Shake-Table Test on Statue Pedestals with Sliding Isolators

Tetsuhiko Aoki (Aichi Institute of Technology, Seismic Resistance Experiment Center)
Kimio Kawaguchi (The National Museum of Western Art)

1. Introduction

Art museum displays that safeguard statues, paintings, and other art objects against earthquakes are of great importance. Statues are especially prone to tumbling when subjected to strong seismic excitation because their centers of gravity are higher compared to the position of their bases.

Seismic resistance braces, vibration control devices, and seismic isolators have been primarily used in the past to prevent earthquake damage to buildings and residential houses. However, due to its small size, simplicity, and affordability, seismic isolation is considered to be a more effective measure in protecting small art objects resting on the floor. The seismic isolator consists of a sliding or rolling isolator, a side-sway mechanism with links, and a combination of these features.

In this study, the efficiency of a slide-plate type isolator attached to a stainless steel plate under a statue pedestal is experimentally verified by the shake-table test under a relatively large vertical and horizontal seismic excitation. To ensure a smooth slide, a Teflon sheet is applied to the bottom surface of the sliding stainless steel plate. This slide-plate isolator is simply placed on the museum floor; hence, it is considered the simplest and the smallest device when compared with conventional isolators. It also has the advantage of being less obtrusive, lowering the possibility of museum visitors bumping into the pedestals.

The application of slide-plate isolators to statue pedestals was introduced after observing that several stone statues displayed in the Getty Museum in Malibu, California, could have been prevented from falling or getting damaged by sliding them on the floor when the Northridge earthquake occurred in Santa Monica on January 17, 1997.

Many studies on slide isolators were conducted several decades ago in Japan for buildings (T. Sakata et al. 1999; N. Igawa et al. 2009) and bridge structures (S. Okamoto et al. 1995; H. Kaneji et al. 2006), but few were conducted on museum art objects. For museum display cases, shake-table tests were performed in Canada (Neurohr et al. 2008) in which three museum display cases slid on hardwood flooring and carpet. The results showed that the seismic response depends on flooring material, contact conditions, and floor elevation of the building.

Calio and Marletta (2003) conducted further studies with an art object modeled as a rigid block simply supported on a pedestal with a visco-elastic device. In this study, nonlinear equations of motion for the structural model under seismic excitation were derived with analytical and numerical results.

In the 1995 Kobe earthquake and the Ojiya earthquake of 2004 near Chuetsu, both in Japan, a large vertical excitation of about 800 gal was observed. Few studies have been presented thus far on slide isolation subjected to vertical and horizontal seismic excitation. In our test, the efficiency of the slide-plate isolator is experimentally verified through shake-table testing under the excitation of the vertical and horizontal seismic waves that were recorded simultaneously in the Kobe and Ojiya earthquakes.

Five different flooring materials actually used in the National Museum of Western Art in Japan were replicated in the test and attached to the shake table by bolts. A statue pedestal model was placed unrestrained on the floor center.

The shake-table test of a similar simple slide-plate isolation applied to buildings was introduced by E. Tachibana (2009) in which friction coefficients, maximum displacement, and residual displacement were used as dominant parameters. This test recommends a preferred coefficient of friction around $\mu \fallingdotseq 0.2$, which is derived from the conditions that μ is sufficiently large to be stationary during small-magnitude earthquakes and wind load, while μ is also sufficiently small to allow movement during large-magnitude earthquakes with a maximum acceleration of about 200 cm/sec^2. For this purpose, stainless steel is recommended as a slide plate. When the slide plate was placed at the bottom of a three-story building model and shake-tested, acceleration of every story indicates a 25% to 70% decrease from that of the building model without a sliding isolator.

It is interesting to note that the maximum response acceleration at the base of the building model with the slide plate, but no lubrication is 50% to 400% larger than that of the shake table. When the slide-plate test with a very low coefficient of friction shows the maximum response acceleration at the base of the building model to be 20% to 50% lower than that of the shake table.

2. Test Plan and Test Procedure

2.1 Test Plan

(1) Statue Pedestal Model and Sliding Plate

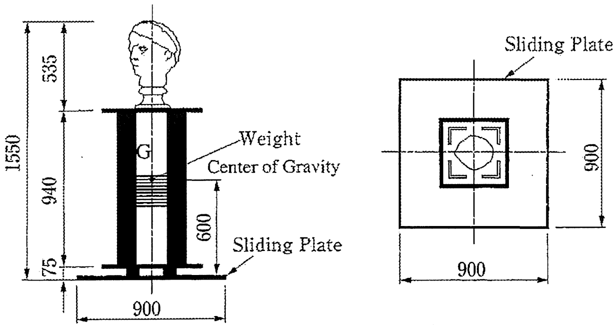
The statue model used in our test is shown in Photo 1. A plaster bust model 535 mm high was bolted to a 1015-mm-high pedestal, resulting in a total height of 1550 mm (Figure 1). The pedestal model was assembled with four 100-mm-long steel legs welded to the upper and lower steel plates. The cross-sectional dimension at the center of the pedestal model was 400 × 400 mm. Near the center, sixteen 16-mm-thick steel plates were fixed as an equivalent weight so that the weight and the center of gravity became the same as in the case of an actual statue.

The slide plate was made of stainless steel (900 × 900 × 5 mm) and was bolted to the bottom of the pedestal model as shown in Photo 1. A 3-mm-thick Teflon sheet was attached to the bottom surface of the sliding plate. The whole pedestal model weighed 332 kg; the center of gravity was 600 mm from the bottom.

Photo 1
Pedestal Model with Slide Plate Isolator

(2) Flooring Material

The five types of flooring used in our test — hard -wood, hard rubber tile, linoleum, carpet tile, and ceramic tile — are all used presently in the National Museum of Western Art in Japan. Each flooring type was fixed to a 2.7 m × 2.7 m × 12 mm plywood deck, which was bolted to the shake table. The pedestal model was placed on the center of the flooring deck as shown in Photo 2.



(a) side View

(b) Plane View

Figure 1
Dimensions of Pedestal Model (mm)

(3) Shake Table

For our experiment, the shake table was newly designed and fabricated at the Seismic Resistant Experiment Center, Aichi Institute of Technology in Japan. The shake table employed two 250 kN MTS dynamic actuators for simultaneous vertical and horizontal excitation and was able to shake an object weighing 5 tf (Photo 2).

The shake table had double-deck steel frames that were built with rolled-and-electric-welded square section steel tubes with a cross-sectional size of 200 × 200 mm. The upper frame (Figure 2(a)) had a 3.5 × 3.5 m plane area and

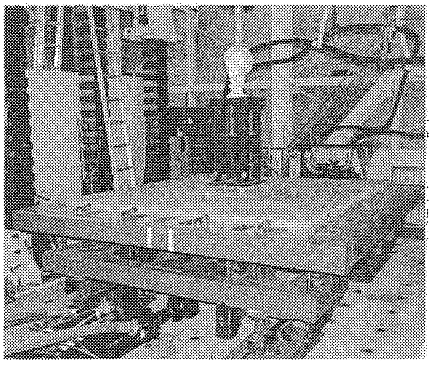
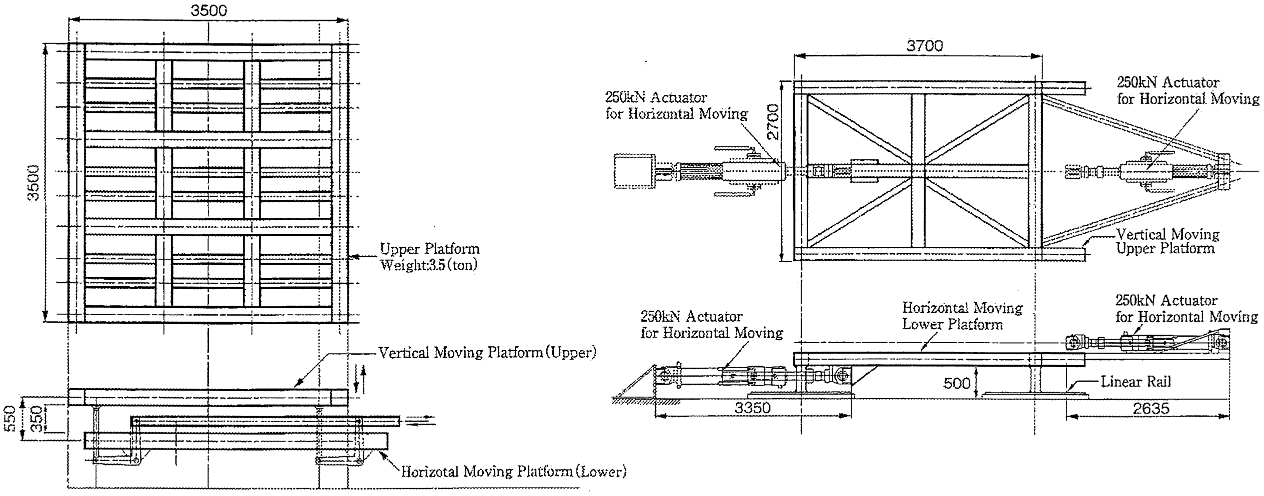


Photo 2 Shake Table and Pedestal Model

weighed 1960 kg. It was supported by four 500-mm vertical rods connected to the lower frame. The other ends of these rods were connected to L-shaped links that transferred horizontal force to vertical force by a second actuator placed on the lower deck.

The lower frame (Figure 2(b)), which measured 2.7 × 3.7 m and weighed 1730 kg, was mounted on linear rails with roller bearings and could move only in a horizontal direction. Therefore, the upper and lower frames could move together horizontally with the same amplitude and the upper frame could simultaneously drive vertically. By introducing this mechanism, deep pit construction to install a long actuator vertically was avoided.



(a) Dimensions of Upper Frame (mm)

(b) Dimensions of Lower Frame (mm)

Figure 2 Shape of Shake Table and its Dimensions

(4) Seismic Acceleration Data

Seismic acceleration data recorded in two sites are used in the test. During the Hyogo-ken Nanbu earthquake in 1995 (also known as the Kobe earthquake), the Japan Meteorological Agency (JMA) recorded peak accelerations of 820 gal horizontally and 333 gal vertically. The other data are taken from the 2004 Niigata-ken Chuetu earthquake. In Ojiya, the JMA recorded peak accelerations of 1140 gal horizontally and 818 gal vertically. Though the seismic wave data are provided as acceleration, these data are differentiated twice to drive the actuators, which require displacement data. Moreover, the high- and low-frequency regions of the original data were removed for the sake of smooth movement of the actuators. For comparison, the acceleration data, which was calculated again by integrating the processed displacement data, are illustrated in Figure 3 with a legend of "original" together with the measured acceleration data. The spectrum diagrams of the re-created acceleration data are shown in Figure 4.

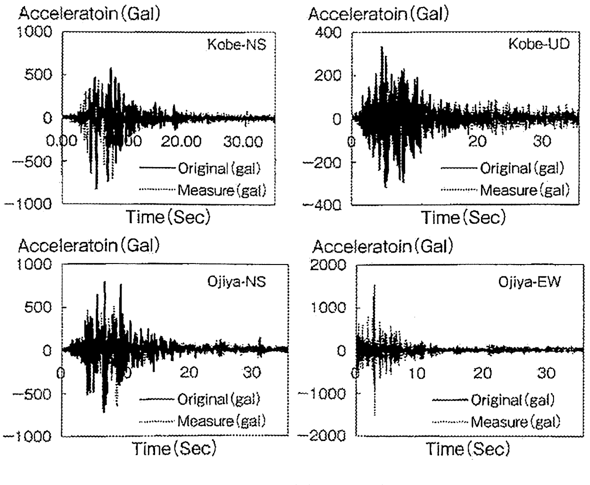


Figure 3 Comparison of Processed Acceleration and Original Data

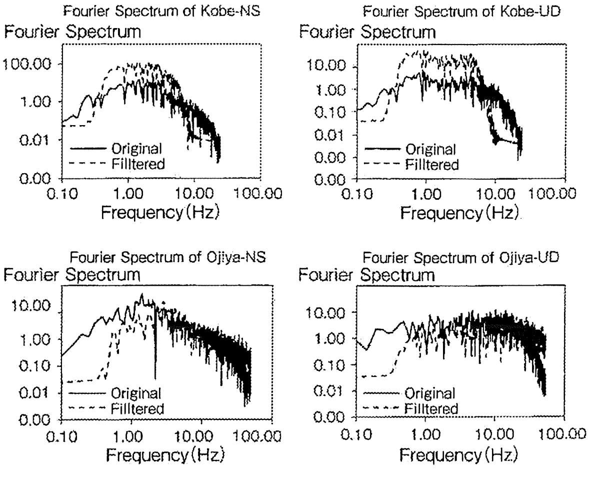


Figure 4 Spectrum Diagram of Processed Acceleration Data

2.2 Test Procedure

(1) Measurement of Acceleration and Displacement

The pedestal model was placed at the center of the floor, which has an area of 2.7 × 2.7 m (Photo 2, Figure 5). Four accelerometers that can measure a maximum of 10 gal in the three orthogonal directions and a laser displacement meter to measure horizontal direction displacement were placed at the lower end of the shake table's upper frame.

(2) Shake-Test Components

The N-S components of the seismic acceleration data, which indicate maximum values between two horizontal components N-S and E-W at both study sites, were selected and used to shake simultaneously with the vertical wave components.

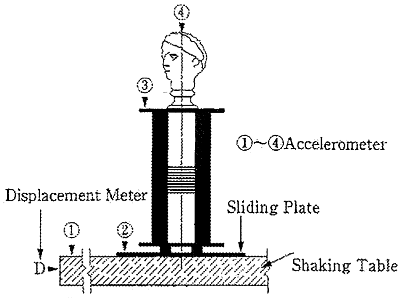


Figure 5 Location of Accelerometers and Displacement Meter

3. Test Results and Considerations

3.1 Results from Visual Observation

As a result of all shake-table tests conducted with simultaneous excitation in both vertical and horizontal directions, it is evident through visual observation that, despite vigorous vibration, the slide-plate type isolation adopted here exhibited steady behavior; no jumping or overturning was observed. It is confirmed that this isolator functioned effectively.

3.2 Measurement Results of Accelerometer

The measured acceleration of the pedestals on each flooring surface is depicted in Figure 6 (a) to (e) in which vertical and horizontal axes indicate height of each accelerometer and acceleration response magnification normalized by shake-table acceleration, respectively. The bold solid and broken lines represent North-South(NS) and up-down (UD) directions for Kobe, and the thin solid and broken lines exhibit NS and UD directions for Ojiya, respectively.

It can be generally said that the responses of seismic waves at Ojiya are larger than those of Kobe. If the pedestal model has no sliding plate, the acceleration response may enlarge with the location of height. If the pedestal model does have a sliding plate, the response magnifications are restrained within a value of about two, except at the top of the bust model for ceramic tile and carpet tile at Ojiya (Figure 6).

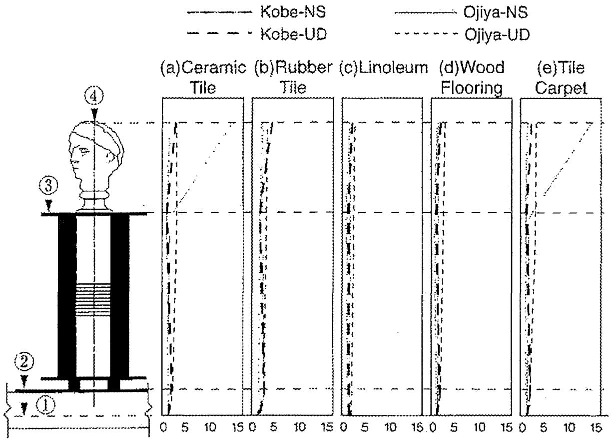


Figure 6 Acceleration Response Magnification for Each Floor Material

Table 1 Pedestal Base Acceleration (m/s²) and Acceleration Response Magnification

	Flooring Material	Kobe(NS)	Kobe(UD)	Ojiya(NS)	Ojiya(UD)
No.1	Ceramic Tile	8.6(0.71)	3.2(1.03)	9.9(1.46)	9.6(1.62)
No.2	Rubber Tile	8.1(0.91)	3.4(1.89)	9.9(1.78)	9.3(1.98)
No.3	Linoleum	8.2(0.81)	3.0(1.15)	9.8(1.27)	12.5(1.38)
No.4	Hardwood Flooring	8.2(0.92)	3.4(1.28)	10.0(1.23)	8.7(1.67)
No.5	Carpet Tile	8.0(0.84)	3.1(1.09)	9.9(1.58)	9.9(1.42)

Table 1 summarizes the peak response acceleration of the pedestal models and their response magnification to the shake table (indicated in parenthesis in the table) for the five flooring materials. It can be seen in Table 1 that the measured peak accelerations are almost the same among the different flooring materials. As seen in Figure 6 and in the values in parenthesis in Table 1, the acceleration response magnification at the base of the pedestal model becomes greater than one, with the exception of Ojiya (NS). This indicates that the acceleration response of the pedestal base is greater than that of the shake table.

Though such phenomena cannot be considered for isolated objects, as mentioned in the introduction, similar results were presented in a study conducted by E. Tachibana (2009) in which three-story buildings were shake-table tested with a slide isolator. In Figure 7, the vertical axis indicates the maximum acceleration response at each floor level, and the horizontal axis represents the corresponding acceleration response. The solid lines show the base of the building fixed to the table; the thin solid line shows the slide isolated without lubricant; the broken lines show the slide isolated with lubricant. As depicted in Figure 7, the maximum acceleration response of the building with the slide isolator is smaller in every story than that of the building without the slide isolator, which resulted in a 25% to 70% decrease of the latter.

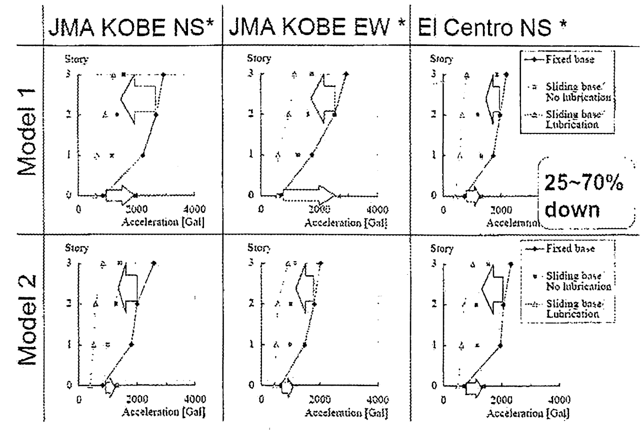


Figure 7 Maximum Acceleration Magnification at Each Floor in the Shake-Table Test for Three-Story Building Model with Base-Slide Isolator

However, at the base of the building in Figure 7, it appears that the maximum acceleration response of the buildings with the slide isolator without lubrication shows an increase 60% to 400% greater than that of the building without the isolator, which is same as the value in the shake table. The author's test results show the same discrepancy. On the other hand, in the case of the building with a lubricated slide isolator, the acceleration responses decrease by 5% to 50% from that of the fixed building case, as is expected.

It can be recognized from the results of these two experiments that when the friction of the slide isolator is sufficiently larger than the specified value, it is possible that the response acceleration of the base position of the structure with the slide isolator shows a value larger than that of the shake table itself.

Though it cannot account for this behavior clearly, it may be assumed that a sudden change in the coefficient of friction takes place when the shake-table movement changes to the opposite direction. The pedestal model also changes its direction just after instantaneous zero velocity. Moreover, as seen in Figure 7, even if the response acceleration at the base of the building model is larger than that of the shake table, the acceleration of the upper part of the building model remains equal to or smaller than that of the building without isolation. This implies that the isolator functions effectively despite the magnitude of base acceleration.

3.3 Relationship Between Displacement Amplitude and Coefficient of Friction

The displacement of a structure with a slide isolator will generally decrease with an increase in magnitude of the slide plate coefficient of friction. In other words, the displacement amplitude is likely in inverse proportion to the coefficient of friction.

Table 2 Horizontal Displacement of Pedestal δ_{max}, Displacement Amplitude δ_A, Residual Displacement δ_R, and Coefficient of Friction μ (for Ojiya Seismic Wave)

	Flooring Material	δ_{max} (mm)	$-\delta_{max}$ (mm)	δ_A (mm)	δ_R (mm)	μ
No.1	Ceramic Tile	+80	−300	380	−180	0.12
No.2	Rubber Tile	+240	−60	300	+9	0.13
No.3	Linoleum	+50	−160	210	−3	0.14
No.4	Hardwood Flooring	+75	−190	265	−75	—
No.5	Carpet Tile	+30	−150	180	−30	0.15

Table 2 summarizes the horizontal maximum and minimum displacement $+\text{-}\delta_{max}$; displacement amplitude δ_A, which is observed by the video image during excitation; and the coefficient of friction of the plate μ during Ojiya seismic excitation for each of the tested floor materials.

Figure 8 shows the relationship between displacement amplitude and the coefficient of friction. It is found from this figure that there is a reverse proportional relationship between both parameters. The displacement amplitude δ_A shows a larger value with the material presented in the order of Table 2; the coefficient of friction is in reverse order. The coefficient of friction is obtained by measurement prior to the shake-table test.

The test results, as was anticipated, show that the pedestal model produces a large displacement along with a small coefficient of friction. Though the coefficient of hard- wood flooring is not measured, it is assumed to be about 0.135 in this graph by applying the displacement amplitude of 260 mm obtained from shake-table test.

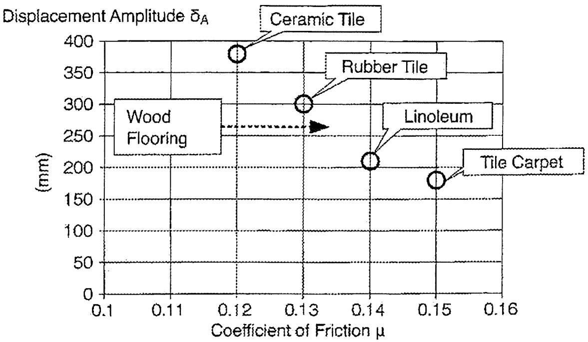


Figure 8 Relationship Between Displacement Amplitude and Coefficient of Friction

When the pedestal does not tumble, it should have a small displacement amplitude in order to avoid collision with museum visitors. Therefore, it is better to have a large coefficient of friction between the flooring and the sliding plate. For example, if the displacement amplitude is desired to be less than 400 mm for visitors' safety, a coefficient of friction greater than 0.12 is required (Figure 8). On the other hand, if the coefficient of friction is small, the sliding displacement will increase, and, consequently, visitors may bump into the pedestal. In the shake-table test in which the maximum level of seismic acceleration is applied horizontally and vertically at the same time, the maximum displacement of 400 mm occurred for the ceramic tile, which is the most slippery flooring. A displacement of this level may not be significant because the distance between statues and visitors is generally at least 1 m. It may be important, however, to realize the possibility that maximum displacement for all flooring materials could occur in museums during severe earthquakes.

When the coefficient of friction of the slide plate becomes larger than a certain level, rocking or tumbling may happen, though the slide displacement becomes small. This critical value of friction depends on the plate's coefficient of friction, the size of the sliding plate, the weight of the pedestal, and the height of its center of gravity. The relationship among them as well as the conditions to initiate rocking is subject for further investigation; moreover, the effects of vertical seismic excitation and other seismic wave data, sliding material other than Teflon, and the development of numerical analysis methods are also subjects for future studies.

From our test results, it is evident that the slide-plate isolator with a Teflon sheet at the bottom of the plate has worked effectively under strong, simultaneous vertical and horizontal seismic excitation for the five different flooring materials used in the museum. If the coefficient of friction is large, the pedestal will begin rocking and tilting. When applying vertical excitation to the pedestal in such a condition, it is evident that the pedestal will likely tumble, which may cause damage to the art object and harm to visitors.

4. Summary and Conclusions

In this study, the simplest slide-plate isolator for a museum pedestal is proposed, and its seismic efficiency was clarified through a shake-table test under simultaneous vertical and horizontal excitation using recently recorded acceleration data in Japan. The slide-plate isolator consists of a single, thin stainless steel plate with a Teflon sheet at the bottom of its surface. It is expected to be less of an obstruction, which museum visitors should appreciate. The following is a summary of our test results;

1) For shake-table testing, a shake table was newly designed and fabricated. The shake-table was oscillated in vertical and horizontal directions simultaneously using the greatest magnitude acceleration data of horizontal (1200 gal) and vertical (800 gal) movement ever recorded, which occurred during the Kobe (1995) and Chuetsu, Niigata, (2004) earthquake.

2) It is clarified from the shake-table test that the proposed slide-plate isolator functions well for the five different flooring materials presently used in the National Museum of Western Art in Japan. The pedestal model with slide isolator performed stably without rocking or tumbling down under the study's strong seismic excitation.

3) The maximum acceleration response at the base of the pedestal with the slide isolator shows greater magnitude than that of the shake table, which is contrary to expectations. It is interesting to note that a large coefficient of friction of the slide plate allows this phenomenon to take place. The test result agrees with data presented by other researchers. The reason for this is not accounted for at this time, but it is assumed that the dynamic coefficient of friction of the sliding plate suddenly changes with the change in direction of the shake table, where the movement stops instantaneously.

4) The displacement amplitude of the pedestal on each flooring material during shaking is measured by video. The coefficients of friction among the pedestal with the sliding plate and the five different flooring materials are measured prior to shake-table testing with values ranging from 0.12 to 0.15. Illustrating the relationship of the coefficients of friction and the displacement amplitudes for the seismic wave at Ojiya, which showed the maximum magnitude of vertical acceleration ever recorded in Japan, an inverse proportional smooth curve emerges at the point where the displacement amplitudes are changed from 380 mm to 180 mm along with the change in the coefficient of friction from a smaller value to a larger one.

5) The maximum displacement amplitude of 380 mm is produced on the ceramic tile, which has the lowest value of coefficient of friction $\mu = 0.12$. On the other hand, the minimum displacement of 180 mm is recorded for the carpet tile, whose coefficient of friction is $\mu = 0.15$. The coefficient of friction of hardwood, whose value was not measured previously, is assumed to be $\mu = 0.134$ by introducing its displacement amplitude of 265 mm into the curve established from the experiment.

6) During the shake-table test, bouncing of the model is not observed despite very strong seismic excitation. Therefore, the effect of vertical seismic excitation on the pedestal with the slide isolator is considered to be small in this experiment. This is because of the smooth slide of the isolator, which did not allow the pedestal model to tilt during excitation. If a tilted model experiences a vertical force, this model may easily increase its incline following overturn.

7) When the coefficient of friction of the sliding plate is small, the sliding distance is large, resulting in a possible collision of visitors with the pedestal. From the shake-table test that used large seismic data, though the maximum displacement of 400 mm occurred on ceramic tile, it may not be considered a serious problem because the distance between visitors and statues is generally at least 1 m. It is important to contain the maximum displacement of the statues with slide isolators on different flooring materials in museums on the supposition of severe earthquakes.

8) When the coefficient of friction of the slide plate becomes larger than a certain value, rocking or overturning may occur even though the slide displacement decreases. The critical value of the coefficient of friction that causes rocking may depend on the coefficient of friction of the materials, the size of slide plate, the weight of pedestal, and its height and seismic characteristics. It is easily assumed that the vertical seismic motion becomes significant if rocking starts. The issues that refer to the rocking are subjects for future study.

There are many museums in Japan, and their displayed or stored art objects need protection against severe earthquakes. But budget restrictions have prevented proper management thus far. Therefore, if low-cost, simple, and effective isolator devices are proposed, many museums may introduce them to protect their assets.

Acknowledgements

The shake-table test was conducted at the Seismic Resistance Experiment Center, Aichi Institute of Technology, in Japan. The writers gratefully acknowledge Mr. Hiroshi Suzuki, a technician at the center, and the students of the Department of Civil and Environment Engineering for helping in this research.

References

1) T. Sakata, S. Okamoto and K. Shibata: Study on a sliding isolator proper to lightweight residential houses (dynamic response analysis of variable friction coefficient type sliding isolator), Japan Society of Machine, Proceedings of Dynamics and Design Conference 99, pp. 16-19, (1999).

2) N. Igawa, H. Yoneda, E. Tachibana and T. Narafu: Shake table test of slide isolator and verification response reducing effect by numerical analysis (Part 2), Journal of Japan Architecture Association, Vol. 15, No. 31, pp. 685-690, (2009).

3) S. Okamoto, Y. Fukazawa, S. Fujii and D. Ozaki: Characteristics of seismic behavior of bridges with slide type isolator, Proceedings of Japan Society of Civil Engr., No. 513/I-31, pp. 191-200, (1995).

4) H. Kaneji. Suzuki, H. Iemura, Y. Takahashi T. Mino, and Y. Takada: Verification of dependency on plate pressure and velocity of low friction type slide isolator and design model construction of floor isolated structure, Proceedings of Japan Association of Civil Engr., A, Vol. 62, No. 4, pp.7 58-771, (2006).

5) T. Neurohr and G. McClue: Shake table testing of museum display cases, Can. J. Civ. Eng. 35, 1353-1364, (2008).

6) I. Calio and M. Marlertta: Passive control of the seismic rocking response of art objects, Engineering Structures, 25, 1009-1018, (2003).

7) E. Tachibana : Introduction of case study in Japan, (1) Low cost slide isolator without restoring mechanism, lecture note on development of low cost isolator techniques, May (2009), http://www.kenken.go.jp/Japanese/information/information/event/Tokyo-2007/ index.htm