

A Review Study of Base Isolation Systems in Seismic Control of Structures

Amit Purohit¹

¹Lecturer, Department of Civil Engineering, Govt. Polytechnic College, Jodhpur, Rajasthan, India

Abstract — Seismic isolation and energy dissipating systems present an effective way to common seismic design for improving the seismic performance of structures. These techniques reduce the seismic forces by changing the stiffness and/or damping in the structures, whereas conventional seismic design is required for an additional strength and ductility to resist seismic forces. In this paper, various base isolation systems using for structural nonlinear vibration control and seismic control of structures is studied. From the past few year base isolation has become one of the most popular tool for earthquake resistant design of structure. The concept of decoupling of building with the help of base isolation is being invented from a century. Many researchers has been worked on base isolation system that it is become acceptable as a whole in engineering field. However so many types of isolation systems are being invented but amongst them few has become accepted thoroughly. Now a days full scale testing is being performed on shake table to test the various characteristics of different isolators. Present review summarizes literature and theoretical aspect available on base isolation system. Some of the papers also deals with the effectiveness of different available isolator and their applicability.

Keywords—Base Isolation System; Seismic Control; Structure

I. INTRODUCTION

1.1 Conventional and Base Isolation Approaches

Seismic isolation consists essentially of the installation of mechanisms, which decouple the structure, and/or its contents, from potentially damaging earthquake-induced ground, or support, motions. This decoupling is achieved by increasing the flexibility of the system, together with providing appropriate damping. In many applications the seismic isolation system is mounted beneath the structure and is referred as ‘base isolation’.

In both the base isolation and conventional approaches, specially selected ductile components are designed to withstand several cycles well beyond yield under reversed loading, the yield levels being chosen so that the forces transmitted to other components of the structure are limited to their elastic or low ductility, range. The yielding lengthens the fundamental period of the structure, detuning the response away from the energetic period range of most of the earthquake ground motion. The ductile behaviour of the selected components ensures sufficient deformation capacity, over a number of cycles of motion, for the structure as a whole to ride out the earthquake attack.

However, base isolation differs fundamentally from conventional seismic design approaches in the method by which the period lengthening and energy dissipating mechanisms are provided

In well-designed conventional structures, the yielding action is designed to occur within the structural members at specially selected locations (plastic hinge zones), e.g. mostly in the beams adjacent to beam-column joints in moment resisting frame structures. Yielding of structural members is an inherently damaging mechanism, even though appropriate selection of the hinge locations and careful detailing can ensure structural integrity. Large deformations within the structure itself are required to withstand strong earthquake motions. These deformations cause problems for the design of components not intended to provide seismic resistance, because it is difficult to ensure that unintended loads are not transmitted to them when the structure is deformed considerably from its rest position. In the conventional approach, it is accepted that considerable earthquake forces and energy will be transmitted to the structure from the ground. The design problem is to provide the structure with the capacity to withstand these substantial forces.

In seismic isolation, the fundamental aim is to reduce substantially the transmission of the earthquake forces and energy into the structure. This is achieved by mounting the structure on an isolating layer with considerable horizontal flexibility, so that during an earthquake, when the ground vibrates strongly under the structure, only moderate motions are induced within the structure itself. Practical isolation systems must tradeoff between the extent of force isolation and acceptable relative displacements across the isolation system during the earthquake motion. As the isolator flexibility increases, movements of the structure relative to the ground may become a problem under other vibrational loads applied above the level of the isolation system, particularly wind loads. Acceptable displacement in conjunction with a large degree of force isolation system can provide the desired properties of isolator flexibility, high damping and force-limitation under horizontal earthquake loads, together with high stiffness under smaller horizontal loads to limit wind induced motions (Skinner 1990).

When a building is built on an isolation system, it should have a fundamental frequency that is lower than both its fixed-base frequency and the dominant frequencies of the ground motion. The first mode of the isolated structure then involves deformation only in the isolation system, the structure above being almost rigid.

1.2 Base Isolation Systems

The design strategy of using base isolation systems in the foundation of critical structures for their protection during a major earthquake has attracted considerable attention in recent years. The main purpose of base isolation devices is to attenuate the detrimental horizontal acceleration transmitted to the superstructure. Numerous designs for base isolators have been suggested. All of these systems have certain features in common, the most important of which are the horizontal flexibility and energy dissipative capacity.

Here, only a few leading base isolation systems, which have been in use, are briefly described.

II. VARIOUS BASE ISOLATION SYSTEMS

2.1 Laminated Rubber Bearings (LRB System)

One of the methods of seismically isolating structures is by mounting them on a laminated rubber bearing (elastomeric bearings). Their main application has been for bridge superstructures, which often undergo substantial dimensional and shape changes due to changes in temperature. More recently their use has been extended to the seismic isolation of buildings and other structures.

These bearings are designed to support large weights while providing only small resistance to large horizontal displacements. A typical design bearing consists of a stack of horizontal rubber layers vulcanized to interleaved steel plates, as shown in the Figure 1 for a cylindrical bearing. For a given bearing area and rubber condition, the load capacity is increased by reducing the thickness of each rubber while the resistance to horizontal and tilting movements is reduced by increasing the total height of the rubber. Rubber bearings also provide adequate isolator centering forces during large displacements (Skinner 1990).

The main isolator of the system consists of alternating layers of rubber and steel with the rubber being vulcanized to the steel plates. Its dominant features consist of the parallel actions of springs and dashpots as shown schematically in Figure 1 (b) (Su et al.1989).

When a rigid structure with a rubber bearing is excited by an earthquake ground acceleration, the equation of motion in terms of the relative horizontal displacement x is given as

$$\ddot{x} + 2\xi\omega_0 \dot{x} + \omega_0^2 x = -\ddot{u}_g \quad (2.1)$$

Here, dot represents differentiation with respect to time, ξ is the effective damping coefficient and ω_0 is the natural frequency of the isolator.

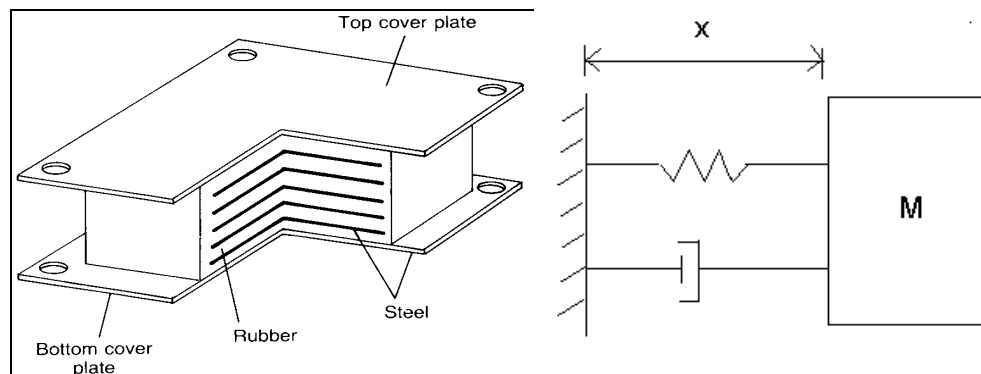


Figure 1 LRB System (a) Physical Model (b) Mathematical Model

2.2 Lead-Rubber Hysteretic Bearings (NZ System)

Laminated Rubber Bearings are able to supply the required displacements for base isolation. By combining these with a lead-plug insert which provides hysteretic energy dissipation, the damping required for a successful seismic isolation can be incorporated in a single compact component. This can be used to support the structure vertically, provide horizontal flexibility together with the restoring force, and provide the required hysteretic damping. An elastomeric bearing is readily converted into a lead-rubber bearing by placing a lead plug down its centre. The hole for the lead plug can be machined through the bearing after manufacture or, the hole can be made in the steel plated and rubber sheets before they are joined together. The lead is then cast directly into the hole or machined into a plug before being pressed into the hole. For both methods of placing the lead, it is imperative that the lead plug is a tight fit in the hole and that it locks with the steel plates and extrudes a little into the layers of rubber. To ensure this lead plug volume is taken 1 percent greater than the hole volume enabling the lead plug to be firmly pressed into the hole. Thus, when the elastomeric bearing is deformed horizontally, the lead insert is forced by the interlocking steel plates to deform in shear throughout its whole volume (Robinson 1982).

It is possibly the cheapest solution to the problems of base isolation in that the one unit supports the base-isolated structure, provides an elastic restoring force and also, by the selection of the appropriate size of lead plug, produces the required amount of damping. Figure 2 shows a schematic diagram of these isolators (Su. et al. 1989)

The expression for hysteretic restoring force, Q , in a hysteretic damper is given as

$$Q(x, \dot{x}) = \alpha \frac{F_y}{Y} x + (1 - \alpha) F_y Z \quad (2.2)$$

The variable Z is given by

$$\dot{Z} = -\gamma |\dot{x}| Z |Z|^{\eta-1} - \beta \dot{x} |Z|^{\eta} + A \dot{x} \quad (2.3)$$

Where

Y = Yield displacement of the hysteretic damper

F_y = Yield force of the hysteretic damper

β, γ, η = Dimensionless parameters

Parameter η is an integer, which controls the smoothness of the transition from elastic to plastic response and α is the post to pre-yielding stiffness ratio. The equation of motion is given as

$$\ddot{x} + 2\xi\omega_0 \dot{x} + \omega_0^2 x + \frac{N}{M} \left(\alpha \frac{F_y}{Y} x + (1 - \alpha) F_y Z \right) = -\ddot{u}_g \quad (2.4)$$

Where, the hysteretic restoring force is determined by Equation 2.2 and

ω = Pre-yielding natural frequency of the system

M = Mass of the structure

N = Number of the hysteretic dampers used.

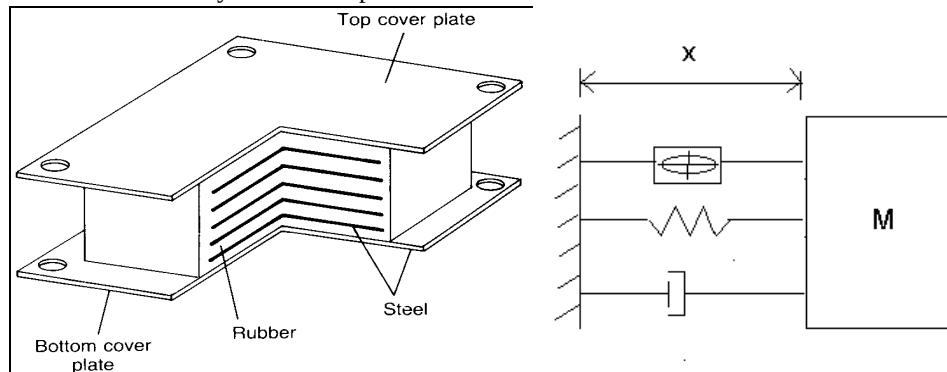


Figure 2 LRHB System (a) Physical Model (b) Mathematical Model

2.3 Pure Friction System (P-F System)

Friction force is a natural and powerful energy dissipation device, which reduces the acceleration, experienced by the structure and associated equipment during an earthquake. The simplest of these is pure friction (PF) system. In the pure-friction isolation systems the isolation mechanism is sliding friction. A schematic diagram of a pure-friction base isolator is shown in the Figure 3. These base isolators are the simplest base isolation systems of all.

When a rigid structure with a pure Coulomb friction base isolator is subjected to horizontal earthquake excitation, assuming that the structure is always in contact with its foundation, the equation of motion in terms of the slip displacement x is given as

$$\ddot{x} + \mu g \operatorname{sgn}(\dot{x}) = -\ddot{u}_g \quad (2.5)$$

Here,

$\ddot{u}_g$ = Horizontal ground acceleration

μ = Friction coefficient

g = Acceleration of gravity

Equation 2.5 describes the behaviour of the system in the sliding phase. Whenever the structure sticks to its foundation, the non-sliding condition holds as long as

$$\dot{x}_b = 0 \quad (2.6)$$

$$\mu g - |\ddot{u}_g| > 0 \quad (2.7)$$

As soon as the stick condition given by the above equation fails, slip will occur and Equation 2.5 applies.

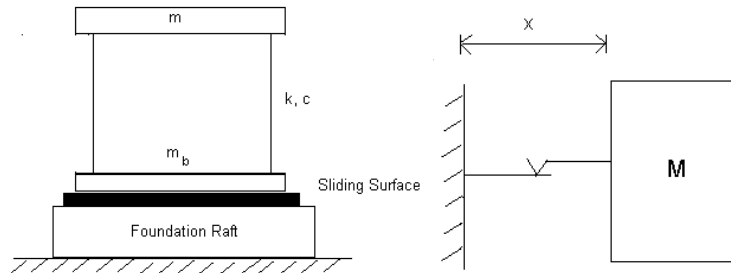


Figure 3 PF System (a) Physical Model (b) Mathematical Model

2.4 Electricite De France System (EDF System)

The advanced friction systems involve pure friction elements in combination with laminated rubber bearings. EDF is one of the isolator systems that use friction force as a dissipation of the energy.

The EDF system involves the use of sliding elastomeric bearing pads. In this system, the building foundation consists of a double raft system in which sliding elastomeric bearing pads are interposed between the two rafts. Each pad consists of a block of elastomeric, reinforced by horizontal steel plates (Figure 4). The reinforced bearing pad has a high vertical stiffness and load carrying capacity, together with a low stiffness to horizontal shear forces. The pads are cast integrally with a concrete slab using stud anchors before installation in the field. The unit is fixed using high strength grout after making adjustment for horizontality. Each pad is mounted with a lead-bronze alloy plate that forms a friction couple with a stainless steel plate stiffened by concrete slab and embedded in the upper raft. The materials are so chosen that the coefficient of friction is 0.2 for a wide range of vertical pressures, lateral movement and sever environmental conditions. Pad is fabricated in alternating layers of neoprene sheets and carbon steel. The reinforcing plates as well as the lead-bronze friction plates are bonded to various layers of elastomeric by vulcanization. The sliding elastomeric bearing pads act as a filter between the structure proper and the ground, the forces transmitted to the structure being dependent on the characteristics of the filter itself (Guiraud et al. 1985).

During low intensity earthquakes, the structure vibrates elastically on the elastomeric blocks and returns to its original position after the earthquake. During the earthquakes of higher intensity the structure vibrates elastically as well as it slides on the frictional surface. The slip can occur in any direction in the horizontal plane and after the seismic shock comes to rest with some permanent offset. Thus in the absence of sliding the bearing behaves as a laminated rubber bearing. The friction plate puts a limitation on the horizontal force that can be transferred to the structure. This force depends on the total vertical force acting on the structure and the coefficient of friction between the friction surfaces. This mechanism of friction surfaces also function as a fail-safe system in the sense that if the rubber bearing were overextended the structure would be carried on the sliding surfaces.

This system is standardized for nuclear power plants in regions of high seismicity. Typically the power plant is built atop a vast monolithic concrete raft that covers several thousands of square meters. This raft is supported by hundreds of base isolators that are in turn supported by a foundation raft built directly on the ground. The main isolator of the EDF system consists of a laminated neoprene pad topped by a lead-bronze plate, which is in frictional contact with a steel plate anchored to the structure. The friction surfaces are designed to have a coefficient of friction = 0.2 during the service life of the base isolation system. The EDF isolator, which essentially uses an elastomeric bearing and friction plate in series, is schematically shown in Figure 2.4 (Su et al. 1989).

The equations of motion in the sliding phase are given as

$$\ddot{x} + \mu g \operatorname{sgn}(\dot{x}) = -\ddot{u}_g - \ddot{y} \quad (2.8)$$

$$2\xi\omega_0 \dot{y} + \omega_0^2 y = \mu g \operatorname{sgn}(\dot{x}) \quad (2.9)$$

During the non-sliding phase, the EDF isolator behaves as a laminated rubber bearing and its motion is governed by

$$\ddot{y} + 2\xi\omega_0 \dot{y} + \omega_0^2 y = -\ddot{u}_g \quad (2.10)$$

$$\dot{x} = 0 \quad (2.11)$$

Here,

x = Slip displacement

y = Displacement of the neoprene pad relative to the ground. The structure sticks to the isolator as long as the following inequality is satisfied and the structure follows Equation 2.6 and 2.7.

$$\mu g - \left| \ddot{u}_g + \ddot{y} \right| > 0 \quad (2.12)$$

As soon as this condition fails, slip occurs and Equations 2.9 and 2.10 apply.

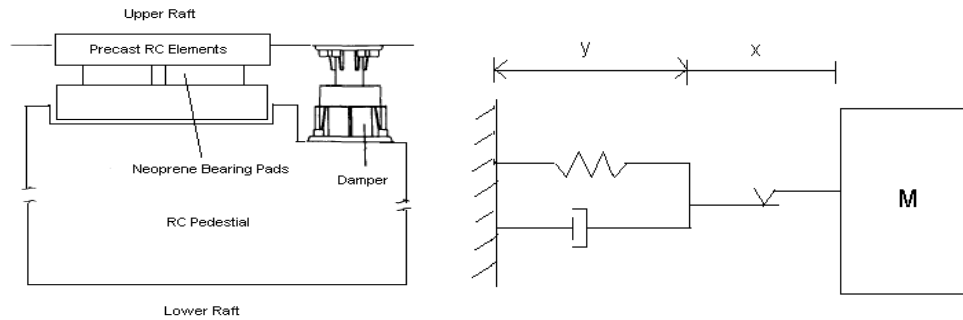


Figure 4 EDF System (a) Physical Model (b) Mathematical Model

2.5 Resilient-Friction Base Isolator (R-FBI System)

Resilient-Friction Base Isolator (R-FBI) is composed of layers of sliding elements with rubber cores. It is composed of a set of flat rings, which can slide on each other with a central rubber core and/or peripheral rubber cores. Also, there is a very flexible rubber cover, which protects the sliding rings from corrosion and dust. To reduce the friction, the sliding rings are Teflon coated. The rubber cores help to distribute the lateral displacement and velocity along the height of the isolator. The R-FBI is characterized by the coefficient of friction of the sliding elements and the total lateral stiffness of the rubber. The damping capability of the rubber is small, and the friction damping is the main energy dissipater of R-FBI. As the rubber cores are only fitted but not bonded to the sliding rings, the construction of an R-FBI can be a relatively simple task (Mostaghel et al. 1987).

R-FBI is designed such that the entire vertical load is carried by the sliding bearings and the rubber cores carry no vertical load. Therefore, the R-FBI is very rigid in the vertical direction. Hence, the R-FBI does not provide isolation against vertical ground motion. The response of structures to vertical ground motion cause non-uniform distribution of vertical load on the isolators leading to variations in frictional force affecting the horizontal sliding displacements. There are two factors, which tend to limit this vertical effect. The sliding of an R-FBI is restrained by the stiffness of the rubber cores and second, higher frequencies are involved in case of the vertical load as compared to the horizontal load. This leads to high degree of decoupling between the horizontal and vertical responses. R-FBI is shown in Figure 5.

This isolator consists of concentric layers of plates that are in friction contact with each other and contains a central core of rubber. The system provides base isolation through the parallel action of friction, damping and restoring springs. Figure 5 shows a schematic diagram of a rigid structure with a resilient-friction base isolator (Su et al.1989).

When subjected to earthquake excitation, the equation of motion in terms of the horizontal relative displacement x is given as

$$\ddot{x} + 2\xi\omega_0\dot{x} + \omega_0^2x\mu_1g\operatorname{sgn}(\dot{x}) = -\ddot{u}_g \quad (2.13)$$

Where,

ξ = Effective damping coefficient

ω_0 = Natural frequency of the isolator

μ_1 = Friction coefficient

g = Acceleration due to the gravity

The structure remains in the non-sliding phase as long as

$$\mu_1g - |\ddot{u}_g + \omega_0^2x| > 0 \quad (2.14)$$

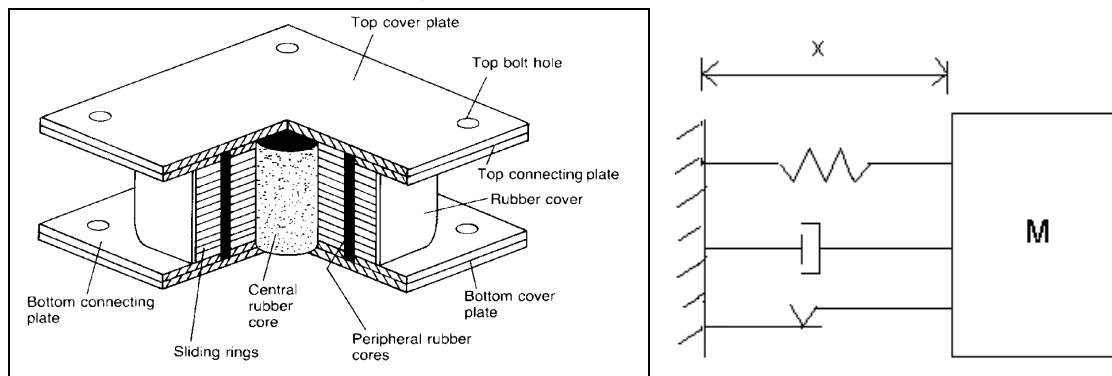


Figure 5 R-FBI System (a) Physical Model (b) Mathematical Model

2.6 Friction Pendulum System (FPS)

Pure friction system is the simplest sliding isolator consisting of a horizontal sliding surface; however, it may experience large sliding and residual displacements, which are often difficult to incorporate in structural design. Several systems have been suggested in the past to accommodate the restoring mechanism along with sliding in order to reduce the sliding and residual displacements to manageable levels. The FPS is based on an innovative way of achieving a pendulum motion.

The friction pendulum isolator bearing (FPI) is a form of sliding bearing consisting of an articulated slider on a spherical surface. Figure 6 shows an FPS bearing. In this system, the sliding surface takes a concave spherical shape so that the sliding and re-centring mechanisms are integrated in one unit. Figure 6 shows a free body diagram of an FPS bearing. The supported structure responds to earthquake motions with small amplitude pendulum motions. Friction damping absorbs the earthquake's energy. The result is a simple, predictable, and stable earthquake response.

The natural period is controlled by the selection of the radius of curvature, R of the concave surface. The natural period of vibration, T , of a rigid mass supported on FPS is determined from the pendulum equation

$$T = 2\pi \sqrt{\frac{R}{g}} \quad (2.15)$$

where g is the acceleration due to gravity. This pendulum period is the period of a mass sliding on FPS isolators, and is the isolated period of vibration of a relatively stiff structure supported on the FPS. The isolated period becomes active once the friction force level of the isolators is exceeded. The lateral restoring stiffness of the activated FPS isolator is,

$$k = \frac{W}{R} \quad (2.16)$$

where W is the supported weight and R is the radius of curvature. This is the stiffness of a simple pendulum. The fact that the stiffness is directly proportional to the supported weight is an important and unique property of the FPS. Also, the period is independent of the structure mass which has advantages in controlling the response of a supported structure. The desired period can be selected by simply choosing the radius of curvature of the concave surface.

The force level at which sliding motion begins is controlled by the selection of the friction bearing material. When the earthquake forces are below the friction force level, an FPS responds like a conventionally supported structure, at its non-isolated period of vibration. Once the friction force is exceeded, the dynamic response is controlled by the FPS isolators and the structure responds at its isolated period of vibration.

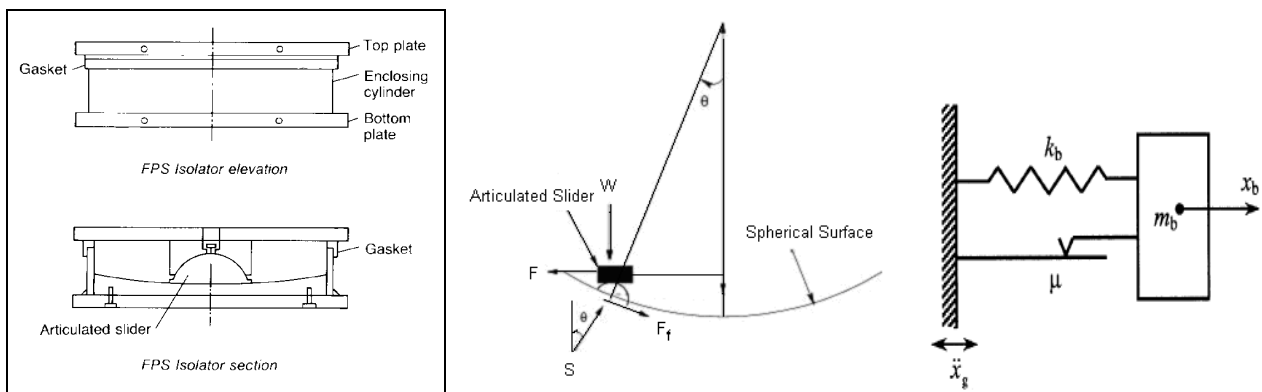


Figure 6 FPS System (a) Physical Model (b) Mathematical Model

2.7 Variable Friction Pendulum System (VFPS)

Panchal and Jangid (2008, 2009) developed VFPS, which is physically similar to FPS, except the coefficient of friction of sliding surfaces varies as per the curve. The variation of friction coefficient (μ) is such that up to a certain value of isolator displacement the frictional force increases and then it decreases with further increase in isolator displacement. This type of curve gives the isolator, initial softness for smaller jerks than provides stiffness for moderate tremors, and finally for strong earthquakes it becomes again soft. Such pattern of variation is selected with the criterion that the isolator displacement and building base shear decrease significantly without much alteration to superstructure acceleration under the near-fault ground motions. The variation of coefficient of friction ($\mu(z_b)$) can be expressed as

$$\mu(z_b) = (\mu_0 + a_1 |z_b|) e^{-a_2 |z_b|} \quad (2.17)$$

where μ_0 is the initial value of friction coefficient; a_1 and a_2 are the parameters that describe the variation of friction coefficient along the sliding surface of VFPS; and z_b is the radial isolator displacement ($z_b = \sqrt{x_b^2 + y_b^2}$). Hwang and Zum Gahr (2003) and Kurtus (2008) showed that the frictional coefficient can be varied by changing the roughness of the sliding surface. However, it is practically not easy to achieve this friction model so a mathematical idealization has been used for the variation of the friction coefficient. Yet, experimental evaluation of seismic performance of structures

isolated by the VFPS has not been carried out. The initial stiffness k_i and corresponding initial period T_i of the VFPS, which are as follows

$$k_i = \frac{\mu_{\max} w}{z_{b\max}} \quad (2.18)$$

$$T_i = 2\pi \sqrt{\frac{m}{k_i}} \quad (2.19)$$

where $\mu_{\max}$ is the peak coefficient of friction of VFPS and $z_{b\max}$ is the resultant isolator displacement corresponding to peak friction coefficient of VFPS; $w = mg$ is the weight supported by the VFPS; m is the mass supported by the VFPS; and g is the acceleration due to gravity. Another relation between $z_{b\max}$, μ_0 and the parameters a_1 and a_2 can be written as

$$z_{b\max} = \frac{a_1 - \mu_0 a_2}{a_1 a_2} \quad (2.20)$$

The parameters a_1 and a_2 can be obtained after deciding the minimum value of friction μ_0 and selecting initial period T_i and peak friction coefficient $\mu_{\max}$ using equations. Jangid (2005) showed that the frictional forces of sliding system presented by both conventional and hysteretic models yielded similar seismic response for the isolated structures. Thus, in the present study, the frictional forces are modelled hysteretically using the Bouc-Wen Model which is expressed in Equation 2.9. The isolator forces offered by VFPS can be expressed as

$$f_x = k_b x_b + \mu(x_b) w z_x \quad (2.21)$$

$$f_y = k_b y_b + \mu(y_b) w z_y \quad (2.22)$$

where z_x and z_y are the hysteretic coefficients; f_x and f_y is the isolator force offered by the VFPS in x and y directions respectively; $k_b = w/R$ is the stiffness of the VFPS; R is the radius of curvature of spherical surface of VFPS and; x_b , and y_b are the isolator displacements in x and y directions respectively.

The important parameters of the VFPS are isolation period (T_b) and the friction coefficient (μ). The later parameter can be defined by two parameters, viz. initial period, T_i and peak friction coefficient, $\mu_{\max}$. in magenta colour, which conspicuously shows that VFPS gives very less isolator displacement with low isolator force as well in comparison to FPS.

2.8 Variable Frequency Pendulum Isolator (VFPI System)

The spherical sliding surface of the FPS isolator provides a relatively constant period of oscillation, resulting in several practical disadvantages. One main disadvantage is that FPS isolators can be effectively designed for a specific level (amplitude and frequency characteristics) of ground excitation. Under more severe ground motions, sliding displacements greater than the design displacements occur. Since the FPS isolator restoring force is linearly proportional to sliding displacement, the additional sliding introduces additional energy in the structure. As a result, the maximum intensity of excitation has a strong influence on FPS design. In general, FPS isolators designed for a particular intensity of excitation may not give satisfactory performance during earthquakes with much lower or higher intensity (Pranesh and Sinha 2002). A new isolator called the Variable Frequency Pendulum Isolator (VFPI) that incorporates the advantages of both the FPS and PF isolators have been developed recently. The most important properties of this system are:

1. Its time period of oscillation depends on sliding displacement, and
2. Restoring force exhibits softening behaviour.

The geometry of the sliding surface has been defined by a second order parametric equation. Using this parametric equation, the isolator properties can be chosen to achieve progressive period shift with variation in sliding displacements. Recent investigations on single-degree-of-freedom (SDOF) systems have shown the VFPI to be very effective for a variety of excitation and structural characteristics. The oscillation frequency of the VFPI continuously decreases with increase in sliding displacement, and the restoring force has an upper bound so that the force transmitted to the structure is bounded. The VFPI performance is found to be effective and stable during low- and medium-intensity excitations, and fail-safe during high-intensity excitations (Figure 7).

The restoring force offered by the curved sliding surface can be defined as the lateral force required to cause a horizontal displacement x . Assuming a point contact the various forces acting on the sliding surface when the block is displaced from its original position at the origin of coordinate axes. At any instant the horizontal restoring force due to weight of the structure is given by

$$f_R = mg \frac{dy}{dx} \quad (2.23)$$

Assuming that the restoring force is mathematically represented by an equivalent nonlinear mass less horizontal spring, the spring force can be expressed as the product of the equivalent spring stiffness and the deformation, i.e.,

$$f_R = k(x)x \quad (2.24)$$

where

$k(x)$ = Instantaneous spring stiffness
 x = Sliding displacement of the mass.

If the mass is modeled as a single-degree-of-freedom oscillator, the spring force (restoring force) can be expressed as the product of the total mass of the system and square of oscillation frequency

$$f_R = m\omega_b^2(x)x \quad (2.25)$$

Here, ω_b is instantaneous isolator frequency, and depends solely on the geometry of sliding surface. In the friction pendulum system, which has a spherical sliding surface, this frequency is almost constant and is approximately equal to

$\sqrt{\frac{g}{R}}$, where R is the radius of curvature of the sliding surface (Pranesh and Sinha 2002).

For accumulation of output of still in the form of distillate water proper arrangement of high strength and non-reactive water pipe were installed. Brackish water in flow is facilitated with similar pipe.

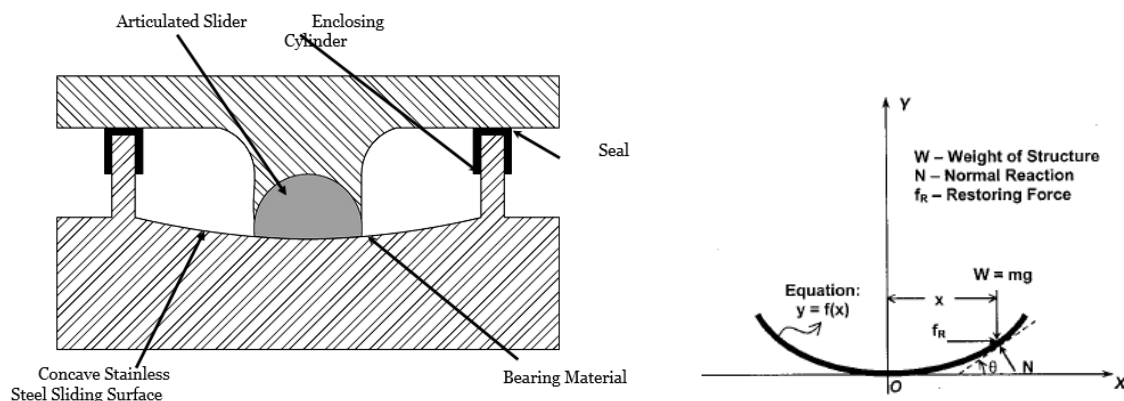


Figure 7 Schematic Diagram of VFPS (a) Physical Model (b) Mathematical Model

2.9 Variable Curvature Friction Pendulum System (VCFPS)

The mechanical behavior of VCFPS developed by Tsai *et al.*, (2003, 2005) is very similar to that of the FPS. The difference between the VCFPS and FPS is that the radii of curvature of the VCFPS can be lengthened with an increase of the isolator displacement similar to VFPI. Hence, the fundamental period of the base-isolated structure can be shifted further away from the predominant periods of near-fault ground motions, and the resonant possibility of the superstructure with earthquakes can be prevented. To describe the VCFPS geometrically, following functions are

$$y = R - \sqrt{R^2 - z_b^2} - f(z_b) \quad (2.26)$$

where R is the radius of curvature at the center of the sliding surface of the VCFPS; z_b is the radial displacement of the isolator; $f(z_b)$ is the function to describe the increase of the radius of curvature with an increase of the horizontal displacement; $f(z_b)$ can be further expressed as

$$f(z_b) = E_v \operatorname{sgn}(z_b) z_b^3 \quad (2.27)$$

where E_v is the parameter that describes the variation of curvature of the concave surface. If the restoring force can bring the slider back to the initial position within the radial sliding displacement r_0 , then the parameter E_v can be determined as

$$E_v = \left(\frac{\frac{wr_0}{\sqrt{R^2 - r_0^2}} - \frac{\mu w}{\cos \theta_0}}{3w \operatorname{sgn}(r_0) r_0^2} \right) \quad (2.28)$$

The instantaneous horizontal stiffness of VCFPS can be expressed as

$$k_b(z_b) = \left[\frac{w}{\sqrt{R^2 - z_b^2}} - \frac{\operatorname{sgn}(z_b) z_b \left(\frac{wr_0}{\sqrt{R^2 - r_0^2}} - \frac{\mu w}{\cos \theta_0} \right)}{\operatorname{sgn}(r_0) r_0^2} \right] \quad (2.29)$$

where θ_0 is the corresponding angle of the slider displacement r_0 and μ is the coefficient of friction of sliding surfaces. The isolator forces offered by the VCFPS in x and y directions by taking the instantaneous stiffness of the VCFPS in respective directions. The important characteristics of the VCFPS are initial isolation period T_i and friction coefficient (μ), which can be used to model the VCFPS. The force-displacement diagram of VCFPS has been shown in blue. VCFPS also offers mild isolator forces at large displacements and thus provides better structural performance at the cost of increase in isolator displacements (Figure 8).

Thus, the study of above variable sliding isolators and FPS in base-isolated benchmark building would reveal their comparative performances and relative efficiencies to improve seismic response of the benchmark building.

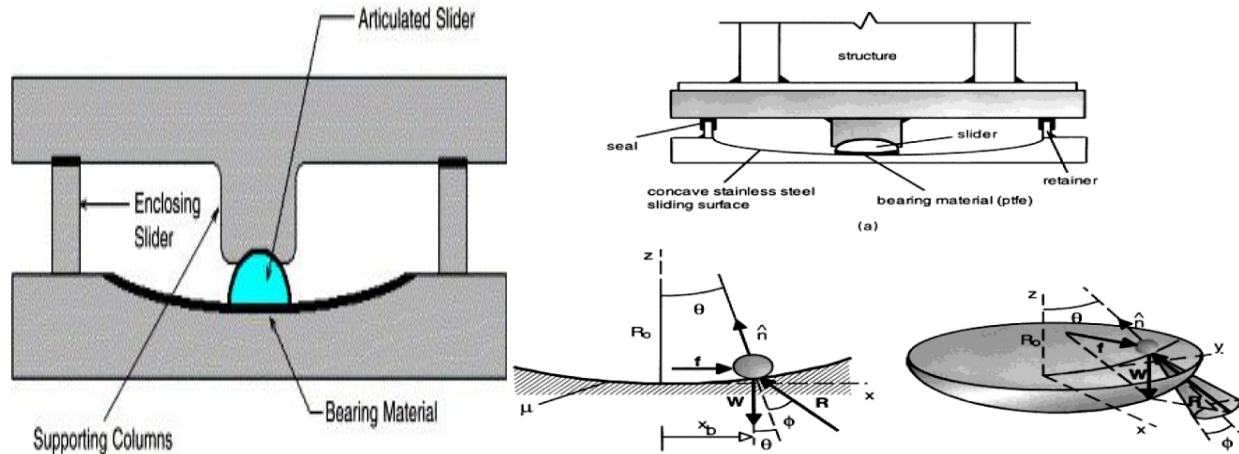


Figure 8 Schematic Diagram of VCFPS (a) Physical Model (b) Mathematical Model

V. CONCLUSION

Different isolation systems are found to be useful in different situations. They are mainly used in the nuclear isolators since the structure as well as the equipment needs to be not affected by the onset of ground motion.

Based on the study of different isolator systems the following conclusions can be drawn:

1. Base-isolation consists of bearings that make the structure flexible in the horizontal direction, a damper for controlling of the displacements.
2. Most of the flexible bearings are rigid in the vertical direction.
3. They cause shifting of the time period of the structure beyond the range of the predominant energy content of the design earthquake.
4. A very efficient way of controlling displacements is application of elements with a high capacity of hysteretic energy dissipation.
5. An alternative solution for the dissipation of energy is through friction. However, most of these devices are not-self centring.
6. The first mode period and damping of an isolated structure are determined primarily by the characteristics of the isolation system and are virtually independent of the period and damping of the structure.
7. The acceleration spectral responses can be reduced by a large factor by introducing isolation.

REFERENCES

- [1] Cheng, F.Y. (2001). Matrix Analysis of Structural Dynamics, First Edition, Marcel Dekker Publication, New York, USA.
- [2] Chopra, A.K. (2001). Dynamics of Structure, Second Edition, Pearson Education Asia, New Delhi.
- [3] Clough, R.K., and Penzien, J (1993). Dynamics of Structures, Second Edition, McGraw-Hill Book Co., Singapore.
- [4] Guiraud, R., Noelleroux, J.P., Livolant, M. and Michalopoulos, A.P. (1985) "Seismic Isolation Using Sliding-Elastomer Bearings." Nuclear Engineering and Design, 84, 363-377
- [5] Hoffmann, G.K. (1985). "Full Base Isolation for Earthquake Protection by Helical Springs and Viscodampers." Nuclear Engineering and Design, 84, 331-338.

- [6] Mostaghel, N., Hejazi, M. and Tanbakuchi, J (1983). "Response of Sliding Structures to Harmonic Support Motion." *Journal of Earthquake Engineering and Structural Dynamics*, 11, 355-366.
- [7] Mostaghel, N., Hejazi, M. and Tanbakuchi, J (1983). "Response of Sliding Structures to Earthquake Support Motion." *Journal of Earthquake Engineering and Structural Dynamics*, 11, 729-748.
- [8] Mostaghel, N. and Khodaverdian, M. (1987). "Dynamics of Resilient-Friction Base Isolator (R-FBI)." *Journal of Earthquake Engineering and Structural Dynamics*, 15, 379-390.
- [9] Pranesh, "VFPI: An Innovative Device for Aseismic Design", PhD Thesis, IIT Bombay, 2002
- [10] Pranesh, M. and Sinha, R. (2002). "Earthquake Resistant Design of Structures using the Variable Frequency Pendulum Isolator." *Journal of Structural Engineering*, 128, 870-880.
- [11] Robinson, W.H. (1982). "Lead-Rubber Hysteretic Bearings Suitable for Protecting Structures During Earthquakes." *Journal of Earthquake Engineering and Structural Dynamics*, 10, 593-604.