PILLOW-SHAPE BASE ISOLATION SYSTEM AND ITS SEISMIC BEHAVIOR

Ali TAYARAN
Graduate Student, Department of Civil Engineering, Faculty of Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran
alitayaran@yahoo.com

Mahmood HOSSEINI
Associate Professor, Structural Engineering Research Center, International Institute of Earthquake Engineeringand Seismology(IIEES), Tehran, Iran
hosseini@iiees.ac.ir

Keywords: Rolling Isolation, Lagrange Equation, Runge-KuttaTechnique, Finite Element Analysis

ABSTRACT

One way to reduce the seismic response of structures is base isolation. In this paper a new isolating system is introduced for short to mid-rise buildings that unlike conventional systems such as LRB and HRB, does not need cutting edge technology and has low manufacturing cost. This system is made up of two orthogonal pairs of pillow-shaped rollers that are located between flat bed and plates. By using this system in two perpendicular directions, building can move in all horizontal directions with respect to its foundation. Due to the pillow shape of the roller, this system has self-centering capability which causes it to return to its original position after the earthquake. The rolling friction force between pillows and their bed creates some damping in the system which prevents it from further oscillationafterearthquake excitations diminish. The purpose of this study is to evaluate the proposedisolationsystem's performance under different earthquake excitations. First of all general features of the proposed isolators have been introduced followed by the analytical equations of the system. Vertical bearing capacity and the effects of the thickness of pillows has been investigated using ABAQUS software. It has been shown that for a pair of pillows of 58 cm width, 45 cm height and 100 cm length the vertical load bearing capacity of the system is more than 300 tons. The period of system with respect to the height and radius of curvature of the rollers, and seismic response of a building, assumed as a rigid body resting on isolators, has been studied subjected to simultaneous effects of horizontal and vertical excitations. It has been shown that the proposed system can reduce the absolute acceleration in the building around 78% in average, while the building's maximum displacement is around 1.77 times of the ground in average.

INTRODUCTION

Base isolation is one of the effective technologies to protect structural systems and equipments or facilities against earthquake. One of the first isolator systems was introduced by Touallonin in 1870, which was made of a sphere between two convex spherical surfaces,(Chong-shien and Tsai, 2012) .During the last decades isolation systems have been developed, and various types including Lead-Rubber Bearing (LRB), High-damping Rubber Bearing (HRB) and Friction Pendulum System (FPS) have been introduced. Jangid et al. (1998),providing a system consisting ofelliptical rolling rods between the base and foundation, evaluated the effectof isolating of a multi-storey buildings against earthquake and showed that byusingelliptical rolling rods, a reduction in the seismic response of structures without major displacements is made. Lee et al.(2003), used cylindrical rollers on V-shaped sloping surfaces and showed that their system can play an important role in structural seismic isolation. When the roller mechanism is fully operational, horizontal forces does not depend on earthquake excitation and after the earthquake, system is returned to its initial position due to the weight of the building.

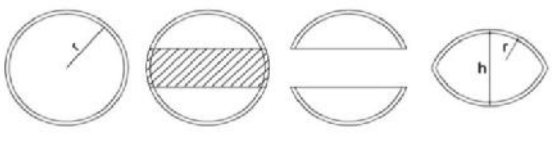
Guerreiroet al. (2007), used an isolating system which leads to increased damping and simultaneously reduced displacement. This typeofisolatingsystems usually suffers from some shortcomings such as low damping, stress concentration, scratching, damaging the contact surfaces during an earthquake, and movement even at service loads such as slight winds.Hosseini and Soroor(2010), introduced orthogonal pair of rollers on concave beds (OPRCB) as a base seismic isolation system for multi-story buildings up to 14 stories, which does not have most of the aforementioned shortcoming. The OPRCB isolators are simpler than other existing isolating systems such LRB and HRB, and can be manufactured with low costs,but they are weak against uplift.

Yang et al., 2011, investigated variable-frequency rocking bearings system. The mechanical behaviorof their proposed system is similar to that of rolling isolators. The lower level has a rocking surface and its upper part is connected to the isolating system by pin-type connection. Selecting the appropriate geometry of the rocking curve leads to specific behaviors required by the designer. Stiffness of system is a function of its displacement and thus its frequency is variable and is determined only by the geometrical parameters and it is independent of the mass of the isolated structure. Harvey et al. (2013), examined responses of nonlinear roller isolators and showed that it is possible to predict the systems' response with an acceptable approximation.

In this paper a new isolating system, called Pillow-Shape Base Isolation System (PSBIS), is introduced to be used in short to mid-rise buildings. Unlike the conventional systems such as LRB and HRB, PSBIS does not need cutting edge technology and has low manufacturing cost. This system is made up of two orthogonal pairs of pillow-shaped rollers that are located between flat bed and plates. Because of placement of two pairs of rollers two perpendicular directions, building can move in all horizontal directions with respect to its foundation. Pillow shape of the roller gives the system the self-centering capability. The rolling friction force between pillows and the bedand plates creates some damping in the system which prevents it from further oscillationafter earthquake excitations diminish. In the paper first the general features of the PSBIS are introduced followed by the analytical equations of the system. Then, variation of the period of PSBIS with respect to the height and radius of curvature of the rollers is presented, and investigation of the vertical bearing capacity and the effect of the wall thickness of pillows byusing ABAQUS software are discussed. Finally, seismic response of a building, assumed as a rigid body resting on isolators, subjected to simultaneous effects of horizontal and vertical excitations of several earthquakes with PGA values of 0.3g to 1.0g and various frequency contents are presented.

GENERAL FEATURES OF THE PSBIS

In the PSBIS each pillow is made by cutting off the middle part of a cylinder of radius (r), which results in a remaining pillow-shape part of height (h)as shown in Figure 1.



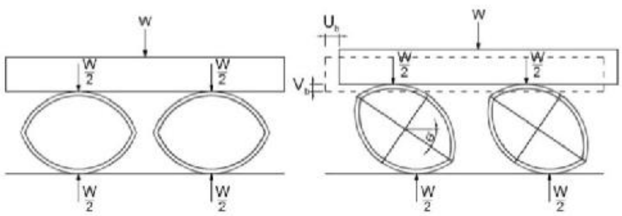


Figure 1: Making a pillow roller of out a cylinder Figure 2: One pair of PSBISundera column's foundation

One pair of pillow rollers of PSBIS is shown in Figure 2 under the foundation of a building's column, imposing a weight of (w) on it. The figure shows the pillow rollers both 'at rest' and during the lateral motion.As shown in Figure 2, in the initial state the larger diameter of pillows is horizontal, thus the vertical load and its reaction are on one vertical line, but when the pillow turns, the vertical load and the reaction are no longer on the same line, and a distance is created between them which creates a restoring moment causingthe pillow to tend to return to its initial position. It can be seen in Figure 2 that rotation of the pillow roller results in both horizontal and vertical displacements of the foundation of the isolated building, indicated in the figure by, respectively,$u_b$andv_b. As it can be seen in Figure 2, the size of pillow rollers is relatively large comparing to other rolling isolation systems.

According to Figure 2, when the horizontal displacement of the isolated structure at base increases, the magnitude of the restoring momentincreases as well, and in this way occurrence of large lateral displacements of the system is prevented. Furthermore, regarding the relatively large size of the pillow rollers, the vertical loads are transferred via a relatively long line between the rollers and their bed, and therefore, the stress concentration can be satisfactorily prevented in the system.

Since it is possible that the extensive vertical acceleration of earthquake causes separation of rollers from their bed, some uplift restrainers are required to prevent this phenomenon. For this purpose, asshown in Figure 3, each pillow has been equipped with two upper and lower U-shapeduplift restrainer, interacting with the pillow and either lower and middle plates or middle and upper plates via the ball bearing connection provided at either end of the U-shape restrainers.

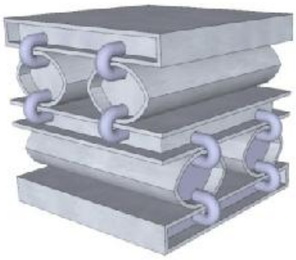


Figure 3: A complete set of the PSBIS with the U-shaped uplift restrainers

EQUATION OF MOTION OF THE PSBIS

It is worth mentioning that the governing equation of motion of the PSBIS cannot be determined using Newton's second law since the forces engaged in the motion of the system have different points of action with different movements. In fact, as shown in Figure 4, the spring and damper forces act on the foundation masswhose horizontal and vertical movement are respectively u_b and v_b, while the rolling resistance forces act at lower and upper points of the pillow roller'sperimeter and their movement is half of the foundation's movement (Tayaran, 2015).

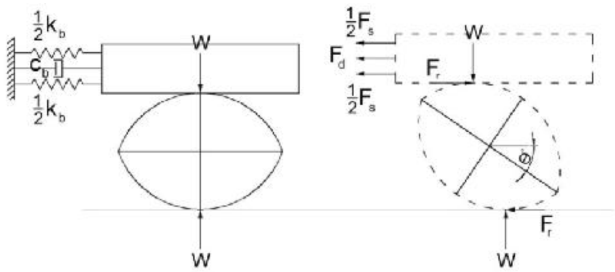


Figure 4: Forces engaged in the motion of the PSBIS

On this basis, energy methods should be used for derivation of equation of motion for this system. In this study Lagrangeequation of motionhasresulted in the following equation in terms of (θ), the angle of rotation of the pillow roller as shown in Figure 4, (Tayaran, 2015).

(1)

$$\ddot{\theta} = \left(\frac{-1}{m_b(h^2 + 4(2r^2 - rh)(1 - \cos\theta))}\right)\Big\{4m_b\dot{\theta}^2(2r^2 - rh)\sin\theta - 2m_b\dot{\theta}^2(2r^2 - rh)\sin\theta$$
$$+ 2k_b\left|2r^2\theta + \left(r - \frac{h}{2}\right)^2 \sin 2\theta - 2r\left(r - \frac{h}{2}\right)\sin\theta - 2r\theta\left(r - \frac{h}{2}\right)\cos\theta\right|$$
$$+ 2m_b g\left(r - \frac{h}{2}\right)\sin\theta$$
$$- \left|-\operatorname{sign}(\dot{\theta})\frac{m_b\,(g + \dot{V}_b + \dot{V}_g)\,b}{r} - c_b\left(2r\theta - 2\left(r - \frac{h}{2}\right)\dot{\theta}\cos\theta\right) - 2\,m_b\dot{U}_g\right|\Big(r$$
$$- \left(r - \frac{h}{2}\right)\cos\theta\Big) - \left(-2\,m_b\dot{V}_g\left(r - \frac{h}{2}\right)\sin\theta\right)\Big\}$$

It should be noted that rolling friction at lower and upper levels of the pillow roller plays the role of damping in the PSBIS, and the corresponding forces (F_r) always act in a direction opposite to the direction of motion of upper and lower contacts points of rollers as shown in Figure 4. The amount of (F_r) are directly proportional to the weight of the isolated structure ($m_b g$), the coefficient of rolling friction (b), and inversely proportional to the pillow's radius of curvature (r). Equation (1), which is highly nonlinear, cannot be solved by any analytical solution and should be solvedby a numerical technique. It this study the fourth orderRunge-Kuttatechnique has been used (Hosseini and soroor, 2010).

One of the main issues in the study of rolling objects is the slippage condition because in the case of slipping, the equations of motion are not valid anymore. So, considering the angle of rotation of the pillow (θ), the maximum value for the system in fully rollingstate is obtained by Eq. (2),(Tayaran, 2015).

$$\tan\theta < \mu \frac{r}{\left(r - \frac{h}{2}\right)} - 1 \tag{2}$$

In the computer program, developed by the authors in MATLAB environment for solving the equation of motion by fourth-order Runge-Kutta technique, inequality (2) has been used as a condition for checking the slippage occurrence.

VERIFYING THE SOLUTION TECHNIQUE

To ensure the accuracy of the derived equations, the fourth-order Runge-Kutta numerical technique, and the code written in MATLAB environment, response of an isolated mass resting on PSBIS subjected to harmonic base excitations has been calculated, and has been compared to the exact solution given in reference books, and stated by Equations (3) to (5).

$$p_{eff}(t) = -m\ddot{u}_o \sin\bar{\omega}t = -100 * 1 * \sin 0.25t \tag{3}$$

$$u(t) = (A\cos\omega_D t + B\sin\omega_D t)e^{-\xi\omega t} + C\sin\bar{\omega}t + D\cos\bar{\omega}t \tag{4}$$

$$u(t) = (-3.8E^{-4}\cos 3.16t + 7.9E^{-3}\sin 3.16t)e^{-0.075t} - 0.10\sin 0.25t + 3.8e - 4\cos 0.25\,t \tag{5}$$

As shown in Figure 5, results obtained by the MATLAB computer program are in very good agreement with exact solution.

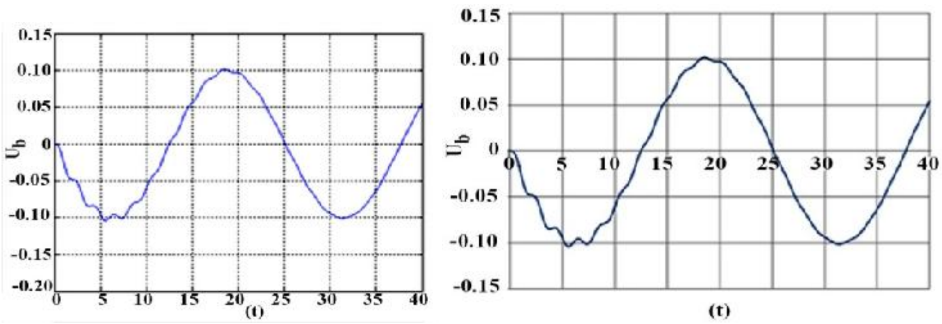


Figure 5: Displacement response history of the system to harmonic loading($\bar{\omega} = 0.25$) obtained by MATLAB (left) and exact solution (right) (m=100 kg, k_b=1000 N/m, c_b=15 N.s/m,$u(0) = 0$, and$\dot{u}(0) = 0$)

OSCILLATION PERIOD OF THE PSBIS

Regarding the nonlinear nature of the system it is not possible to obtain its natural period analytically. To determine the un-damped period of the system by numerical calculations, a rigid body resting on PSBIS, considering r=30 cm and h=40 cm, is initialized by different rotation angles (assuming b=0, c_b=0 and k_b=0), and the displacement response was calculated as shown in Figure 6.

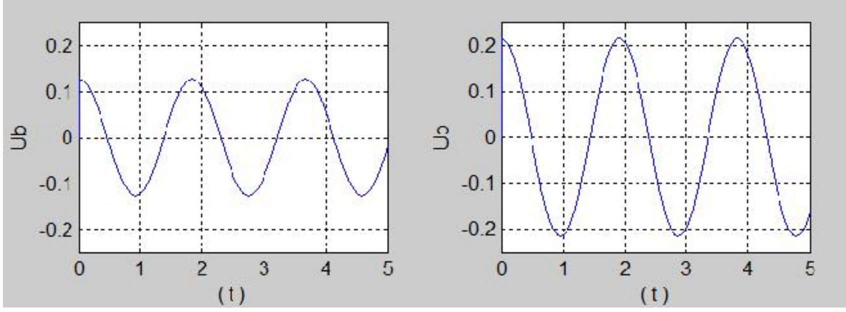


Figure 6: Free vibration response of a rigid body on PSBIS for m=100 kg and θ_0=π/10 (left) and θ_0=π/6 (right)

It can be seen in Figure 6 that the un-damped period of the isolated system is somehow dependent on the initial condition. As Figure 6 shows three complete cycles of oscillation takes 3.7 seconds with θ_0=π/10 and 3.8 seconds withθ_0=π/6. Tofurtheranalyze the effect of the pillow's geometry on the natural period of the system, pillows with a fixed 30cm radius and different heights ranging from 15 to 60 cm, with incremental steps of 1cm, and also a fixed height of 40 cm with different radius values changing from 25 to 40 cm, again with incremental steps of 1 cm, with different θ_0 values were studied, and the natural periods were obtained as shown in Figures 7.

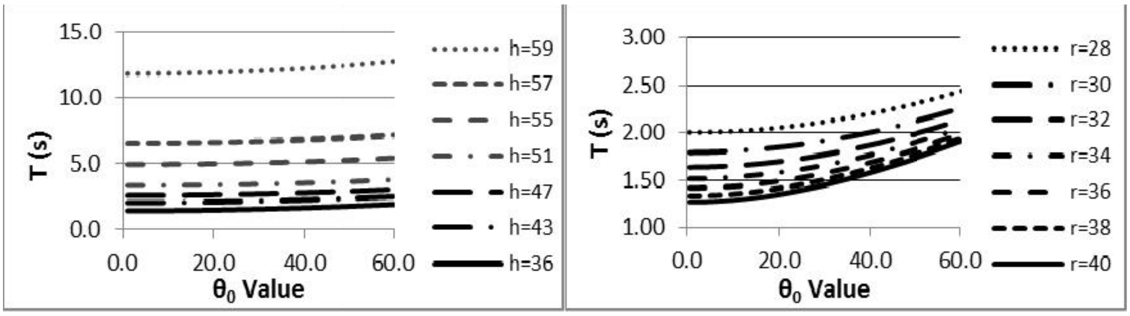


Figure7:PSBISnatural period for r=30 cm and different heights (left), and h=40 cm and different radii (right)

It is seen in Figure 7 that, as expected, natural period of PSBIS increases by increase of (h) for a given value of (r) and by decrease of (r) for a given value of (h). It can be also seen in the figure that sensitivity of the natural period of the system to variation of (h) is more than of that to variation of (r). Figure7also shows that the dependence of natural period on the θ_0 value is mostly affected by value of (r) rather than the value of (h). However, it can be understood form Figure 7 that for θ_0 values less than 15 degrees the amount of natural period is only a function of the (h) and basically (r), and is almostindependent ofθ_0 value.

BEARING CAPACITY EVALUTION OF PSBISBY FINITE ELEMENT ANALYSIS

One of the most important factors in applications of rolling isolators is their vertical bearing capacity. An advantage of the proposed PSBIS over other rolling-based ones is its load transfer capability via a relatively long line of surface to surface contact because of large size of pillow rollers. It should be noted that by increasing the radius of pillows, the contact area of two surfaces is increased and the vertical load bearing capacity of the system also increases.Tomake sure on the vertical load bearing capacity of the proposed system, ABAQUS finite element simulations were carried out to see if the stress level does not exceed the elastic limits in system's components. For this purpose the system with 100 cm length, 45 cmheight and 30 cm pillow radius was modeled by using sufficiently fine mesh, and various values of 5 to 80 mm with an incremental step of 5 mmwere assumed for the pillow wall thickness (t), and the maximum load bearing capacity were obtained in each case based on von Mises stress value. The load bearing capacity in each case was found based on yielding of the pillow wall due to either excessive bending or stress concentration in the contact area, whichever happens earlier. Results of these finite element analyses are shown in Figure 8.

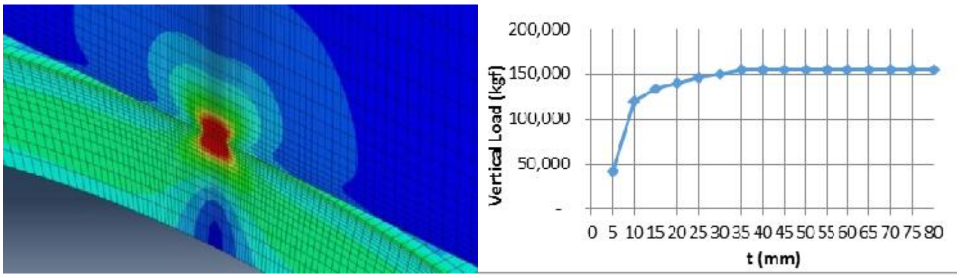


Figure8: Stress concentration in the pillow and its adjacent surface (left) and vertical load bearing capacity ofonepillow roller with variouswallthickness values (right)

According to Figure 8, in the pillow with the considered dimensions, for wall thicknesses over 35 mm the load bearing capacity is controlled by stress concentration rather than bending of the pillow wall, and remains constant regardless of the pillow wall thickness. On this basis and according to Figure 8, the vertical load bearing capacity for a pair of pillow rollers is more than 300 tons.

PSBIS RESPONSE SUBJECTED TO EARTHQUAKE EXCITATION

In order to evaluate PSBISseismicperformance, a rigid body of m=100 kg restingon one pair of the isolators of the PSBIS with r=30 cm and h=45 cm, was considered and its responses were obtained subjected to fourteen two-component accelerogramsgiven in Table 1.

Table 1. The earthquakes whose accelerograms have been used in this study

No.	Record/Component	Earthquake	Vertical Component			NS Component		
			PGA (g)	PGV (cm/s)	PGD (cm)	PGA (g)	PGV (cm/s)	PGD (cm)
1	CAPEMEND/CPM	Cape Mendocino 1992/04/25	0.754	63.00	109.48	1.039	42.00	12.39
2	COALINGA/F-CHP	Coalinga 1983/07/25	0.332	8.40	0.61	0.733	37.60	5.24
3	KOBE/KJM	Kobe 1995/01/16 20:46	0.343	38.30	10.29	0.599	74.30	19.95
4	VICT/CPE	Victoria, Mexico 1980/06/09	0.304	12.10	4.90	0.587	19.90	9.40
5	DUZCE/DZC	Duzce, Turkey 1999/11/12	0.357	22.60	19.40	0.535	83.50	51.59
6	NORTHR/ORR	Northridge 1994/01/17	0.217	12.40	1.94	0.514	52.20	2.41
7	ERZIKAN/ERZ	Erzincan, Turkey 1992/03/13	0.248	18.30	7.86	0.496	64.30	22.78
8	MAMMOTH/I-CVK	Mammoth Lakes 1980/05/25	0.388	20.50	5.93	0.442	23.10	5.42
9	MAMMOTH/B-CVK	Mammoth Lakes 1980/05/25	0.345	6.20	0.52	0.432	21.00	2.31
10	TABAS/DAY	Tabas, Iran 1978/09/16	0.183	12.00	4.97	0.406	26.50	8.75
11	COALINGA/D-PVY	Coalinga 1983/07/22	0.316	12.90	0.92	0.327	12.10	2.33
12	MAMMOTH/L-CVK	Mammoth Lakes 1980/05/27	0.188	9.60	1.62	0.316	16.20	3.19
13	COALINGA/H-CAK	Coalinga 1983/05/02	0.094	5.10	1.86	0.281	25.80	3.71
14	COYOTELK/CYC	Coyote Lake 1979/08/06	0.121	6.40	0.67	0.279	20.30	2.33

Acceleration values at ground level and the amount of acceleration transferred to the isolated rigid body via the isolator, as well as the relative displacement of the rigid body with respect to the ground are obtained through time history analyses by using the fourth order Runge-Kutta technique for solving the nonlinear equation of motion. Figures 9 to 12 show the acceleration and displacement histories for only a few ones of the employed earthquakes due to the lack of space, and more results of this type can be found in the main report of the study (Tayaran 2015), (Tayaran, 2015).

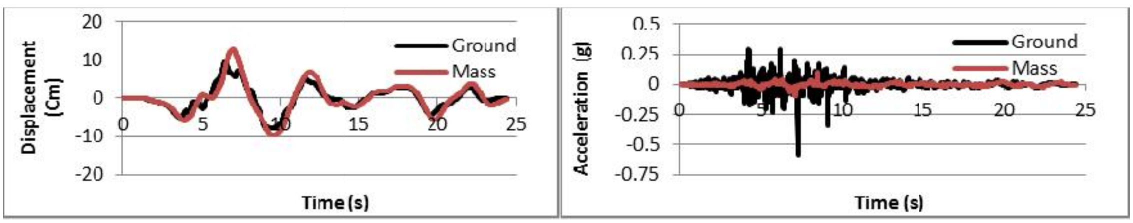


Figure 9:Displacement and acceleration time histories related to Victoria, Mexico(1980)earthquake

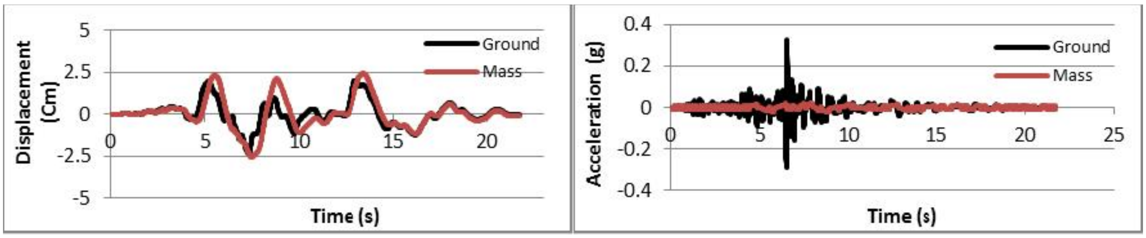


Figure 10: Displacement and acceleration time histories related toCoalinga (1983/07/22) earthquake

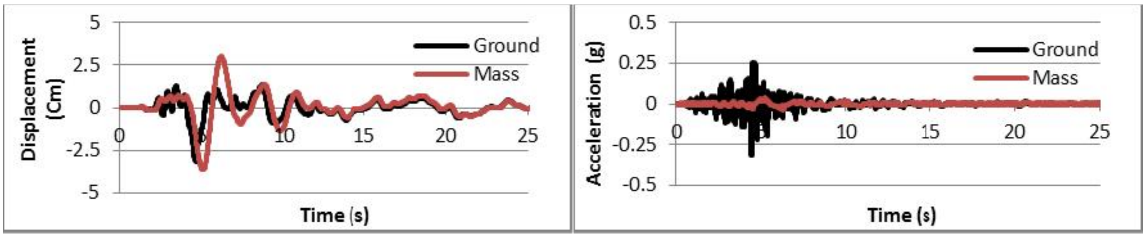


Figure 11: Displacement and acceleration time histories related toMammoth Lakes (1980/05/27)earthquake

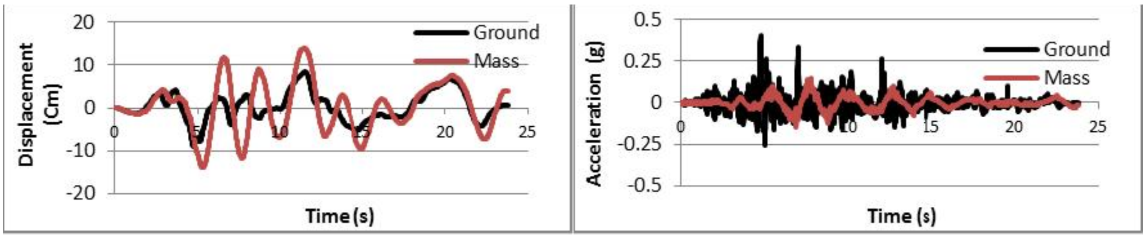


Figure 12:Displacement and acceleration time histories related to Tabas(1978/09/16)earthquake

It can be seen in Figure 9 that in Victoria, Mexico earthquake the system have displaced more than the ground and the value has increased from 9 cm to 14 cm. On the other hand, acceleration transferred to the rigid body has dropped from 0.59g to 0.25g, around 40% of the base acceleration. Among the excitation cases of this study, Coalinga and Mammoth Lakes have PGAvaluesaround0.3g, the average code value. According to Figures 10 and 11 in these two cases the system has shownverygood performance and has reduced the maximum acceleration response to 0.05g and 0.07g respectively.However, the amount of absolute acceleration reduction in case of Tabas earthquake is not as good as the previous earthquakes as shown in Figure 12, although the amount of reduction is satisfactory.

To summarize the response calculations, the ratios of maximum relative displacement and maximum absolute acceleration of the isolated body to the corresponding values of ground motion during all fourteen employed earthquakes are shown in Figure 13.

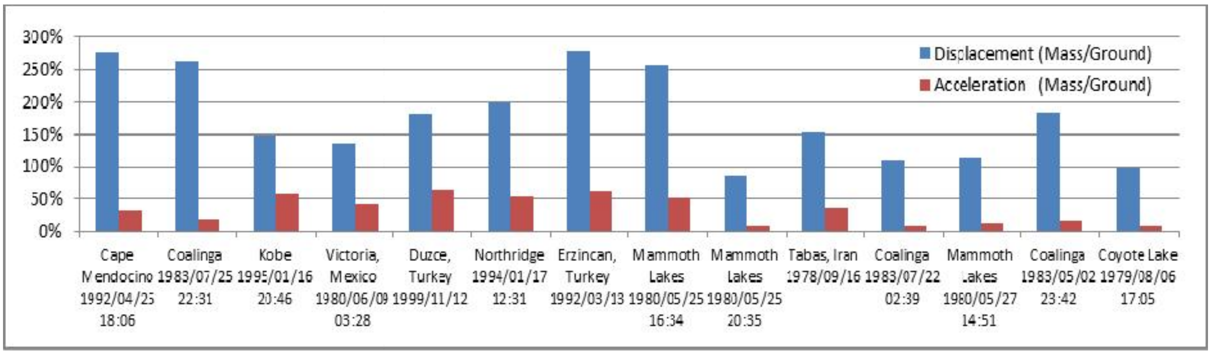


Figure 13: Ratios of relative displacement and absolute acceleration responses of PSBIS
for all fourteen employed earthquakes

Figure 13 shows the very good performance of the system in reducing the seismic responses. Based on this figure it can be said that using PSBIS leads to a considerable reduction of the absolute acceleration transferred to the isolated body which is around 77% in average, while the amount of increase in the relative displacement response is in average around 1.77 times of the maximum ground motion, which is relatively less that this amount for other types of seismic isolation systems.

CONCLUSIONS

Based on the numerical results obtained from extensive time history analyses of the proposed seismic isolation system it can be concluded that:

- The proposed isolating system lead to around 78% acceleration reduction while increases the displacement only around 1.77 times, which is remarkably less that other isolating systems.
- For a pair of pillows of 58 cm width, 45 cm height and 100 cm length the vertical load bearing capacity of the system is more than 300 tons, which is quite sufficient for the base load of a typical middle column of a 10-story or even taller building.
- The isolating system proposed in this paper has resolved some problems of previous systems such as low dampingcapacity, high stress concentration due to the small contact area,wearand scratch resistance of the ball type isolation systems during the earthquake and uplift and instability due to vertical component of earthquake force.
- Another benefit of using the proposed isolating system is its simple and low cost manufacturing process. This merit can encouraging in using this type of isolating system in practice, particularly in developing countries.

REFERENCES

Chong-Shien A and Tsai CS (2012) Advanced Base Isolation Systems for Light Weight Equipments, INTECH Open Access Publisher

Guerreiro L, Azevedo J and Muhr AH (2007) Seismic Tests and Numerical Modeling Of a Rolling-ball Isolation System, *Journal of Earthquake Engineering*, 11(1):49-66

Harvey PS, Wiebe R and Gavin HP (2013) On the Chaotic Response of a Nonlinear Rolling Isolation System, *Physica D: Nonlinear Phenomena*, 256, 36-42

Hosseini M and Soroor A (2010) Using Orthogonal Pairs of Rollers on Concave Beds (OPRCB) as a base isolation system—part i: analytical, experimental and numerical studies of OPRCB isolators, The Structural Design of Tall and Special Buildings, 20(8), 928-950

Jangid RS and Londhe YB (1998) Effectiveness of Elliptical Rolling Rods for Base Isolation, *Journal of Structural Engineering*, 124(4), 469-472

Lee CG and Liang Z (2003) A Sloping Surface Roller Bearing and Its lateral Stiffness Measurement, Proceedings ofthe 19th US–*Japan bridge engineering workshop*, pp. 27–29

Tayaran A (2015) Pillow-type Base Isolation System and Its Effect in Seismic Response Reductionof Buildings, M.Sc. Thesis under supervision of Prof.MahmoodHosseini, Islamic Azad University South of Tehran Branch, Tehran, Iran

Yang C, Hsieh C, Chung L, Chen H and Wu L (2011) Effectiveness Of An Eccentric Rolling Isolation System With Friction Damping, Journal of Vibration and Control, , 1077546311428633