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Facility Performance Indexes and Rapid Test Feasibility Evaluation Method of Shaking Tables

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Abstract

Shaking table test is widely used as the main experimental approach to evaluate seismic performance of structures, and it usually consumes huge funds and labors. To ensure success of the tests, it is essential to evaluate the feasibility and accuracy before the test is conducted. However, research on test feasibility has rarely been reported. In recent years, complexity of shaking table tests has increased significantly due to the increasing demand of testing facility performance. Hence, feasibility evaluation becomes more and more important. In this paper, main performance indexes of the shaking table facility are expounded. According to the performance indexes of actuator parameters, a rapid feasibility evaluation method is then proposed based on the equilibrium between the facility capacity and the table output demand. Subsequently, applicability of the evaluation method is validated by evaluating the practical tests. The results show that the maximum acceleration targets in horizontal and vertical direction are mutually restrained under three-dimensional excitations. For the feasibility evaluation of large-scale model tests, the eccentric and overturning moment of specimen are the main performance control indexes due to their adverse influences on the facility. And the overturn-resistance of shaking table will be enhanced significantly by vertical actuators during the absence of vertical excitations. In the shaking table array test, millimeter-scale relative displacement between tables may lead to accidental damage of the test specimen or not working of the facility when the reinforced concrete foundation crosses the shaking tables. Therefore, attentions should be paid to the design of the test scheme.

Keywords: *shaking table test, performance indexes, test feasibility, test accuracy, rapid evaluation method, shaking table array*

1. Introduction

Researches on the seismic performance of civil engineering structures have always been a crucial issue in earthquake engineering (Elnashai and Di Sarno, 2008). In order to investigate the structural seismic performance and failure mechanism under strong earthquakes, experimental methods such as pseudo static test, pseudo dynamic test and shaking table test are often utilized. Among them, shaking table test is more widely used because it can replicate the true and dynamic ground motion (Severn, 2011; Crewe and Severn, 2001). In recent 20 years, a large number of complex and new type structures have emerged with the development of economy and technology, and seismic performances of these structures often need to be evaluated by tests (Guo *et al*., 2019), especially for non-structural components (Cosenza *et al*., 2015; Di Sarno *et al*., 2015, 2018). This directly promotes the construction and development of shaking table.

Development of shaking table has experienced three stages, corresponding to three types of shaking table: mechanical type, electromagnetic type and electrohydraulic type. The earliest known shaking table, a type of mechanical table, can be traced back to the hand-powered table created at the end of 19th century (Wood *et al*., 1988). Mechanical type is a device with unidirectional excitation and can only produce sinusoidal motion. In comparison, electromagnetic type has more advantages, such as a broad band of frequency, random wave producing, high quality wave shape and easy controllability (Li *et al*., 2014). However, the maximum displacement of the electromagnetic type is only 25 mm. It is difficult to carry out tests with large displacement demand. With the advancement of hydraulic actuators, control technology and digital computation, electrohydraulic shaking table that can meet larger loading and displacement demand than electromagnetic type has been constructed extensively. In 1971, the first three-axis shaking table with size of 6.1 m × 6.1 m was built at University of California, Berkeley, which marked the successful application of electrohydraulic shaking table to the field of seismic engineering (Severn, 2011; Rea and Penzien, 1973). To test performance of long-span structures under multi-support seismic excitation, shaking table array system has also been constructed. In 1979, Civil Research Institute of Japanese

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Construction Ministry built the first table array system worldwide. It consists of four unidirectional tables and each table is 3 m × 2 m. Subsequently, University at Buffalo, the State University of New York built an array system composed by two 3.6 m × 3.6 m tables in 2003. The same year, University of Nevada at Reno created an array system with three 4.3 m × 4.6 m tables (Ji *et al*., 2011).

In China, the construction of shaking table began in 1960 (Gao *et al*., 2014). Subsequently, many colleges and research institutes gradually began to build shaking tables. Among them, the shaking table in Tongji University has completed more than one thousand experiments since the 1980s. Recent years, the construction and control technology of shaking table has developed rapidly in China. Many shaking table array systems have been built, such as two 3 m × 6 m tables array system in Chongqing Communications Technology Research and Design Institute, nine 1 m × 1 m tables array system in Beijing University of Technology, three tables array system with one 4 m × 4 m and two 2.5 m × 2.5 m in Fuzhou University, four 6 m × 4 m tables array system in Tongji University and four 4 m × 4 m tables array system in Central South University (CSU) (Guo *et al*., 2013; Guo *et al*., 2016). At present, more than one hundred shaking tables have been built worldwide, most of them located in Japan, U.S. and China. In view of the construction history of shaking table, it gradually develops into large, table array, and multi degrees of freedom (DOFs). Some shaking table array systems and the corresponding technical indicators are summarized in Appendix 1.

The early study on shaking table was mainly concerned with the feasibility of large shaking table construction (Severn, 2011). Penzien demonstrated the feasibility for construction or renewal of large-scale shaking table (Penzien *et al*., 1967; Second, 1987). Sato and Ogawa stated the construction process and technological development of large-scale shaking table at National Research Institute for Earth Science and Disaster Prevention (Sato *et al*., 2004; Ogawa *et al*., 2001). Also, the basic performance indexes that reflect overall performance of the shaking table facility were illustrated. Guo (Guo *et al*., 2013) assessed the basic performance indexes of shaking table at CSU based on the actuator parameters. It also pointed out that basic performance indexes were closely related to the actuator parameters, the test specimen and the load cases (Guo *et al*., 2013). Crewe evaluated performance of four shaking tables via an European collaborative program. The results showed that although the overall performance of shaking tables met the requirements, the existing control systems were out of date (Crewe and Severn, 2001). Because the control system plays a pivotal role in shaking table system, massive control techniques were proposed to improve the fidelity of time waveform replication and the robustness against modeling uncertainty and nonlinearities (Yang *et al*., 2015; Nakata, 2010; Stehman and Nakata, 2013; Shen *et al*., 2011; Tagawa and Kajiwara, 2007; Xu *et al*., 2008). After improving the control system, numerical model of the shaking table system can be generally established to evaluate and ameliorate performance of the facility (Twitchell and Symans, 2003; Kakegawa *et al*., 2003; Blondet and Esparza, 2010; Ryu and Reinhorn, 2016). And more accurate performance indexes can be obtained by the numerical model.

Although many excellent achievements have been provided in previous studies, the evaluation of test feasibility has rarely been reported. Before the test is conducted, a detailed test scheme design is usually indispensable. Research on the scheme design is generally concern with similarity design, model design, and boundary condition setup (Liu *et al*., 2015; Zhou and Lu, 2016; Enokida *et al*., 2008; Chen *et al*., 2017). However, the test feasibility only depends on the basic performance indexes of shaking table. And the test feasibility and table output accuracy are closely related to the table-structure system, the basic performance indexes need to be reassessed in the specific tests[8]. Hence, further evaluation for test feasibility and accuracy based on the actuator parameters or the numerical model of shaking table is necessary.

In last decade, more and more complex structures emerge, such as long-span and supertall structures, which increase the difficulty of performing shaking table test and the performance requirement of testing facilities. Therefore, the test feasibility evaluation becomes more and more important, especially for tests with high acceleration and accuracy demands, as well as shaking table array test. In this study, facility performance indexes are elaborated from three levels, which are respectively based on the basic indexes, actuator parameters and numerical model of shaking table. Combining with the actuator performance indexes, a rapid evaluation method for test feasibility is presented based on the equivalence of facility capacity and table output demand. To verify the applicability of this evaluation method, feasibility of tests conducted in the shaking table array system of CSU are assessed by the proposed method. Finally, synchronism of table array test is discussed, as well as the estimated accuracy and expected performance.

2. Performance Indexes of Shaking Table Facility

2.1 Basic Performance Indexes

Basic performance indexes are often used to evaluate the overall performance of shaking tables. It mainly contains the maximum table size, maximum test weight, frequency range and so on. Table 1 lists the basic indexes of shaking table built at CSU. Meanwhile, performance curve that can reflect the basic performance indexes is shown in Fig. 1. It is a multi-axis curve that describes the relationship between frequency and displacement-velocity-acceleration. In this curve, the performance limits, such as the maximum displacement output, the maximum speed output and the maximum acceleration output, can be obtained. From Fig. 1, the maximum displacement, speed and acceleration are read as 250 mm, 0.87 m/s, and 1.0 g, respectively. These three performance limits are respectively related to maximum displacement of the actuator, oil source capacity and maximum force output of the actuator.

Table 1. Basic Indexes of the Shaking Table at Central South University (CSU)

Parameters	Technical indicators	Parameters	Technical indicators
Table size (m)	4 × 4	Maximum speed (mm·s^{-1})	Sine wave: 750
			Seismic wave: 1000
Table mass (ton)	14	Maximum acceleration (m·s^{-2})	*x*, *y*: 1.0 g (20t), 0.8 g (30t),
			z: 2.0 g (20t), 1.6 g (30t),
maximum test weight (ton)	30	Frequency range (Hz)	0.1 – 50
Maximum displacement (mm)	*x*, *y*: 250	Maximum overturning moment (ton·m)	30
	z: 160	Maximum eccentric moment (ton·m)	20

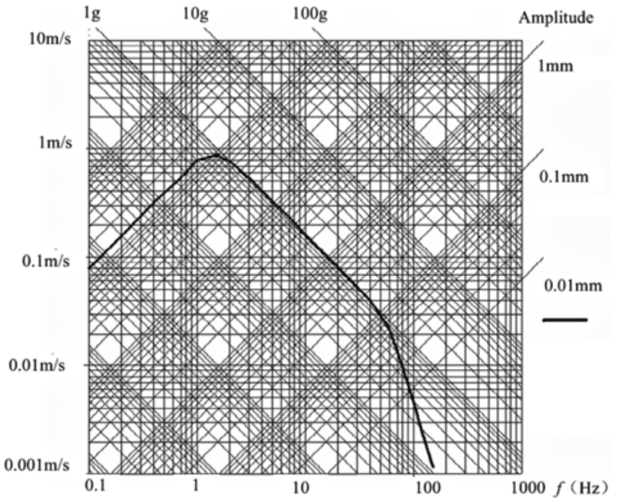


Fig. 1. Performance Curve for Shaking Table of CSU with 20ton Test Weight

Basic performance indexes on the above are often adopted as a reference for purchasing equipment and representing the overall test capacity of the facility. Moreover, method that uses the basic performance indexes to evaluate the test feasibility is usually adopted by engineers. However, this method doesn't consider the performance of actuators and the arrangement of test specimens completely. It's not possible to assess the acceleration target and accuracy of the tests. For instance, it is difficult to demonstrate the test accuracy and feasibility of large and complex test specimens, such as high-rise buildings and large span buildings.

2.2 Performance Indexes based on Actuator Parameters

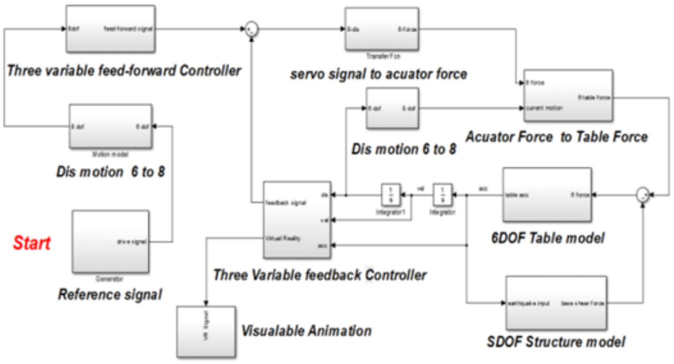
Actuators are the executive device of shaking table system. It determines the basic performance indexes. So it is of more practical significance to study the performance indexes and evaluate the test feasibility based on the actuator parameters. The main performance parameters of the actuator include loading capacity, working frequency and working displacement. Among them, the loading capacity involves static and dynamic output force, and the magnitude of the output force is directly related to the effective working area of the actuator and the operating pressure of oil source. The demand of flow rate of oil source is determined by the effective working area of actuator and the move speed of table. It will be reduced during the process of checking the capacity of oil source, due to supplement function of the accumulator. Moreover, it is necessary to know the arrangement of the actuators around the table. It has a significant effect on the calculation of performance indexes. Table 2 lists the main technical parameters of the actuators of the shaking table at CSU. The strategy that uses the performance indexes based on the actuator parameters to evaluate test feasibility is adopted in this paper. And a rapid evaluation method based on the facility capacity and table output demand will be established in the Section 3. In this method, the characteristics of actuator and test specimen are taken into account appropriately. It can effectively consider the feasibility under different test weight and ground motion. Hence, the test feasibility evaluation can be effectively completed.

2.3 Performance Indexes based on the Numerical Model of Shaking Table

To consider the internal structure and working mechanism of shaking table and evaluate the fidelity of seismic wave reproduction accurately, a more effective way is to build a numerical simulation model for shaking table system, and evaluate the test performance according to the input signal and characteristics of test specimen. Based on the simulation model, not only the performance indexes of shaking table can be obtained, but also the test feasibility can be analyzed. By the simulation results, the test scheme design can be

Table 2. The Main Actuator Parameters of Shaking Table at CSU

Parameter	Technical indicators	Parameter	Technical indicators
Effective area (mm^2)	6450	Oil flow rate (L/min)	1320
Maximum displacement (mm)	*x*, *y*:250	Accumulator volume (L)	216
Load capacity (kN)	Static output force: 174.2 (270 bar)	Distance from horizontal actuator to table center (m)	2.55
	Dynamic output force: 145 (280 bar)	Distance from vertical actuator to table center (m)	1.25



(a)

(b)

Fig. 2. Numerical Model of Shaking Table System at CSU: (a) Numerical Simulation Model Program of Shaking Table with Six DOFs, (b) The Graphical User Interface of Numerical Simulation Model by Matlab/Simulink

guided and optimized. Also the requirement for fidelity of seismic waveform and acceleration target can be met by tuning the control system and parameters of test specimen. Fig. 2(a) depicts the numerical simulation model of shaking table system with six DOFs at CSU. Fig. 2(b) displays the corresponding graphical user interface for pre and post processing. Although the evaluation method based on the performance indexes of numerical model has high test accuracy, it is not convenient for the civil engineer to conduct due to the high requirement of theory. And it will be time consuming to establish the numerical model and tune the system to be accurate.

3. Feasibility Evaluation Method of Shaking Table Test

During the test feasibility evaluation, the prime concern is to ensure the test can be carried out and the desired acceleration can be achieved. Then the test accuracy of seismic wave reproduction, which is not only related to the characteristics of the facility, but also affected by the system control algorithm, would be valued. As mentioned above, the test accuracy can be more effectively evaluated by establishing the shaking table numerical model. But this evaluation method will not be discussed in this study, and only the feasibility related to the desired acceleration is considered. A rapid feasibility evaluation method based on the equivalence between facility capacity and the table output demand will be presented in this section. The capacity depends on the performance indexes of actuator parameters. The output demand is determined by the earthquake excitation, test weight and arrangement of test specimen. Fig. 3 describes the procedure of the rapid feasibility evaluation method. In general, the greater the difference value of capacity-demand is, the higher the test accuracy is, and the easier it is to conduct the test. To a certain degree, this rapid method can estimate the test accuracy according to the capacity-demand difference value. Compared with the evaluation method based on shaking table numerical model, this method is easier and faster to be performed.

3.1 Facility Capacity *R*

3.1.1 Capacity of Force Output

For earthquake simulation shaking table system, 8 is a reasonable number of actuators required for shaking table testing that is able to utilize the available actuator forces to maximum effect in the directions in which they are most needed in earthquake engineering studies, that is, in the three translational DOFs, and at the same time exercise control over the six DOFs (Severn, 2011). Thus, the shaking table system with 8 actuators, including two in each

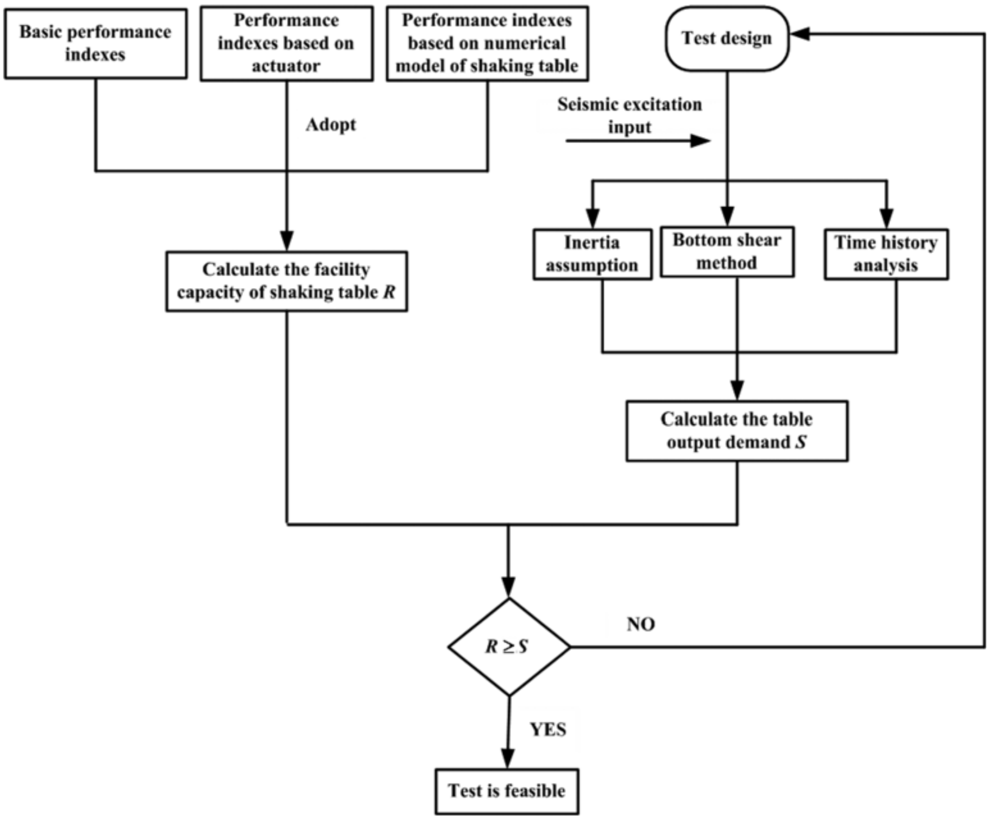


Fig. 3. Flowchart of Test Feasibility Evaluation Method based on Facility Capacity and Table Output Demand

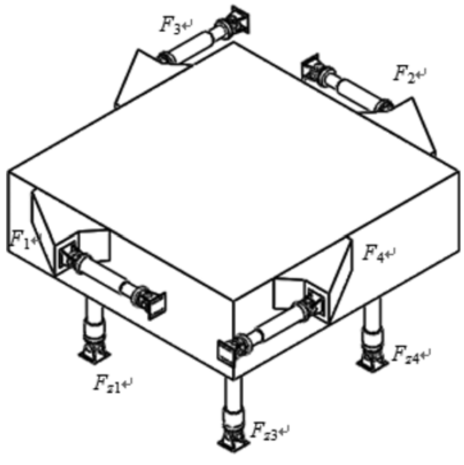


Fig. 4. Arrangement of the Actuators

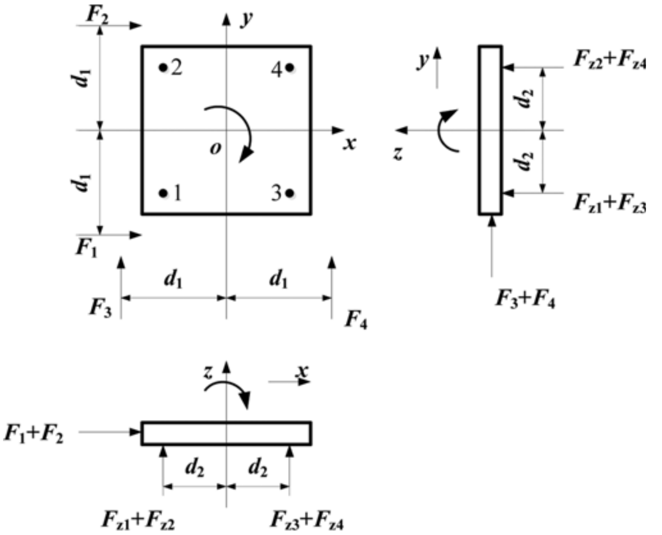


Fig. 5. Mechanical Model of Shaking Table System

horizontal direction (*x* and *y*) and 4 in the vertical direction, is adopted to illustrate the method proposed in this paper. It is noteworthy that this method can be applied or extended to other shaking table systems. The actuators are evenly distributed around the rigid working table, and their arrangement can be described as shown in Fig. 4. The corresponding mechanical model of this system is depicted in Fig. 5. All the actuators have same performance parameters. The force output capacity of actuators can be expressed as:

$$R_F = A_p P_s \tag{1}$$

where R_F is the force output capacity, when the acceleration reaches the peak value, it is calculated based on the static output due to the phase difference between velocity and acceleration; A_p is the effective working area of the actuators; P_s is the oil pressure of system operating.

3.1.2 Capacity of Eccentric-resistance

When the center of the test specimen doesn't coincide with the center of the table, eccentric moment will be generated during the vibration in the horizontal direction, and it will be balanced by the output force of the horizontal actuators. So the output force of horizontal actuators consists of two parts: one is to provide power for horizontal acceleration, and the other part is to meet the requirement of eccentric moment (Guo *et al.*, 2013). The eccentric-resistance of the table is given by:

$$R_e = \left(4R_F - \sum_{i=1}^{4} F_i\right) \times d_1 \tag{2}$$

where, F_i is the output demand of each actuator under horizontal excitation, its value will be given in Section 3.2; d_1 is the distance between horizontal actuators and the center of the table.

3.1.3 Capacity of Overturn-Resistance

The horizontal vibration will cause overturning moment on the shaking table. And the overturning moment will be balanced by the output force of the vertical actuators. So the output of the vertical actuator consists of two parts: one is to provide the power to generate vertical acceleration, and the other is to meet the requirement of overturning moment (Guo *et al.*, 2013). Because the total mass of the test specimen and the table is balanced by the static support system of the vertical actuator, the overturn–resistance of the shaking table is obtained as:

$$R_T = \left(4R_F - \sum_{i=1}^{4} F_{zi}\right) \times d_2 \tag{3}$$

where, F_{zi} is the output demand of each actuator under vertical excitation, its value will be given in Section 3.2; d_2 is the distance from the vertical actuators to the center of the table.

3.1.4 Capacity of Oil Source

Oil source is an important part in the shaking table system, and it drives the motion of the actuators via the high oil pressure. Capacity of the oil source is determined by the oil supply equipment, and it can be expressed as:

$$R_o = Q_{\max} \tag{4}$$

where, $Q_{\max}$ is the maximum oil flow rate of the oil supply equipment. For the shaking table at CSU, it's 1320 L/min, as listed in Table 2.

3.2 Table Output Demand *S*

Assuming that the test specimen is a rigid system, the relationship between the output force of each actuator and the acceleration target can be calculated as following:

$$F_1 + F_2 = F_3 + F_4 = (m + m_t)a \tag{5}$$

$$\sum_{i=1}^{4} F_{zi} = (m + m_t)a_z \tag{6}$$

where, m is the specimen mass, m_t is the table mass; a is acceleration in x direction and y direction, and the acceleration targets of x direction and y direction are identical; a_z is the vertical acceleration target. If the layout of specimen is symmetry and the mass distribute evenly, it can be deemed that F_1 equals to F_2, F_3 equals to F_4, and F_{zi} equal to each other. For the multiple shaking tables test, the checking calculation can be performed by simplifying the test to be single shaking table test according to the mechanical characteristics of the shaking table-structure system. The actuator demand can be expressed as:

$$S_F = \max\{F_i, F_{zi}\} \tag{7}$$

Similarly, according to the assumption of inertia, the demand for eccentric and overturning moment of the shaking table can be calculated as:

$$S_e = ma(e_x + e_y) \tag{8}$$

$$S_T = \frac{1}{2} m\alpha a h \tag{9}$$

where, S_e and S_T are the demand of eccentric and overturning moment respectively; e_x and e_y are the eccentric distance of specimens in x direction and y direction respectively; h is the height of the specimen, and it is assumed that the specimen mass distributes evenly along the height of test specimen; α is the horizontal acceleration amplification factor and can be adopt as 2.25 according to the Chinese code (GB 50011-2010, 2010).

Oil flow rate demand of the equipment is related to the move speed of shaking table, and it can be calculated as following:

$$S_o = 8A_P V + Q_1 \tag{10}$$

where, S_o is the oil flow rate demand; V is the peak velocity of the input excitation, and peak velocity for each direction is regard as equal; Q_1 is extra oil flow rate that is required for oil compression, leakage and other factors. Considering the beneficial effect of the accumulator, one third of the peak ground velocity would be used as V (Guo *et al.*, 2013; Penzien *et al.*, 1967).

On the above, table output demands are obtained based on the assumption of inertia. But if taking natural vibration characteristics of the test specimen into account, auxiliary calculation, such as base shear method and time history analysis, is sometimes needed to improve the precision of calculation.

3.3 Equilibrium of Capacity and Demand

According to the Section 3.1 and 3.2, the test feasibility can be evaluated by the following formulas:

$$S_F \le R_F \tag{11}$$

$$S_e \le R_e \tag{12}$$

$$S_T \le R_T \tag{13}$$

$$S_o \le R_o \tag{14}$$

Substituting the equal sign into Eqs. (12) and (13), and then integrating the formulas, the maximum performance of the horizontal and vertical acceleration can be obtained as:

$$a = \frac{4R_F}{m\left(e_x + e_y\right)/d_1 + 2\left(m + m_t\right)} \tag{15}$$

$$a_z = \left(4R_F - \frac{m\alpha ah}{2d_2}\right)\Big/\left(m + m_t\right) \tag{16}$$

It should be noted that the Eq. (11) should be checked according to output force of each actuator after calculating the maximum acceleration from Eqs. (15) and (16). If the equation is not met, it should be calculated again according to output force capacity of the actuators. Moreover, if Eq. (14) cannot be met, the ground motion should be selected again.

From the Eqs. (15) and (16), it can be found that the horizontal acceleration performance is controlled by eccentricity and mass. Hence, the center of test specimens should coincide with the center of shaking table, and bidirectional eccentricity should be avoided as far as possible. The vertical acceleration performance is inversely proportional to the horizontal acceleration and the height of test specimen. It reveals that the horizontal and vertical acceleration performances are restricted to each other under action of three-dimensional excitation.

4. Test Feasibility Evaluation

The calculation principle and evaluation method have been given above. However, it still needs to evaluate for specific test in combination with the corresponding arrangement of table-specimen system. To verify the applicability of the rapid evaluation method, in this section, the shaking table tests conducted at CSU will be evaluated by the proposed method. High-speed railway multi-function shaking table array system of CSU has completed the construction of six DOFs system. It equips with one fixed table and three mobile tables. Total mass of each table and its annex is $m_t = 14.8$ ton, and the other major technical indicators have been listed in Table 1. The arrangement of actuators has plotted in Fig. 4 and the actuator parameters have been shown in Table 2.

4.1 Feasibility Evaluation of Single Shaking Table Test

Three tests using single shaking table would be evaluated here. Fig. 6 shows the test model of the high speed railway station. The test specimen arranged symmetrically, and only the horizontal acceleration input. Maximum mass of the specimen is 23 ton (Liu *et al*., 2016). Because the layout is symmetrical, the test weight doesn't exceed the load capacity and without vertical excitation, the eccentric and overturning demands are met easily. Fig. 7 shows the test model of high speed railway station hall. Center of this specimen coincides with the center of table. Mass of the specimen is 6.8 ton, and the acceleration input only in vertical direction (Yu *et al*., 2014). Due to no excitation in the horizontal direction and the symmetry of the specimen, there is no eccentric and overturning moment approximately. Fig. 8 displays the test model of twin tower in the Shenyang metro depot. Its total mass is 21.48 ton, and the excitation is only in the

Fig. 6. Test Model of High Speed Railway Station

Fig. 7. Test Model of High Speed Railway Station Hall

Fig. 8. Test Model of the Twin Tower

Table 3. The Capacity and Demand of Actuators

Test number	Test name	Acceleration target set in test (g)	Actuator demand S_F (kN)	Actuator capacity R_F (kN)	(R-S)/R	Feasibility
A	High speed railway station test	1.14	215.5	174.2	-24%	Infeasible
B	High speed railway station hall test	1.989	103.4		41%	Feasible
C	The twin towers test	1.01	183.2		-5%	Infeasible

horizontal direction (Li *et al*., 2017). Considering the eccentric distance and the height of test specimen are both small, as well as without vertical excitation, the demands for eccentric and overturning performance are easy to be met. Therefore, the feasibility of the above tests is determined by the capacity and demand of the actuator force output. Table 3 calculates the actuator capability and demand via the proposed method.

From Table 3, it can be observed that the capacity in the test A is obviously smaller than the demand, so the setting acceleration target cannot be realized. Measured maximum acceleration of test A is 0.75 g (Liu *et al*., 2016), which is much smaller than the setting value. The capacity in test B is much larger than the demand, and the setting acceleration target is easy to be achieved. Measured maximum acceleration of test B is 1.986 g (Yu *et al*., 2014), which matches well with the setting value. In test C, the demand exceeds the capacity by 5%. It is deemed that the acceleration target cannot be attained. But 5% is an acceptable error in the actual project, and measured maximum acceleration of test C attains 1.01 g (Li *et al*., 2017). The above tests all used one shaking table, and the demands of overturning and eccentricity can be met easily. In this kind of routine test, the performance control indexes are the specimen mass and the acceleration target.

4.2 Feasibility Evaluation of Shaking Table Array Test

In large-scale model or table array test, the feasibility evaluation will be more complex due to the significant effect of eccentricity or overturning effect. To evaluate the feasibility for this kind of test, a practical test performed at CSU is taken as an evaluation example. This test uses two shaking tales, and it’s vulnerable to eccentric and overturning moment.

4.2.1 The Test Model

Prototype structure of the test model is a three-story residential building, and the test similarity scaling factors are shown in Table 4. Dimensions of the test structure are 4.5 m high, 4.8 m length and 2.55 m wide, and each story height is 1.5 m. All structural components are connected by the high strength bolts. The floor plan of the test model is shown in Fig. 9, and the elevation view of the test structure is described in Fig. 11. A rigid foundation of reinforced concrete with a plane size of 5.8 m length and 3.5 m wide is made to support the test structure. It composes of the base plate and the foundation beam. The thickness of the base plate is 200 mm, and the total height of the rigid foundation is 400 mm. Fig. 10 depicts the rigid foundation model.

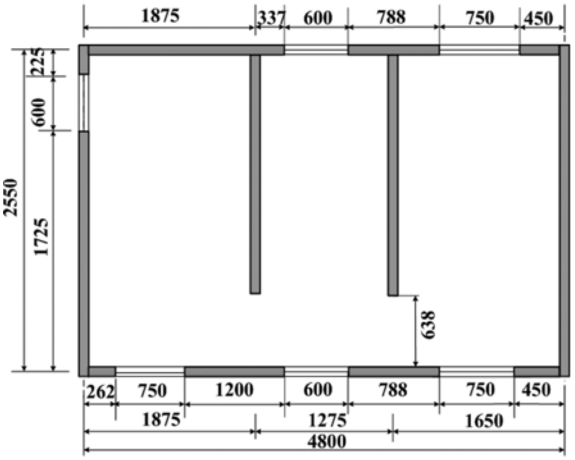


Fig. 9. Floor Plan of the Test Model (unit: mm)

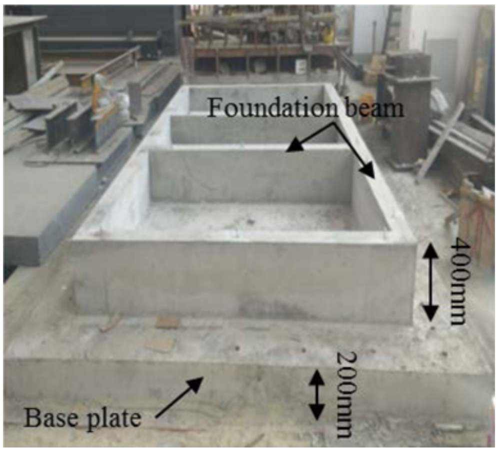


Fig. 10. The Rigid Foundation Model

Total mass of the test model distributed on two shaking tables is 39.9 ton, including the superstructure mass 20.8 ton, the rigid foundation mass 13.1 ton, the dead and live load 6.0 ton. According to the load capacity of shaking table, two tables are adopted in this test. By debugging the relative position, 1.265 m is selected as the distance between the two tables. Layout of the test specimen and tables is described in Fig. 12. The assembled structure model is shown in Fig. 13. The two tables are completely disconnected. The foundation is connected to the tables by high strength bolts, and sliding is not allowed during the test. According to the experimental design, the seismic excitation is only input in horizontal directions, and the acceleration target, *a*, is set as 0.8 g.

4.2.2 Feasibility Evaluation

According to layout of the test model, the eccentric moment on

Table 4. Similarity Scaling Factors of the Test Model

Physical parameter	Scaling ratio	Physical parameter	Scaling ratio	Physical parameter	Scaling ratio
Length	0.5	Mass	0.125	Period	0.5
Strain	1.0	Force	0.25	Frequency	2
Elastic modulus	1.0	Line load	0.5	Velocity	1.0
Stress	1.0	Area load	1.0	Acceleration	2
Density	1.0	Moment	0.125	Gravity acceleration	1.0

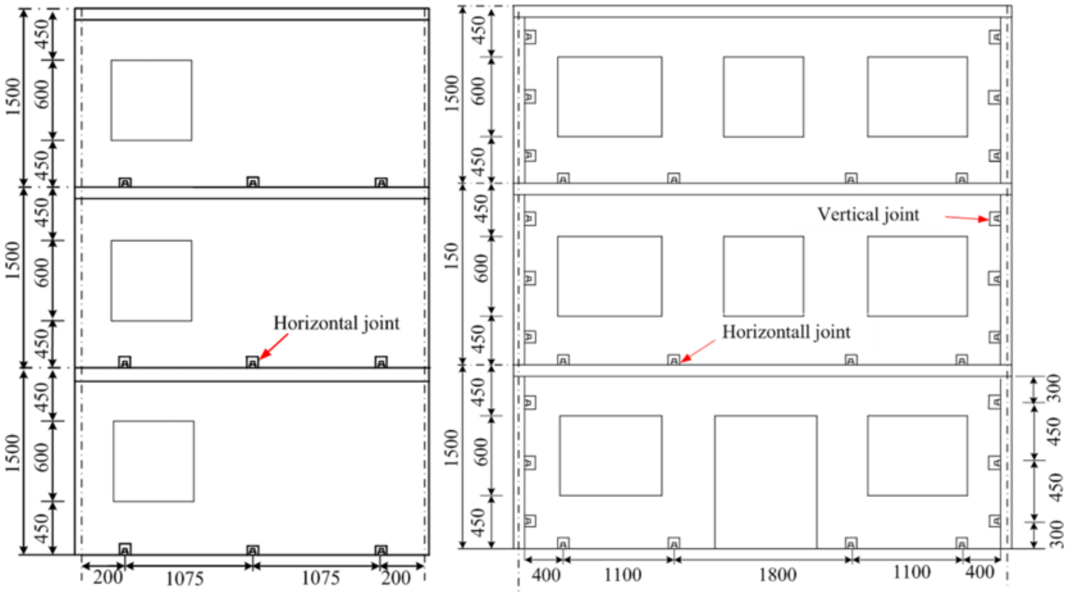


Fig. 11. Elevation View of the Test Structure (unit: mm)

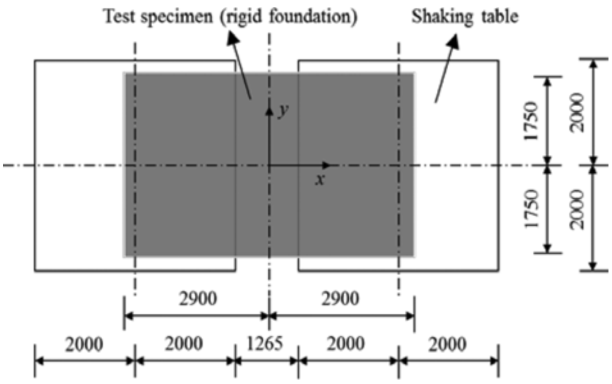


Fig. 12. Layout of the Test Model and Shaking Tables (unit: mm)

Fig. 13. The Test Model

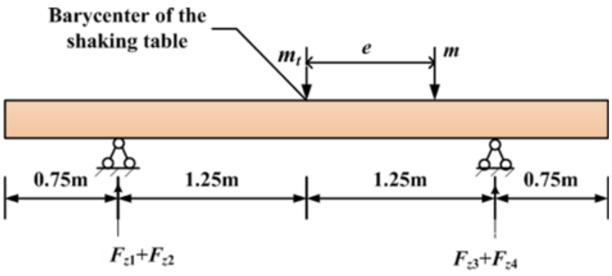


Fig. 14. Equivalent Calculation Model of Single Table

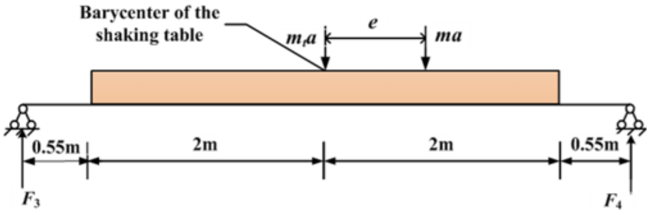


Fig. 15. Calculation Diagram of y Directional Vibration

the table can be neglected under x directional vibration. But there is a significant eccentric effect under y directional vibration. Due to the eccentric effect, the basic performance indexes cannot be used to evaluate the test feasibility. Considering the symmetry of test specimen, a half-edge structure is advisable and an equivalent calculation model for single shaking table can be acquired, as shown in Fig. 14. In this equivalent model, the vertical actuator output force F_{z1} equals to F_{z2}, F_{z3} equals to F_{z4}, and the specimen mass, m, equals to19.95 ton. Assuming that the feedwback force of the test structure on the working table distributes evenly, the eccentric distance, e, can be calculated as 0.866 m.

The x directional actuators don't contribute to the eccentric-resistance as a result of equal output force ($F_1 = F_2$). Combined with the single table equivalent model, the calculation diagram of the specimen in y directional vibration is obtained and described in Fig. 15. The hinge supports in the figure are the positions of two y-directional actuators. Through calculating the moment at left hinge joint and combining with the method in Section 3, it can be obtained that $F_1 = F_2 = 139$ kN, $F_3 = 112$ kN, $F_4 = 166$ kN. Since no vertical excitation is input, the force of vertical actuators $F_{zi} = 0$. As the mass of the rigid foundation is comparable to that of the test specimen, the overturning demand should be calculated by superposition of overturning moment of the foundation and the superstructure. In addition, the oil flow rate for pilot valve and leakage of the actuators are respectively estimated to be 70 L/min and 32 L/min. The peak velocity of the selected seismic excitations is 49.9 cm/s as shown in Fig. 16. According to the analysis above, the capacity and demand of the facility can be obtained by the method in the Section 3, as listed in Table 5. The results indicate that the facility capacities are greater than the demands, and the eccentric-resistance, overturn-resistance and oil source capacity are all surplus. Hence, it’s deemed that the acceleration target can be achieved and the test is feasible.

From the Eq. (15), the maximum acceleration target can be calculated as 0.91 g. And the corresponding demands of the actuators is $F_1 = F_2 = 158.1$ kN, $F_3 = 127.4$ kN, $F_4 = 188.8$ kN. It is can be found that the actuator capacity $R_F = 174.2$ kN is unable to meet the requirement. So the maximum acceleration should be calculated according to the actuator capacity, and the demands for the actuators are $F_1 = F_2 = 145.9$ kN, $F_3 = 117.7$ kN, $F_4 = 174.2$ kN. The corresponding maximum acceleration is 0.84 g. Meanwhile, the overturning demand is calculated as 69.7 ton·m, that is, the overturning capacity meets the demand. Therefore, maximum achievable acceleration performance of the test is 0.84 g.

If there is no eccentricity in this test, the maximum acceleration will reach up to 1.0 g. It reveals that eccentricity has a great influence on the test performance. Moreover, although the test is large-scaled and the total height reaches up to 5.1 m, the overturning demand is still easy to be met. Hence, it is deemed that the overturning capacity of the shaking table can generally meet the demand when no vertical excitation is input in the test.

4.2.3 Revalidation of Overturn-resistance

Nonlinear time history analysis and base shear method can

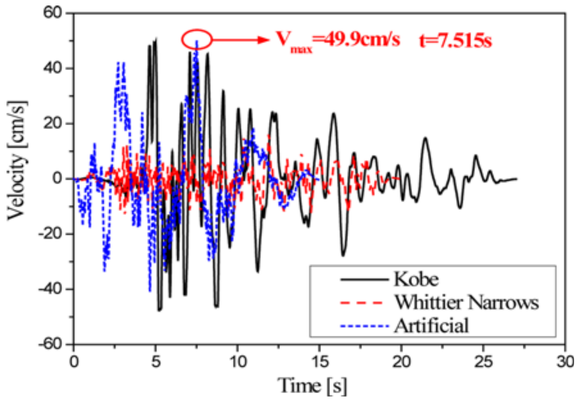


Fig. 16. Velocity Time Histories of Earthquake Waves

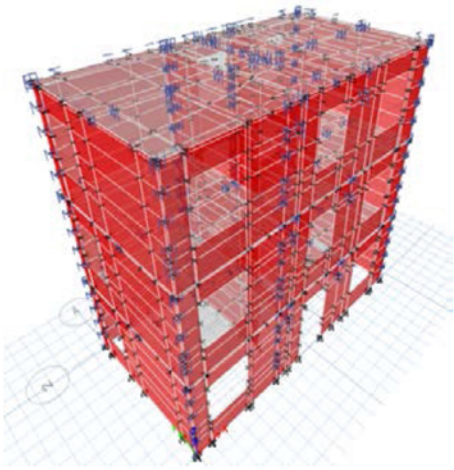


Fig. 17. Finite Element Model of Prototype Structure

Table 5. The Facility Capacity and Table Output Demand

Evaluation items	Facility capacity *R*	Seismic demand *S*	(*R-S*)/*R*	Feasibility
Output force of actuator	174.2 kN	166 kN	5%	Feasible
Eccentric moment	35.9 ton·m	13.8t on·m	62%	
Overturning moment	87.1 ton·m	66.3 ton·m	24%	
Oil source flow rate	1320 L/min	617 L/min	53%	

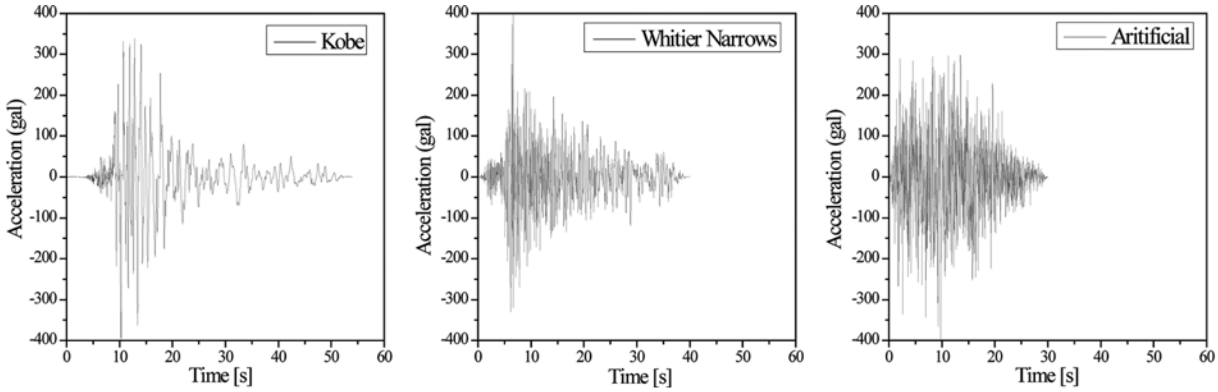


Fig. 18. Acceleration Time Histories

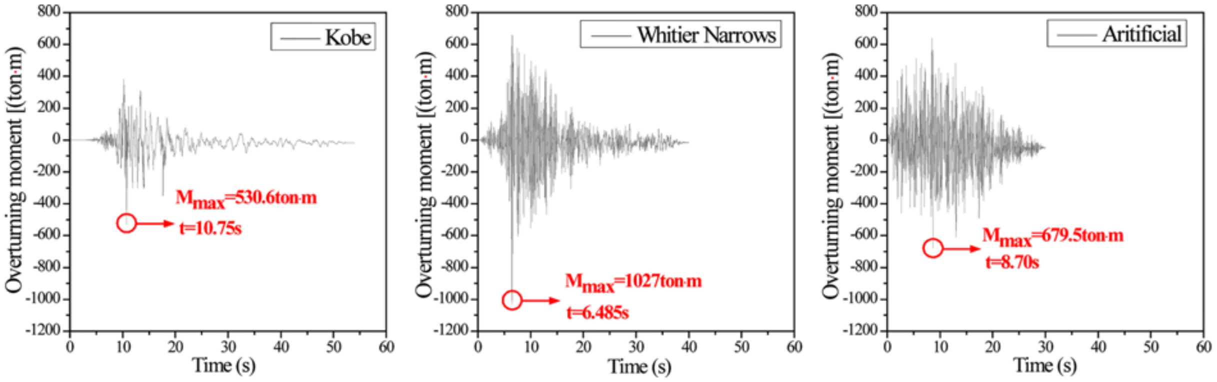


Fig. 19. Overturning Moment Time Histories

also be used to calculate the demand of overturning moment. In this section, the overturning demand is further computed by the two methods. Finite element model of the prototype structure is established by ETABS (Computers and Structures, Inc., CA., 2016), as depicted in Fig. 17. According to the test scheme design, two earthquake records (Kobe, 1995; Whittier Narrows, 1987) and an artificial seismic wave are selected as the input excitations. The acceleration time histories of seismic excitations and the structural overturning moment time histories obtained by nonlinear time history analysis are displayed in Fig. 18 and Fig. 19, respectively. It shows that peak values of the overturning moment corresponding to the three excitations are 5,30.6 ton·m, 1,027.0 ton·m and 679.5 ton·m, respectively. That is, the maximum overturning demand is 1027.0 ton·m. According to the similarity scaling ratios, the maximum overturning demand of the test is 128.4 ton·m, and the maximum overturning demand for single shaking table is 64.2 ton·m. This result reveals that the overturning capacity, $R_T = 87.1$ ton·m, exceeds the demand. The requirement of overturning performance is met.

Meanwhile, the overturning moment of prototype structure can also be calculated via base shear method using a simplified story model. Based on the finite element analysis, the fundamental period of prototype structure is $T_1 = 0.112$s. According to the Chinese code (GB 50011-2010, 2010), the design characteristic period of ground motion, T_g, which refers to the period value corresponding to the starting point of the descending segment in the design response spectrum, is adopted as 0.35s. Total seismic force of the structure is computed as $F_{EK} = 1{,}533$ kN. Table 6 lists the seismic force of each story. Overturning moment of the structure is calculated as 1073.7 ton·m from this table. According to the similar relationship, overturning demand of the test is 1,34.2 ton·m, and for the single shaking table is 67.1 ton·m. Hence, the demand for overturning is met. In addition, the maximum overturning demand calculated by the base shear method and the time history analysis is almost equal to the result shown in Table 5, and the maximum relative difference is only 3%.

Table 6. Seismic Force of Each Story

The story level	Representative value of gravity load (kN)	Calculation height (m)	Seismic force (kN)
First story	671.1	3	256.7
Second story	662.0	6	506.5
Third story	670.7	9	769.8

4.2.4 Synchronism of Shaking Table Array Test

Under the action of gravity load, output force of each vertical actuator in the static support system can be calculated by the equivalent calculation model in Fig. 14. The output forces are obtained as follows: $F'_{z1} = F'_{z2} = 52.3$ kN, $F'_{z3} = F'_{z4} = 121.5$ kN. Because the output forces between the vertical actuators have a significant difference, the shaking table may be induced to tilt during the lifting process. Furthermore, it may cause the damage of reinforced concrete rigid foundation and test specimen. The greater the difference is, the higher the risk of structural damage is. In order to reduce the risk, an effective method is to add counterweight on the shaking table. The counterweight should be close to the outside of the table as far as possible. Fig. 20 shows an example to add counterweight. Yet the extra counterweight will result in a decrease of acceleration performance inevitably. To ensure that the acceleration target can be achieved, counterweight should be reasonably controlled. If the conditions permit, it's suggested to reduce the weight of reinforced concrete rigid

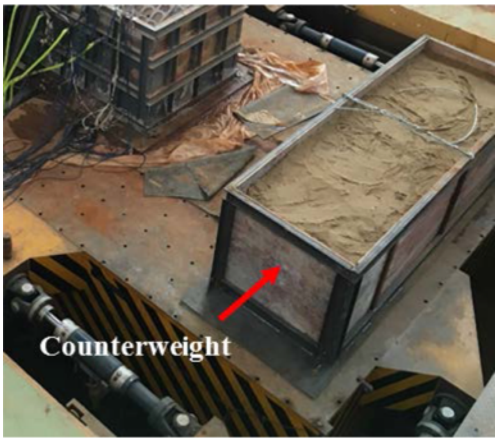


Fig. 20. Schematic Plot of Counterweight

foundation in the case of adequate foundation stiffness.

When two or more shaking tables are utilized in the test, relative displacement between the tables may be generated. Although the influence of the millimeter-scale relative displacement on the bridge structure test can be ignored, it cannot be accepted for the reinforced concrete rigid foundation that crosses the tables. It may cause the device to stop working, even result in the failure of rigid foundation and test specimen. Therefore, the influence caused by the relative displacement is analyzed through the finite element model of prototype structure. According to the layout of the test model, the ground displacement load is applied to the corresponding base node (nodes on one of the two shaking tables). Fig. 21 shows the deformation of the structure under the 2 mm displacement load in vertical direction. The feedback force of the prototype structure and the test model are obtained, as listed in Table 7. It can be observed that even millimeter-scale relative displacement has caused great feedback force. It will affect the stability and reproduction accuracy of the shaking table system, and may cause serious damage to the test specimen. To deal with this problem, a solution is to tune the controller and adopt a unified control system for the two shaking tables. Thereby, relative displacement between the shaking tables can be confined.

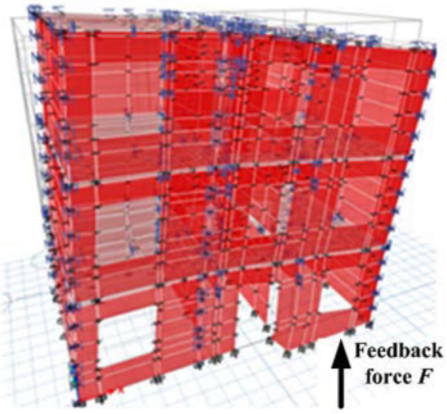


Fig. 21. Deformation of Prototype Structure Under Vertical Displacement Load

Table 7. Ground Displacement Load and Feedback Force

Load direction	Displacement load /mm	Feedback force of prototype F (kN)	Feedback force of test model (kN)
x	2	2,500.0	625.0
y	2	4,325.2	1,081.3
z	2	1,342.4	335.6

5. Discussions on Estimated Accuracy and Expected Performance

The model test of twin-tower connecting structure conducted by the author's group recently, in which the output signal is measured, is evaluated by the proposed method to discuss the estimated accuracy and expected performance. The model's similarity scaling factors of dimension and acceleration are 1/45 and 3, respectively. The test model is composed of tower A, tower B and rigid base, the mass and height of each part is shown in Fig. 22. The two towers have different height and mass, the maximum height of the test model attains to 7.05 m, which both present a challenge for the overturning capacity of the facility under three-direction input. Two critical loading cases are proposed: 1) the target acceleration in each direction is $a_x = 0.3$ g, $a_y = 0.255$ g and $a_z = 0.195$ g, respectively; 2) the target acceleration in each direction is $a_x = 0.66$g, $a_y = 0.561$ g and $a_z = 0.429$ g, respectively. The facility capacity and table output demand are listed in Table 8, which can be calculated by the equations derived in Appendix 2 and Appendix 3.

In the rapid test feasibility evaluation method, the capacity-demand difference value determines the test accuracy and performance. Thus, the capacity margin factor defined as $(R\text{-}S)/R$ is adopted to assess the test accuracy and performance. For this test model, overturning moment is the control index. Under loading case 1, the capacity margin factor of overturning moment equals 41%, indicating that the desired test accuracy and expected acceleration performance would be achieved, which is validated by Fig. 23 that shows the comparison of the target and measured

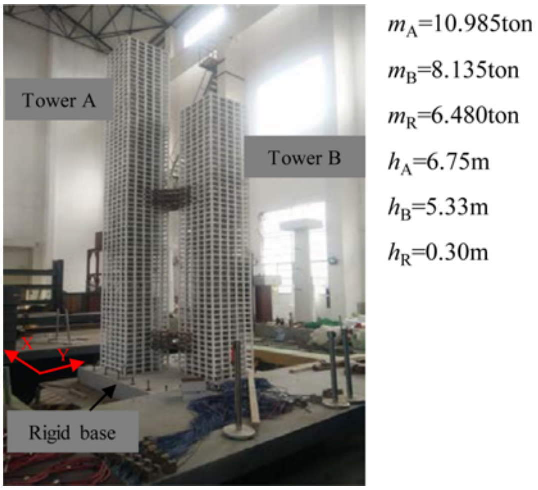
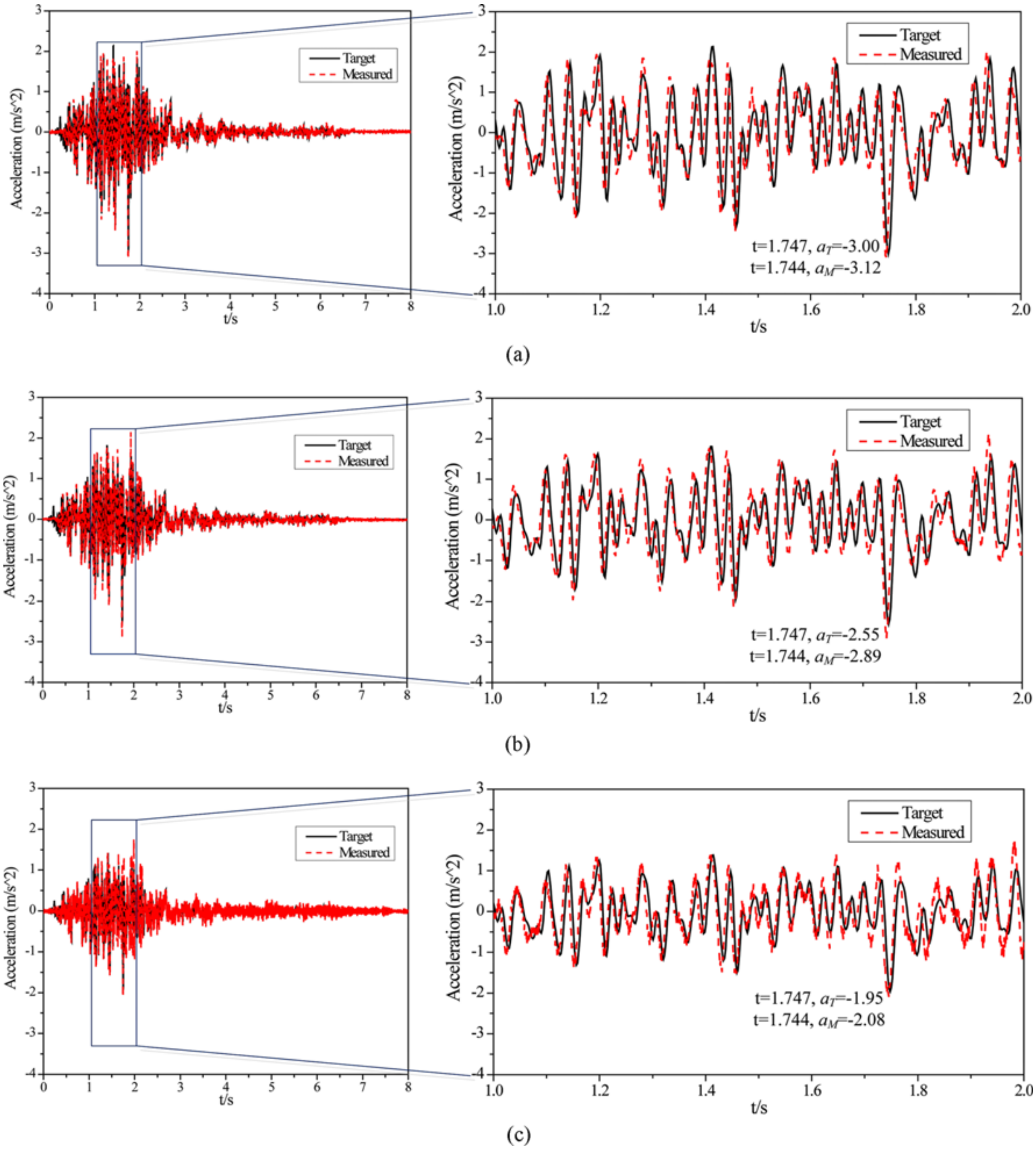


Fig. 22. Test Model of Twin-tower Connecting Structure

Table 8. The Facility Capacity and Table Output Demand

Evaluation items	Case 1: $a_x = 0.3$ g; $a_y = 0.255$ g; $a_z = 0.195$ g				Case 2: $a_x = 0.66$ g; $a_y = 0.561$ g; $a_z = 0.429$ g			
	Facility capacity R	Seismic demand S	$(R\text{-}S)/R$	Feasibility	Facility capacity R	Seismic demand S	$(R\text{-}S)/R$	Feasibility
Output force of actuator	174.2 kN	61.4 kN	65%	Feasible	174.2 kN	135.2 kN	22%	Infeasible
Eccentric moment	12.05 ton·m	1.31 ton·m	89%		5.19 ton·m	2.87 ton·m	45%	
Overturning moment	72.0 ton·m	42.3 ton·m	41%		65.4 ton·m	93.0 ton·m	-42%	



(a)

(b)

(c)

Fig. 23. Comparison of the Target and Measured Signal in Each Direction: (a) *x* Direction, (b) *y* Direction, (c) *z* Direction

signal. Under loading case 2, the capacity margin factor of overturning moment equals -42%, indicating that this case is infeasible. Therefore, the loading case 2 haven't been performed. In summary, the estimated accuracy and expected performance of the proposed rapid evaluation method are reliable. In order to ensure the test accuracy, it suggests that the capacity margin factor of the control index should be larger than 10% in the view of engineering perspective.

6. Conclusions

Shaking table test is an important experimental method to investigate the seismic performance of structures. To ensure successful completion of the tests, the feasibility evaluation is prerequisite. However, research on test feasibility has rarely been reported in literatures. In this study, facility performance indexes of the shaking table are elaborated from three levels, and a fast feasibility evaluation method based on facility capacity and table output demand is proposed. Then, feasibility of the practical tests is evaluated by the present method. And the following conclusions are drawn:

1. The applicability of presented fast test feasibility evaluation method is validated by the practical tests. It's more effective than the method using basic performance indexes, and more convenient than the method using numerical model of shaking table system.
2. The horizontal and vertical acceleration performances are mutually restricted under three-dimensional seismic exci-

tations. Therefore, horizontal and vertical acceleration target should be reasonably controlled during the test.

3. For the test with regular arrangement, low structural height and single shaking table used, the feasibility is generally easy to be met because the eccentricity and overturning can be ignored, and the performance control indexes are the specimen mass and acceleration target. Hence the test similarity design and structural materials should be controlled.
4. The test performance will be greatly affected by the obvious eccentricity and overturning effect in the large-scaled test, and the eccentric and overturning performance will be the main control indexes. If only horizontal excitation is input, the overturn-resistance of shaking table will be enhanced significantly by the vertical actuators. To ensure the test accuracy, it suggests that the capacity margin factor of the control index should be larger than 10%.
5. In shaking table array tests, synchronism of the multiple tables should be paid attention to. The relative displacement between tables may lead the rigid foundation and superstructure to be damaged. Even more it may result in the failure of the test.

Acknowledgements

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Appendix 1. Summary of Shaking Table Array Systems

Table 9. Some Shaking Table Array Systems

Institution	Shaking table number	DOFs	Table size (m)	Maximum Payload of single table (ton)	Frequency (Hz)	Maximum acceleration (g)	Maximum displacement (mm)	Maximum velocity (m/s)
Japanese Construction Ministry, 1979	4	1	3 × 2	2.5	0 – 50	0.7	±75	0.6
University at Buffalo, America, 2003	2	3	3.6 × 3.6	50	0 – 50	1.15	±150	x, y: 1.25 z: 0.5
University of Nevada, America,2003	3	2	4.3 × 4.6	45	0 – 50	1.0	±300	1.27
New Saclay Testing Facility, France	2	2	6 × 6	100	0 – 100	1.0	±500	1.0
University of Naples, Italy	2	2	3 × 3	20	0 – 50	x, y: 1.0	±250	1.0
Chongqing Communications Technology Research and Design Institute, China, 2004	2	6	3 × 6	35	0.1 – 50	1.0	x, y: ±150 z: ±100	0.8
Beijing University of Technology, China, 2006	9	6	1 × 1	5	0.4 – 50	1.5	±75	0.6
Central South University, China, 2007	4	6	4 × 4	30	0.1 – 50	x, y: 0.8 z: 1.6	x, y: ±250 z: ±160	1.0
Tsinghua University, China, 2009	2		1.5 × 1.5					
Fuzhou University, China,2009	3	2	4 × 4(1)/2.5 × 2.5(2)	22/10	0.1 – 50	x: 1.5 y: 1.2	±250	x, y: 1.0 z: 0.95
Institute of Engineering Mechanics, China Earthquake Administration, 2009	2	6	5 × 5/ 3.5 × 3.5	30/6	0.1 – 100	x, y: 4.0 z: 3.0	x, y: ±500 z: ±200	x, y: 2.4 z: 1.8
Tongji University, China, 2011	4	3	4 × 6	50(2)/30(2)	0.1 – 50	1.5	±500	1.0
Tianjin University, China	2	6	diameter 3.6	20/12	0.1 – 100	x, y: 1.5 z: 1.2	x, y: ±300 z: ±200	x, y: 1.0 z: 0.8
Beijing University of Civil Engineering and Architecture, China (under construction)	4	6	5 × 5	60	0.1 – 50	x, y: 1.5 z: 1.2	x, y: ±400 z: ±200	x, y: 1.0 z: 1.0

Appendix 2. Equivalent structural model

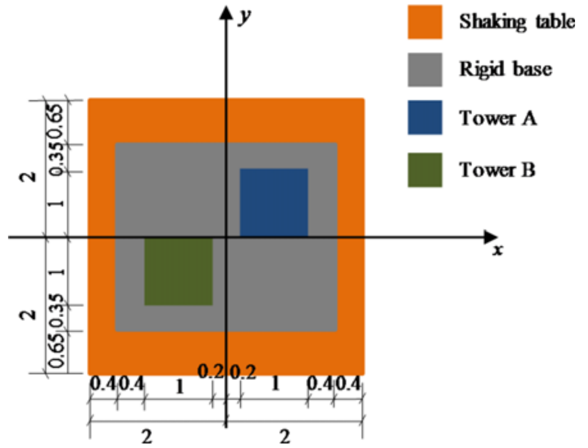

Fig. 24. Layout of the twin-tower connecting structural model and shaking table (unit: m)

Figure 24 shows the layout of the twin-tower connecting structural model and shaking table. Due to height and mass of the two towers are different, so it needs to simplify the structural model. The coordinate, (e_y, e_x), and height, h_{eq}, of the equivalent structural model can be calculated by Eqs. (17) – (19).

$$e_x = (m_A \times 0.5 - m_B \times 0.5 + m_R \times 0)/(m_A + m_B + +m_R) = 0.056\text{m} \tag{17}$$

$$e_y = (m_A \times 1.2 - m_B \times 1.2 + m_R \times 0)/(m_A + m_B + m_R) = 0.134\text{m} \tag{18}$$

$$h_{eq} = [m_A \times (h_A + h_R) + m_B \times (h_B + h_R)]/(m_A + m_B) - h_R = 6.15\text{m} \tag{19}$$

Appendix 3. Performance Calculation

Figures 25 and 26 are the calculation diagram of horizontal and vertical vibration, respectively. Considering the eccentric distance e_x is small, it can assume $F_{z1} = F_{z2}$, $F_{z3} = F_{z4}$ for vertical vibration. According to the proposed rapid evaluation method, the facility capacities and table output demands can be obtained by Eqs. (20) –(23).

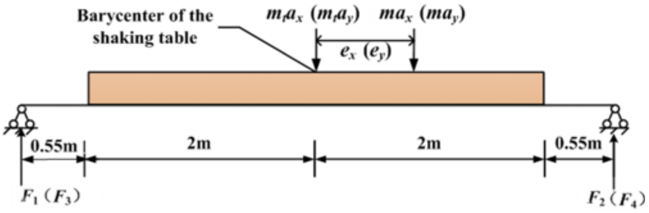

Fig. 25. Calculation Diagram of Horizontal Vibration

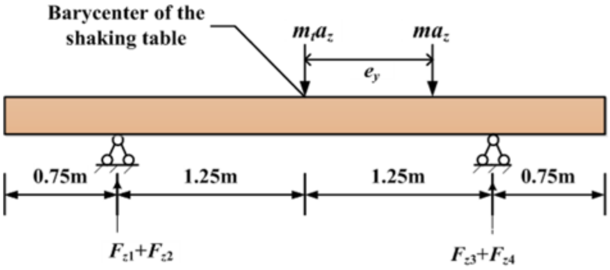

Fig. 26. Calculation Diagram of Vertical Vibration

$$\begin{cases} m = m_A + m_B + m_R \\ F_1 + F_2 = (m + m_t)a_x \\ (F_1 - F_2)d_1 = ma_xe_x \\ F_3 + F_4 = (m + m_t)a_y \\ (F_3 - F_4)d_1 = ma_ye_y \end{cases} \tag{20}$$

$$S_e = m(a_xe_x + a_ye_y); R_e = \left(4R_F - \sum_{i=1}^{4} F_i\right)d_1 \tag{21}$$

$$\begin{aligned} S_T &= \frac{1}{2}m_R\alpha a_x h_R + \frac{1}{2}(m_A + m_B)\alpha a_x (h_{eq} + h_R); R_T \\ &= [4R_F - (m + m_t)a_z]d_2 \end{aligned} \tag{22}$$

$$\begin{cases} \sum_{i=1}^{4} F_{zi} = (m + m_t)a_z \\ (F_{z1} + F_{z2})d_2 - (F_{z3} + F_{z4})d_2 = ma_ze_y \end{cases} \tag{23}$$