# Shaking Table Model Test of Isolated Structure on Soft Site and Analysis on Its Isolation Efficiency

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**Abstract:** Adopting a soft site model built on soft interlayer soil foundation , a shaking table test for soft interlayer soil-isolated structure interaction is conducted to investigate the seismic response of isolated structure on soft site, and analyze its isolation effect. Test results show that the test can reflect the earthquake response characteristics of isolated structure on soft site. It is on soft site that the dynamic characteristics of isolated structure, acceleration magnification factor (AMF) of isolated structure and isolation efficiency of the isolation layer differ from those on rigid foundation with an soil-structure interaction (SSI) effect, represented by the reduction in fundamental vibration frequency of isolated structure and the increase of damping ratio with changes of the SSI effect. SSI can either increase or decrease AMF of isolated structure on soft site, depending on the characteristics of earthquake motion input. Furthermore, the isolation efficiency of isolation layer on soft site is decreased with the SSI effect, which is related to the peak ground acceleration (PGA) and the characteristics of earthquake motion input.

**Key words:** isolated structure; shaking table model test; soil-structure interaction (SSI); seismic response; isolation efficiency

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## 0 Introduction

Base-isolated structure has been widely used to reduce the earthquake damages for many kinds of structures. However, base-isolated structure may be built on a soft site in practical engineering, whose basal earthquake motion will become a long-period motion under strong earthquake. The dynamic soil-structure interaction (SSI) thus significantly influences the dynamic characteristic and earthquake response of the isolated structure[1], which in turn affects the isolation efficiency of the isolation layer. Therefore, the SSI effect should be considered in the seismic design of the isolated structures on a soft site.

As a dominant method used to study soft soil-isolated structure interaction system at the present time, numerical simulation has reported some findings[2-5]. However, the method of numerical simulation relies on some simplifications and assumptions, the findings of numerical simulation are not validated by the measured and experimental data. In recent years, domestic scholars have carried out exploratory shaking table test for soil-isolated structure interaction system. For example, Zai Jingming and Yu Xu carried out a shaking table test on lead core rubber bearing isolated structure with the SSI effect[6], and the test results show that the isolation effect of isolated structure with SSI is lower than those without SSI, wherein the foundation is fine sand foundation. Li Changping and Liu Weiqing also performed a shaking table test for a high-rise isolated structure on the soft soil foundation[7], and investigated the dynamic characteristic and seismic re-

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sponse of the high-rise isolated structure on the soft soil foundation. They pointed out that the aspect ratio of high-rise isolated structure was larger (its aspect ratio is 4.1) in contrast to the requirement that the aspect ratio of the isolated structure should be minor (no more than 4.0) in Chinese Code for Seismic Design of Building (GB50011—2010). Therefore, the minor aspect ratio of isolated structure on soft site should be studied specifically.

Based on the existing shaking table test and theoretical research on isolated structure, a shaking table model test for the minor aspect ratio of isolated structure on a soft site is designed, considering that the foundation, model material, ground motion and aspect ratio of the isolated structure should meet the requirements of Chinese Code for Seismic Design of Building. The test uses a soft interlayer soil foundation to model the soft site, on which SSI influences on the dynamic characteristics and the seismic response of soil-isolated structure interaction system is studied through the shaking table tests. Some conclusions in previous literatures are verified by this experiment. At the same time, new findings are reported, which will supplement the seismic design theory of the isolated structure on a soft foundation.

# 1 Shaking Table Test

## 1.1 Similitude ratio design

When the shaking table test is used to model the soil-structure interaction system with two or more types of materials, it is sophisticated to make all the physical quantities have consistent similitude ratio completely. However, based on the main dynamic characteristics of the interaction system, some important quantities to decide the main seismic behaviors of the interaction system must be selected and their similitude ratios should be consistent as soon as possible. According to the Bukingham theory, the similitude ratios of physical dimension, the stress and the modulus, are selected as the basic similitude ratios, and others can be deduced by the relations among them. The similitude ratios and the relations of interaction system are given in Ref. [8].

## 1.2 Loading method

Vibration testing method of an interaction system is a one-way vibration. The EI-Centro earthquake wave (EI wave), the Kobe earthquake wave (KB wave), and the Nanjing artificial earthquake wave (NJ wave), are selected as the input motions. According to the similitude ratio of time, the time step of input motion is adjusted to be 0.004 5 s. Load schedules of interaction system for shaking table test are shown in Table 1.

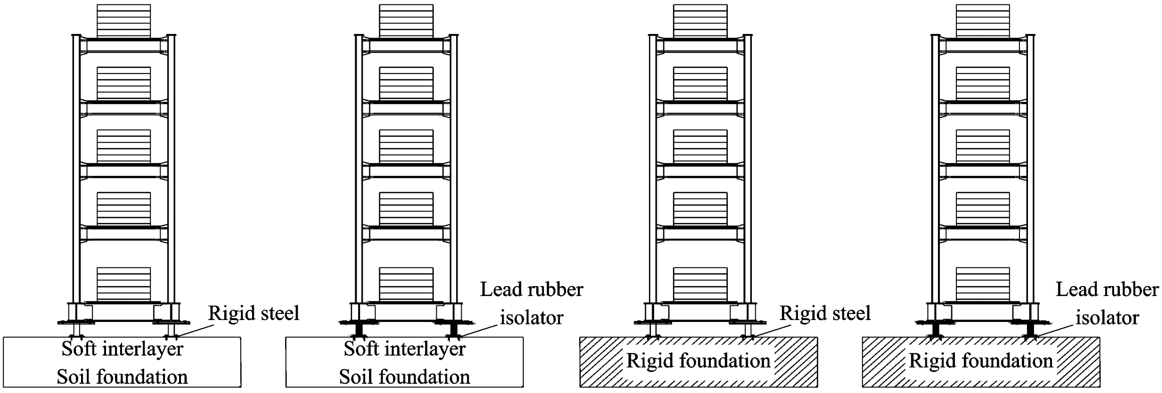
**Table 1 Load schedules for shaking table test**

| No. of test | Load No. | | Name of input wave | PGA | |
|---|---|---|---|---|---|
| | Soft interlayer soil foundation | Rigid foundation | | Soft interlayer soil foundation | Rigid foundation |
| 1 | JTWN1 | WN1 | White noise | 0.05$g$ | 0.07$g$ |
| 2 | JTEI1 | EL1 | EI-Centro | 0.05$g$ | 0.1$g$ |
| 3 | JTNJ1 | NJ1 | Nanjing | 0.05$g$ | 0.1$g$ |
| 4 | JTKB1 | KB1 | Kobe | 0.05$g$ | 0.1$g$ |
| 5 | JTEI2 | EL2 | EI-Centro | 0.15$g$ | 0.2$g$ |
| 6 | JTNJ2 | NJ2 | Nanjing | 0.15$g$ | 0.2$g$ |
| 7 | JTKB2 | KB2 | Kobe | 0.15$g$ | 0.2$g$ |
| 8 | JTEI3 | EL3 | EI-Centro | 0.3$g$ | 0.3$g$ |
| 9 | JTFNJ3 | NJ3 | Nanjing | 0.3$g$ | 0.3$g$ |
| 10 | JTFKB3 | KB3 | Kobe | 0.3$g$ | 0.3$g$ |
| 11 | JTEI4 | EL4 | EI-Centro | 0.5$g$ | 0.5$g$ |
| 12 | JTFKB4 | KB4 | Kobe | 0.5$g$ | 0.5$g$ |
| 13 | JTWN2 | WN2 | White noise | 0.05$g$ | 0.07$g$ |

### 1.3 Soil foundation and model isolated structure

A four-floor steel frame structure is constructed by square steel tubes with the columns and H-shaped steel used as the beams[9]. The aspect ratio of model structure in the vibration direction is 2.625. The model isolators are designed with 100 mm diameter of the transection. The mass of model structure is 0.32 t. To consider the similitude ratio of gravity as soon as possible, the additional mass is added in each layer of model structure with 0.736 t. The total mass of the model structure and the additional mass is about 4.0 t. It is on soil foundation and rigid foundation that the model isolated structure has the same size of the upper structure, as well as the same mechanical quantities of model isolators, which is given by Ref. [10] in detail.

Soil foundation has three-layer soil mineral, with the total soil thickness of 130 cm. The top layer soil mineral of the foundation is dry sand, whose thickness is 30 cm, density is 1 760 kg/m$^3$ and moisture content is 8.2%—9.0%. The middle layer soil mineral of the foundation is 40 cm thick clay, with the density of 1 933 kg/m$^3$, and the moisture content of 27.2%—30.0%. The bottom layer soil mineral of the foundation is saturated and firm sands. Its thickness is 60 cm, density is 1 920 kg/m$^3$, and moisture content is 26.2%—27.0%. Due to the above layering soil, the soil foundation is described as ″soft interlayer soil foundation″. The preparation of soil foundation is controlled by moisture content and compaction degree, which adopts water immersion method. Soil filling is stratified by hand. The shear velocity of model soil foundation is about 35—40 m/s, which meets experimental requirement of soft site. A laminar shear box designed by Chen Guoxing [11] is used to hold the soil. This test box has been proved by designers that it can greatly reduce the reflected wave on the boundary and can be used to simulate the soil boundary condition of model soil foundation efficiently. Pile foundation is designed as the model which is reinforced foundation of isolated structure. The pile bearing is designed to be a rigid block with dimensions of 1.2 m (vibration direction) × 1.0 m (vertical to the vibration direction) × 0.1 m (thickness). The pile foundation have six piles whose cross section is 0.035 m×0.035 m. Two shaking table tests are designed to model the dynamic response of a four-floor structure under two different conditions, i.e., the non-isolated structure on the soft interlayer soil foundation, the base-isolated structure on soft inerlayer soil foundation. The two tests are presented in Figs. 1(a, b). Another two shaking table tests have been finished to model the dynamic response of a four-floor structure on rigid foundation in 2009, as shown in Figs. 1(c, d). The sketch of model system arrangement on the soft interlayer soil foundation is illustrated in Fig. 2. The photo of test model is presented in Fig. 3.



(a) Test Ⅰ (b) Test Ⅱ (c) Test Ⅲ (d) Test Ⅳ

Fig. 1 Shaking table tests designed to model four different conditions

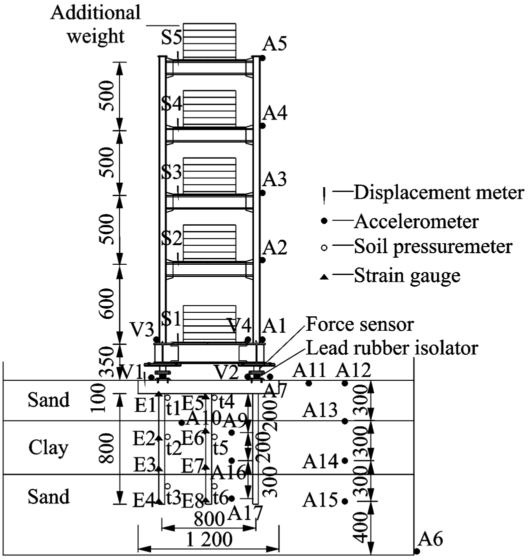


Fig. 2 Sketch of model system arrangement and measuring point arrangement

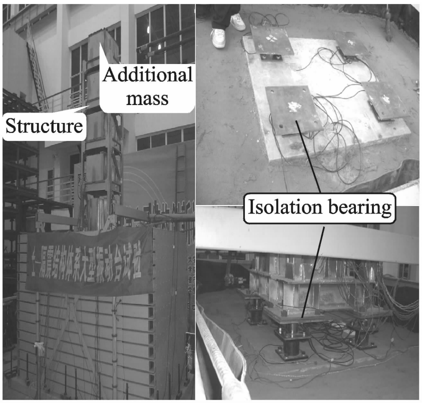


Fig. 3 Photo of test model

## 1.4 Sensors′ distribution and measurement method

In shaking table test, the measured parameters include horizontal displacement and acceleration of upper isolated structure, vertical and horizontal force of isolator, acceleration of soil foundation, horizontal and vertical acceleration of pile bearing, soil pressure of interface between pile and soil, and compressive strain of pile body. The distribution of sensors is shown in Fig. 2, where No. A1—A17 are the horizontal accelerometers, No. V1—V4 the vertical accelerometer, No. S1—S5 the displacementmeters, No. t1—t6 the soil pressuremeters, and No. E1—E5 the strain gauge. Target-detecting method[12] is used to measure the shear deformation of upper isolated structure and laminar shear box.

## 2 Test Results

### 2.1 Dynamic characteristics of isolated structure

The fundamental vibration frequency and damping ratio of the base-isolated structure are deduced[13] by the dynamic response of the isolated structure with the white noise input, as given in Table 2. Compared with the test result of the isolated structure fixed on rigid foundation, the fundamental vibration frequency damping ratio of the isolated structure on soft interlayer soil foundation changes notably. On the whole, the main laws are as follows: (1) The fundamental vibration frequency of the isolated structure with the SSI effect is smaller than those without it. The decreasing rate is 9.5%. However, the damping ratios of the isolated structure with the SSI effect are obviously larger than those without it, and the increasing rate is 78.3%. (2) Without the SSI effect, the fundamental vibration frequency and damping ratio is not obviously affected by the increasing peak ground acceleration (PGA) of input motions. However, with the SSI effect, the fundamental vibration frequency becomes smaller obviously after the test. To the damping ratio, it increases quickly with the increasing PGA of input motion, especially after the test.

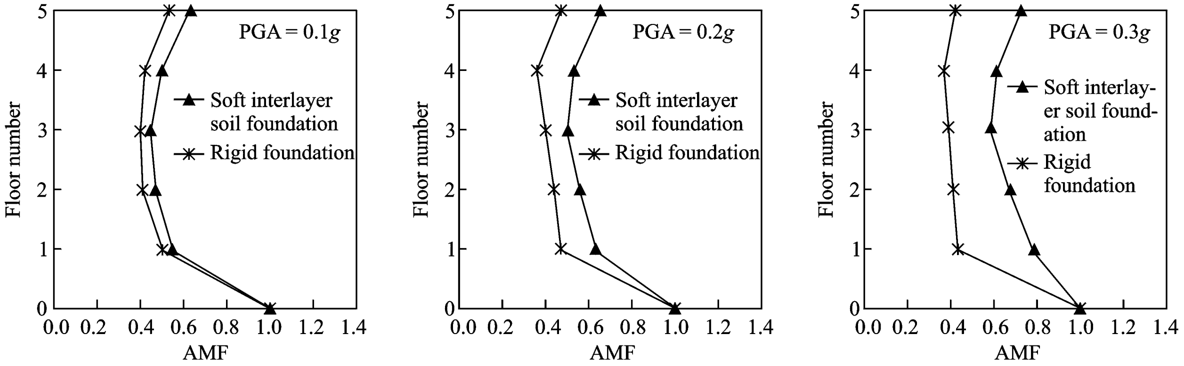
**Table 2 Fundamental vibration frequency and damping ratio of based-isolated structure**

| Load No. | Soft interlayer soil foundation | | Rigid foundation | |
|---|---|---|---|---|
| | Frequency/Hz | Damping ratio/% | Frequency/Hz | Damping ratio/% |
| JTWN1/WN1 | 2.4 | 14.8 | 2.65 | 8.3 |
| JTWN2/WN2 | 2.27 | 18.4 | 2.62 | 8.8 |

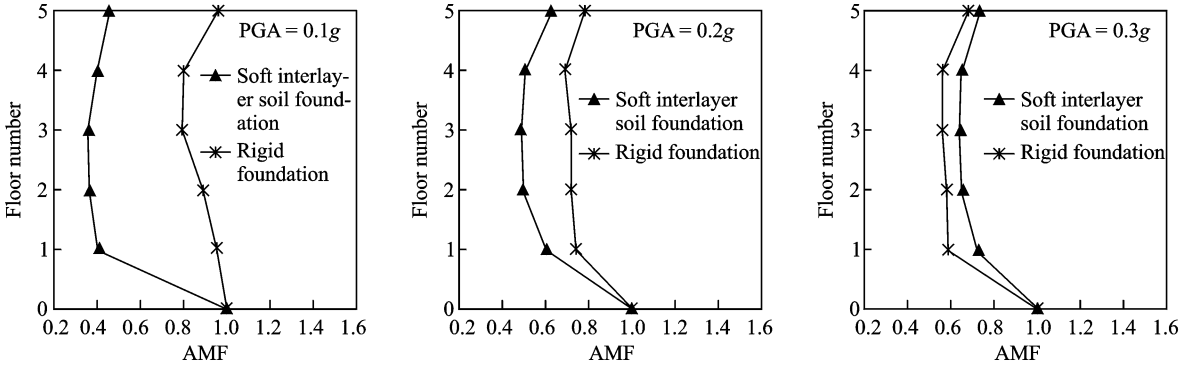
Compared with the test results of Ref. [7], it shows that the influence of the SSI effect on the dynamic characteristic of larger aspect ratio of isolated structure is different from those of minor aspect ratio of isolated structure, which is due to the difference of soil foundation stiffness and the aspect ratio of isolated structure. In Ref. [7], the damping ratios of larger aspect ratio of isolated structure with the SSI effect are larger than those without it, at an increased rate of 36%. Besides, with the SSI effect, the dynamic characteristics of the larger aspect ratio of isolated structure is not obviously affected by the increasing PGA of input motions. The above analysis results show that the influence of the SSI effect on the dynamic characteristics of isolated structure on soft soil foundation is closely related to soil foundation stiffness and the aspect ratio of isolated structure.

### 2.2 Acceleration response of isolated structure

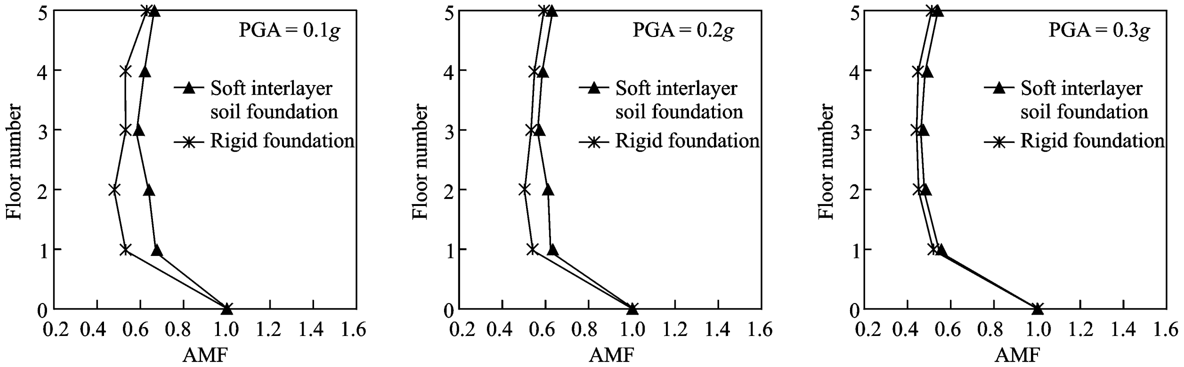
Acceleration magnification factor (AMF) in this paper is defined as the PGA of acceleration response at each floor of structure divided by the PGA of input motion. To compare with AMFs of isolated structure on rigid foundations and soft interlayer soil foundation, AMFs of structure on soft interlayer soil foundation (with the SSI effect) are calculated by the quadratic interpolation method to set PGA of input motion according to the tests for structure fixed on rigid foundation (without the SSI effect), which are 0.1*g*, 0.2*g* and 0.3*g*, respectively. Comparison of AMFs of isolated structure is shown in Fig. 4, where floor number zero represents the surface of foundation.



(a) El-Centro wave



(b) Kobe wave



(c) Nanjing artificial wave

Fig. 4 AMFs of isolated structure on different foundations

According to Fig. 4, for the base-isolated structure, AMFs with the SSI effect are bigger than those without it when EI-Centro earthquake wave is inputted. However, when PGA of Kobe earthquake wave is 0.3$g$, AMFs with the SSI effect are bigger than those without it. When PGA of Kobe earthquake wave is 0.1$g$, AMFs with the SSI effect are smaller than those without it. Additionally, when Nanjing artificial earthquake wave is inputted, AMFs with the SSI effect are slightly bigger than those without it. The above analysis results show that the SSI effect can increase or decrease AMFs of isolated structure on the soft interlayer soil foundation.

As PGA of input motion is larger, Fig. 4 also shows that AMFs of isolated structure on rigid foundations become smaller, indicating that the isolation efficiency of isolated structure on rigid foundations becomes stronger as the input motion becomes stronger. However, the isolation efficiency of isolated structure on the soft interlayer soil foundation is different from those on rigid foundation. It is observed that AMFs of isolated structure on the soft interlayer soil foundations become larger as PGA of EI-Centro earthquake wave and Kobe earthquake wave becomes larger, which is different from those on rigid foundation. While Nanjing artificial earthquake wave is inputted, AMFs of isolated structure on the soft interlayer soil foundations become smaller as PGA of input motion become larger, which is similar to those on rigid foundation. The above analysis results show that the influence of the SSI effect on AMFs of isolated structure on soft interlayer soil foundation is closely related to the characteristics and PGA of input motion.

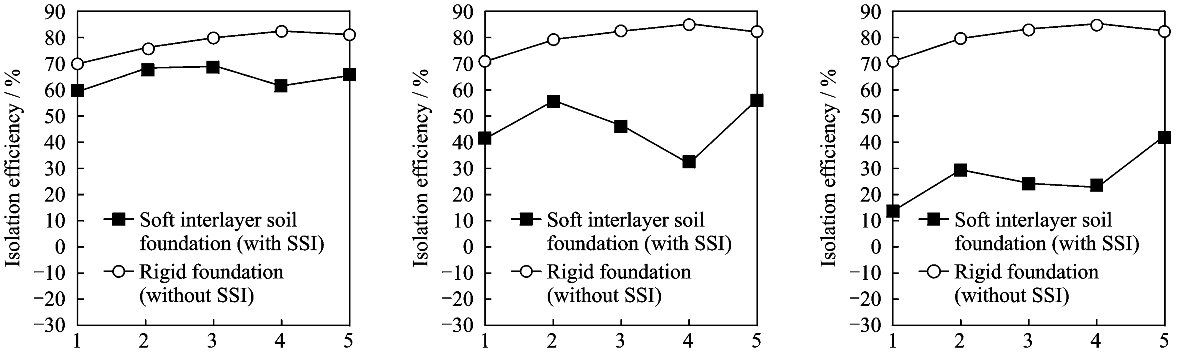
### 2.3 Isolation efficiency of isolation layer

To study the influence degree of the SSI effect on the isolation efficiency of isolation layer, the isolation efficiency factor can be defined by

$$\eta_s = [(a_s - a'_s)/a_s] \times 100\% \tag{3}$$

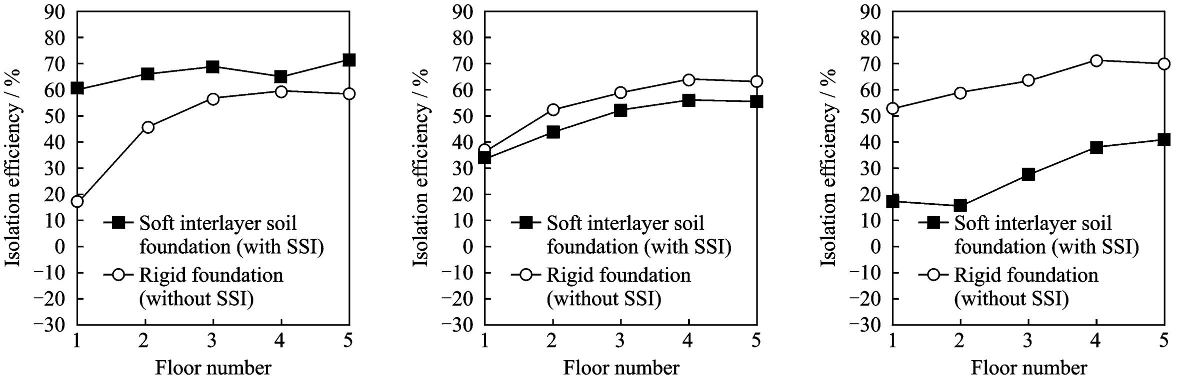
where $a_s$ is the maximal acceleration response at each floor of non-isolated structure on different foundations (The calculation method is the same as those of Section 2.2) and $a'_s$ the maximal acceleration response of base-isolated structure.

The isolation efficiency of isolation layer on different foundations is shown in Figs. 5—7. According to Figs. 5—7, the isolation efficiency of isolation layer on soft interlayer soil foundation is lower than those on rigid foundation. With different earthquake waves, the influence of the SSI effect on the isolation efficiency of isolation layer on soft interlayer soil foundation is obviously different. Some conclusions can be drawn as follows: (1) The isolation efficiency of the isolation layer is related to foundation stiffness, with the exception of low intensity of Kobe earthquake wave. The isolation efficiencies of the isolation layer on rigid foundation are bigger than those on the soft interlayer soil foundation. (2) The isolation efficiency of the isolation layer is related to PGA and characteristics of input earthquake motion. For the isolated structure on rigid foundation, the larger PGA of input motion is, the str-



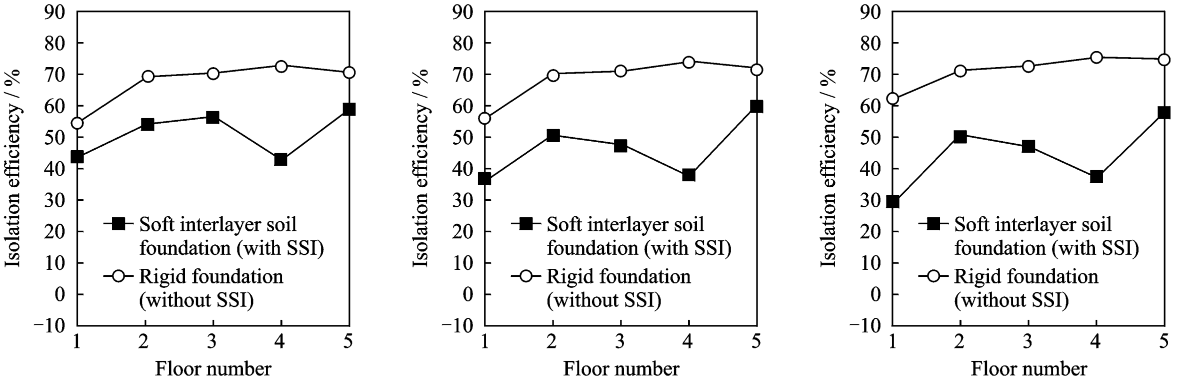
(a) PGA = 0.1$g$ (b) PGA = 0.2$g$ (c) PGA = 0.3$g$

Fig. 5 Isolation efficiency at each floor of base-isolated structure on different foundations (El-centro wave inputted)



(a) PGA = 0.1$g$ (b) PGA = 0.2$g$ (c) PGA = 0.3$g$

Fig. 6 Isolation efficiency at each floor of base-isolated structure on different foundations (Kobe wave inputted)



(a) PGA = 0.1$g$ (b) PGA = 0.2$g$ (c) PGA = 0.3$g$

Fig. 7 Isolation efficiency at each floor of base-isolated structure on different foundations (Nanjing wave inputted)

onger the isolation efficiency of the isolation layer becomes. For the isolated structure on soft interlayer soil foundation, with increase of PGA of input motion, the isolation efficiency is obviously lower, especially with EI-Centro wave as input motion, the decreased rate is 45.7%.

## 3 Conclusions

To estimate the influence of the SSI effect on the seismic response of the base-isolated structure on a soft site, the soft interlayer soil foundation is used to model the soft site, and four shaking table tests are accomplished. As far as the tested system is concerned, the main conclusion and new findings are obtained:

(1) With the SSI effect, the fundamental vibration frequency of isolated structure on the soft site is smaller than those on the rigid foundation. But the difference between them is finite. However, the damping ratio of isolated structure on the soft interlayer soil foundation is larger than those on the rigid foundation, exhibiting a remarkable difference. The change principle of fundamental vibration frequecy and damping ratio is affected by soil foundation stiffness and the aspect ratio of isolated structure.

(2) For the SSI effect, AMF of isolated structures on the soft site may be either larger or smaller than those on the rigid foundation, which is related to PGA and the characteristics of earthquake motion input, and this problem should be deeply studied by numerical simulation in subsequent research.

(3) For the SSI effect, the isolation efficiency of isolation layer on the soft site is lower than those on the rigid foundation, which is related to PGA and characteristics of input earthquake motion.

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