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Dynamic Performance Analysis of Sawdust Mixed Clay Site Model in Shaking Table Test

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ABSTRACT

A series of shaking table model tests on a sawdust mixed clay site model were conducted at the shaking table testing system with 9 sub-tables in Beijing University of Technology. The tests were performed using a rigid prefabricated continuous model box with dimensions of 7.7 meters long, 3.2 meters wide, and 1.2 meters high. The test system was subjected to strong ground motions from El Centro record and Tianjin record. Through shaking table tests, the dynamic characteristics of the model site were obtained, including the peak ground accelerations and their amplification factors, acceleration time histories, and their Fourier spectra for the site responses. The test results show that: (1) With the increase of intensity of input ground motion, the peak ground acceleration of the site response at the same test point increases, but its acceleration amplification factor decreases. (2) The main frequency components move from high to low frequency. It means that the soil became soften and soil modulus decreased gradually with the increase of intensity of input ground motion.

KEYWORDS: shaking table; model test; sawdust

INTRODUCTION

Since the 1995 Kobe earthquake, there has been serious damage to the subway station, which has caused the attention of earthquake engineering experts and engineers around the world to the seismic problems of underground structures. Shaking table test is an important method to research earthquake engineering problems. The dynamic similarity relation is the key to obtain the reliable results. At present, in the experiment of underground structure shaking table model, only the model structure is simulated, and the foundation soil usually adopts the prototype soil material, such as Meymand, Chen J. , Chen G.X. and so on. The stiffness of this kind of model test of structure, quality and other characteristics according to the similarity criterion for the reduction, but the foundation soil has not been reduced. It will make the stiffness ratio of soil to structure not consistent between model test and the prototype. And thus, the soil - structure dynamic interaction law derived from the model test is bound to be different from the prototype soil -structure dynamic system, and even the wrong conclusions are drawn. Therefore, it should be necessary and valuable to conduct in-depth study on the model soil based on the model tests with the purpose of soil- structure interaction.

For the underground structure shaking model test, the key of model soil similarity relation is to reduce the ratio between stiffness and mass of the model soil. Soil parameters can be changed through adding other materials to the soil. At present, there are several ways to reduce the ratio: (1) Soil is mixed with iron powder or iron crystal sand(Zhang Q.Y.), the density of soil increased, but the modulus basicly remains the same, and the method cost is higher, drawing is not convenient and iron rust easily, and will be affected by shaking table load limit; (2) Soil is mixed with rubber particles(Senetakis K.,2012; Nakhaei A.,2012), and the density of the soil decreases, and the modulus decreases. (3) Soil is mixed with sawdust(Xu B.W, 2009; Yan X.,2015; Chen Z.Y.,2015), the shear modulus of soil can be significantly reduced, and the density of soil can be reduced to a certain extent, and the cost of sawdust is low and the materials are easy to draw. In this paper, the third method was used. Taking clay in the Beijing area as the prototype, based on the structure and foundation soil similar design principle, the matching period by using similarity relation to simplify the design of model soil, compound sawdust and add right amount water preparation test model of foundation soil. Model soil design in detail can be seen in the literature (Chen H.J., 2017).

In this paper, a series of shaking table model tests on a sawdust mixed clay site model were conducted. The dynamic response of model site under seismic excitation in horizontal directions (in longitudinal and transversal directions) is investigated. The tests result has laid a foundation for the experiment of underground structure, and can provide reference for similar experiments.

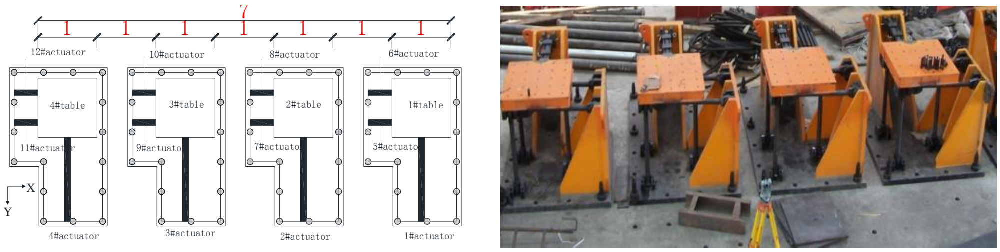
TEST APPARATUS AND SOIL MODEL

Shaking table test of the free field is part of the soil - tunnel structure model test. So, in the free field test model design, model similarity of the soil - structure interaction relationship is considered. The soil was used gravity distortion model. It is very hard to satisfy all the scale factors. In this paper, a simplified model was adopted. Based on the principle of structure and foundation soil matched similarity relation, soil mixed with sawdust is used to design the model foundation soil of shaking table test through predominant period similarity relation. After the scale factor of geometry, elastic modulus and density are decided, scale factors among the physical quantities can be deduced using the Buckingham π law (Chen Z.Y.,2015) . The scale factors of the model structure and model site are listed in Table1.

The tests were performed in the shake-table array system in Beijing University of Technology. The system consists of nine independent shake tables in total with 1m ×1m that can be used for shake tests singly or in combination, depending on the experimental requirements. The shake-table array systems were arranged in a straight line, and two adjacent sub-tables were spaced 1m apart, including four shake tables and 12 actuators, as shown in FIG. 1. Furthermore, the verifications for the shake tables are done in the literature (Li, X., 2015).

Table 1. Similitude relations of model structure and soil

Physical quantities	Similitude relations	Model structure	Model soil
Length	S_L	1/60	1/60
Linear displacement	$S_\delta = S_L$	1/60	1/60
Equivalent density	S_{ρ_e}	2	0.65
Elastic modulus	S_E	1/4	1/12.4
Duration	$S_T = S_L\sqrt{S_{\rho_e} / S_E}$	0.047	0.047
Frequency	$S_\omega = 1 / S_T$	21.28	21.28
Acceleration	$S_a = S_E / (S_L S_{\rho_e})$	7.5	7.5



(a) The design layout (b) Physical layout

FIG. 1. Shaking table array (unit: m). (a) The design layout.(b) Physical layout.

A rigid prefabricated continuous model box with dimensions of 7.7m (long) ×3.2 m (wide) ×1.2 m (high) was designed which can achieved uniform and non-uniform earthquake excitation input. To minimize the effect of rigid boundary on structural dynamic response, 20cm thick polystyrene foam sheet was lined on the sides of the model box.

The prototype soil was clay in Beijing. Through soil dynamic tests in laboratory, the mass ratio of sawdust to clay was1:3. The density of the mixture was 1320kg/m^3. During the experiment, the soil was placed into the soil container layer by layer. Each layer was compacted to have thickness of approximately 10cm. After loading, the top soil layer covers the plastic film to prevent evaporation of water, and put the weight block in static pressure. The soil site is shown in FIG.2.

FIG. 2. The completed model site.

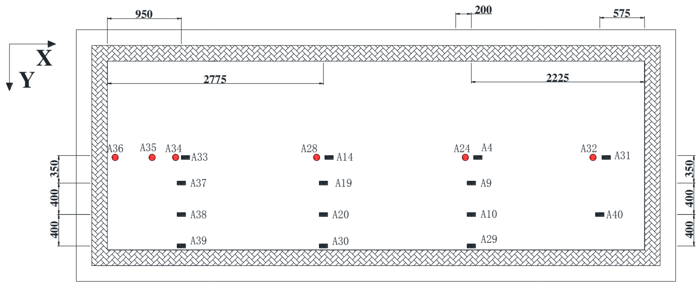
TEST PROGRAM

Several accelerometers are arranged on the model soil surface (X and Y direction) to verify the boundary effect of the model box, see FIG.3. A series of accelerometers(A1-A4 and A21-A24) are arranged along the vertical center line of the model site to investigate the propagation law of seismic waves in soil. The heights of different soil story are 0, 25, 58, 80 cm respectively. In FIG. 3, the circle represents the accelerometers in X direction and the rectangle represents the accelerometers in Y direction.

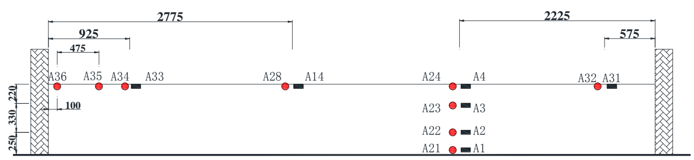
To investigate the dynamic characteristics of sawdust mixed clay site model, El Centro record and Tianjin record were selected. FIG. 4 presents the acceleration time histories and Fourier spectra of the two records. For the purpose of investigating the dynamic characteristics under different intensities and types of ground motions, the two ground motions were scaled to three levels (0.25, 0.75 and 1.5g). White noise was used to check the changes in the model. Table 2 gives the test cases.

BOUNDARY EFFECT

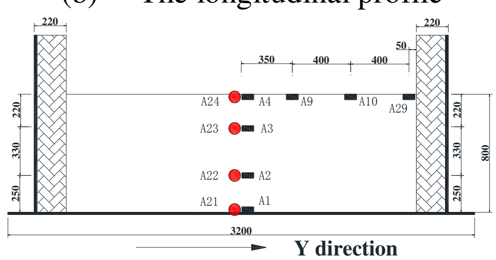
Boundary effect of soil box is unavoidable in all soil–structure interaction dynamic tests. In order to examine the boundary effect, the usual way is taking the response of test points in the soil layer center as the standard, the responses of other test points in the soil layer are compared with it, the responses of the two test points is closer that the boundary effect is smaller.



(a) On soil surface

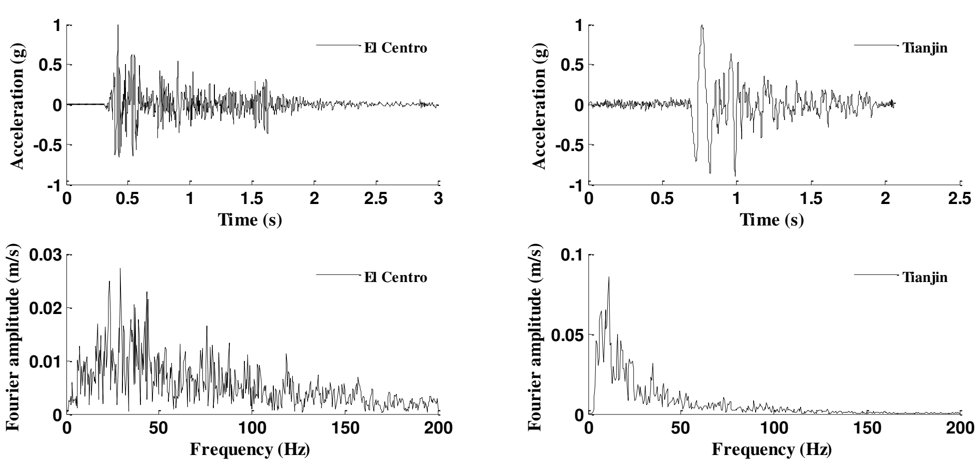


(b) The longitudinal profile



(c) Profile

FIG. 3. Acceleration sensor arrangement (unit: mm). (a) On soil surface. (b) The longitudinal profile. (c) Profile.



(a) El Centro (b) Tianjin

FIG. 4. Acceleration records and Fourier spectra. (a) El Centro. (b) Tianjin.

Table 2. Loading conditions

Seismic input	Test No.1	Test No.2	Test No.3
White noise	0.07gX	0.07gX	0.07gX
White noise	0.07gY	0.07gY	0.07gY
El Centro	0.25gX	0.75gX	1.5gX
Tianjin	0.25gX	0.75gX	1.5gX
El Centro	0.25gY	0.75gY	1.5gY
Tianjin	0.25gY	0.75gY	1.5gY

There are two ways to validate the boundary effect of soil box. One is the direct comparison method(Turan A.,2009) and the other is the 2-Norms deviation method(Chen J. , 2010) . The direct comparison method is more intuitive, but it lacks quantitative analysis. Boundary effect of model box can be studied through the 2-Norms deviation method quantitatively and comprehensively. So the 2-Norms deviation method is used in the paper.

Dynamic characteristics of model box and model box - soil system

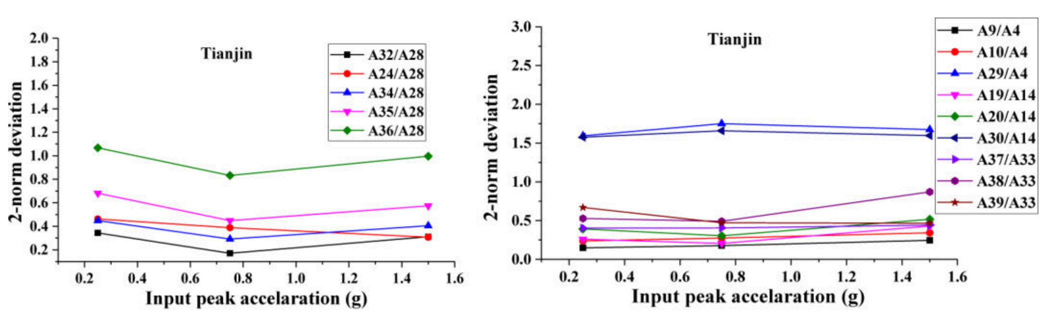
In essence, the fundamental frequency problem present in the model box and site is strongly relation to the boundary effect problem. The fundamental frequencies of both the empty box and the soil-box system were tested using random excitation at a limited amplitude. A spectral analysis was performed on the acceleration time history recording of the empty box from sensors installed on the box to identify the predominant frequency. A similar process was performed on the records at point A4 (A14) and A24 (A28) in the soil-box system. The fundamental frequencies of the empty soil box were determined to be 15.63 Hz and 13.87 Hz in the X- and Y-directions, respectively, and those of the box-soil system were observed at 10.74 Hz and 7.81 Hz in the X- and Y-directions, respectively.

Boundary effect of soil box

In this paper, an index based on 2-Norms deviation is introduced to quantify the boundary effect of the shear box, and the index μ is calculated using the following equation:

$$\mu = \frac{\left\| x_i - x_j \right\|}{\left\| x_i \right\|} = \sqrt{\frac{\sum (x_i - x_j)^2}{\sum (x_i)^2}} \tag{1}$$

where x_i, x_j are quantities of reference sensor and target sensor, respectively. x_i, x_j can be taken as the response time histories or even the spectra curve. The smaller the value of μ is, the better boundary effect is eliminated. If the value of μ is zero, the two signals are identical.



(a) X (b) Y

FIG. 5. 2-norm deviation of acceleration.

FIG. 5 shows 2-norm index μ calculated using acceleration responses in free-field tests, where A28 and A4, A14, A33 are taken as the record of central sensors in X and Y direction, respectively. It can be observed from FIG.5 that most of the values are less than 0.5, except for individual points and the corresponding sensors are not placed in a valid range in the future. The present study believes that boundary effect of the model box used is small and negligible in the test, which corresponds with previously reported data (Chen J., 2010).

TEST RESULT AND ANALYSIS

Limited to space, only the result under seismic input in Y direction are given.

Peak acceleration

Peak values of accelerometers A1, A2, A3 and A4 under El Centro and Tianjin ground motion at different intensities are presented in FIG. 6

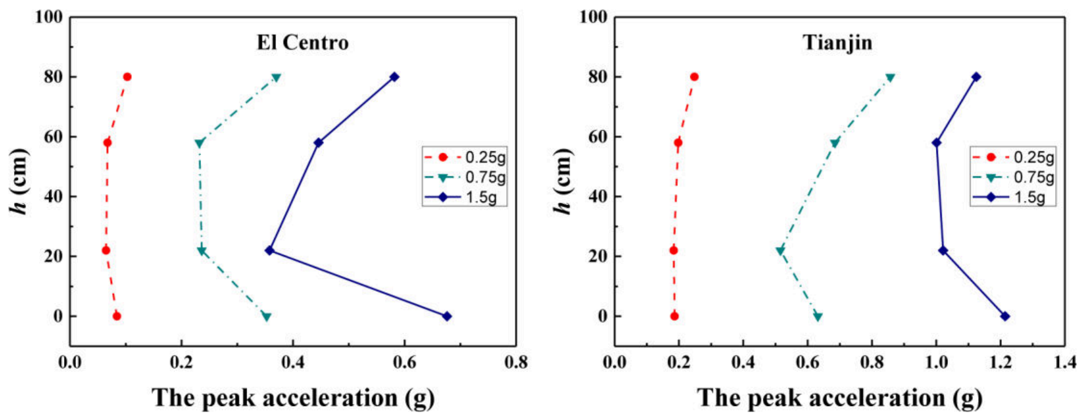


FIG. 6 PGAs of site responses at different depths (Y).

It can be seen from FIG. 6 that: (1) The peak acceleration of the same test point(accelerometers) generally increases with the increase of the input intensity of ground motion. (2) Under the same intensity of ground motion input, the peak acceleration of each test point from bottom to top shows the trend of decreasing firstly and then increasing. (3) Under the same intensity of ground motion input, peak values of the same accelerometers under Tianjin ground motion is larger than that under El Centro ground motion. This is mainly due to that the excellent frequency of Tianjin ground motion is closer to the natural frequency of box-soil system. It is easy to resonance, and the acceleration response is larger.

Amplification factor

The variation of acceleration amplification factor with input PGA is depicted in FIG.7 for vibration in the Y direction. The amplification factor is designed as the ratio of peak value of accelerometers A1, A2, A3 and A4 to peak value of A1 (see FIG.7).

It can be seen from FIG. 7 that: (1) The amplification factor of the same accelerometer generally decreases with the increase of the input intensity. It is consistent with the literature (Chen G.X.,2015), and this may be due to the soil shear strain level increases, the shear modulus decrease with the increase of the input PGA(Peak Ground Acceleration). (2) When ground motion input is 0.25g level, amplification factor from bottom to top of site decreases firstly and then increases obviously and the value is greater than 1. (3) When ground motion input is 0.75g level, amplification factor from bottom to top of site decreases firstly and then increases, only the value of accelerometer at the surface is greater than 1, the others are less than 1. (4) When ground motion input is 1.5g level, amplification factor from bottom to top of site decreases firstly and then increases, but the increasing amplitude is small, except the value of individual point is greater than 1, others are less than 1, which is caused by the soil nonlinear. (5) For the above conclusions based on sawdust mixed land basis in the tests, they are consistent with the conclusions of non-sawdust mixed soil in the experiment of Chen J. 2010 and Chen G. X.,2015.

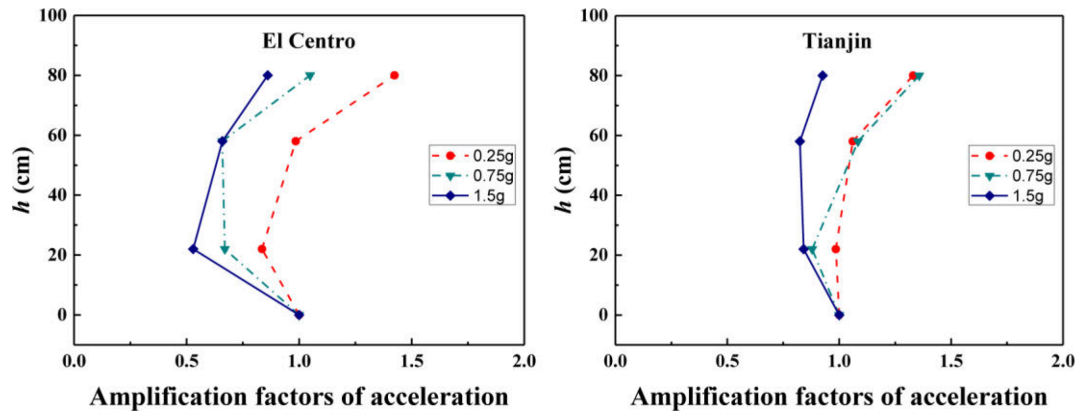


FIG. 7 Amplification factors of PGAs at different depths (Y).

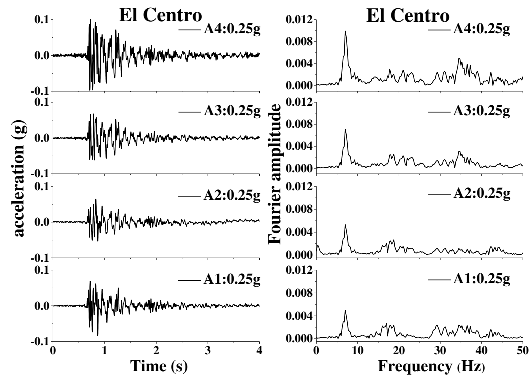
Acceleration time histories and Fourier spectra

FIG.8 and FIG.9 presents acceleration time histories and Fourier spectra of different accelerometers under El Centro and Tianjin ground motion, respectively.

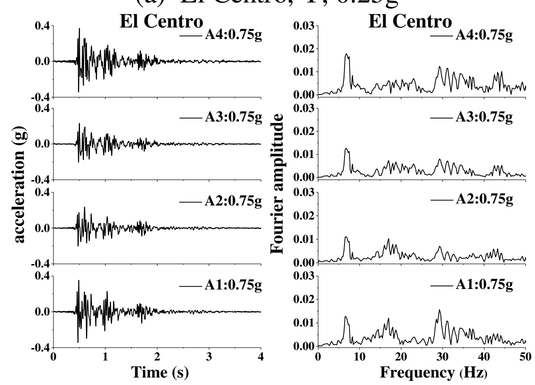
It can be seen from FIG. 8 and FIG.9 that: (1) Under El Centro ground motion input, at the input intensity of 0.25g, the spectra of the acceleration Fourier spectra (FFTs) of the test points A1~A4 are mainly concentrated in frequency of 8~10Hz. At the input intensity of 0.75g, the acceleration Fourier spectra of the test points A1~A4 are still concentrated in the frequency of 8~10Hz, but the proportion of 10~45Hz components is significantly higher than that of 0.25g. At the input intensity of 1.5g, the acceleration Fourier spectra of the test point A1~A4 are rich in the range of 0~50Hz. Under Tianjin ground motion input, the spectra of the acceleration Fourier spectra (FFTs) of the test points A1~A4 are mainly concentrated in frequency of 4~10Hz. (2) Under El Centro and Tianjin ground motion input, the acceleration Fourier spectra values gradually increase from the bottom to top of the soil in the frequency range of 8~10Hz and 4~10Hz, respectively. The ground motion of soil has low frequency amplification. (3) The acceleration Fourier spectra values increase with the increase of the seismic input. Under El Centro and Tianjin ground motion input, at the input intensity of 0.25g, 0.75g and 1.5g, the values of acceleration Fourier spectra are 0.01, 0.02, 0.03 and 0.025, 0.06, 0.12, respectively. (4) Under El Centro and Tianjin ground motion input, the maximum corresponding frequency of the acceleration Fourier spectra values are 7.0Hz, 6.75Hz, 6.5Hz and 6.75Hz, 5.75Hz, 4.75Hz, respectively. With the increase of the input ground motion intensity , the main frequency components move from high to low frequency. It means that the soil became soften and soil modulus decreased gradually.

CONCLUSIONS

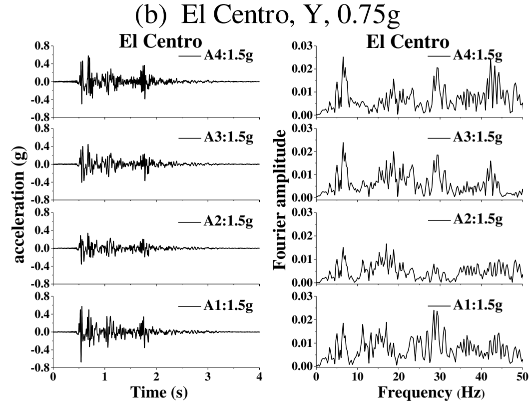
Through the tests, the dynamic performance and its change law of the sawdust mixed soil model is studied, mainly including peak ground accelerations and their amplification factors, acceleration time histories and their Fourier spectra of test points at different depth in the soil. This research can provide reference for related topics. Conclusions are as follows:



(a) El Centro, Y, 0.25g



(b) El Centro, Y, 0.75g

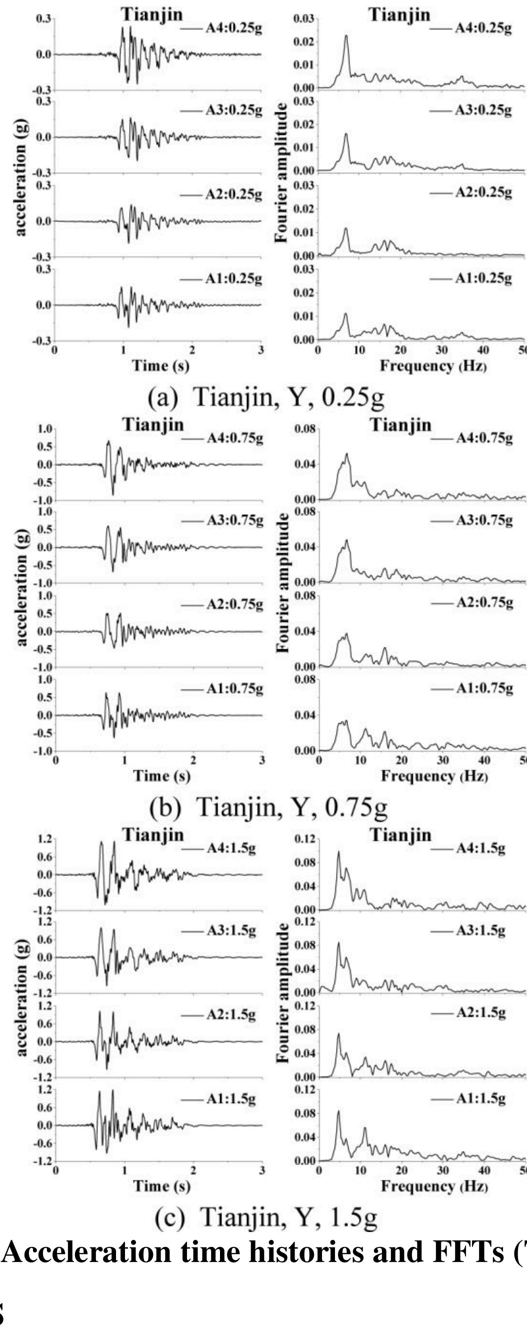


(c) El Centro, Y, 1.5g

FIG. 8 Acceleration time histories and FFTs (El Centro).

(1) A 2-Norms index was employed to quantify the boundary effect. The results demonstrate that the designed model box did not impose significant boundary effect.
(2) The peak acceleration of the same test point generally increases with the increase of the input intensity of ground motion. The peak acceleration of each test point from bottom to top shows the trend of decreasing firstly and then increasing.
(3) The acceleration amplification factor of the same test point generally decreases with the increase of the input intensity.
(4) With the increase of the input ground motion intensity , the main frequency components

move from high to low frequency. It means that the soil became soften and soil modulus decreased gradually.



(a) Tianjin, Y, 0.25g

(b) Tianjin, Y, 0.75g

(c) Tianjin, Y, 1.5g

FIG. 9 Acceleration time histories and FFTs (Tianjin).

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