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Design Method for Shaking Table Test on Isolated Structures Using Friction Pendulum Bearings

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ABSTRACT
Friction pendulum bearing (FPB) has been gradually used worldwide for its large vertical force capacity, controlled period, and temperature insensitivity. When FPB is used for isolated tall buildings, the isolation effect such as overturning moment should be give special attention to. Thus, a shaking table test on a FPB isolated building is to be designed. The simulitude relationship between the prototype and model FPBs will deeply affect the control effect of the shaking table test. In this paper, the design method of the model FPB is put forward including the similitude rules for the global model, the similarity of the isolation layer, and the number and parameters of model FPBs. The proposed design method is verified by use of a 15-story FPB isolated building.

KEYWORDS: *friction pendulum bearing, isolated structure, shaking table test, design method, similitude rule*

1. INTRODUCTION

Seismic isolation technology has changed the traditional earthquake-resistant design. Using isolators between the foundation and superstructure, it can weaken or alter the ground motion’s intensity and further restrict the seismic energy into the superstructure. Thus, seismic isolation could achieve the purpose of reducing the structural vibration, mitigating the earthquake damage of engineering buildings and saving people's lives and property. Seismic isolation technology has been widely used in engineering.

As a novel friction seismic isolation bearing, friction pendulum bearing (FPB) gradually shows its advantages. It’s a sliding system with circular surface using the principle of pendulum to lengthen the natural period of the isolated structure, so that the strong earthquake forces can be reduced. During an earthquake, the supported structure moves with small pendulum motions. The earthquake-induced displacement occurs primarily in the bearings, so the lateral loads and shaking movement transmitted to the structure are greatly reduced. This type of system also possesses features like re-centering capability, large vertical force capacity, and temperature insensitivity, so it has been used in tall buildings [1].

Novel and complex structures, which are beyond the design specification and difficult to be analyzed with existing theoretical methods, often need to make a reasonable assessment of the seismic performance through shaking table tests. Shaking table tests input seismic wave, then drive structure’s reaction and vibration on the shaking table. Shaking table tests could reproduce the earthquake process so that the weak parts of the structure can be found and the failure mechanism can be analyzed. Thus, shaking table test is one of the most direct way of studying the seismic response and failure mechanism of structure [2], and it is also one of the most important methods of studying and evaluating the seismic performance like damping and isolation effect [3].

The model design of shaking table test is the first step of the test, which directly determines the results of the seismic test’s objective, and is important to the success of the seismic test [2]. Since a shaking table test model design on a FPB isolated building is significant, this paper aims to solve the core issues of shaking table test model design on a FPB isolated building.

2. THE ISOLATED PROTOTYPE STRUCTURE WITH FRICTION PENDULUM BEARINGS

The target isolated building is a seventeen-story hotel located in Xichang, Sichuan Province, China, with a total height of 58.3 meters. The story height is 5.4 meters for the first floor, 3.6 meters for the second to thirteenth floor, and 1.5 meters, 4.4 meters and 3.8 meters for the fourteenth, the fifteenth and the sixteenth floor, respectively, as shown in Figure 2.1 [4]. The reinforced concrete frame-tube structure system is applied for the building.

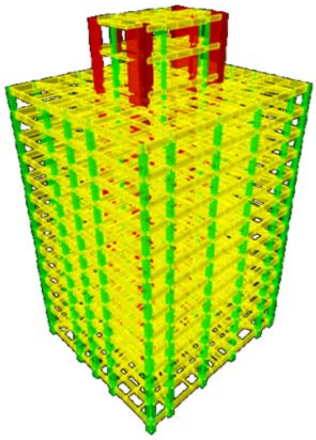

Figure 2.1 3-D model of the high-rise isolated building

The base isolation is designed by use of FPB. In total thirty FPB were placed under the columns and shear walls symmetrically. The FPB parameters are given in Table 2.1. A shaking table test is supposed to be conducted to check whether the isolated structure can meet the expected objective of isolation and whether the pendulum bearings can perform well under strong earthquakes.

Table 2.1 Prototype parameters of friction pendulum bearing

Physical quantities	Unit	Quantity
Radius R^p	mm	2350
Yield displacement D_y^p	mm	3
Designed displacement D_d^p	mm	1000
Coefficient of kinetic friction μ^p	1	6%
Superstructure mass m^p	t	19845

Note: In this paper, superscript *p* stands for the physical quantities of the prototype structure, superscript *m* stands for those of the model structure.

3. THE DESIGN PARAMETERS OF THE FRICTION PENDULUM BEARINGS

The horizontal force *F* of the FPB can be represented as the sum of restoring force and frictional force and when the rotation angle is small enough. There is [5]:

$$F = \frac{W}{R} d + \mu W \,\mathrm{sgn}(\dot{\theta}) \tag{3.1}$$

where *R* stands for the radius of the sliding surface, θ stands for the angle of which the slide slides off from the equilibrium position, d stands for the horizontal relative displacement, *W* stands for the vertical pressure on the bearing coming from the superstructure, μ stands for the coefficient of kinetic friction, $\mathrm{sgn}(\dot{\theta})$ is sign function, when $\dot{\theta} > 0$, $\mathrm{sgn}(\dot{\theta}) = 1$, when $\dot{\theta} < 0$, $\mathrm{sgn}(\dot{\theta}) = -1$.

We can get the theoretical hysteresis curve model of FPB, as shown in Figure 3.1 [5].

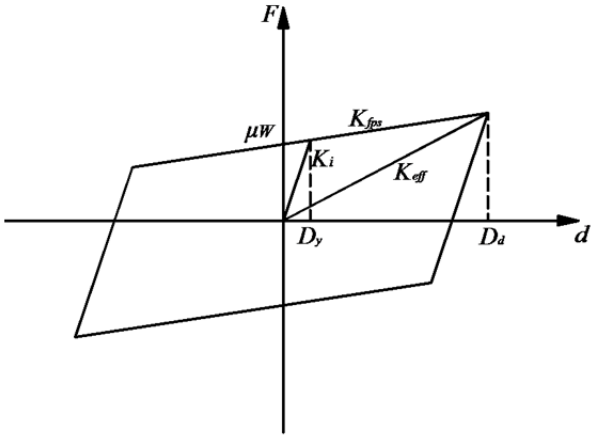

Figure 3.1 Hysteretic loop model of friction pendulum bearings

In the design of bearing, the physical meanings of three key parameters are as follows: K_i stands for initial stiffness, $K_i = \mu W / D_y$, D_y is yield displacement, K_{fps} stands for swing stiffness of the friction pendulum bearing, $K_{fps} = W / R$. Therefore, the natural period of friction pendulum bearing can be expressed as a formula below.

$$T_0 = 2\pi\sqrt{\frac{R}{g}} \tag{3.2}$$

The equivalent linear stiffness and the equivalent viscous damping ratio of the bearing can be obtained by equivalent linearization method, the formulas of which are given below.

$$K_{eff} = F / D_d = \frac{W}{R} + \frac{\mu W}{D_d} \tag{3.3}$$

$$\zeta_{eff} = \frac{2}{\pi}\left[\frac{\mu}{\mu + D_d / R}\right] \tag{3.4}$$

where K_{eff} stands for the equivalent stiffness, ζ_{eff} stands for the equivalent damping ratio, and D_d stands for the designed displacement.
Assuming the stiffness of the superstructure of the friction pendulum bearing is K_u, K_e, the equivalent stiffness of the isolation system, equals to the series stiffness of the seismic isolation bearings.

$$K_e = \frac{K_u K_{eff}}{K_u + K_{eff}} \tag{3.5}$$

For seismic isolated structures, generally, $K_u >> K_{eff}$, as a result, $K_e \approx K_{eff}$, the equivalent natural period of the isolated structures with friction pendulum system can be calculated by the formula below.

$$T = 2\pi\sqrt{\frac{W}{gK_{eff}}} = 2\pi\sqrt{\frac{D_d R}{g(D_d + \mu R)}} \tag{3.6}$$

4. THE DESIGN METHOD OF THE ISOLATED MODAL STRUCTURE WITH FRICTION PENDULUM BEARINGS

4.1 Similitude Relation of the Whole Model

The key issue of the model design is to determine the similarity relation between a model structure and a prototype structure appropriately. However, similarity relation is controlled by the performance parameters of a shaking table. The parameter of the shaking table in State Key Laboratory of Disaster Reduction in Civil Engineering of Tongji University is given in Table 4.1.

Table 4.1 Performance parameters of the shaking table

performance		index
size		4m×4m
payload		25t
excitation orientation		X, Y, Z
controlling degree of freedom		6 degrees of freedom
maximum drive displacement		X: ±100mm Y&Z: ±50mm
maximum drive velocity		X: 10000mm/s Y&Z: 600mm/s
maximum drive acceleration	X	4.0g (vacancy) 1.2g (15t loading) 0.8g (25t loading)
	Y	2.0g (vacancy) 0.8g (15t loading) 0.6g (25t loading)
	Z	4.0g (vacancy) 0.7g (15t loading) 0.5g (25t loading)
range of working frequency		0.1~50Hz
data collection system		STEX3: 128 channel

The design methods in shaking table test design are given as follows [6]:
Firstly, three controlling scaling factors needs to be determined. That is the scaling factor of length, stress, and acceleration. Considering the size of shaking table and the crane walking height, the length scaling factor is taken as 1/15. Then according to the strength ratio between micro-concrete in modal design and reinforced concrete in prototype design, stress scaling factor is taken as 0.2. Considering the noise of the table, the craning capacity and peak ground acceleration of prototype structure, the acceleration scaling factor is taken as 1.5.

Secondly, on the basis of equation analysis method and dimension analysis method, scaling factors of the physical parameters in a shaking table test should meet the similarity equation (4.1):

$$\frac{S_E}{S_\rho S_a S_l} = 1 \tag{4.1}$$

And density scaling factor which satisfy similarity equation above is taken as 2.0. Then the other scaling factors are determined by dimension analysis method and are shown in Table 4.2.

Table 4.2 Similitude relationship of the model

Physical property	Physical parameters	Relationship equation	Similar constants
Geometrical performance	length l	S_l	**1/15**
Material characteristics	strain ε	$S_\varepsilon = S_\sigma / S_E$	1.00
	Stress σ	S_σ	**0.20**
	elasticity modulus E	$S_E = S_\sigma$	0.20
	density ρ	S_ρ	2.0
	mass m	$S_m = S_\rho \cdot S_l^3$	5.93×10^{-4}

Load characteristics	concentrated force F	$S_F = S_\sigma \cdot S_l^2$	8.89×10^{-4}
	line load p	$S_p = S_\sigma \cdot S_l$	1.33×10^{-2}
	area load q	$S_q = S_\sigma$	0.20
	moment M	$S_M = S_\sigma \cdot S_l^3$	5.93×10^{-5}
dynamic characteristics	stiffness K	$S_K = S_\sigma \cdot S_l$	1.33×10^{-2}
	period T	$S_T = (S_l / S_a)^{0.5}$	0.211
	frequence f	$S_f = (S_a / S_l)^{0.5}$	4.74
	acceleration a	S_a	**1.5**
	acceleration of gravity g	S_g	**1.00**

4.2 Quantity of Isolated Bearings

There are 30 friction pendulum bearings installed at the prototype structure. However, due to the limit of the size of model bearing and the restriction of installation conditions, the one-to-one similarity between the prototype and the model structure cannot be realized in the shaking table test. Taking all the limits into consideration, the scheme of six bearings is chosen to simulate 30 friction pendulum bearings. Four of them are mounted at four corners of the model structure and two of them are mounted at the bottom of core tube, as shown in Figure 4.1.

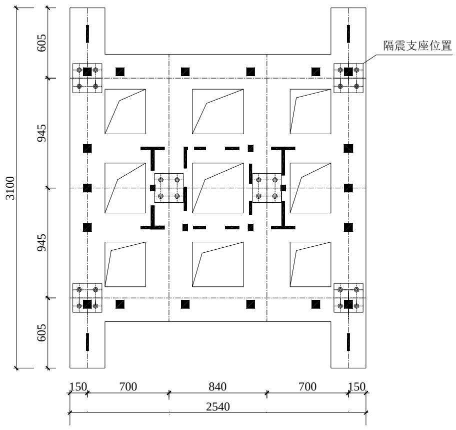

Figure 4.1 Layout of isolators in the model structure

4.3 Similitude Design of the Isolation Layer

In the similitude design of the isolated structure, considering model hoisting and the connection between isolation bearings and the shaking table, a rigid foundation should be mounted at the base of structure model. And then the superstructure is connected to the shaking table by isolation bearings. Thus, the mass above isolation layer include not only the model superstructure, but also the rigid foundation Subsequently the update mass scaling factor S_m^i of the isolation layer is obtained. With the update mass scaling factor S_m^i, the vertical-force scaling factor S_W^i and the stiffness scaling factor S_k^i of isolation layer can be obtained, and isolation layer parameters are determined more accurately in the model design.

The target building is taken as an example to demonstrate the similarity process of the isolation layer design. The total mass of the prototype structure m^p is equal to 19845 ton. According to Table 4.2, the equivalent mass of superstructure m^p is equal to 11.77 ton. The mass of rigid foundation m_b is equal to 4 ton, so the total mass above isolation layer m_t is equal to 15.77ton.

Therefore, the mass scaling factor of the isolation layer:

$S_m^i = m_t / m^p = 15.77 / 19845 = 7.94 \times 10^{-4}$

So, the vertical-force scaling factor:

$S_W^i = S_m^i \cdot S_g = 7.94 \times 10^{-4} \times 1.0 = 7.94 \times 10^{-4}$

The stiffness scaling factor:

$S_k^i = S_m^i \cdot S_a / S_l = 7.94 \times 10^{-4} \times 1.5 / (1/15) = 1.79 \times 10^{-2}$

4.4 Similar Design of the Period and Stiffness of Isolation Layer

Damping coefficient is a significant parameter in the isolated structural design. Here it is assumed that the model structure and the prototype have the same damping coefficient. That means the period of isolated and fixed structure should satisfy similitude relationship[6]. That is,

$$T^m = S_T \cdot T^p \tag{4.2}$$

The natural vibration period of friction pendulum bearings is not related to load. It's merely determined by radius of friction pendulum bearings. Correspondingly, the equivalent natural vibration period of friction pendulum bearings and superstructure are decided by bearings radius, design displacement and dynamic friction coefficient.
The natural vibration period of friction pendulum bearings:
$T_0^p = 2\pi\sqrt{R^p / g} = 3.077\,\text{s}$
The equivalent natural vibration period of the isolation layer:
$T^p = 2\pi\sqrt{D_d^p R^p / (\mu^p R^p + D_d^p) g} = 2.880\,\text{s}$
The period scaling factor of the isolation layer:
$S_T = (S_l / S_a)^{0.5} = 0.211$

The period of the model structure after similitude design:
The natural vibration period of friction pendulum bearings:
$T_0^m = S_T \cdot T_0^p = 0.211 \times 3.077 = 0.649\,\text{s}$
The equivalent natural vibration period of isolation layer:
$T^m = S_T \cdot T^p = 0.211 \times 2.880 = 0.608\,\text{s}$
Stiffness of isolation layer of structure model should satisfy similar relationship as equation (4.3):

$$K^m = S_K \cdot K^p \tag{4.3}$$

According to mechanic property of friction pendulum bearings and upper load, we can calculate the total stiffness of prototype friction pendulum bearings.
The total initial rigidity:
$\sum K^p = \mu^p W^p / D_y^p = 6\% \times 9.8 \times 19845 / 3 = 3889.620\,\text{kN/mm}$
The total stiffness:
$\sum K_{fps}^p = W^p / R^p = 9.8 \times 19845 / 2350 = 82.758\,\text{kN/mm}$
The total equivalent stiffness:
$\sum K_{eff}^p = \mu^p W^p / D_d^p + W^p / R^p = 6\% \times 9.8 \times 19845 / 1000 + 9.8 \times 19845 / 2350 = 94.427\,\text{kN/mm}$
The stiffness scaling factor of isolation layer:
$S_K = S_\sigma \cdot S_l = 1.33 \times 10^{-2}$
The adjusted stiffness scaling factor of isolation layer S_k^i is 1.79×10^{-2}, so the stiffness of friction pendulum bearings in model structure which has been designed by similitude relation can be calculated as follows:
The total initial rigidity:
$\sum K^m = S_K^i \cdot \sum K^p = 1.79 \times 10^{-2} \times 3889.62 = 69.502\,\text{kN/mm}$
The total rigidity:
$\sum K_{fps}^m = S_K^i \cdot \sum K_{fps}^p = 1.79 \times 10^{-2} \times 82.758 = 1.479\,\text{kN/mm}$
The total equivalent rigidity:
$\sum K_{eff}^m = S_K^i \cdot \sum K_{eff}^p = 1.79 \times 10^{-2} \times 94.427 = 1.687\,\text{kN/mm}$
According to the 12.2.4 Rule of Code for Seismic Design of Buildings[7], the total stiffness in horizontal direction of isolation layer can be obtained by adding all the stiffness of each isolation bearings. So dividing the above-mentioned parameters of isolation layer by the number of isolation bearing, stiffness parameters of each isolation bearings can be obtained. Then, the parameters of isolation bearings can be calculated accordingly and the corresponding models can be produced.

Stiffness of each friction pendulum bearing:
Initial stiffness:
$K^m = \sum K^m / 6 = 11.584\,\text{kN/mm}$
Stiffness:
$K_{fps}^m = \sum K_{fps}^m / 6 = 0.246\,\text{kN/mm}$
Equivalent stiffness:

$K_{eff}^m = \sum K_{eff}^m / 6 = 0.281\text{kN/ mm}$
The equivalence of vertical load:
Assuming that the load was distributed equally to six bearings, so that the load of each bearing can be caculated. The vertical load scaling factor S_W after adjusting is 7.94×10^{-4}, so the vertical load is:
$W^m = S_W \cdot m^p \cdot g / 6 = 25.741\text{kN}$
Then, the stiffness, cycle period and the vertical load of single friction pendulum bearing is obtained, shown in Table 4.3.

Table 4.3 Stiffness, period and loading of model friction pendulum bearings

Physical quantity	Unit	Quantity
Initial stiffness K^m	kN/mm	11.584
stiffness K_{fps}^m	kN/mm	0.246
Equivalent stiffness K_{eff}^m	kN/mm	0.281
Natural Period T_0^m	s	0.649
equivalent period T^m	s	0.608
vertical load W^m	kN	25.741

4.5 Parameters Determination of Model Friction Pendulum

According to the stiffness, cycle period and the vertical load, the specific parameters of friction pendulum bearing of a single model can be determined in Table 4.4.

Table 4.4 Parameters of model friction pendulum bearings

Physical quantity	Unit	magnitude
radius R^m	mm	104
yield displacement D_y^m	mm	0.13
designed displacement D_d^m	mm	44
Coefficient of kinetic friction μ^m	1	6%
vertical load W^m	kN	25.741

4.6 Key Issues of Model Design for Isolated Buildings Using Friction Pendulum Bearings

Some key issues of the model design for isolated buildings using FPB are summarized as below.
(1) It is crucial to meet the similarity requirements of the mass, stiffness, period and vertical load of isolation story.
(2) The parameters of model isolation bearings, such as friction displacement D_y^m, design displacement D_d^m and radius of curvature R^m are not obtained by use of length similarity constant S_l, but deduced from corresponding formulas following the similarity of stiffness and period.
(3) It is inappropriate to design model friction pendulum bearings one by one, and the correct method is to take all the bearings as a whole and deduce the parameters of every model bearing complying with the similarity of general stiffness.
(4) To ensure the effect of isolation, it is important to consider the mass of the rigid foundation of the model structure and adjust the scaling factor of mass, vertical load and stiffness, correspondingly.

5. Conclusions

This paper introduces the model design method for shaking table test on isolated structures using friction pendulum bearings. Based on a high-rise isolated structure, the main issues of model design of isolated structures using friction pendulum bearings are analyzed, including the similitude rules for the general test model, the number of isolation bearings, the similitude for the isolation layer, namely the similitude of stiffness, period and the determination of parameters of model bearings. This study can provide reference for the future shaking table test model design of friction pendulum bearing isolated structures.

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