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A Study on Pendulum Seismic Isolators for High-Rise Buildings

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Abstract

Seismic isolation systems have recently been adopted for several high-rise buildings in Japan. If high-rises are to be isolated effectively from earthquake-induced motions, they need to have a longer period and higher reliability than those provided by conventional seismic isolation systems.

The authors, who are developing seismic isolation systems based on the principle of pendulums, have shown that seismic isolation systems using translational pendulums are free from the influence of the weight of the structure they bear and are functionally stable. The authors have recently expanded the study and found that non-parallel swing systems can provide longer periods effectively. In this paper, a pendulum with supports that deviate from or come closer to each other symmetrically are referred to as the non-parallel swing system.

This paper presents an experimental study on the effectiveness of the non-parallel swing system and on its applicability to high-rise structures.

Keywords: Pendulum; Isolator; Seismic; Experiment; High-Rise

1. Introduction

In spite of recent developments in earthquake resistant engineering, earthquakes still inflict widespread damage in various countries. Seismic isolation is a very effective measure for protecting structures from earthquake damage. In Japan, the construction of seismically isolated structures progressed significantly following the Hyogoken-Nanbu Earthquake (with a magnitude of 7.2) in 1995; the number of structures provided with such measures now exceeds 1,000 (excluding seismically isolated wooden residences). This figure is among the largest in the world.

The most commonly used seismic isolation device globally is the laminated rubber bearing, which comprises layers of rubber and steel plates. However, the dynamic characteristics of laminated rubber bearings vary depending on bearing stress, displacement, temperature and so on. Especially, the natural period of laminated rubber bearings is affected by the weight of the structure, which places considerable restrictions on the design of structures with such bearings. Laminated rubber isolators are difficult to apply to lightweight structures and the center of gravity of the upper structure must coincide with the stiffness center of the isolation device. In addition, when applied to high-rise buildings or structures constructed on soft ground, the commonly used seismic isolation system has to be re-designed to have a longer natural period.

In order to address these issues, various combinations of seismic isolation devices, including laminated rubber bearings, are being studied, and those provided with sliding mechanisms have been developed. However, a device to replace the laminated rubber bearing has yet to be achieved.

The authors have been studying a seismic isolation system with higher performance and reliability that uses bearings acting like pendulums[1)2)3)]. The authors conducted analytical and experimental studies of pendulums symmetrically hung from two supports including translational pendulums as special examples, and presented the structural behavior of pendulums hung from two supports[4)]. The same study also noted the possibility of developing a seismic isolation system using the characteristics of pendulums hung by non-parallel hangers from four supports that enable the natural period of an isolated structure to be adjusted.

2. Principle of pendulum seismic isolators

The pendulum is one of the basic methods of seismic isolation, and is also used as the basic mechanism of seismographs. However, pendulums are rarely used for seismic isolation of structures.[5)]

As shown in Figure 1, pendulums used for engineering purposes include: (a) simple pendulums, (b) physical pendulums, and (c) translational pendulums.

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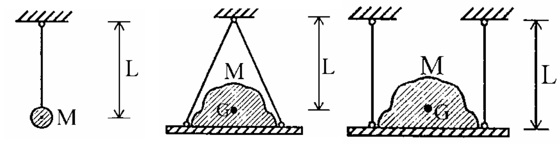


(a) Simple (b) Physical (c) Translational

Fig. 1. Various pendulum systems

It is known that the natural period T of a simple pendulum with arc L is given as follows, where g is gravitational acceleration:

$$T = 2\pi\sqrt{\frac{L}{g}} \tag{1}$$

One advantage of the pendulum seismic isolator is that the length of the hanger L is the only parameter governing its natural period, and the mass of the object to be isolated or the tension of the hanger has no effect at all. Thus, the desired period can be obtained merely by changing the hanger length. This is the greatest advantage of the pendulum seismic isolator compared to laminated rubber bearing seismic isolators in which the natural period is determined by the mass and rigidity of the isolation structure.

As with the amplitude of a pendulum, its natural period is elongated if the amplitude is made larger. The elongation, however, is minute, as indicated by the fact that for an amplitude as large as 60° on one side, the increment in natural period is only about 8%. Thus, the above equation can be considered valid for practical purposes. This is another advantage of pendulum seismic isolators compared to laminated rubber bearings, of which the deformability is limited.

A wide selection of materials is available for the hanger. For example, technology for fireproofing has already reached a mature state if steel is to be used. Another point to note is that when tensile force is applied to a pendulum seismic isolator, compression stress is borne by the hanger. A steel hanger can withstand this well, provided sufficient measures have been provided to prevent buckling. As discussed above, seismic isolators using the pendulum principle possess considerable merits.

Considering that seismic isolators must also function as a part of the structural support, the simple pendulum shown in (a) of Figure 1 is obviously difficult to use. The natural period of the physical pendulum shown in (b), on the other hand, fluctuates with the location of the center of mass of the object to be supported. Thus, the translational pendulum shown in (c), whose natural period is only affected by the hanger length as in the simple pendulum, would be appropriate for use as a seismic isolation device.

3. Application for seismic isolation of floors

One possible application of the translational pendulum seismic isolator is for individual floors.

This isolation system has a more interesting aspect: the floor swings the same way regardless of the height of the center of gravity of the substance above the floor (Figure 2).

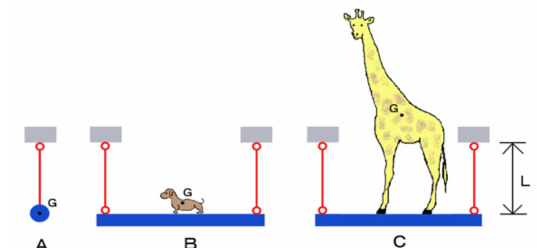


Fig. 2. Sinple pendulum and translational pendulum systems

A floor suspended from a girder of a building frame as shown in Figure 3 was adopted for the exhibition rooms of an actual museum "Ceramics Park MINO" for pottery and porcelain (architectural design: Arata Isozaki & Associates, Structural design: Kawaguchi & Engineers, Completion: May 2002). Photograph 1 shows the outside of the building and Figure 4 presents an isometric drawing of the isolated floor. The area of the suspended floor is about 900 m^2, and its mass is about 1,000 tons. Hinges having universal joints are used for the upper and lower ends of the hanger as shown in Photograph 2. If the hanger is made to be 4.5 m long, Equation (1) yields a natural period of more than 4 seconds, which is considered sufficiently long for seismic isolation. The results of seismic isolation tests performed to confirm the design are described below.

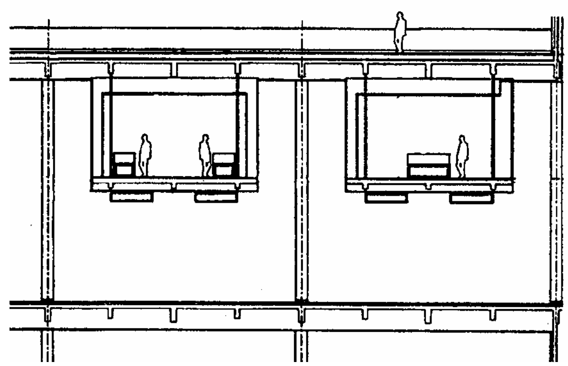


Fig. 3. Concept of the floor with pendulum isolator

Photograph 1. Outside of the building
(courtesy of Arata Isozaki & Associates)

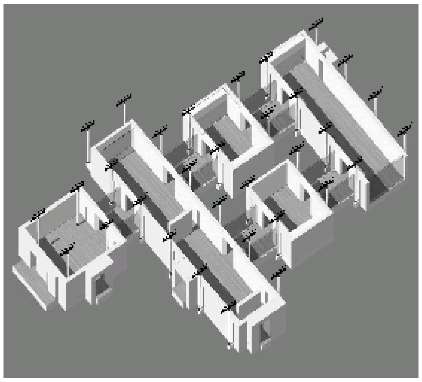
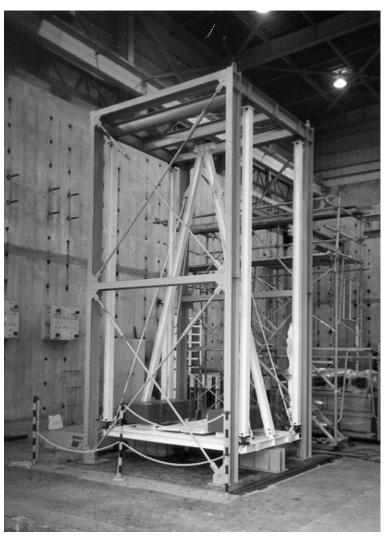


Fig. 4. Isometric drawing of seismically isolated floor

Photograph 2. Installing the hangers

The specimen comprises a test floor, suspended by four hangers from a frame, as shown in Photograph 3. The length of the hangers was made equal to that used in the actual structure. The dimensions of the suspended floor were 1.5 m by 2.5 m.



Photograph 3. Specimen on the shaking table

The specimen was placed on a shaking table vibrating both vertically and horizontally, and vibratory motions induced by white noise and the actual seismic records were applied. Figure 5 shows the change with time in horizontal accelerations of the shaking table and the suspended floor, under the vibration based on the El Centro 1940 N-S. It indicates sufficient isolation of the floor suspended as a translational pendulum.

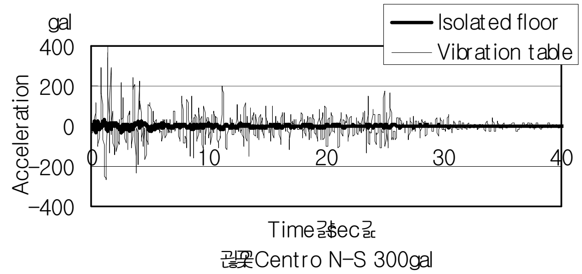


Fig. 5. Acceleration response of test floor

Figure 6 shows a frequency response function under horizontal vibration by white noise. As shown in the figure, the rate of amplification in response between the shaking table and suspension frame was about 1, which indicates that the suspension frame is sufficiently rigid to convey the vibration of the table to the suspension anchor. The isolated floor resonated significantly with the input vibration in the vicinity of a period of 4 seconds. When the prevalent period of input seismic motion is less than 2.7 seconds, however, the isolated floor functioned well to reduce the response. The input acceleration was reduced to about a half when the period was 2 seconds, and to less than 10% when it was 1 second or shorter.

Furthermore, a free vibration test was conducted for the Ceramics Park MINO during construction to identify the period, friction and damping characteristics of the suspended floor of the actual structure.

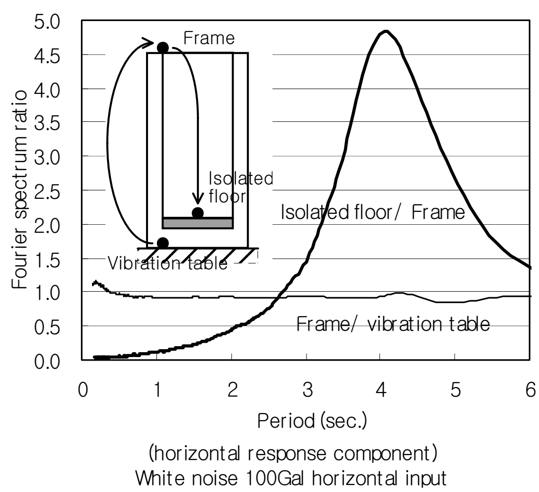


Fig. 6. Frequency response function for the input white noise

4. Application to seismic isolation of high-rise buildings

4.1 Concept

Seismic isolation is now being applied to structures with slender elevations. Although stress due to seismic motion generated in structural members is not a major issue for high-rise buildings, seismic isolation is desirable for the comfort of occupants and safety against overturning.

In the case of laminated rubber bearings, however, the rigidity of the bearings is significantly reduced when subjected to tensile force, and therefore its application to high-rise buildings is deemed difficult if uplift due to overturning moment of the structure is considered. Thus, another possibility is application of a system that uses a pendulum for base isolation of high-rise buildings.

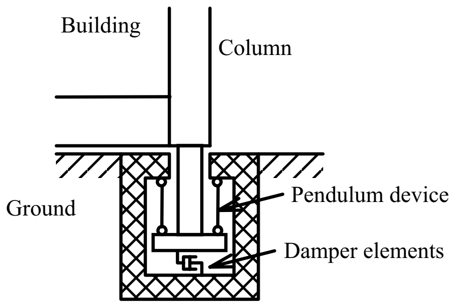


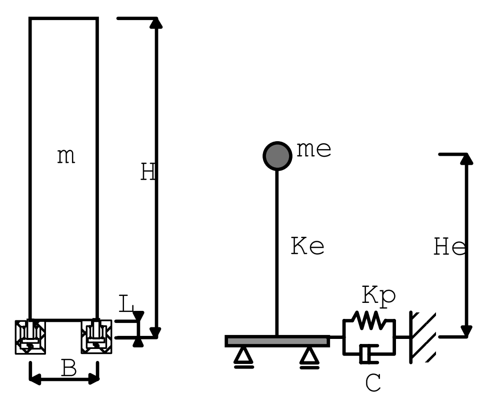
Fig. 7. Conceptual drawing of pendulum for base isolation

4.2 Studies based on earthquake response analyses

An earthquake response analysis was performed for a high-rise structure provided with a pendulum seismic isolation mechanism at its base, simulated by a single-mass system as shown in Figure 8 (a).

Even when uplift is generated at the base of the structure due to overturning moment, the period of the pendulum is determined only by the hanger length *L*, provided the hanger is a rod or other elements that are compression-resistant. Therefore, the pendulum can be simulated by a spring with equivalent natural period, and modeled as shown in Figure 8 (b). Here, *me, He*, and *Ke* represent the equivalent mass and height of the building, and spring constant, respectively. *Kp* represents the equivalent spring constant of the pendulum.

For simplicity, it was assumed that *me = m* and *He = 0.5H*. The equivalent spring constant of the pendulum was simulated by Equation (2), as it was



(a) high-rise building (b) Modeling

Fig. 8. Modeling of pendulum isolator for a high-rise building

evident from the analysis results that the amplitude is sufficiently small.

$$Kp = m_e \frac{g}{L} \tag{2}$$

A high-rise building with an aspect ratio *H/B* of 10 (the building 100-m tall with a natural period of 2 seconds, and damping constant of the structure being 3%) was studied as an example. The frequency of the pendulum seismic isolator was assumed to be 4 seconds, and the damping constant *h* as 10%. The total mass of the building was 2,000 tons. The input seismic motion was that of the Hachinohe (1968) N-S, and the maximum input acceleration was 500 gal. The analysis method was that by direct integration.

Table 1 shows the maximum response values. Also shown for comparison are the results for cases with fixed foundation and that without a damper. The response displacement between the ground and foundation represents the amplitude of the pendulum. The angular amplitude of the pendulum was 5.7° for an input motion of 500 gal, which is equivalent to a great earthquake. Hence, period shift does not need to be considered.

The magnitude of response displacement between the foundation and building structure represents the magnitude of base shear. The obtained results were in a range between 0.25 and 0.3 times those obtained for a case with fixed foundation, which is a significant reduction. The maximum response uplift was insignificant, being about 66 tons even for cases without a damper, when the weight of the building itself (1,000 tons) was subtracted.

Thus, it was concluded that pendulum seismic isolators having a long period are effective for high-rise buildings.

Table 1. Maximum response values (Hachinohe N-S, maximum input acceleration of 500 gal)

		Fixed foundation	Pendulum isolator	
			h=10%	h=0%
Maximum response displacement (m)	Between the ground and foundation	0.00	0.37	0.43
	Between the foundation and building	0.35	0.10	0.11
Maximum response acceleration (gal)	Foundation	500	148	159
	Building	349	97	105
Maximum response uplift (ton)		3,542	982	1,066

5. A study on the non-parallel swing system for seismic isolation

5.1 Concept of non-parallel swing system

In the field of architecture, translational pendulums have played a central role in seismic isolation because of their high applicability. From a geometric viewpoint, there exists another type of pendulum system between (b) and (c) in Figure 1. The type adopts pendulums that are hung symmetrically. The distance between the supports may be either longer or shorter than that for the translational pendulums in (c).

Swinging bars in a park are an example of this concept. In this chapter, a pendulum with supports that deviate from or come closer to each other symmetrically are referred to as the pendulum symmetrically hung from two supports, and its vibration properties are identified. A method for applying the useful characteristics of the pendulum symmetrically hung from four supports to seismically isolated structures is proposed and a basic model test is conducted.

5.2 Natural period of a pendulum symmetrically hung from two supports

A solution that provides the natural period of the pendulum symmetrically hung from two supports is a general solution applicable either to the physical (Figure 1 (b)) or translational (c) pendulum. Figure 9 shows a vibration model of a pendulum symmetrically hung from two supports. As is obvious from Figure 9, the center of gravity *G* of the object supported by the pendulum rocks due to vibration. A special solution without rocking is applicable to the case of a translational pendulum shown in Figure 1 (c) *(a=b).*

The ratio of the length of the suspended floor *A-B* to the distance between the supports *C-D* is expressed by $\beta=b/a$. $\beta=0$ and $\beta=1$ represent the physical and translational pendulums, respectively. When $\beta<1$ (left figure), the hangers (*A-C* and *B-D*) and the suspended floor rock in the same direction. When $\beta>1$, the hangers and the suspended floor rock in opposite directions. When $\beta=1$ (in the case of a translational pendulum), the suspended floor does not rock.

A rigid object was placed on the suspended floor of the model and free vibration was applied. The period was obtained according to the mechanical energy conservation law (Equation (3)). The suspended floor (*A-B*) was assumed to have sufficient rigidity.

$$T = 2\pi\sqrt{\frac{h}{g}}\cos\alpha\sqrt{\frac{\left\{1-(1-\beta)\frac{h_G}{h}\right\}^2+\frac{I}{Mh^2}(1-\beta)^2}{1-(1-\beta)\sin^2\alpha-\frac{h_G}{h}(1-\beta)^2\cos^2\alpha}} \quad (3)$$

where, $\alpha = \tan^{-1}\frac{b-a}{h}, \beta = \frac{b}{a}$

where, $\boldsymbol{h_G}$ is the height of center of gravity, and $\boldsymbol{I}$ is the moment of inertia around the center of gravity of the rigid object. The masses of the suspended floor and the hangers were ignored. Figure 10 shows changes in natural period according to $\boldsymbol{\beta=b/a}$ using $\boldsymbol{h_G/h}$ as a parameter. The figure shows that the natural period fluctuated substantially when the distance between the supports of the hangers was varied. The higher $\boldsymbol{h_G/h}$, the greater the fluctuation.

The natural period can be made longer than that of the translational pendulum by adjusting the distance between the supports of the hangers. This is very effective for seismic isolation.

5.3 Method of application to a seismic isolation system

A system using the characteristics of the pendulum symmetrically hung from two supports can provide a structure with a longer natural period than the seismic isolation system with the translational pendulum. The structure supported by the pendulum symmetrically hung from two supports is, however, subject to rocking. Rocking is very detrimental to seismic isolation systems because amenity may be adversely affected or the seismic response of certain stories may not be reduced effectively. In this study, a seismic isolation system that can control rocking while using the characteristics of the pendulum symmetrically hung from two supports is discussed.

The seismic isolation system can be made by connecting the columns supported by the pendulums symmetrically hung from two supports to the superstructure by hinges. A conceptual view of the system is shown in Figure 11. The columns ***Cs*** supported by the pendulums rock due to vibration, but the column tops ***E*** and ***F*** remain at the same elevation.

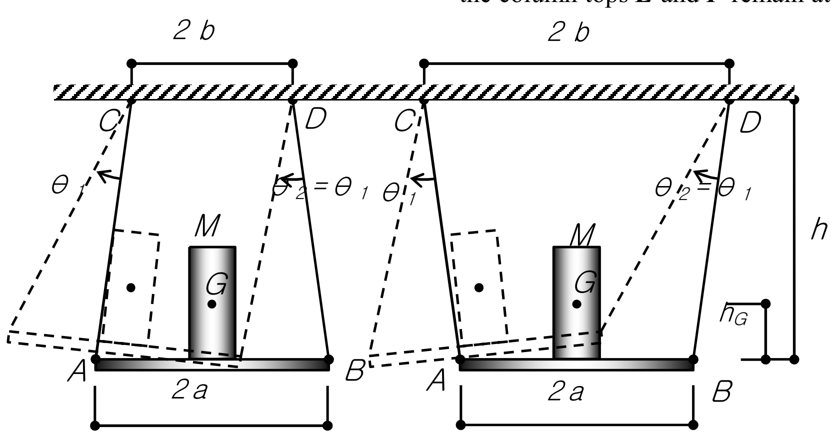


Fig. 9. Vibration model of a pendulum symmetrically hung from two supports

Thus, translational movement is predominant for the superstructure. Slight vertical displacement naturally occurs in the superstructure as the restoring force of the pendulums is generated.

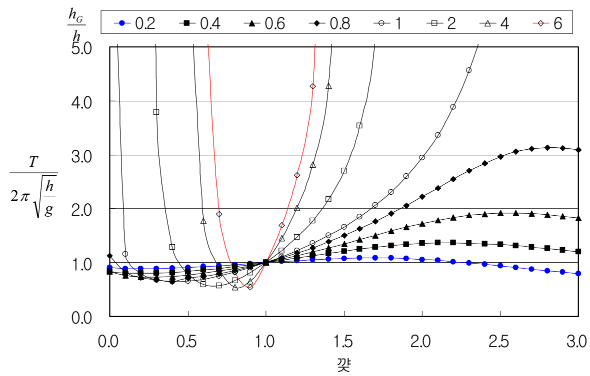


Fig. 10. Natural period of a pendulum symmetrically hung from from two supports

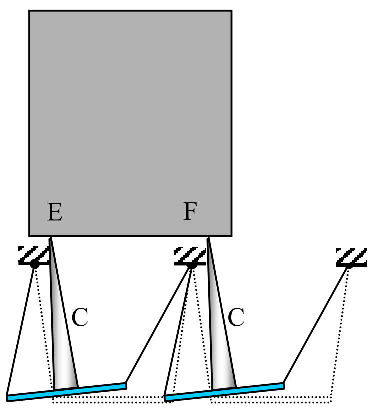


Fig. 11. Conceptual view of application to a seismic isolation system

5.4 Experimental study on application of pendulum seismic isolators to high-rise buildings

However, a pendulum symmetrically hung from two supports considered only horizontal one-directional movement. Therefore, the seismic isolation system of the pendulum with four symmetrical hangers is suggested as an advanced system as shown in Figure 12. The natural period T of this system can be similarly expressed as Equation (3) using the sign shown in Figure 12. The system can deal with three-dimensional movement by changing the distance of the top ends of the hangers spatially.

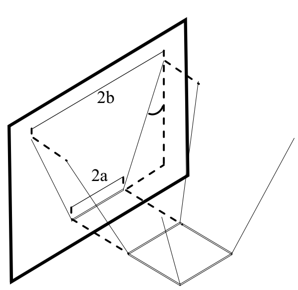


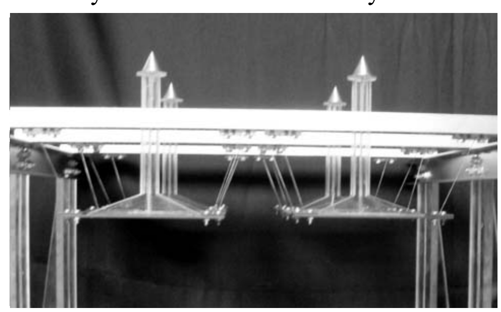
Fig. 12. Conceptual view of the pendulum with four symmetrical hangers

The effectiveness of a seismic isolation system with the pendulums symmetrically hung from four supports was examined by a vibration test using a scale model. In the test, a tower structure with an aspect ratio of approximately ten that simulated a high-rise building was adopted to facilitate testing.

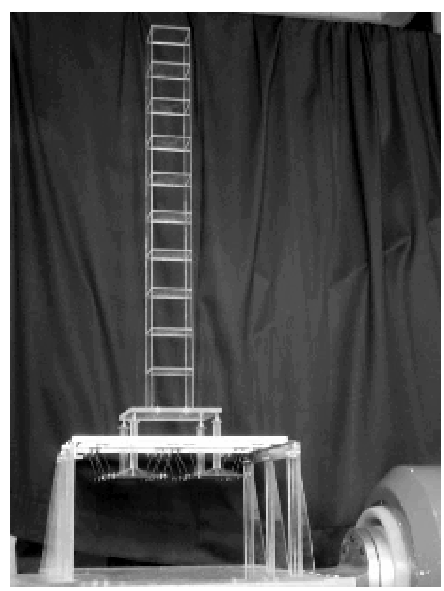
The test models are composed of an upper structure and four base isolation devices. Photograph 4 shows four base isolation devices and Photograph 5 shows the specimen on the shaking table. The superstructure was 100 cm high and 10 cm wide and was made of acrylic resin boards. The distance between the supports of the hangers was adjustable.

The upper model simulates high-rise buildings of 100 m, 200 m and 300 m height. Those simulated models produce the first mode natural periods of 2 sec, 4 sec and 6 sec, respectively. To perform these simulations, the time scales for the earthquakes are compressed by scaling laws.

Simultaneously with the experiment, we also performed numerical analysis. The upper model is replaced by a two-dimensional dynamic analysis



Photograph 4. Specimen of four base isolation devices



Photograph 5. Upper model on four base isolation devices

model of 10-mass structure, and the isolation devices are substituted by equivalent linear axial spring elements. In addition, the viscous damping of the test model is replaced by a stiffness-proportional damping element using the first-mode damping ratio obtained by the experiments as a criterion.

First, a free vibration test was conducted. Figure 13 shows the rate of increase in natural period in relation to the natural period of the translational pendulum (*β=1*). Two kinds of experiments, the case where the upper structure simulates high-rise buildings, and the case where the upper structure is rigid, were conducted. In Figure 13, the square mark and the round mark show each experiment result respectively. The calculated value from Equation (3) and the two-dimensional eigenvalue analysis result are given in Figure 13 for comparison.

Figure 13 indicates good agreement between the analytical value and the measurement. In the case where the upper structure is rigid the effect of the coupled vibration of the superstructure and the isolation layer on the natural period was eliminated. Figure 13 shows a decreasing rate of increase in period of the specimen because of the coupled effect of the vibration of the superstructure. It was, however, evident that the effect of the increase in period owing to the seismic isolation system of the pendulum with four symmetrical hangers was maintained.

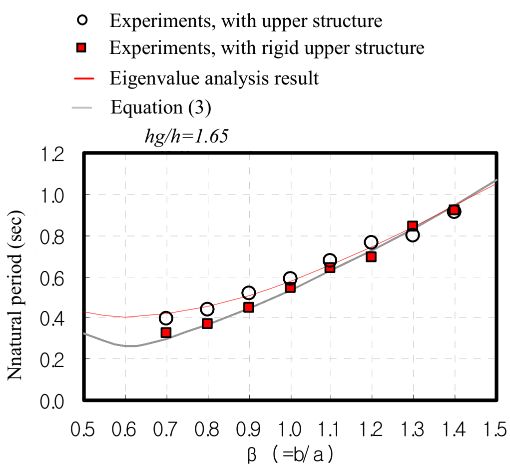


Fig. 13. Natural period of isolated superstructure

Figure 14 shows the rates of the observed acceleration responses when the seismic motion based on the records of actual earthquakes were applied to the vibration table. As shown, the response in the upper structure on the isolating layer was reduced sufficiently. It was also confirmed that the effect depended on the distance of the top ends of hangers β .

Figure 15 shows one of the results of shaking experiments and earthquake response analyses. The figure indicates good agreement between the analytical value and the measurement.

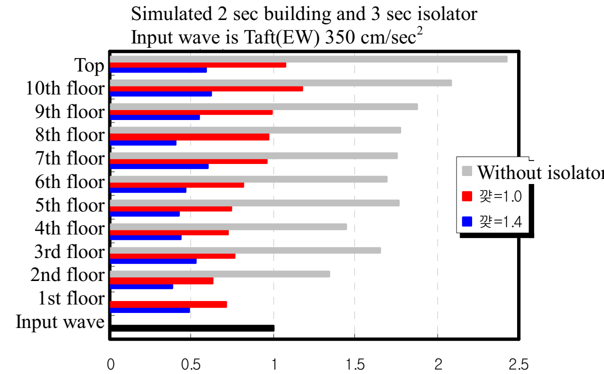


Fig. 14. Isolation effects of the maximum response acceleration based on actual earthquakes

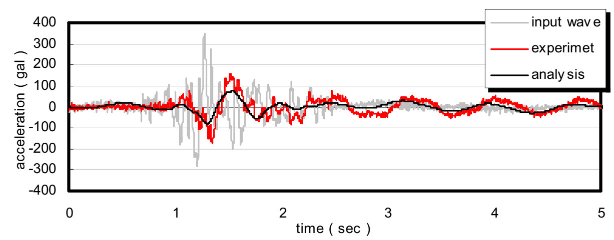


Fig. 15. Results of experiment and analysis

6. Conclusions

The authors have been developing highly reliable high-performance seismic isolation systems based on the simple principle of the pendulum. For applying the pendulum principle to seismic isolation, translational pendulums are easier to use than any other type of pendulum. In this study, we developed a seismic isolation system with pendulums symmetrically hung from four supports, which could use the benefits of translational pendulums and provide enhanced capacity.

1) This system can lengthen the first mode natural period by increasing the length of hangers and by extending the distance of the top ends of hangers.
2) Extending the distance of the top ends of hangers can reduce the seismic behavior of upper buildings when lengthening the natural period by a translational pendulum does not provide sufficient effect.

The system may be able to isolate ultra-long-period motions and used to isolate structures with predominant long-period components such as high-rise buildings.

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