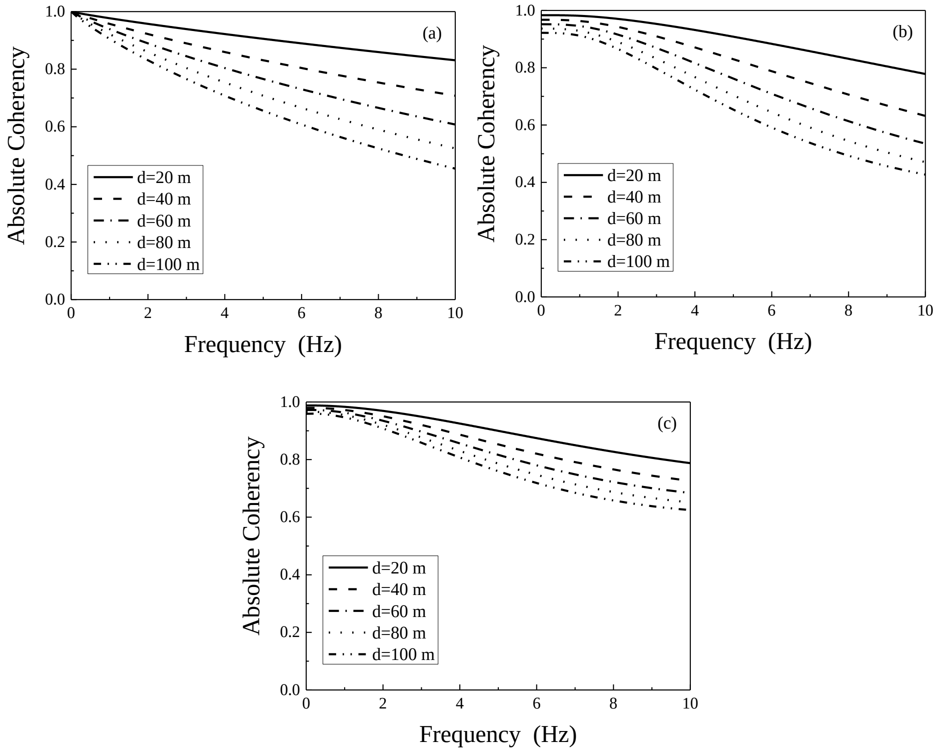

Fig. 4. Coherency Models: (a) H-N; (b) H-V; (c) Q-W-W

As shown in Table 2, there are four test cases for both 3D dynamic analysis and 2D free field analysis, which are consisted of uniform excitation (Case 1) and three cases for three models, including Case 2 is of H-N model, Case 3 is of H-V model and Case 4 is of Q-W-W model, respectively. Fig. 5 depicts the time histories of the synthetic ground motions. The peak ground motion is 0.1g. In this paper, trigonometric series simulation algorithm put forward by Hao [19] to simulate multi-support ground motion time histories are adopted. The power spectrum model $S(\omega)$ (Eq. (4)) proposed by Clough and Penzien [20] is adopted to simulate ground motions. The expression of this model is shown as:

$$S\left(\omega\right)=\frac{\omega_g^4+4\xi_g^2\omega_g^2\omega^2}{\left(\omega_g^2-\omega^2\right)^2+4\xi_g^2\omega_g^2\omega^2}\bullet\frac{\omega^4}{\left(\omega_f^2-\omega^2\right)^2+4\xi_f^2\omega_f^2\omega^2}S_0 \tag{4}$$

Where, S_0 is spectral intensity factor; ω is the angular frequency; ω_g and ξ_g are the resonant frequency and damping ratio of the first filter, which are relative to the site condition; ω_f and ξ_f are those of the second filter. The filter parameters corresponding to this soil type of Clough and Penzien power spectrum model are determined: S_0=0.0123347; ω_g= 9.67; ξ_g=0.9; ω_f=1.934; ξ_f=0.9. To consider the non-stationary of ground motion, the envelope function adopted in this paper was proposed by Amin and Ang [21], and its expression shown as following:

$$f(t)=\begin{cases}(t/t_1)^2, 0\le t\le t_1;\\ 1, t_1<t\le t_2;\\ exp\left[-c(t-t_2)\right], t>t_2\end{cases} \tag{5}$$

Where, c is the attenuation coefficient; t_1 and t_2 are the beginning and the ending moment of the stationary vibration stage, respectively. The parameters in Eq. (5) can be obtained as c=0.15, t_1=1.6s, t_2=12s.

Table 2. Detailed information of numerical analysis cases

Case name	Type of excitation	Coherency model
Case 1	Uniform	—
Case 2	Incoherent	Hindy and Novak coherency model
Case 3	Incoherent	Harichandran and Vanmarcke coherency model
Case 4	Incoherent	Qu-Wang-Wang coherency model

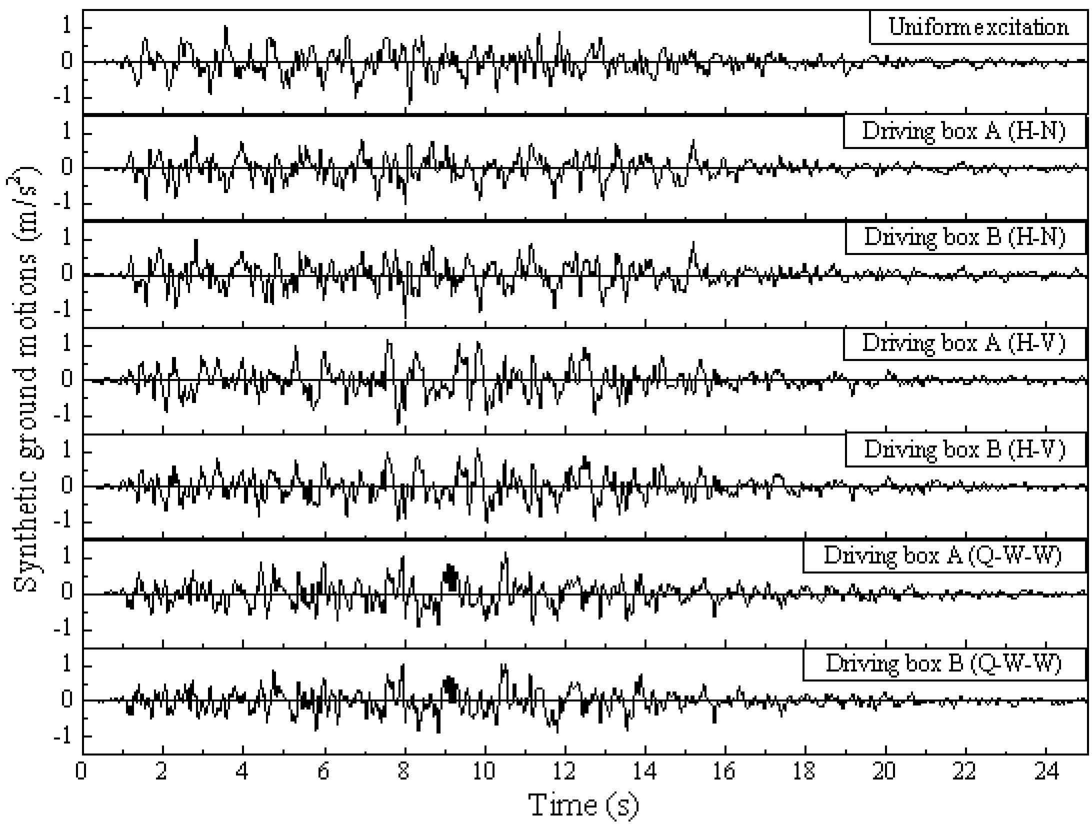

Fig. 5. Time histories of the synthetic ground motions

4 Numerical analysis results and discussions

Fig. 6 depicts the profile of longitudinal distribution of the peak acceleration response of soil on ground surface. Peak acceleration responses of points L1-L41, whose locations are shown in Fig. 2, are selected to study. Non-uniform excitation causes differentia of acceleration response of soil among different locations in longitudinal direction. As shown in Fig. 6, the peak acceleration responses of soil are almost the same under uniform excitation (Case 1), while the profiles of distribution of the peak acceleration response of soil are asymmetric under non-uniform excitation (Case 2, Case 3 and Case 4).

No matter under uniform excitation or non-uniform excitation, the profile of distribution of the peak acceleration response of soil of 3D dynamic analysis basically overlap that of 2D free field analysis, which the soil is cased in the continuum model box. It illustrates that a continuum model box has almost no influence on the acceleration response of soil in longitudinal direction. The effectiveness of continuum model box used in shaking table test under non-uniform excitation is verified. More results and discussions are shown from different aspects to verify the effectiveness of continuum model box in the following.

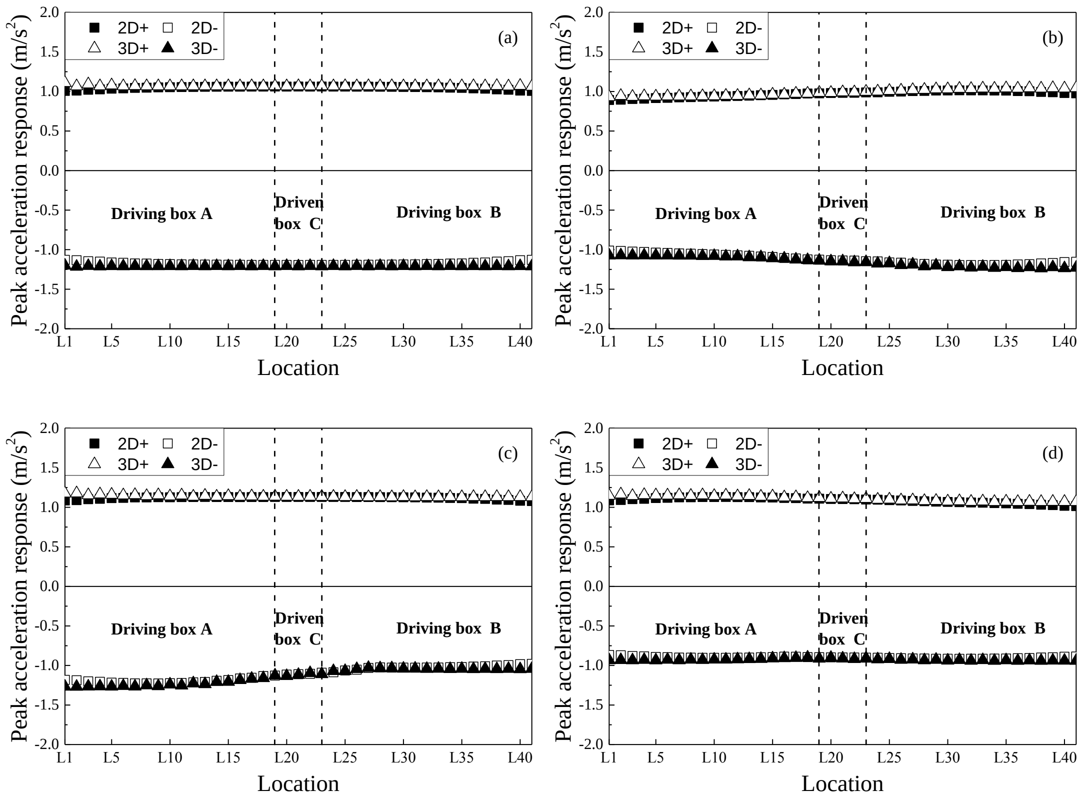

Fig. 6. Profile of longitudinal distribution of the peak acceleration response of soil: (a) Case 1; (b) Case 2; (c) Case 3; (d) Case 4

Fig. 7 shows the profile of vertical distribution of the peak acceleration response of soil. It should be noted that the peak acceleration response is normalized to the peak value of the input ground motion. Totally seven equidistant locations in vertical above each the middle point of the driving box A, driven box C and driving box B are selected to studied. In Fig. 7, H represents the height of the soil cased in the continuum model box as stated before. There is an amplification effect of soil acceleration response. The maximum amplification factor is

1.03, which means there is 3% larger than the peak value of the input ground motion, since the height of the soil is too small of only 9cm.

Like in longitudinal direction, the profile of vertical distribution of the peak acceleration response of soil of 3D dynamic analysis is almost consistent with that of 2D free field analysis, especially for driven box C. Although it seems there exists great difference between the calculation results of 3D and 2D analysis in driving model box A (Fig. 7(c)), the greatest differential is less than 3% actually. Thus, it states that continuum model box has limited influence on the acceleration response of soil in vertical direction, and the effectiveness of continuum model box is also verified.

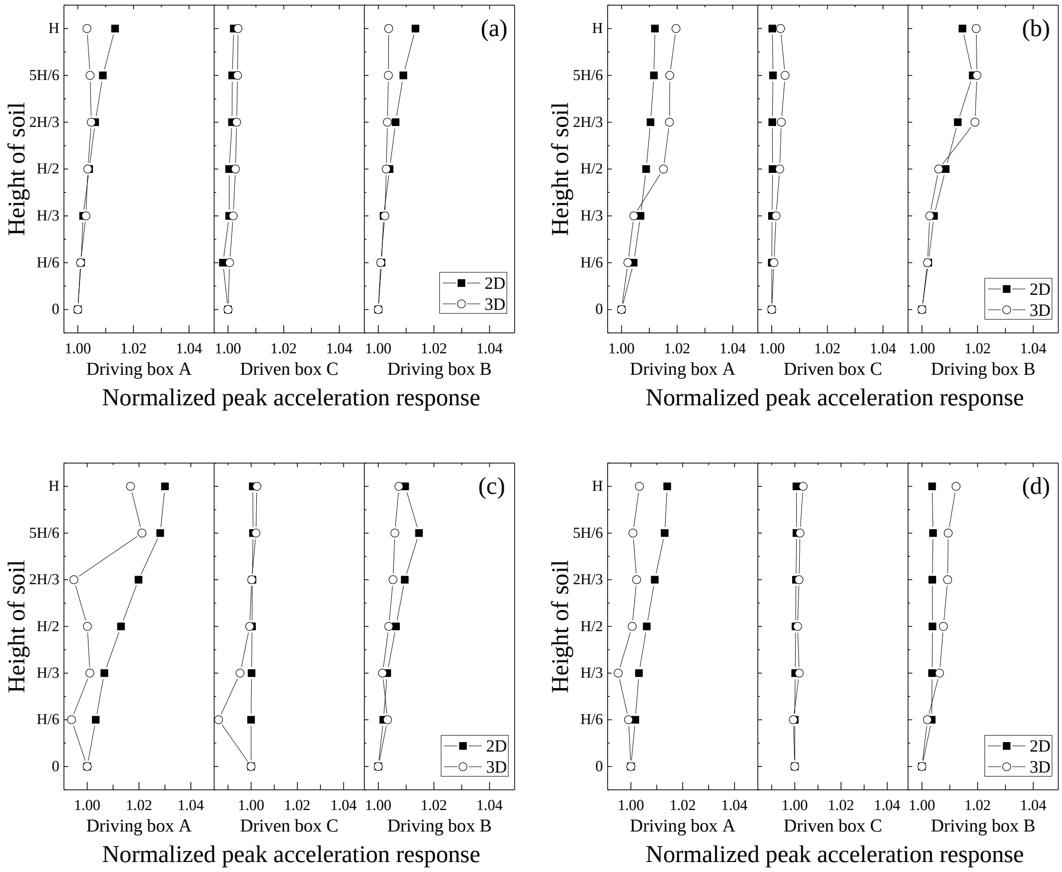

Fig. 7. Profile of vertical distribution of the peak acceleration response of soil: (a) Case 1; (b) Case 2; (c) Case 3; (d) Case 4

Fourier Spectrum is used to study the differential of frequency contents of soil acceleration response between 3D dynamic analysis with continuum model box and 2D free field analysis. Due to space limitation, only the Fourier Spectrum of surface soil acceleration responses above the middle point of driving box A, driven box C and driving box B under Case 1 (uniform excitation) and Case 2 (non-uniform excitation) are depicted in this presented paper. Fig. 8 and Fig. 9 show the Fourier Spectrum of soil acceleration responses under Case 1 and Case 2, respectively. Under uniform excitation, the frequency contents of soil acceleration response in different locations are identical along the longitudinal direction (Fig. 8). There are some differences among the frequency contents of soil acceleration response in different locations due to non-uniform excitation (Fig. 9). For example, the predominant frequencies of soil acceleration responses of driving box A and driving box B are 1.56 and 0.73Hz, respectively.

Under both uniform excitation and non-uniform excitation Cases, the frequency contents of soil acceleration response of 3D dynamic analysis with continuum model box are basically identical with that of 2D free field analysis. It means continuum model box has little influence on the frequency contents of soil acceleration response. The effectiveness of continuum model box is demonstrated.

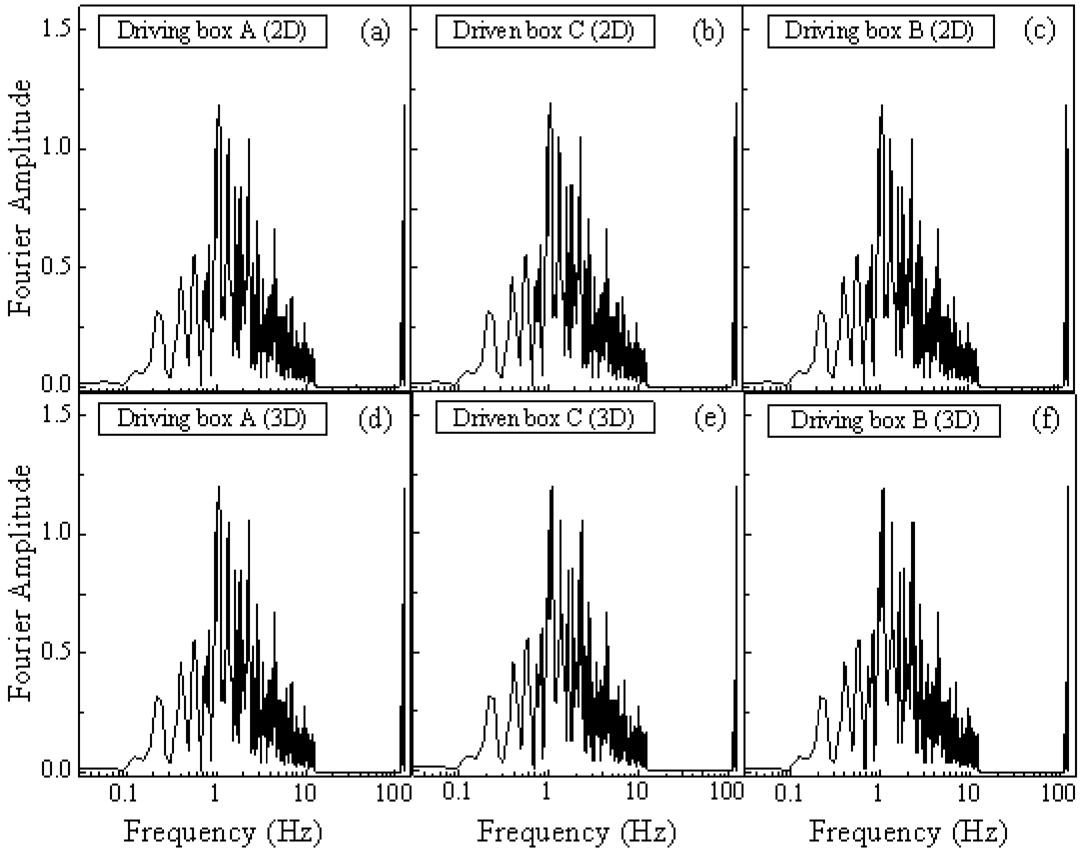

Fig. 8. Fourier Spectrum of soil acceleration response under uniform excitation (Case 1)

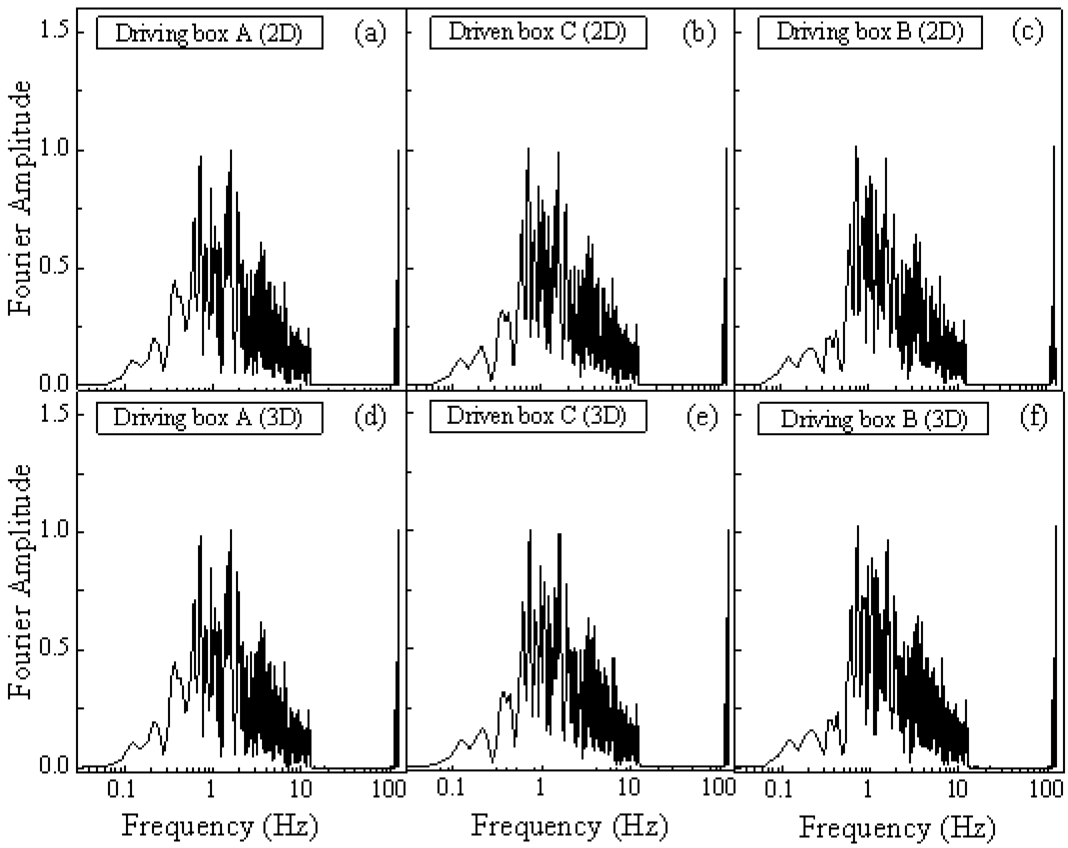

Fig. 9. Fourier Spectrum of soil acceleration response under non-uniform excitation (Case 2)

5 Conclusion

The goal of this presented paper is to verify the effectiveness of continuum model box connecting different shaking tables. A full-scale 3D entity finite element model of soil and model box is simulated to study, and 2D free field analysis is conducted as a reference standard. To avoid the randomness of calculation results, three conventional coherency models are adopted to synthetize non-uniform ground motions as input excitations, respectively. The calculation results, including the distributions of peak acceleration response in longitudinal and vertical direction and Fourier Spectrum of soil acceleration response, show that continuum model box has very limited influence on soil acceleration responses. The effectiveness of continuum model box connecting different shaking tables is verified. In the end, the conclusion of the presented paper could be valuable to the non-uniform excitation shaking table test of underground structure.

Acknowledgments

This research was supported by the National Natural Science Foundation of China (Grant No. 41472246) and the Fundamental Research Funds for the Central Universities. All support is gratefully acknowledged.

References

[1] Santa-Cruz, S., Heredia-Zavoni, E. and Harichandran, R. S. (2000) Low-frequency behavior of coherency for strong ground motions in Mexico City and Japan, In: *Proceedings 12th World Conference on Earthquake Engineering*, Auckland, New Zealand, Paper No. 0076.

[2] Der, Kiureghian, A. (1996) A coherency model for spatially varying ground motions, *Earthquake Engineering and Structural Dynamic* **25**, 99-111.

[3] Hashash, Y., Tseng, W.S. and Krimotat, A. (1998) Seismic soil-structure interaction analysis for immersed tube tunnels retrofit, ASCE *Geotechnical Earthquake Engineering and Soil Dynamics* **III**, 1380-1391.

[4] Anastasopoulos, I., Gerolymos, N., Drosos, V., Kourkoulis, R., Georgarakos, T. and Gazetas, G. (2007) Nonlinear response of deep immersed tunnel to strong seismic shaking, *Journal of Geotechnical and Geoenvironmental Engineering* **133**, 1067-1090.

[5] Park, D., Sagong, M., Kwak, D. Y. and Jeong, C. G. (2009) Simulation of tunnel response under spatially varying ground motion, *Soil Dynamics and Earthquake Engineering* **29**, 1417-1424.

[6] Yu, H. T., Yuan, Y., Qiao, Z. Z., Yun, G., Yang, Z. H. and Li, X. D. (2013) Seismic analysis of a long tunnel based on multi-scale method, *Engineering Structures* **49**, 572-587.

[7] Li, P. and Song, E. X. (2015) Three-dimensional numerical analysis for the longitudinal seismic response of tunnels under an asynchronous wave input, *Computers and Geotechnics* **63**, 229-243.

[8] Tamari, Y. and Towhata, I. (2003) Seismic soil–structure interaction of cross sections of flexible underground structures subjected to soil liquefaction, *Soils and Foundations* **43**, 69-87.

[9] Chen, G. X., Wang, Z. H., Zuo, X., Du, X. L. and Gao, H. M. (2013) Shaking table test on the seismic failure characteristics of a subway station structure on liquefiable ground, *Earthquake Engineering and Structural Dynamics* **42**, 1489-1507.

[10] Moss, R. E. S. and Crosariol, V. A. (2013) Scale model shake table testing of an underground tunnel cross section in soft clay, *Earthquake Spectra* **29**, 1413-1440.

[11] Gopal, Madabhushi, S. P. (2004) Modelling of earthquake damage using geotechnical centrifuges, *Geotechnics and Earthquake* **87**, 10-25.

[12] Pitilakis, D., Dietz, M., Wood, D. M., Clouteau, D. and Modaressi, A. (2008) Numerical simulation of dynamic soil-structure interaction in shaking table testing, *Soil Dynamics and Earthquake Engineering* **28**, 453-467.

[13] Chen, J., Shi, X. J. and Li, J. (2010) Shaking table test of utility tunnel under non-uniform earthquake wave excitation, *Soil Dynamics and Earthquake Engineering* **30**, 1400-1416.

[14] ABAQUS, Inc. (2010) *ABAQUS/Analysis user's manual—version 6.9., Providence*, **RI 02909-2499**, USA.

[15] Hindy, A. and Novak, M. (1980) Pipeline response to random ground motion, ASCE, *Journal of Engineering Mechanics* **106**, 339-360.

[16] Harichandran, R. S. and Vanmarcke, E. H. (1986) Stochastic variation of earthquake ground motion in space and time. ASCE, *Journal of Engineering Mechanics* **112**, 154-174.

[17] Harichandran, R. S. (1991) Estimating the spatial variation of earthquake ground motion from dense array recordings, *Structural Safety* **10**, 219-233.

[18] Qu, T. J., Wang, J. J. and Wang, Q. X. (1996) A Practical Model for the Power Spectrum of SpatiallyVariant Ground Motion, *Acta Seismologica Sinica* **9**, 69-80.

[19] Hao, H. (1989) Effects of spatial variation of ground motions on large multiple supported structures, University of California, Berkeley, USA.

[20] Clough, R. W. and Penzien, J. (1993) *Dynamics of Structures*, **2nd edition**, McGraw-Hill, Inc., New York.

[21] Amin, M. and Ang, A. H. S. (1968) Non-stationary stochastic model of earthquake motions, ASCE, *Journal of Engineering Mechanics* **94**, 559-583.