Free-filed soil response to bidirectional horizontal non-uniform ground motion from multi-point shaking table tests

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Abstract

This paper assesses the dynamic nonlinear free-field soil response under bidirectional horizontal non-uniform excitation through a series of multi-point 1g shaking table tests. The soil bed was enclosed in an innovative soil box supported by an array of three shake tables and was subjected to uniform and non-uniform ground motions in one and two horizontal directions. The soil response to bidirectional and unidirectional excitations, both uniform and non-uniform, were compared and discussed in terms of acceleration time history and Fourier spectra, acceleration amplification factor and soil settlement, as well as shear stress-shear strain behavior. The comparison of soil responses to bidirectional and unidirectional shakings demonstrated that the trends of peak acceleration amplification factors are similar along soil depth, but the response to bidirectional shaking is increasingly higher along the soil profile towards the ground surface, especially for uniform excitation. The variations of soil settlement, shear stress-strain and damping curves under bidirectional excitation were similar to that under the longitudinal excitation; however, they were much different than those observed under the transverse excitation. The soil damping in Y-direction under non-uniform excitation was larger than that under uniform excitation. These different site response characteristics under bidirectional non-uniform excitation should be properly considered in the seismic design of extended infrastructure.

1 Introduction

Underground structures are restrained by the surrounding soil, and thus their dynamic behavior mainly depends on the site response (Liang and Sun 2000). Earthquake excitations are multidirectional in nature and their amplitudes and orientation change constantly. Numerous studies attempted to evaluate soil seismic response under bidirectional uniform seismic excitation. Meanwhile, the effects of spatial non-uniform earthquake excitation on extended underground structures are important (Bi and Hao 2012; Yu et al. 2017; Zerva 1993). However, there is a lack of in depth and systematic research considering both multi-directional and non-uniform ground motions as revealed from the literature review below.

Pyke et al. (1975) conducted unidirectional (UD) and bidirectional (BD) shaking table tests on sand beds and demonstrated the significant influence of bidirectional seismic shear on their settlements. Based on the observed results, they concluded that the settlements caused by combined horizontal excitations were roughly equal to the sum of the settlements caused separately by the loading components. Subsequently, numerous laboratory tests involving bidirectional monotonic and cyclic shearing of soils have been reported in the literature. (Bhaumik et al. 2017; Ishihara and Nagase 1988; Kammerer et al. 2005; Matsuda et al. 2011; Yang et al. 2016) However, owing to the irregularities and complexities of seismic loading, it is difficult to apply realistic seismic loading to the soil specimen in the laboratory bidirectional monotonic and cyclic shear tests. In recent years, the advent of test equipment including geotechnical centrifuges and shake tables, and numerical simulation technology enabled more sophisticated investigations of the dynamic response of soil under bidirectional excitation.

Ng et al. (2004) conducted centrifuge shaking table tests on saturated embankment soil slopes under bidirectional shaking. Their results revealed that the crest settlement during the BD shaking was about 27% larger than that of the UD shearing test. On the other hand, Su and Li (2005; 2008) completed a series of BD shearing centrifuge tests on saturated sand employing a cylindrical laminar box and reported a minor increase of sand settlements due to BD shaking. El Shafee et al. (2017) and Zeghal et al. (2018) performed centrifuge tests on level saturated-sand deposits to examine the common practice method that the biaxial soil response can be represented by increasing the uniaxial shaking component by 10% (1D10%SA). Their results demonstrated that increasing the uniaxial shaking component by 40% (1D40%SA) was more accurate, and the shear-strain magnitude of the biaxial component was smaller than the test 1D40%SA. Reyes et al. (2019) developed a three-dimensional (3D) finite difference numerical model, which was validated with the results of the centrifuge tests conducted by Su and Li (2005; 2008). The numerical results showed that the settlement under the BD shearing was nearly 80% higher and developed as at a faster rate than those under the corresponding UD shearing. Nie et al. (2017) investigated the impact of BD shearing on dry sands numerically. The results indicated that the increase of settlement caused by BD over UD shearing varies between 50% and 130%. Chen et al. (2011) reported that the soil acceleration amplification factor increased by approximately 6.2% for the BD shaking compared with UD shaking.

The above studies improved our understanding of the dynamic response of soil under bidirectional shearing. However, while some of them indicated a significant increase in free-field soil response due to bidirectional shearing, other studies reported insignificant effects. These contradictory observations can be attributed to the difference between these studies in the relative density of soil, the peak loading acceleration, and the Arias intensity of seismic excitation. Therefore, more comprehensive studies should be undertaken to evaluate the dynamic response of soil considering varying parameters, especially ground motion incoherence.

Several researchers investigated the influence of non-uniform ground motion on site response through multi-array shaking table systems. Chen et al. (2010) conducted pioneering shaking table tests on scaled utility tunnel models and free-field soil under non-uniform earthquake excitation. The dynamic response of free-field soil under non-uniform excitation was demonstrated in terms of the soil acceleration, settlement and shear stress-shear strain curve, as well as acceleration amplification factors. However, the soil was discontinuous in their experimental setup. Similarly, Yan et al. (2015) performed a series of shaking table tests on soil models enclosed in twelve rigid model boxes connected in a series to simulate field conditions. The test results showed that non-uniform excitation waveform, peak acceleration and direction may lead to different dynamic response. Han et al. (2020) reported a series of multi-point shaking table tests to elucidate the effect of soil non-linearity on free-field soil response under uniform and non-uniform shakings. They reported that non-uniform excitations lead to stronger nonlinear behavior and decrease of soil shear modulus and acceleration amplification factors. The above studies reveal the important influence of non-uniform excitation on site dynamic response, which should be considered in the seismic design of long underground structures. In addition, the soil models in all the above shaking table tests were subjected to either longitudinal or transversal excitation separately.

However, the research on site response under bidirectional non-uniform seismic excitations is generally lacking.

In this paper, the dynamic response of free-field soil is investigated under unidirectional and bidirectional non-uniform seismic excitations with the aid of multi-point shaking table tests. The experimental results for the free-field soil under bidirectional excitation are compared with those obtained under unidirectional excitation in terms of the soil acceleration time history and Fourier spectra, acceleration amplification factor and settlement as well as variation of soil shear stress-strain and damping with strain.

2 Experimental Investigation

2.1 Shaking table array

The tests were conducted using the multi-dimensional and multi-point seismic shaking table array system of Beijing University of Technology, which has six degrees of freedom and can apply sine waves, white noise, seismic waves, and other waveforms in three-directions. The array system consists of nine 1m×1m tables, each of them can carry maximum payload of 5 tons. The shaking tables could vibrate with maximum horizontal direction (X, Y) accelerations of 2.0 g and maximum vertical direction (Z) accelerations of 1.0 g with working frequency ranging from 0.1Hz to 50Hz. The tests were performed on soil beds enclosed in an innovative soil box supported by three tables of the array system that were set on the ground anchor hole, and referred to hereafter as table A, table B, and table C. The side-to-side distance of each table is 2m as shown in Fig. 1.

2.2 Suspension continuum model box

The soil was enclosed in a suspension continuum modeling box (SCMB), which comprised three rigid boxes and two suspension soft connection boxes. The bottom plate and side facade of the rigid boxes were assembled with 10mm thick steel board, welded steel L-sections (L50 × 5) and I20a joist steel. Black wooden boards were used as side walls inside the rigid box, and black rubber boards were used as side and bottom walls inside the soft connection box to ensure that the SCMB can be stretched, compressed longitudinally and rotate horizontally during vibration. Foam cushions 20mm thick were placed around the model box to minimize the boundary effect. The overall dimensions of SCMB were 7.3m × 1.4m × 1.2m (length × width × height) as shown in the Fig. 2. The design details of SCMB are provided elsewhere (Han et al. 2020).

2.3 Similarity ratio design

The reliability of prototype simulation is directly related to the similitude relation. This free-field soil test is a part of the seismic response analysis of buried pipelines; therefore, it is necessary to consider the pipe-soil dynamic interaction, and the model soil and the pipeline should follow the same dynamic similarity relationship as much as possible. Due to the complexity and particularity of the soil, it is difficult to consider all aspects of the similarity relationships in the underground structure model tests (Yan et al. 2015). The model pipeline and the model soil adopted partly different similarity ratios; the similarity

ratios of the model pipeline were all satisfied; however, as to model soil, they are partially satisfied. The similarity ratios of geometry l , density ρ , and elastic modulus E were selected as essential parameters and were used to calculate other similarity ratios by employing the Buckingham- π theorem (Chen et al. 2021; Wang et al. 2018). The similarity relations of model soil are listed in Table 1.

Table 1
Key similitude relationships of model test

Physical quantities	Symbol	Model/Prototype
Geometry	S_l	1/10
Elastic modulus	S_E	1/4
Density	S_ρ	1
Stress	S_σ	1/4
Strain	S_ε	1
Frequency	S_f	5
Acceleration	S_a	2.5
Acceleration of gravity	S_g	/

2.4 Model soil

The model soil was collected from an underground project of the Beijing Metro Line No.14 at a depth of 10 m below ground surface. The soil density was 1740kg/m^3 , and its natural moisture content was 8.78%. The soil was medium dense sand with particles size greater than 0.25mm of 77% as can be gleaned from the sieving test results shown in Fig. 3. Considering the load capacity of the shaking table and model box effect, the overall size of model soil was $7.0\text{m} \times 1.0\text{m} \times 1.0\text{m}$ (length $\times$ width $\times$ height), as shown in Fig. 4. After each excitation, the model soil was compacted using a hammer of 20cm diameter, and then samples of each layer of soil were taken out to determine their thickness and density.

2.5 Seismic excitation loading scheme

El-Centro earthquake seismogram (Imperial valley-02, 1940, EL Centro array #9, $V_{s30}=213.11\text{m/s}$, N-S component), Kobe earthquake seismogram (Kobe Japan, 1995, Takatori, $V_{s30}=256\text{m/s}$, N-S component), and the Beijing synthetic seismogram (Beijing China, 2001, Suzhoujie,) were selected as the input ground motion. Time history and Fourier spectrum of input motions are shown in Fig. 5. The main loading intensity was divided into three levels, for prototype test, the peak accelerations were 0.1g, 0.2g, 0.4g corresponding to the seismic intensity of 7, 8, and 9 in *Code of Aseismic Design of Buildings* (China), then they were adjusted to 0.25g, 0.5g, 1.0g according to the similar relationship in the model test. The loading schedule of the shaking table tests were shown in Table 2. There are two types of ground motion

excitation methods in present tests: uniform excitation and non-uniform excitation, both of them were completely executed according to Table 2. When uniform excitation was executed, the time interval and peak acceleration of the input ground motion were adjusted according to the similarity relationship. For non-uniform excitation, besides the above processing during uniform excitation, traveling wave effect was also considered, both X-direction and Y-direction loading accounted for the time lag in the propagation direction (X direction), which was determined by the distance between shaking tables, and the propagation speed. However, the time delay was very short due to space limitations of the test; thus, to highlight the impact of non-uniform incentives, time delay between adjacent tables was set as 1 s.

Table 2
Loading schedule of the shaking table tests

Test phase	Vibration direction	Input wave form	PGA(g)
Phase 1: Longitudinal excitation	X	EL-Centro (EL);	L1: 0.25g
		Kobe (KB);	L2: 0.5g
		Beijing Artificial seismic excitation;	L3: 1.0g
Phase 2: transverse excitation	Y	(BJ)	T1: 0.25g
			T2: 0.5g
			T3: 1.0g
Phase 3: Bidirectional excitation	X+Y		B1: 0.25g
			B2: 0.5g
			B3: 1.0g

2.6 Sensor layout

The sensors used in the shaking table tests included accelerometers and displacement gauges and their arrangement was consistent in all tests. The sensor layout of observation sections and soil surface is as shown in Fig. 6. Boxes No.1, No.3, and No.5 were rigid boxes, while boxes No.2 and No.4 were flexible connection boxes. Terminologies used to describe the sensors are as follows: ZA for accelerometers, D for displacement gauges, X and Y represent longitudinal and transversal direction respectively. To study the seismic response along the soil profiles, accelerometers in X and Y directions were both installed along the vertical centerline of boxes No.3, No.4, and No.5, as shown in Fig. 7 and Fig. 8. Three laser displacement gauges were arranged above the soil surface of boxes No.1, No.3, and No.5 to monitor the settlement of ground surface. A total of 60 sensors were deployed, including fifty-seven accelerometers and three laser displacement gauges.

3 Test Results And Analysis

The shaking table tests comprised fifty-four loading cases. The results were presented here in terms of comparison of the seismic response in the X direction under longitudinal excitations (UX) and the seismic response in the X direction under bidirectional excitation (BX), as well as the comparison of the seismic response in the Y direction under transverse excitation (UY) and the seismic response in the Y direction under bidirectional excitation (BY). The acceleration responses of soils in different boxes were found to be similar under longitudinal uniform and non-uniform excitation. (Han et al. 2022) Therefore, the data from box No.3 was selected for acceleration response analysis herein.

3.1 Acceleration time history and Fourier spectrum of soil profile

The acceleration response of box No.3 under bidirectional seismic excitation was investigated. From bottom to top, acceleration sensors arranged on the monitoring section 1 in X-direction were ZA_{X18} , ZA_{X17} , ZA_{X16} , ZA_{X15} , ZA_{X14} , and sensors arranged in Y-direction were ZA_{Y31} , ZA_{Y29} , ZA_{Y27} , ZA_{Y25} , ZA_{Y22} .

Figure 9 and Fig. 10 display the acceleration time histories and Fourier spectra measured at section 1 under EL-B3 uniform and non-uniform excitations. The acceleration time histories for the uniform excitation in BX show that the peak acceleration at the bottom of model soil were smallest, and the frequency content was distributed over a wider band comparing with shallower monitoring points. As the height of monitor point increases, acceleration waveforms were nearly unchanged, but the amplitudes increased gradually, and the main frequency shifted to 3-8Hz. The trend of the acceleration histories and Fourier spectra in BY were similar to that in BX; however, as the height of the monitoring point increased, the acceleration amplitude decreased first due to the relative rigidity of the soil box at the bottom then increased due to the amplification of ground motion and perhaps the relative flexibility of the soil box top.

Under non-uniform excitation, the BX acceleration records measured at the bottom of soil displayed many low-frequency components (i.e., 1-2Hz), which may be due to the environmental vibration (from other sources in the laboratory) interference during the test. However, as the seismic motion propagated upwards, the soil gradually filtered out the interference frequency, and the final Fourier spectra at different depths were almost the same. It is worth noting that the high-frequency components of all measured accelerations increased under non-uniform excitation, especially, in the range of 15-25Hz in BY.

Table 3 presents the peak acceleration amplification factors (PAAF) of monitoring point at soil surface in Box No.3 under EL-B3 uniform and non-uniform excitations. The PAAF is defined as the ratio of peak acceleration at the monitoring point to the peak acceleration of the bottom point, i.e.,

$$PAAF_i = \frac{\max |a_i(t)|}{\max |a_{table}(t)|}$$

Where $PAAF_i$ is the peak amplification factor at different soil height, $a_i(t)$ is measured acceleration at different soil heights and $a_{table}(t)$ is the shake table acceleration.

Under uniform excitation, the PAAFs in BX and BY were both greater than 1, which indicated a certain degree of acceleration amplification at soil surface comparing to input record. Meanwhile, the PAAFs in BX for non-uniform excitation cases were < 1 and were ≥ 1 in BY. These results reveal that non-uniform excitation significantly reduces the acceleration amplification effect of soil surface in BX but has little effect on BY. Therefore, the values of BX/BY become much smaller under non-uniform excitation.

Table 3
Comparison of PAAF on soil surface in two directions under bidirectional seismic excitation

Loading intensity	BX		BY		BX/BY	
	Uniform	Non-uniform	Uniform	Non-uniform	Uniform	Non-uniform
EL-B1	1.789	0.845	1.408	1.230	1.271	0.687
EL-B2	2.265	0.889	1.120	1.013	2.014	0.877
EL-B3	1.355	0.876	0.890	0.956	1.522	0.916

3.2 Peak acceleration amplification factor

The variations of PAAF in the soil profile 1 under longitudinal, transversal, and bidirectional seismic excitations are depicted in Fig. 11 and Fig. 12. The PAAFs of soil under BD excitation and UD excitation were similar in trend along soil depth but different in values. The PAAFs in UX and BX under uniform excitation increased with height from bottom, and the values were > 1 . Meanwhile, the PAAFs in UX and BX under non-uniform excitation and Y-direction results under both uniform and non-uniform excitations first decreased and then increased from the bottom to surface, and PAAF values at all points below soil surface were < 1 .

Table 4 and Table 5 present the PAAFs at soil surface of different loading cases. The PAAFs at soil surface decreased as the loading intensity increased under transversal and bidirectional excitations with both methods, and the values of BY were 10%-37% larger than UY values. This might attribute to the soil nonlinearity due to increased soil shear strain, which resulted in reduced soil shear modulus. This observation is similar to the finding from Chen's numerical study (Chen et al. 2011) on dynamic response of soil deposits under multidirectional earthquake loading.

Table 4
Comparison of PAAF on soil surface under BD and UD uniform excitation

Loading intensity	Unidirectional excitation (UD)		Bidirectional excitation (BD)		BD/UD	
	UX	UY	BX	BY	X	Y
0.25g	1.560	1.025	1.789	1.408	1.147	1.373
0.5g	1.931	0.960	2.265	1.120	1.173	1.167
1.0g	1.964	0.764	1.355	0.890	0.690	1.177

Table 5
Comparison of PAAF on soil surface under BD and UD non-uniform excitation

Loading intensity	Unidirectional excitation (UD)		Bidirectional excitation (BD)		BD/UD	
	UX	UY	BX	BY	X	Y
0.25g	0.943	1.100	0.896	1.408	0.896	1.119
0.5g	1.015	0.915	0.877	1.120	0.877	1.107
1.0g	0.695	0.791	1.260	0.890	1.260	1.210

To investigate the variation of PAAFs between UD and BD excitations, the influences of the load intensity and ground motion type were ignored, and the difference (μ) of the PAAF values at different buried depths were calculated and are presented in Fig. 13. At the same height, the average level of μ during non-uniform excitation was much smaller than that of uniform excitation, and its fluctuation was also smaller, indicating that the PAAFs of soil under bidirectional non-uniform excitations were closer to unidirectional responses. Moreover, the non-uniformity of excitation had no effect on μ in Y-direction; for both uniform and non-uniform excitations, μ increased in both directions as the height increased.

3.3 Soil settlement

Three laser displacement gauges D1, D2, and D3 were arranged above box No.5, box No.3, and box No.1 respectively, to measure the movement of soil surface. Fig. 14 shows the time-histories of soil surface settlement during bidirectional El Centro ground motions, and Fig. 15 compares the settlement time histories for the UD and BD excitations at loading intensity of 1.0g. In Figs. 14 and 15, 0 represents the initial height of soil surface, positive values represent the uplift of soil surface, and negative values represent settlement.

The results in Fig. 14 demonstrate that for bidirectional uniform excitation, there was almost no fluctuation of the soil surface under PGA = 0.25g; the settlement initially appeared during PGA = 0.5g, then the soil surface fluctuated significantly during shaking with PGA = 1.0g (3-9 times that of PGA = 0.5g shaking). For the non-uniform BD excitation, the soil surface fluctuated during PGA = 0.25g excitation, and as the loading intensity increased, the fluctuation range increased. Compared with the uniform excitation, the fluctuation amplitudes were larger, and the duration was longer, but the final settlements were smaller. The fluctuation of the soil surface may be caused by the combined effect of soil elastic

fluctuation and the contraction of the soil volume. The lower-level uniform excitations had little impact on the soil structure, free-field soil remains elastic, and the higher-level uniform excitation had some impact on the soil structure, which was manifested in the shrinkage of soil volume and final settlement. For non-uniform excitation, the soil structure was impacted at lower loading intensity, and that increased rapidly with the increase of loading intensity. Under uniform excitation, different boxes moved together at the same time, and the soil particles could be redistributed in the entire model box, and the settlements in different boxes were more consistent. However, the asynchronous movement of different model boxes under non-uniform excitation made the soil of adjacent boxes longitudinally squeeze and expand, causing the soil surface to fluctuate. The asynchronous movement also hindered the process of redistribution of soil particles and reduced the settlement.

Figure 15 shows that the final heights of the soil surface of different rigid boxes all decreased under unidirectional and bidirectional excitations, indicating that the volume of the whole model soil finally shrank. Under uniform and non-uniform excitations, the soil surface settlement under bidirectional excitation were the same as that of longitudinal unidirectional excitation. Under non-uniform excitation, the fluctuation amplitudes under BD and longitudinal excitations were larger than the transversal excitation. However, the final settlement under transversal excitation was larger than that of BD excitation. This behaviour may be attributed to the different vibration modes (longitudinal extension-compression and transverse shear) under non-uniform excitation of X and Y. Nevertheless, the BY and UY fluctuations were not significant under non-uniform excitation, but the end settlements of BY and UY were relatively larger. This may be attributed to the decrease in the frequency band and increases in damping (i.e., increase in energy dissipation of UY and BY).

3.4 Dynamic shear stress-strain behaviour

Considering a 2D shear beam model, the acceleration records measured at different depths along the soil section were used to evaluate the soil shear stresses and strains. This technique provides non-parametric estimates of shear stress–strain histories utilizing only acceleration records provided by vertical arrays of accelerometers (El Shafee et al. 2017; Zeghal et al. 2018). Fig. 16 and Fig. 17 compare the shear stress-strain hysteresis curves between UD and BD excitations of El Centro ground motion with different loading intensities. The classical soil dynamic constitutive model regards the soil as visco-elastoplastic body with elastic, plastic and viscous properties, and the area of the dynamic hysteresis curve of the soil includes viscous and plastic energy dissipation. In addition, it can be used to evaluate the soil damping. In the present test, the complex shear stress-shear strain curves were decomposed into several independent hysteresis loops, The sum of areas of these hysteresis loops was regarded as the energy dissipation during the entire seismic loading process. Fig. 18 shows the time history curves of energy dissipation under EL-L3, EL-T3, and EL-B3.

Figure 16 shows that Under uniform excitation and non-uniform excitation with the same loading intensity, the shear stress and shear strain magnitudes of UX and BX were basically equivalent, both of them gradually increase with the increasing loading intensity. The energy dissipation of UX and BX has no noticeably difference as well. under uniform excitation, the hysteresis curve mainly shows linear

reciprocating oscillation, and the area of hysteresis loop is smaller than non-uniform excitation, although the magnitudes of shear stress and shear strain under non-uniform excitation are smaller, the hysteresis loops were plumper.

Figure 17 and Fig. 18 show that the shear stress and shear strain magnitudes and the energy dissipation of BY were lower than that of UY under uniform and non-uniform excitations. Furthermore, under non-uniform excitation, the energy dissipation of soil in UY and BY was approximately 17% greater than for uniform excitation. In addition, under 1.0g non-uniform excitation, the center of hysteresis curve gradually shifted away from the origin, indicating that the soil has undergone visible plastic deformation. It is worth noting that the energy dissipation caused by the Y-direction movement of the soil is 7-15 times that of the X-direction, but the corresponding relationship of shear strain magnitude was only 2-4 times.

Given that the energy dissipation is a manifestation of the damping magnitude, it is obvious that the damping characteristics of the model soil were different in the two directions. On the one hand, the larger damping of the soil in the Y-direction reduced the difference in the soil acceleration response under different excitation methods, which explains why μ in the Y-direction was smaller. On the other hand, there was larger energy dissipation when soil was subjected to UD excitation in Y direction, indicating that the movement between the soil particles was more intense, and the redistribution of soil particles was more thorough. This may explain the larger soil settlement in the Y-direction. The BD excitation hindered the movement of soil particles in the Y direction, resulting in lower energy dissipation compared to UD excitation.

4 Conclusions

The effect of bidirectional non-uniform ground motion on the seismic response of free-field soil was investigated by using multi-array shaking table tests. The soil responses under bidirectional and unidirectional excitations were compared in terms of acceleration time histories and Fourier spectra, peak acceleration amplification factor and settlement of soil surface, as well as dynamic shear stress-strain behavior. The main conclusions derived from the test observations are as follows:

(1) Under bidirectional uniform and non-uniform excitations, the acceleration wave form in BX and BY were approximately the same as the input acceleration, but the frequency content changes. The frequency content is concentrated in the range of 3-8Hz for BX and BY under uniform excitation, while the frequency band was wider in BX and BY under non-uniform excitation, with notable amplitudes appearing at 15-25Hz for BY. Compared with uniform excitation, the PAAF at soil surface was relatively small in BX and BY under non-uniform excitation; the values in BX were less than 1.

(2) The PAAFs of soil under bidirectional and unidirectional excitations were similar in trend along soil depth but different in values; as the elevation increased, the difference of the PAAF values between them increased. The PAAFs at soil surface decreased as the loading intensity increased under transversal and bidirectional excitations, and the values of BY were 10%-37% larger than the UY values. Compared with the uniform excitation, the average level and fluctuation degree of μ in non-uniform excitation were much

smaller, which indicates that for non-uniform excitation, the PAAFs of soil under bidirectional and unidirectional excitations were relatively close.

(3) Under both bidirectional and unidirectional excitations, the volume of entire soil model eventually shrank. The soil surface fluctuated more intensely in different boxes under non-uniform excitation in contrast to under uniform excitation. The soil surface settlement curves under bidirectional uniform and non-uniform excitations were consistent with the longitudinal excitation; nevertheless, the final settlement was much greater under transversal uniform excitation.

(4) For both bidirectional and unidirectional excitations, the shear stress-shear strain curves in UX and BX were similar at the same loading intensity, and the stress and strain magnitudes gradually increased as the loading intensity increased. The energy dissipation in UX and BX had no noticeable difference. However, the soil shear strain in the UY and BY was larger than that of UX and BX, and the energy dissipation was almost 10 times that of BX. Under uniform and non-uniform excitations, the shear strain and energy dissipation were 35% smaller in BY than that of UY, and the energy dissipation of soil in UY and BY were approximately 17% greater than for uniform excitation. The above findings indicate that the dynamic response of soil may be overestimated if evaluated by superposing the results of separate seismic excitations in two directions.

Declarations

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CRediT authorship contribution statement

Junyan Han: Conceptualization, Methodology, Investigation, Formal analysis, Zhike Guo: Data curation, Writing - original draft, preparation, Software. Zilan Zhong: Investigation, Data curation, Supervision. M. Hesham El Naggar: Validation, Writing - review & editing, Proofread the English grammar. Huiquan Miao: Validation. Formal analysis. Xiuli Du: Supervision, Funding acquisition.

Declaration of competing interest

We declare that we have no conflict of interest with other people or organizations.

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Figures

Figure 1

Three-shake table system

Figure 2

Suspension continuum modeling box

Figure 3

Grain size diagram

Figure 4

Shaking table model test of the free field soil

Figure 5

Earthquake acceleration time histories and Fourier transform spectrum

Figure 6

Layout of measuring sensors in continuum modeling soil box (mm)

Figure 7

Layout of profile A-A measuring sensors (mm)

(a) BX direction

(b) BY direction

Figure 9

Acceleration along monitoring section 1 under El Centro 1.0g uniform excitation

(a) BX direction

(b) BY direction

Figure 10

Acceleration along monitoring section 1 under El Centro 1.0g non-uniform excitation

Figure 11

Variation of PAAF along monitoring section 1 in X direction

Figure 12

Variation of PAAF along monitoring section 1 in Y direction

Figure 13

Box plots of PAAF difference between BD excitation and UD excitation at different depths

Figure 14

Settlement curves of soil surface under El Centro BD excitation of 3 loading intensities

(a) uniform excitation

(b) non-uniform excitation

Figure 15

Settlement curves of soil surface under El Centro BD and UD excitation

(a) uniform excitation

(b) non-uniform excitation

Figure 16

Shear stress- strain curves in the X direction

(a) uniform excitation

(b) non-uniform excitation

Figure 17

Shear stress- strain curves in the Y direction

(a) uniform excitation

(b) non-uniform excitation

Figure 18

Time history curves of energy dissipation under 1.0g El Centro excitation