Pillow-Shape Base Isolation System and Its Seismic Behavior

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Abstract

In this paper a new isolating system is introduced for short to mid-rise buildings. In comparison to conventional systems such as LRB and HRB, the proposed system has the advantage of no need to 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 oscillation after earthquake excitations diminish. The purpose of this study is to evaluate the proposed isolation system'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.

1. Introduction

Base isolation is one of the effective technologies to protect structural systems and equipment 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, [1]. Based on the available publications it seems that the use of rolling isolation goes back to early 80s. Arnold (1983), [2], published a paper entitled 'rolling with the punch of earthquakes-base isolation is used in two New-Zealand office buildings. Later, Pham (1988), [3], proposed a base-isolation design using spherically-ended rollers and telescopic shock absorbers to be used for upgrading of the seismic strength of 16 valve damping resistors in the HVDC transmission network of the Electricity Corporation of New Zealand. He has claimed that the design analysis is relatively simple, and the designer can control and have confidence in the performance of the rollers without having to carry out exhaustive testing to establish the performance parameters. Furthermore, he has expressed that for a seismic strength are simple to install

and thus the outage time required for erection can be kept to a minimum. For an electrical system, this outage time is critical and often determines the economics of earthquake strengthening. Finally he has stated that the rollers are relatively cheap and easy to fabricate. It should be noted that due to relatively small width of the proposed spherically-ended rollers stress concentration is very likely at either edge of the rollers, however, Pham has not addressed this phenomenon in his study.

Su and his colleagues(1989), [4], carried out a comparative study on effectiveness of various base isolators, including the laminated rubber bearing with and without lead plug, and a few frictional base isolation systems. They modeled the structure as a rigid mass and used the accelerograms of the NOOW component of the El Centro 1940 earthquake and the N90W component of the Mexico City 1985 earthquake. Combining the desirable features of various systems, they developed a new design for a friction base isolator and studied its performance. They showed that, under design conditions, all base isolators can significantly reduce the acceleration transmitted to the superstructure.

Lin and Hone (1993), [5], proposed using free rolling rods under basement as a new base isolation method for the

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protection of structures. Their device consisted of two sets of mutually orthogonal free rolling rods under the basement of the structure. Since the coefficient of rolling friction of the rods is very small in practice, the structure can be isolated excellently from the support excitation. In that study, the analytical method and the response of the isolated system for different parameters, such as the periods of the structure, the coefficient of rolling friction and the masses of rolling rods, were presented. The results indicated that their proposed method was very effective in isolating the structure from support excitations. Lin and his colleagues (1995), [6], also conducted an experimental study by using a one-story, 326-kg structure mounted on a set of free rolling rods, on a 3" x 3" shaking-table. The dynamic behavior of the isolated structure was studied and used to verify the analytical results. In their Isolation system, the coefficient of kinetic rolling friction, measured at different angular velocities. The coefficients were reduced by decreasing the angular velocities, ranging from 0.0007 to 0.0016. Two earthquakes, a short-period and a long-period motion in Taiwan, were utilized as the input signals. They claimed that the accelerations experienced by the superstructure were decreased by factors of 56 and 60 in comparison with the fixed-base condition for the two input earthquakes. Also, for each test, the peak relative displacement of the basement was nearly equal to the peak ground displacement, and the permanent displacement of the basement was present after the end of the earthquake. Finally, tests of the system with a recentering-force device were undertaken, where a soft spring added to the basement reduced efficiently the permanent displacement. Comparisons showed a good agreement between experimental and theoretical results.

Jangid and his colleagues (1998), [7], providing a system consisting of elliptical rolling rods between the base and foundation, evaluated the effect of isolating of a multi-storey buildings against earthquake and showed that by using elliptical rolling rods, a remarkable reduction in the seismic response of structures without major displacements is made. Also Jangid (2000), [8], investigated the stochastic response to earthquake motion of flexible multi-storey shear type buildings isolated by rolling rods with a re-centering device. The used re-centering device was in the form of a spring or cantilever beam attached to the base of the structure. He considered the stochastic model of the El-Centro 1940 earthquake which preserves the non-stationary evolution of amplitude and frequency content as an earthquake excitation, and obtained the non-stationary response of the isolated structural system using a time-dependent equivalent linearization technique since the force–deformation behavior of the rolling rods is highly non-linear. The effectiveness of rolling rods in isolating the structure was investigated under variations of important parametric, including the time period of the superstructure (as a fixed base), the period of isolation and the friction coefficient of the rolling rods. It was shown that the rolling rods are quite effective in reducing the stochastic response of the

structure against earthquake excitation, and that the presence of the re-centering device significantly reduces the relative base displacement without transmitting additional accelerations into the superstructure. In addition, there exists an optimum value of the friction coefficient of the rolling rods for which the acceleration response of the superstructure attains the minimum value.

Lee and his colleagues (2003), [9], used cylindrical rollers on V-shaped sloping surfaces and showed that their system can play an important role in structural seismic isolation. Based on their study 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.

Tsai and his colleagues (2006), [10], studied the material behavior and isolation benefits of ball pendulum system. Their study was aimed at a damped rolling type base isolation system named the ball pendulum system to be installed under the motion sensitive equipment. The isolation device can isolate earthquake from buildings or equipment in any direction by rolling motions and damping materials. That study has conducted a series of component tests and shaking table tests for examining the behaviors of materials and earthquake proof benefits. From the experiment results, it was found that their device can reduce more than 80% of acceleration response under earthquakes with peak ground acceleration of 450 gal.

Guerreiro and his colleague (2007), [11], used an isolating system which leads to increased damping and simultaneously reduced displacement. This type of isolating systems 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.

Following his previous studies, Tsai and his colleagues (2008), [12], conducted shaking table tests of motion sensitive equipment isolated with static dynamics interchangeable-ball pendulum system. Mentioning that 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, and that damage to high-tech equipment during earthquakes will cause huge loss in economy, offered a solution to aforementioned problem, by proposing a base isolator called the static dynamics interchangeable-ball pendulum system (SDI-BPS). That 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%.

Ismail and his colleagues (2009, 2010), [13, 14], presented a rolling-based seismic isolation bearing for motion-sensitive equipment. They called their system 'roll-n-cage' (RNC) isolator, and described, modeled and characterized it and numerically assessed its effectiveness considering the case of equipment housed in upper floors of a building, where the accelerations were amplified and the motion contains strong components at long periods. Their numerical results reveal that the proposed RNC isolator device can attenuate seismic responses effectively under different ground motion excitations while exhibiting robust performance for a wide range of structure–equipment systems. They have claimed that RNC isolator incorporates isolation, energy dissipation, buffer and inherent gravity-based restoring force mechanisms in a single unit, and also provides adequate wind resistance, a great range of horizontal flexibility and always exhibits no uplift during its lateral motion. They have briefly explained principles of operation and force–displacement relationships of the RNC isolator. Further, they have presented its performance evaluation via implementation in heavy-mass structures.

Tu and his colleagues (2010), [15], presented the sub-structuring approach and associated controller designs for performance testing of an aseismic base-isolation system, comprised of roller-pendulum isolators and controllable, nonlinear magneto-rheological dampers. They have mentioned that dynamic sub-structuring enables full-size, critical components to be physically tested within a laboratory (as physical substructures), while the remaining parts are simulated in real-time (as numerical substructures). Roller-pendulum isolators are typically mounted between the protected structure and its foundation and have a fundamental period of oscillation far-away from the predominant periods of any earthquake. They have claimed that such semi-active damper systems can ensure safety and performance requirements, whereas the implementation of purely active systems can be problematic in this respect.

Yang and his colleagues (2011), [16], investigated variable-frequency rocking bearings system. The mechanical behavior of 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.

Hosseini and Soroor (2012), [17], 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, however, they are weak against uplift.

In continuation of their studies on RNC isolators, Ismail and his colleagues (2012), [18], presented the application of an RNC base isolator to mitigate the seismic response of light weight structures. From a functional point of view, RNC is essentially an isolation bearing, while it offers a significant resistance to wind and minor vibrations. Rolling is the basic mechanical principle adopted to offer a great range of horizontal flexibility, which is complemented with an energy dissipation mechanism. The device is designed to have several practical controls to ensure buffer, re-centering and no uplift during motion. In that study, the principles of operation and force–displacement relationships of the novel RNC isolator were presented, along with its implementation and performance evaluation considering a wide range of structural, isolator and ground motion characteristics. The numerical results show that the proposed bearing is a useful tool for isolating light- to moderate-mass systems, and it can mitigate the seismic response under a variety of ground motion excitations while exhibiting the robust performance for a wide range of structures. It should be mentioned that their proposed isolator is rather complex and its manufacturing is not easy and needs high technology.

Ding and Wang (2013), [19], proposed a metallic isolator utilizing two orthogonal roller layers to realize the bidirectional isolation. They have claimed that one of the advantages of the proposed metallic isolator is the low friction coefficient to realize a long period, and the other is the large tension resistance in the vertical direction, and have concluded that these features make it easy to be used in high-rise buildings. Their metallic isolator consists of top and bottom plats, two layers of rolling shafts, a middle plat, L-shaped anti-tension connecting plates, and some filling plates. When being compressed, the rolling shafts roll on the surface of the middle plate, providing very low friction force. While being tensioned, a sliding mechanism forms between the L-shaped anti-tension connecting plates and filling plates, and the isolation effect depends on the friction coefficient of the contact pairs. By virtue of the two roller layers set in orthogonal directions, the top plate is able to move in any horizontal direction relative to the bottom plate. They investigated the mechanical properties of their base isolation device experimentally. The isolator was tested under the compression from 100 kN to 1000 kN. A few horizontal loading directions were selected as 0, 30 and 45 degrees to simulate the motion in any horizontal direction. The loading frequency changed from 0.05 Hz to 0.3 Hz with the amplitude varying from 20 mm to 150 mm. It has been demonstrated that the metallic isolator is able to move smoothly in any direction with a relatively constant coefficient ranging from 0.02 to 0.04. The dependency on the vertical compression and the horizontal velocity is quite low and the mechanical property is stable and reliable. In spite of the resistance of their device against

uplift forces, the gap between the middle and upper parts seems to create some problems when the device is subjected to extensive vertical ground excitations.

In continuation of their previous studies, Hosseini and Soroor (2013), [20], conducted a study on the application of orthogonal pairs of rollers on concave beds (OPRCB) isolating system to short- and mid-rise buildings. In that study at first, the analytical formulation of the set of equations, governing the motion of Multi Degree of Freedom (MDOF) systems, isolated by OPRCB isolators, has been developed. Then, some multi-story regular buildings of shear type have been considered, once on fixed bases and once installed on the OPRCB isolators. Next, some horizontal and vertical accelerograms of both far- and near-fault earthquakes with low- to high-frequency content, particularly those with remarkable peak ground displacement values, have been selected and normalized to three peak ground acceleration levels of 0.15g, 0.35g and 0.70g, and their stronger horizontal component simultaneous with their vertical component have been used for response analysis of the considered buildings. Story drifts and absolute acceleration response histories of isolated buildings have been calculated by using a program, developed in MATLAB environment by using the fourth-order Runge–Kutta method, considering the geometrically nonlinear behavior of isolators. Maximum relative displacement and story drifts as well as absolute acceleration responses of considered isolated buildings for various earthquakes have been compared with those of corresponding fixed-base buildings to show the high efficiency of using OPRCB isolators in multi-story and tall regular buildings. In spite of the advantages of the OPRCB isolators they are weak against uplift.

Harvey and his colleagues (2013, 2014), [21-22] mentioning that an assessment of the ability of lightly- and heavily-damped rolling isolation systems (RISs) to mitigate the hazard of seismically-induced failures requires high-fidelity models that can adequately capture the system's intrinsic non-linear behavior, and that the light damping of steel bearings rolling between steel plates can be augmented by adhering thin rubber sheets to the plates, increasing the rolling resistance and decreasing the displacement demand on the RIS, have discussed a simplified model, which is applicable to RISs with any potential energy function, and is amenable to both lightly- and heavily damped RISs, and is also validated through the successful prediction of peak responses for a wide range of disturbance frequencies and intensities. The damping provided by rolling between thin viscoelastic sheets increases the allowable floor motion intensity by a factor of two-to-three, depending on the period of motion. Acceleration responses of isolation systems with damping supplied in this fashion grow with increased damping, at short-period excitations. It should be noted that their device uses rolling balls, which are subjected to high stress concentration, and therefore cannot be used for multi-story buildings.

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 bed and plates creates some damping in the system which prevents it from further oscillation after 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 by using ABAQUS software, version 6.13, 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.

2. 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.
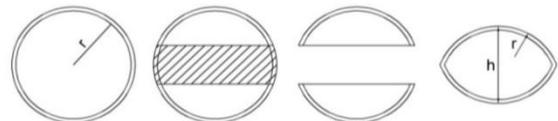

Figure 1: Making a pillow roller of out a cylinder Figure
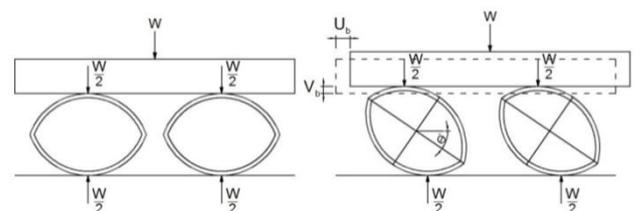

Figure 2: One pair of PSBIS under a column's foundation

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 causing the 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 and v_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 moment increases 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, as shown in Figure 3, each pillow has been equipped with two upper and lower U-shaped uplift 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.
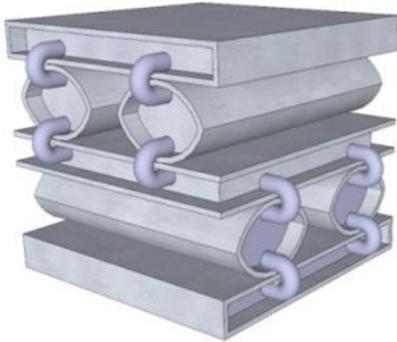

Figure 3: A complete set of the PSBIS with the U-shaped uplift restrainers

3. Equation of motion of 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 mass whose 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's perimeter and their movement is half of the foundation's movement (Tayaran 2015), [8].
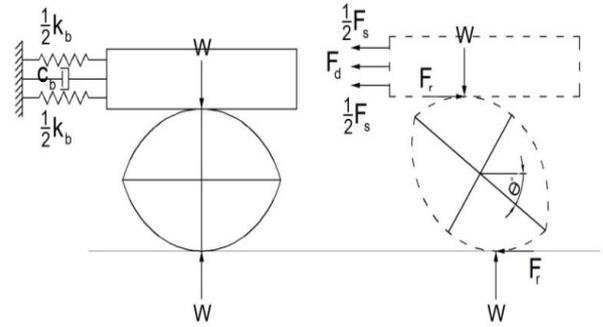

Figure 4: Forces engaged in the motion of the PSBIS

On this basis, energy methods should be used for derivation of equation of motion for this system. In this study LaGrange equation of motion has resulted in the following equation in terms of (θ), the angle of rotation of the pillow roller as shown in Figure 4, [8].

$$\ddot{\theta} = \left(\frac{-1}{m_b(h^2 + 4(2r^2 - rh)(1 - \cos\theta))}\right)\left\{4m_b\dot{\theta}^2(2r^2 - rh)\sin\theta - 2m_b\dot{\theta}^2(2r^2 - rh)\sin\theta \right.$$

$$+ 2k_b\left[2r^2\theta + \left(r - \frac{h}{2}\right)^2\sin 2\theta - 2r\left(r - \frac{h}{2}\right)\sin\theta\right.$$

$$\left. - 2r\theta\left(r - \frac{h}{2}\right)\cos\theta\right] + 2m_bg\left(r - \frac{h}{2}\right)\sin\theta$$

$$- \left[- \text{sign}(\dot{\theta})\frac{m_b\,(g + \ddot{V}_b + \ddot{V}_g)\,b}{r} - c_b(2r\dot{\theta}\right.$$

$$\left. - 2\left(r - \frac{h}{2}\right)\dot{\theta}\cos\theta\right) - 2\,m_b\ddot{U}_g\right]\left(r - \left(r - \frac{h}{2}\right)\cos\theta\right)$$

$$\left. - \left(-2\,m_b\ddot{V}_g\left(r - \frac{h}{2}\right)\sin\theta\,\right)\right\}$$

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_bg), 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 solved by a numerical technique. It this study

the fourth order Runge-Kutta technique has been used, [17].

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 rolling state is obtained by Eq. (2), [8].

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

In the computer program, developed by the authors in MATLAB environment, version R2012a (7.14.0.739) 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.

4. 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).

$$p_{eff}(t) = -m\ddot{u}_0 \sin \overline{\omega} t = -100 * 1 * \sin 0.25t \qquad (3)$$

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

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

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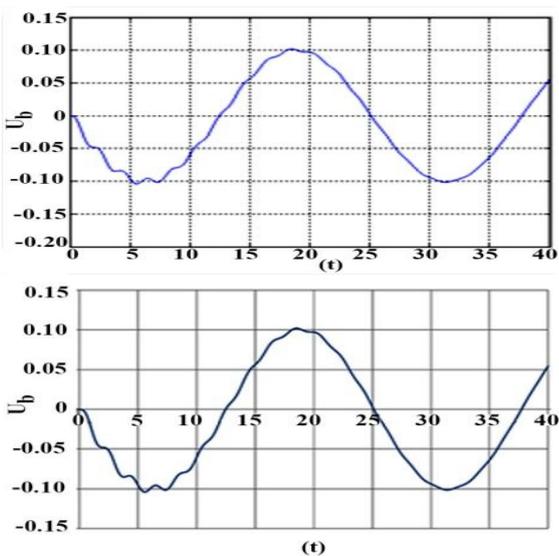

Figure 5: Displacement response history of the system to harmonic loading ($\overline{\omega} = 0.25$) obtained by MATLAB (left) and exact solution (right) (m=100 kg, k_b=1000 N/m, c_b=15 N.s/m, $u(0) = 0$, and $\dot{u}(0) = 0$)

5. 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.
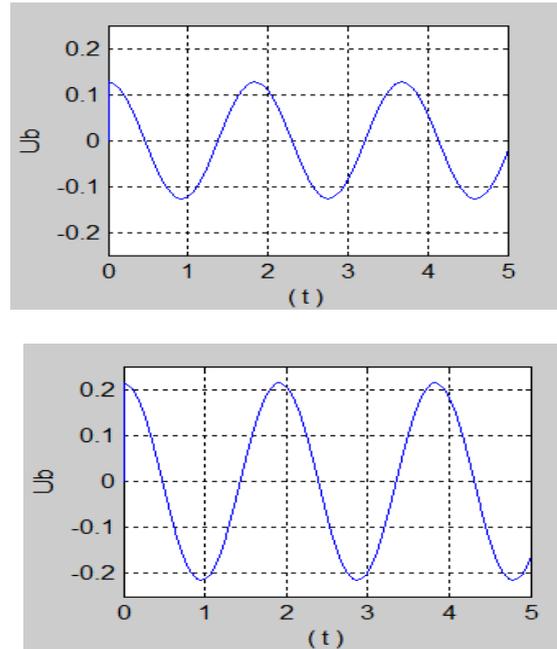

Figure 6: Free vibration response of a rigid body on PSBIS for m=100 kg and θ_0=π/10 (left) and θ_0=π/6 (right)

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 with θ_0=π/6. To further analyze 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.

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 value less than 15 degrees the amount of natural period is only a function of
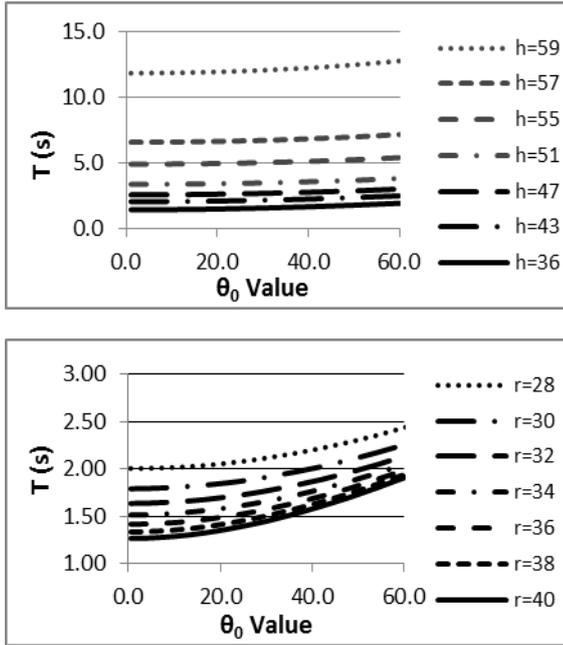
Figure7:PSBISnatural period for r=30 cm and different heights (left), and h=40 cm and different radii (right)

the (h) and basically (r), and is almost independent of θ_0 value.

6. Bearing capacity evaluation of PSBIS by 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. To make 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 cm height 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 mm were assumed for the pillow wall thickness (t), and the maximum load bearing capacity were obtained in each case based on von Mises stress value. In using ABAQUS software, three parts was defined for modeling the PSBIS, including lower and upper plates, and the roller. Then the contact between the outer surface of roller and lower and upper plates was defined by using the Interaction Module, considering the surfaces of plates as Master and the outer surface of the roller as Slave. The sliding friction between the surfaces was defined by Penalty Equation using a friction coefficient of 0.35. The used material properties include elastic modulus of steel, as 2,100,000 kgf/cm2,

and Poisson ratio, as 0.3. The finite elements used in modeling were 8-Node Linear Solid Elements, called CPS4R, and loading and analysis was of General Static type, considering large displacements. 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.
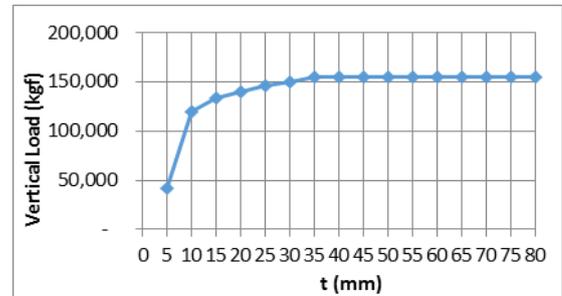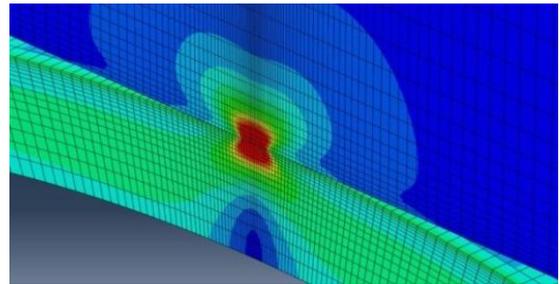

Figure8: Stress concentration in the pillow and its adjacent surface (left) and vertical load bearing capacity of one pillow roller with various wall thickness values (right)

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.

7. PSBIS response subjected to earthquake excitation

In order to evaluate PSBIS seismic performance, a rigid body of m=100 kg resting on 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 accelerograms given in Table 1.

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

No.	Record/Component	Earthquake	Station Name
1	CAPEMEND/CPM	Cape Mendocino 1992/04/25	89005 Cape Mendocino
2	COALINGA/F-CHP	Coalinga 1983/07/25	46T04 CHP (temp)
3	KOBE/KJM	Kobe 1995/01/16 20:46	0 FUK
4	VICT/CPE	Victoria, Mexico 1980/06/09	6604 Cerro Prieto
5	DUZCE/DZC	Duzce, Turkey 1999/11/12	Duzce
6	NORTHR/ORR	Northridge 1994/01/17	24278 Castaic - Old Ridge Route
7	ERZIKAN/ERZ	Erzincan, Turkey 1992/03/13	95 Erzincan
8	MAMMOTH/I-CVK	Mammoth Lakes 1980/05/25	54099 Convict Creek
9	MAMMOTH/B-CVK	Mammoth Lakes 1980/05/25	54099 Convict Creek
10	TABAS/DAY	Tabas, Iran 1978/09/16	9102 Dayhook
11	COALINGA/D-PVY	Coalinga 1983/07/22	1162 Pleasant Valley P.P. - yard
12	MAMMOTH/L-CVK	Mammoth Lakes 1980/05/27	54099 Convict Creek
13	COALINGA/H-CAK	Coalinga 1983/05/02	46314 Cantua Creek School
14	COYOTELK/CYC	Coyote Lake 1979/08/06	GILROY ARRAY #2

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), [23].
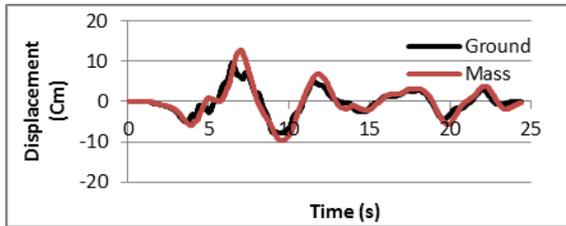

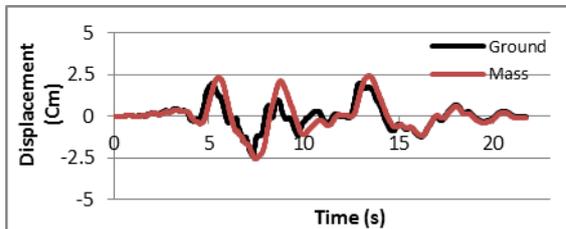Figure 9:Displacement and acceleration time histories related to Victoria, Mexico(1980)earthquake

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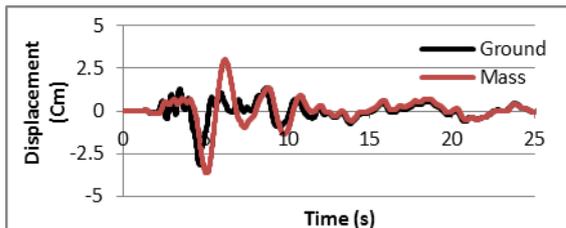

Figure 11: Displacement and acceleration time histories related to Mammoth Lakes (1980/05/27) earthquake
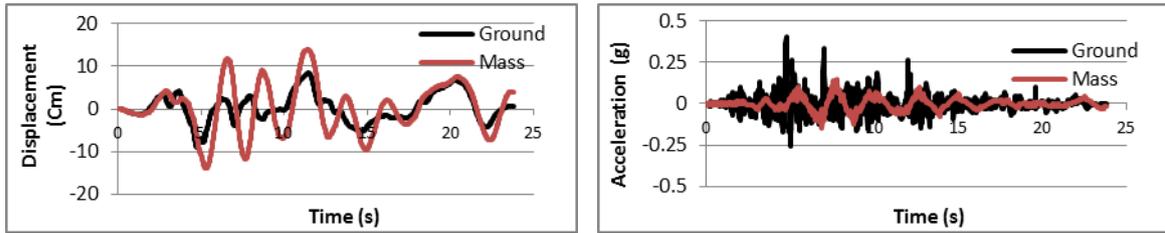
Figure 12: Displacement and acceleration time histories related to Tabas(1978/09/16)earthquake

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 PGA values around 0.3g, the average code value. According to Figures 10 and 11 in these two cases the system has shown very good 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.
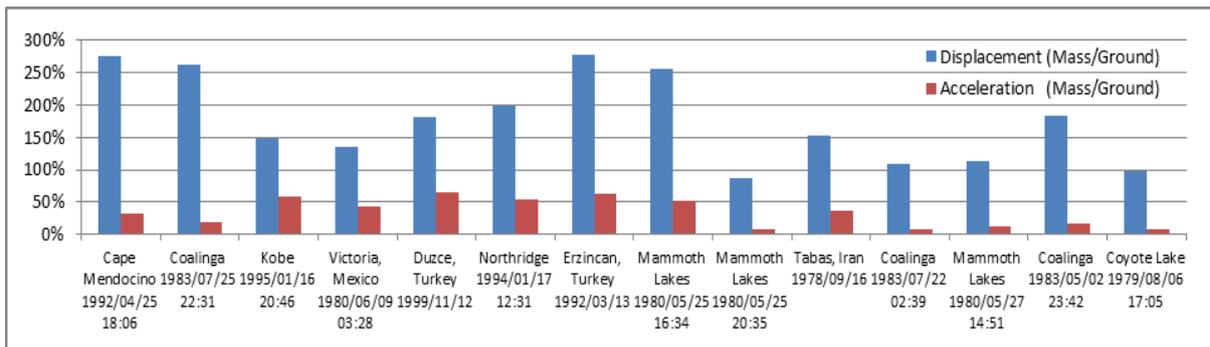

Figure 13: Ratios of relative displacement and absolute acceleration responses of PSBIS for all fourteen employed earthquakes

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.

8. 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 damping capacity, high stress concentration due to the small contact area, wear and 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 be encouraging in using this type of isolating system in practice, particularly in developing countries.

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