Shaking Table Tests of Motion Sensitive Equipment Isolated with Static Dynamics Interchangeable-Ball Pendulum System

C. S. Tsai[1], Wen-Shin Chen[2], Yung-Chang Lin[3], Ching-Pei Tsou[4]
Chia-Chi Chen[4], Chia-Lu Lin[4]

[1] *Professor, Department of Civil Engineering, Feng Chia University, Taichung, Chinese Taiwan.*
[2] *Ph. D., Graduate Institute of Civil and Hydraulic Engineering, Feng Chia University, Taichung, Chinese Taiwan.*
[3] *Ph. D. Candidate, Graduate Institute of Civil and Hydraulic Engineering, Feng Chia University, Taichung, Chinese Taiwan.*
[4] *Master, Department of Civil Engineering, Feng Chia University, Taichung, Chinese Taiwan*
Email: cstsai@fcu.edu.tw

ABSTRACT:
Motion sensitive equipment for high-technology industries, which include nano-technology, photonics technology and communication technology industries, etc., located in a building is much more valuable than the building itself. Damage to high-tech equipment during earthquakes will cause huge loss in economy. To offer a solution to aforementioned problem, in this study a novel base isolator called the static dynamics interchangeable-ball pendulum system (SDI-BPS) is proposed. This isolation system uses steel balls to support the primary static load when the system is in service and the rubber steel balls to provide damping for controlling the isolator displacement when subjected to ground motions. The efficiency of the proposed isolation system has been proven through a series of full scale shaking table tests in the Center for Research on Earthquake Engineering (NCREE) in Taiwan. The experimental results show that the acceleration responses of motion sensitive equipment isolated with SDI-BPS isolators were reduced by more than 80%. It is concluded that the static dynamics interchangeable-ball pendulum system is a promising isolation system for protecting critical equipment from earthquake damage.
KEYWORDS: Earthquake Engineering, Isolation System, Isolator, Equipment, Non-structure Components

1. INTRODUCTION

The earthquake is a highly unpredictable and dubitable natural disaster. The damage caused by earthquakes affects the economic development of the affected countries. Recently, the isolation technology has been acknowledged as an effective method to promote the earthquake resistant capacity of the structures in seismic mitigation on the basis of theoretical and experimental results and earthquake events. However, motion sensitive equipments located in these industrial buildings are vulnerable during earthquakes, which may cause huge economic loss. In order to protect the motion sensitive equipment from earthquakes, a ball pendulum system (BPS) was proposed by Tsai et al. [1, 2] in 2006; it comprises two spherical concave surfaces and a steel rolling ball covered with a special damping material to provide horizontal and vertical damping to correct the aforementioned problems. It has been proven through a series of shaking table tests that the BPS isolator can upgrade the ductility capacity of motion sensitive equipments in seismic mitigation [1, 2]. In this study, a new isolation system called the static dynamics interchangeable–ball pendulum system (SDI-BPS), as shown in Figures 1a and 1b, is proposed in this study. The proposed system comprises not only two spherical concave surfaces and a steel rolling ball covered with a special damping material to provide damping and prevent any damage and scratches to the concave surfaces during the dynamic motions but also several small steel balls that are used to support the static weight to prevent any plastic deformation or damage to the damping material during the long term of service loadings. Because the concave surfaces are protected by the damping material covering the steel ball from damage and scratches, they may be designed as desired shapes in geometry. In this study, a series of shaking table tests of the motion sensitive equipment isolated with SDI-BPS isolators under tri-directional earthquakes were carried out. The experimental results of the shaking table tests of the motion sensitive equipment isolated with the SDI-BPS isolators under tri-directional earthquakes illustrate that the SDI-BPS isolator is able to provide good protection for the motion sensitive equipment under strong seismic loadings and offer a significant damping effect to the entire isolated system for simultaneously reducing the bearing displacement and size.

2. SHAKING TABLE TESTS OF MOTION SENSITIVE EQUIPMENT WITH SDI-BPS ISOLATORS UNDER TRI-DIRECTIONAL EARTHQUAKES

In order to examine the efficiency of the SDI-BPS isolator installed in the motion sensitive equipment under tri-directional earthquakes, a series of shaking table tests of the motion sensitive equipment isolated with the SDI-BPS isolator under tri-directional earthquakes were performed at the Center for Research on Earthquake Engineering, Chinese Taiwan. The motion sensitive equipment was shown in Figure 3 and the masses located at each layer were changed. A mass of 108 kg at each layer from the first to the third layer and 54 kg each at the rest of the layers was added. In the case of the fixed base, the natural frequency was 5.66 Hz, as shown in Figure 4. In the isolated case, four SDI-BPS isolators with a radius of curvature of 1.0 m were installed beneath the equipment. The tested ground motions included the 1995 Kobe and the 1999 Chi-Chi (TCU084 station and TCU129 station) earthquakes. Tables 1 and 2 show a comparison between the acceleration responses in X and Y directions at each layer of the equipment in the fixed base and the SDI-BPS-isolated systems subjected to tri-directional earthquakes with various levels of PGAs. The test results under the tri-directional earthquakes illustrate that a large amount of the acceleration response in the X and Y directions at each layer of the equipment has been significantly reduced. Figures 5 through 10 show the comparison between the X- and Y-directional acceleration responses at the top layer of the equipment in the fixed base and SDI-BPS-isolated systems under various tri-directional earthquakes. It is observed from these figures that the SDI-BPS isolator can effectively isolate the earthquake energy trying to enter the motion sensitive equipment during earthquakes. Figures 11 through 13 show the hysteresis loops of the SDI-BPS isolator under the various tri-directional earthquakes. These figures illustrate that the SDI-BPS isolator can provide damping to limit the bearing displacement, and accordingly, the bearing size is decreased. Figures 14 through 15 are the Fourier transmissibility for the acceleration responses of the SDI-BPS-isolated system. By comparing the results of the Fourier transmissibility given in these two figures to that of the fixed-base system, it is clearly shown that the natural period of the system has been lengthened by the proposed isolator.

3. CONCLUSIONS

The SDI-BPS isolator proposed in this study has rectified the drawbacks of the old ball isolation system, such as little damping provided by the system, highly concentrated stress produced by the supporting ball due to the small contact area, and scratches and damage to the concave surfaces caused by the ball motions during earthquakes. The SDI-BPS isolator not only effectively lengthens the natural period of the motion sensitive equipment but also provides significant damping to reduce the large bearing displacement and size. In addition, the SDI-BPS isolator can isolate energy induced by earthquakes to ensure the safety and functionality of the motion sensitive equipment located in a building.

ACKNOWLEDGEMENT

The authors would like to thank the Taiwan Science Council for the financial support (Project No. NSC 95-2221-E-035-112).

REFERENCES

[1] Tsai CS, Lin YC, Chen WS, Chen MJ and Tsou CP. The material behavior and isolation benefits of ball pendulum system. *Seismic Engineering 2006, ASME*, Edited by James F. Cory, Vancouver, BC, Canada., July 23–27,2006; No. PVP2006-ICPVT11-93252.

[2]T. C. Chiang (2007), "Earthquake Protection Efficiency Tests of Static-Dynamic Interchangeable Ball Pendulum System for Sensitive Equipment", Master Dissertation, Feng-Chia University, Taichung, Chinese Taiwan.

Table 1 Comparison between maximum acceleration in X-Direction at each layer of fixed-base and SDI-BPS-isolated systems under tri-directional earthquakes

Earthquakes	Layer	Fixed-Base System (g)	Isolated System (g)	Reduction(%)
Kobe X0.388g + Y0.265g + Z0.116g	1st	0.369g	0.147g	53.8%
	2nd	0.313g	0.126g	59.7%
	3rd	0.532g	0.186g	65.0%
	4th	0.449g	0.151g	66.3%
	5th	0.724g	0.285g	60.7%
	6th	0.803g	0.303g	62.2%
Chi-Chi (TCU084) X0.673g + Y0.271g + Z0.159g	1st	0.651g	0.217g	68.6%
	2nd	0.581g	0.234g	59.7%
	3rd	0.833g	0.322g	61.3%
	4th	0.608g	0.177g	70.9%
	5th	1.009g	0.268g	73.5%
	6th	1.053g	0.289g	72.5%
Chi-Chi (TCU129) X0.960g + Y0.589g + Z0.218g	1st	0.949g	0.163g	82.9%
	2nd	0.831g	0.219g	73.6%
	3rd	1.212g	0.356g	70.7%
	4th	0.971g	0.229g	76.4%
	5th	1.584g	0.353g	77.7%
	6th	1.768g	0.358g	79.7%

Table 2 Comparison between maximum acceleration in Y-Direction at each layer of fixed-base and SDI-BPS-isolated systems under tri-directional earthquakes

Earthquakes	Layer	Fixed-Base System (g)	Isolated System (g)	Reduction (%)
Kobe X0.388g + Y0.265g + Z0.116g	1st	0.235g	0.131g	44.3%
	2nd	0.378g	0.195g	48.4%
	3rd	0.371	0.209g	43.7%
	4th	0.497g	0.222g	55.3%
	5th	0.515g	0.202g	60.8%
	6th	0.518g	0.177g	65.8%
Chi-Chi (TCU084) X0.673g + Y0.271g + Z0.159g	1st	0.223g	0.117g	47.5%
	2nd	0.354g	0.182g	48.6%
	3rd	0.315g	0.150g	52.4%
	4th	0.413g	0.180g	56.4%
	5th	0.446g	0.184g	58.7%
	6th	0.531g	0.214g	59.7%
Chi-Chi (TCU129) X0.960g + Y0.589g + Z0.218g	1st	0.526g	0.163g	69.0%
	2nd	0.686g	0.211g	69.2%
	3rd	0.611g	0.183g	70.0%
	4th	0.902g	0.259g	71.3%
	5th	1.053g	0.277g	73.7%
	6th	1.137g	0.303g	73.4%

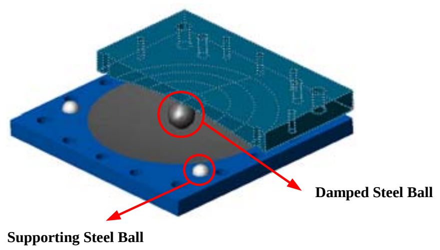

Figure 1 Exploded perspective view of Static Dynamics Interchangeable–Ball Pendulum System

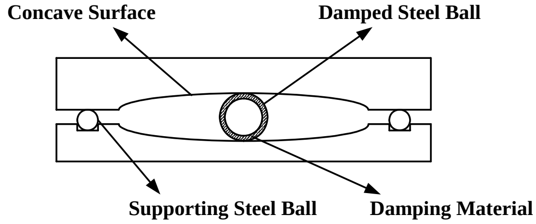

Figure 2 Cross-sectional view of Static Dynamics Interchangeable–Ball Pendulum System

Figure 3 Motion sensitive equipment with the SDI-BPS isolators

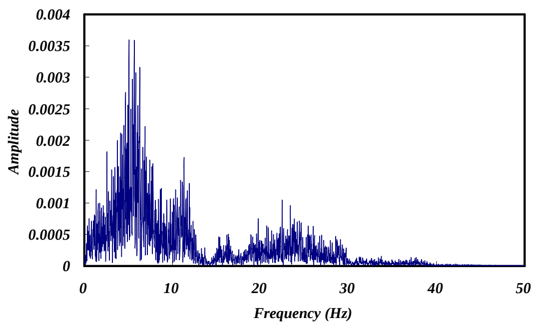

Figure 4 Fourier transformation for acceleration response at top layer of fixed-base equipment under white noise ground motions

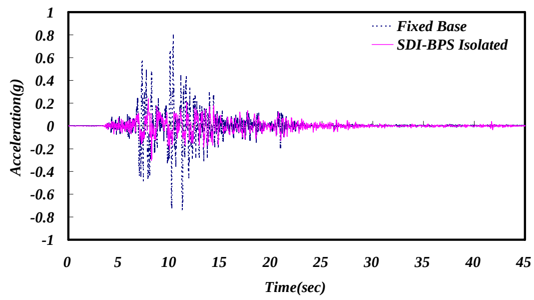

Figure 5 Comparison between the X-directional acceleration response at top layer of fixed-base and SDI-BPS-isolated systems under tri-directional Kobe earthquake (PGA = X0.388g + Y0.265g + Z0.116g)

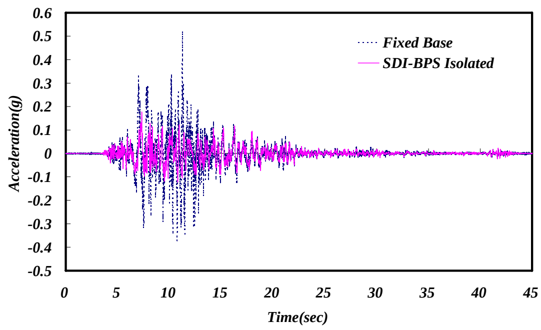

Figure 6 Comparison between the Y-directional acceleration response at top layer of fixed-base and SDI-BPS-isolated systems under tri-directional Kobe earthquake (PGA = X0.388g + Y0.265g + Z0.116g)

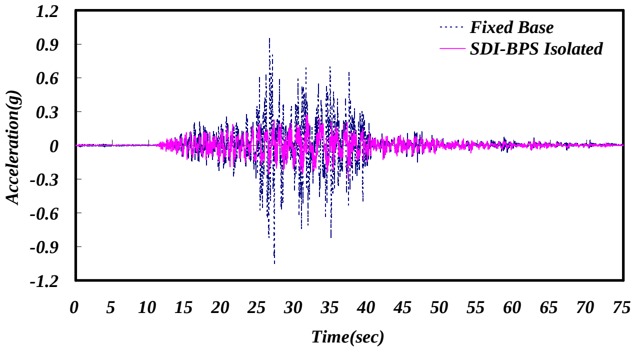

Figure 7 Comparison between acceleration response in X-direction at top layer of fixed-base and SDI-BPS-isolated systems under tri-directional Chi-Chi (TCU084 Station) earthquake (PGA = X0.673g + Y0.271g + Z0.159g)

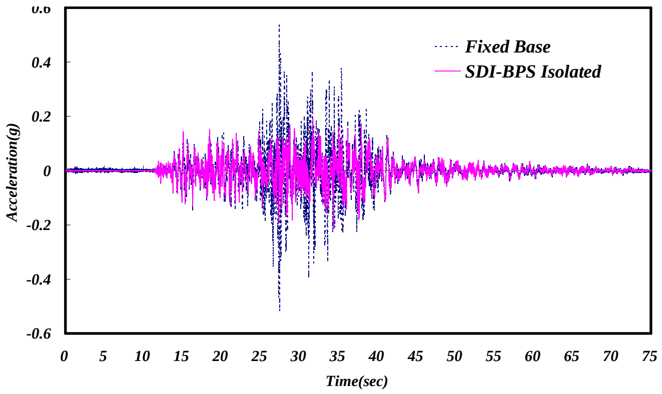

Figure 8 Comparison between acceleration response in Y-direction at top layer of fixed-base and SDI-BPS-isolated systems under tri-directional Chi-Chi (TCU084 Station) earthquake (PGA = X0.673g + Y0.271g + Z0.159g)

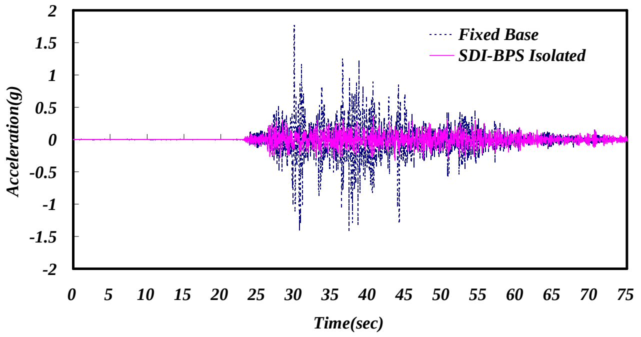

Figure 9 Comparison between acceleration response in X-direction at top layer of the fixed-base and SDI-BPS-isolated systems under tri-directional Chi-Chi (TCU129 Station) earthquake (PGA = X0.960g + Y0.589g + Z0.218g)

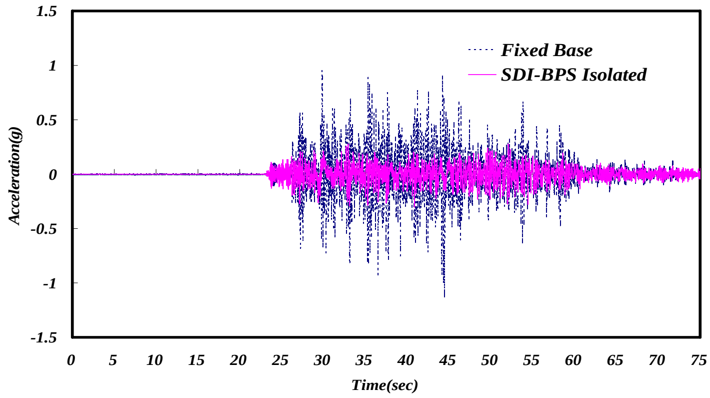

Figure 10 Comparison between acceleration response in Y-direction at top layer of the fixed-base and SDI-BPS-isolated systems under tri-directional Chi-Chi (TCU129 Station) earthquake (PGA = X0.960g + Y0.589g + Z0.218g)

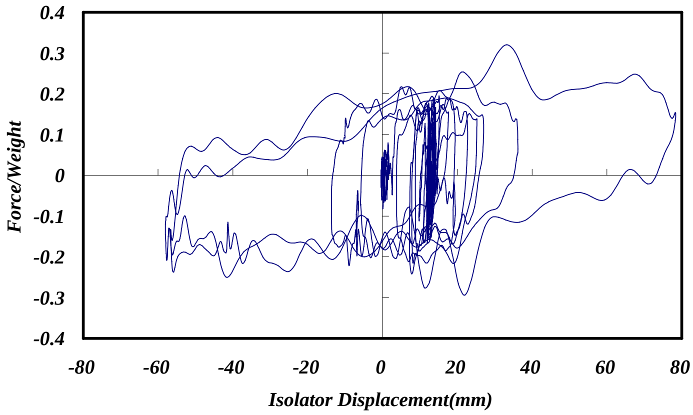

Figure 11 Hysteresis loops of SDI-BPS isolator in X direction under tri-directional Kobe earthquake (PGA = X0.388g + Y0.265g + Z0.116g)

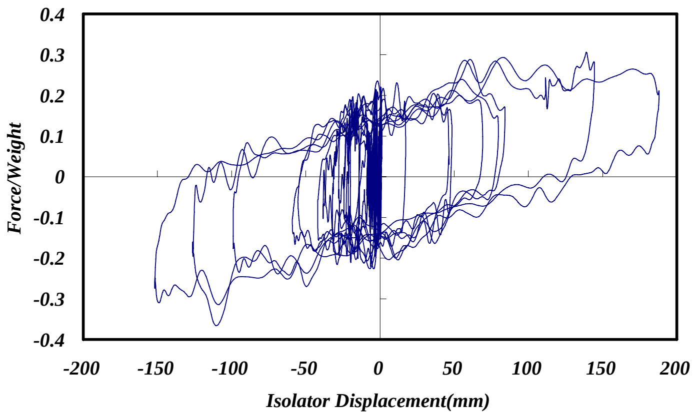

Figure 12 Hysteresis loops of SDI-BPS isolator in X direction under tri-directional Chi-Chi (TCU084 Station) earthquake (PGA = X0.673g + Y0.271g + Z0.159g)

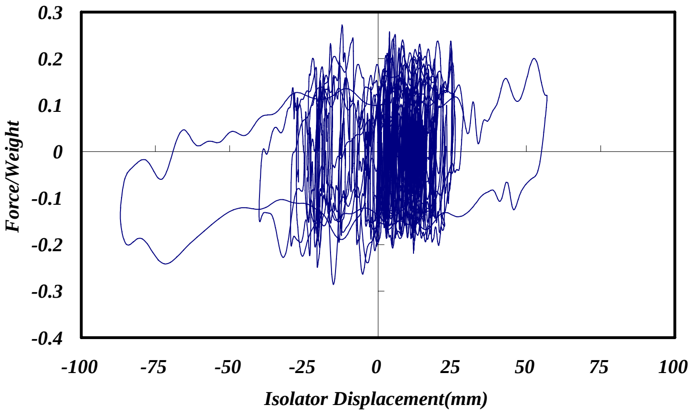

Figure 13 Hysteresis loops of SDI-BPS isolator in X direction under tri-directional Chi-Chi (TCU129 Station) earthquake (PGA = X0.960g + Y0.589g + Z0.218g)

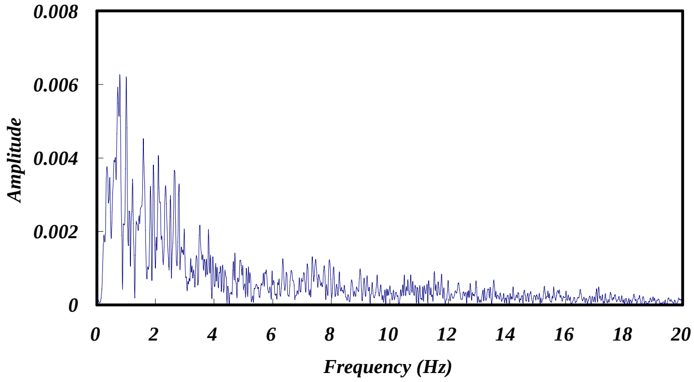

Figure 14 Fourier transmissibility for acceleration response in X-direction of the SDI-BPS-isolated equipment under Kobe earthquake

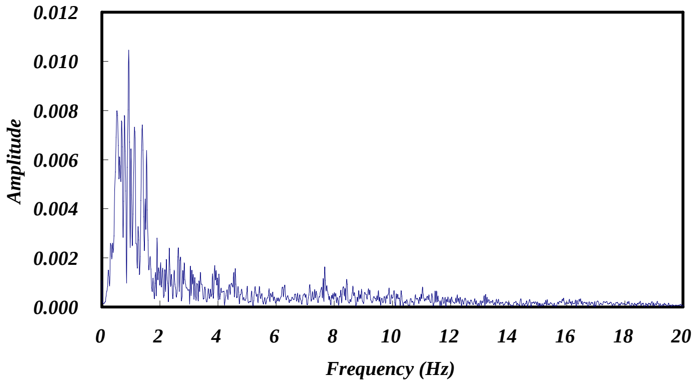

Figure 15 Fourier transmissibility for acceleration response in X-direction of SDI-BPS-isolated equipment under Chi-Chi (TCU084 Station) earthquake