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Sliding Isolation Systems: State-of-the-Art Review

Malu Girish[1], Murnal Pranesh[2]
[1] *Ph.D. Scholar, Shivaji University, Kolhapur, India*
[2] *Head and Professor, Dept. of Applied Mechanics, Government College of Engineering, Aurangabad, India*

ABSTRACT : *An update state-of-the-art review of the earlier and current sliding base isolation systems is presented. The Base Isolation is one of the passive control techniques to reduce the earthquake effect on the structure up to negligible level. Base isolation system are, Elastomeric Bearing, Sliding Isolation System and Combined Systems. Elastomeric bearing has a problem of tearing of rubber under severe earthquake. Sliding isolation system consists of deflecting the earthquake energy by incorporating flexible device between foundation and super structure. In combined system elastomeric and sliding system act in parallel. Sliding isolation system found to be more effective under all types of earthquake, since it has large sliding displacement. In present paper review of earlier and current sliding isolation system such as PF, FPS, CFPI, VFPI, PFPI, VFPS, VFFPI and VFI is given.*

Keywords *–Base Isolation, Passive control, Sliding isolation system, Ground motion*

1. INTRODUCTION

If it is possible at one and the same time to hold up the building and let the ground move underneath then the large displacements, story drift and hence damage to the super structure will be greatly reduced [1]. Base isolators reduce the structural response by filtering the seismic excitation and by dissipating energy, there by reducing the energy that need to be dissipated by structure. The ground accelerations induce large displacements at the isolator level and minimize the acceleration and story drift of super structure. The isolation system does not absorb the earthquake energy, but rather deflect it through the dynamics of the system. Most of the isolators work through a combination of deflecting seismic energy and dissipating energy through suitable mechanism.

The basic concept of base isolation is to increase the time period of the structure by incorporating flexible elements between the super structure and foundation. Conventional structures have relatively lower time period and they match with predominant period of most of the earthquakes. As a result they experience large accelerations and hence large forces. In contrast the base isolated structure has a longer time period resulting in lower acceleration. Consequently the conventional structures experience lower displacements and base isolated structure high displacement at isolated level. Since large displacement is at isolator level, the super structure displaces as a rigid body in case of base isolated structure.

2. PRINCIPLE OF SLIDING ISOLATION SYSTEM

Sliding isolator works on principle of friction. This approach is based on the premise that the lower the friction coefficient, the less the shear transmitted [2]. In sliding isolator, two pure flat stainless steel plates or spherical surface and articulated friction slider slide over each other during earthquake excitation. For initiation of sliding the intensity of exciting force must be more than frictional force of isolator. Hence during earthquake excitation, the frequency of which is not harmonic, the isolator displacement is of stick-slip nature.

3. PURE FRICTION SYSTEM (PF SYSTEM)

PF system isolator works on principle of pure friction. In PF system, two true flat stainless steel plates slide over each other. The upper plate slides over the lower plate under excitation force. The structure resting on upper plate displace as a rigid mass during earthquake. The only necessary condition for triggering of isolator is, excitation force greater than frictional force ($m \times \mu \times g$) of isolator. Hence level of acceleration response is independent of frequency and amplitude of excitation, which is the main advantage of this isolator. This implies that PF isolator can be used for all kinds of sites [2]. The earthquake excitation is not exactly of harmonic nature. Hence some abnormal stops may occur in the sliding isolator. High viscous damping reduce, even can eliminate, number of abnormal stops per cycle. Constant coulomb and linear coulomb oscillators were developed at first stage. They do not postulate symmetric type of motion. To avoid this limitation, velocity dependent frictional oscillator is developed. Velocity dependent frictional oscillator gives response predominately on velocity of oscillator and not on intensity of excitation force. Velocity dependent frictional oscillator exhibits smaller number of stops per cycle.

Besides above advantages of PF system have some limitations. The main drawback of PF system is the geometry of sliding surface. Sliding surface is true flat, which may result in large sliding and residual displacements. Residual displacement is mainly due to lack of restoring force. To provide adequate resistance and avoid unnecessary movement, a fairly high value of friction coefficient is needed. [3] But high value of friction coefficient results more input force requirement for sliding of isolator. Hence under low level of earthquake excitation isolator remains in non-sliding phase and structure behaves as fixed base structure. This results in displacement and acceleration in top mass.

4. FRICTION PENDULUM SYSTEM (FPS)

Friction Pendulum System is the advancement on the PF system to overcome the main drawback of restoring force of PF system. It is based on well-known principle of pendulum motion. The FPS has emerged as an effective vibration control system incorporating isolation, energy dissipation and restoring mechanism in one unit [4].

The FPS has a spherical concave surface as a base of isolator and an articulated element as a slider. The PTFE bearing material is provided in between base and slider. In an earthquake the slider will slide over concave surface so as to achieve isolation. Due to concavity of base, at the end of earthquake, the slider will come back to its original position under action of gravitational force. Hence restoring the structure at its original position and minimizing residual displacement. During ground shaking, the slider moves on the spherical surface lifting the structure and dissipating energy by friction between the spherical surface and the slider. The control on natural period of supported structure is achieved by selection of the radius of curvature *r*, of the concave surface. The natural period *T*, of the rigid mass supported on FPS isolator is determined by, $T = 2\pi\sqrt{r/g}$ [4].

Once the friction force level is exceeded, the FPS isolator controls the dynamic response, and the structure responds at its isolated period of vibration. At this dynamic stage, as exciting force increases the percentage of acceleration transmitted to the structure decrease. The observations and experiments show, an ideal bilinear response of the FPS with no observable degradation under repeated cyclic loading. The FPS isolators retain their full strength and stability throughout their displacement range. Also it is shown that increasing the sliding period reduces the base shear and increases the displacement. Again decreasing the friction coefficient reduces the base shear and increases the displacement. Thus the friction coefficient should be such that it should provide enough rigidity as well as the isolation by shifting the effective period from the duration of pulses. The lateral restoring stiffness of activated FPS connection is, $k = W/r$ [4]
where, W is supported weight and r is radius of curvature of concave surface.

It is seen in the above discussion that FPS has lot of advantages. But the main limitation of FPS is that, the sliding surface of FPS is spherical so that it has a constant time period, which solely depends upon the radius of curvature. Hence FPS needs to be designed for a specific level (intensity) of ground excitation. In general FPS may not give satisfactory performance under lower or higher intensity than considered for design. If the excitation period and isolator period of FPS coincides then the FPS faces the problem of resonance. [5]

5. VARIABLE FREQUENCY PENDULUM ISOLATOR (VFPI)

VFPI combines the advantages and at the same time overrules the disadvantages of both PF and FPS. The limitation of both PF and FPS is due to the geometry of their sliding surfaces. Hence the golden mean is that the geometry of sliding surface of isolator should not be true flat nor to be true spherical. The geometry of VFPI is derived from elliptical shape. This geometry of VFPI is chosen to achieve a progressive period shift at different response levels. The VFPI retains the advantages of both PF and FPS, due to amplitude dependent time period and softening mechanism of isolator restoring force. VFPI is relatively flatter than FPS, which results in smaller vertical displacement for similar sliding displacements. Flatter sliding surface will result in the generation of smaller overturning forces in the structure. If the slider has to have a single point of contact with the sliding surface, the varying radius of curvature does not interfere with smooth movement of the slider. This can be easily achieved in VFPI, hence improving its advantage.

Under low level of excitation, the behavior of VFPI is similar to FPS for smaller displacement (with desired high initial stiffness). Under high level of excitation, the behavior of VFPI is similar to PF system for very large displacement (with large sliding displacement of isolator but without significant residual displacement). The frequency of VFPI is kept varying for its better performance under all levels of excitation. The pendulum effect of isolator will provide necessary restoring force. The geometry of VFPI is derived from equation of an ellipse. [6] The geometry is given by:

$$y = b\left[1 - \frac{\sqrt{d^2 + 2dx\,\mathrm{sgn}(x)}}{d + x\,\mathrm{sgn}(x)}\right] \tag{1}$$

The frequency of isolator is derived as:

$$\omega_b^{\,2}(x) = \frac{\omega_I^{\,2}}{(1+r)^2\sqrt{1+2r}} \tag{2}$$

where, $\omega_I^{\,2} = gb/d^2$ = square of initial frequency of the isolator (at zero displacement)

b & d are geometrical parameters of VFPI.

$r = x\,\mathrm{sgn}(x)/d$

x is the isolator displacement at any instant.

VFPI is less effective under the action of near-fault ground motions and low frequency ground motion. Under both the above excitations the sliding displacements are found to be large [6].

6. CONICAL FRICTION PENDULUM ISOLATOR (CFPI)

The sliding surface of CFPI is basically derived from spherical surface of FPS [7]. The surface is identical to FPS up to d_b, after that it becomes tangential to the spherical surface. The parameter d_b and R are important for defining the geometry of a CFPI isolator, i.e.:

$$y(x) = \begin{cases} R - \sqrt{R^2 - x^2} & \text{for} \quad |x| \le d_b \\ c_1 + c_2\left(|x| - d_b\right) & \qquad\quad d_b < |x| \end{cases} \tag{3}$$

where,

$$c_1 = R - \sqrt{R^2 - d_b^2} \quad \text{and} \quad c_2 = d_b \Big/ \sqrt{R^2 - d_b^2} \tag{4}$$

The frequency of the isolator can be calculated by approximate formula as:

$$\omega_b = \sqrt{g\ddot{y}(x)} \tag{5}$$

Hence after substituting $y(x)$ from “equation 3” in “equation 5” and taking second derivative, one may conclude that $\omega_b\,(x) = 0$ for $x > d_b$. This implies that the isolation system possesses no predominant frequency when the isolation displacement exceeds d_b. For CFPI, the restoring force becomes a constant when the isolator displacement exceeds d_b. CFPI has zero frequency after d_b. Due to which the isolator behaves as PF system after d_b, but with restoring force. Since the value of d_b is small the isolator acts as PF in its major part.

Comparison of geometric shape of PF, FPS, CFPI and VFPI is presented in “Fig. 1”.

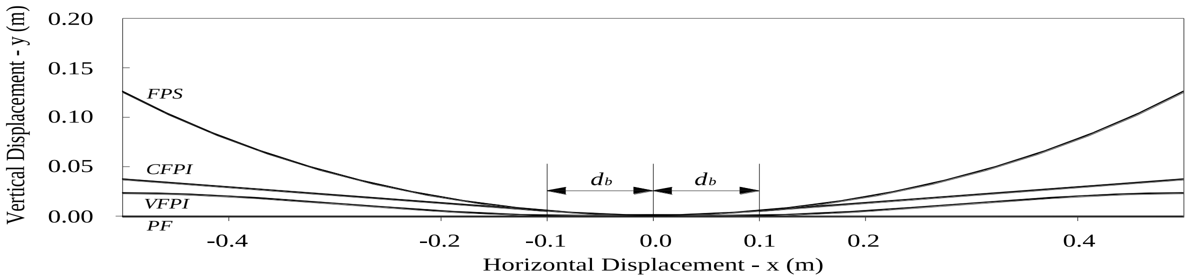

Figure 1: Comparison of geometric shapes of PF, FPS, CFPI and VFPI

It is investigated by many researcher that sliding isolation is not much effective under the action of near-fault (pulse type excitation) and low frequency ground motions. The sliding of isolator found to be too high. In case of FPS sliding may be up to the geometric limit of isolator under the action of low frequency ground motions. Hence to improve the performance of sliding system many researchers suggested different geometry of isolator and variable friction along the surface of isolator.

7. POLYNOMIAL FRICTION PENDULUM ISOLATOR (PFPI)

Lu et. al. [8] proposed a PFPI to overcome the resonant problem of FPS. The isolator is similar to a typical FPS, but the sliding surface has been made of an axially symmetric surface with a variable curvature, rather than a spherical surface with a constant radius, so the isolation frequency becomes a function of the isolator displacement. A polynomial function has been employed to define the geometry of the sliding surface. The following fifth order polynomial function has been chosen to define $y'(x)$ of the PFPI:

$$y'(x) = u_r(x)/P = ax^5 + cx^3 + ex \tag{6}$$

$y'(x)$ can be treated as a restoring force $u_r(x)$ normalized with respect to the vertical load *P*. Similarly, $y''(x)$ can be treated as the normalized isolator stiffness, which can be obtained as:

$$y''(x) = k_r(x)/P = 5ax^4 + 3cx^2 + e \tag{7}$$

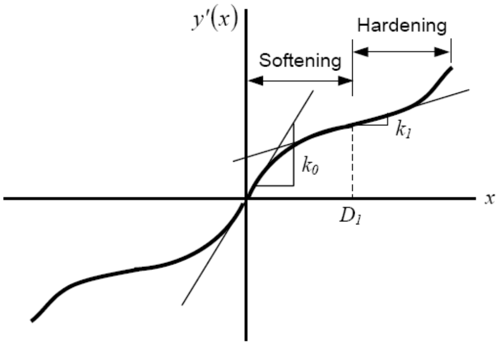

Figure 2: Normalised restoring force $y'(x)$

By properly choosing the values of the three polynomial coefficients *a*, *c* and *e* in "equation 6", the restoring-force function $y'(x)$ of a PFPI will possess a softening section followed by a hardening section, when the isolator displacement *x* is increased. In the softening section, the normalized stiffness $y''(x)$ is decreased, while in the hardening section the stiffness $y''(x)$ is increased. The purpose of the softening section is to mitigate the acceleration response for an earthquake below the design level; while, the purpose of the hardening section is to reduce the isolator drift during a sever earthquake, which exceeds the design level, and to prevent the possible stability problem of the isolation system. In brief, the softening and hardening sections aim to control the structural acceleration and isolator drift, respectively. Because the polynomial coefficients *a*, *c*, *e* in "equation 6" have no engineering meaning, they are replaced by a three design parameters k_0 , k_1 , D_1 (see "Fig. 2"): (i) k_0 is the normalized initial stiffness at $x = 0$, i.e., $y''(0) = k_0$. (ii) D_1 is the critical isolator drift, after which the PFPI system will switch from the acceleration control to displacement control. Geometrically, this means that $x = D_1$ is a retroflexion point of the $y'(x)$ function, i.e., $y'''(D_1) = 0$. (iii) k_1 is the normalized isolator stiffness at $x = D_1$, i.e., $y''(D_1) = k_1$. Next, by using the above three conditions, one may obtain the following relation between the polynomial coefficients and the design parameters, i.e:

$$a = \frac{-k_0 + k_1}{-5(D_1)^4}, c = \frac{2(-k_0 + k_1)}{3(D_1)^2}, e = k_0 \tag{8}$$

Numerical study has demonstrated that, when subjected to a long-period pulse-like earthquake, the PFPI is able to simultaneously reduce the isolator drift and structural acceleration, as compared with FPS system.

8. VARIABLE FRICTION PENDULUM SYSTEM (VFPS)

Panchal and Jangid [9] proposed VFPS. VFPS is similar to FPS except for the fact that the friction coefficient of VFPS is varied in form of curve and is an exponential function. The equation to define the curve for friction coefficient of VFPS is:

$$\mu = (\mu_0 + a_1|x_b|)e^{-a_2|x_b|} \tag{9}$$

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 x_b is the isolator displacement.

The initial stiffness, k_1 of the VFPS can be written as, $k_i = \dfrac{\mu_{\max} W}{x_{b\max}}$ (10)

where, $\mu_{\max}$ is peak friction coefficient of the VFPS, $x_{b\max}$ is the isolator displacement corresponding to peak friction coefficient of VFPS: $W = Mg$ is the effective weight.

Accordingly, the initial time period T_i of the VFPS is given by, $T_i = 2\pi\sqrt{M/k_i}$ (11)

The value of $x_{b\max}$ can be found out by maximizing the friction coefficient of VFPS and is given by:

$$x_{b\max} = \frac{a_1 - \mu_0 a_2}{a_1 a_2} \tag{12}$$

The restoring force of the VFPS is expressed by, $F_b = k_b x_b + F_x$

where, F_x is the frictional force in the VFPS and x_b is the stiffness of the VFPS.

The limiting value of the frictional force, *Q*, to which the VFPS can be subjected (before sliding) is:

$$Q = \mu W \tag{13}$$

The stiffness k_b is designed so as to provide the specific value of the isolation T_b, expressed as:

$$T_b = 2\pi M/k_b \tag{14}$$

Thus, the modeling of VFPS requires the specification of two parameters, namely the isolation period, T_b and the friction coefficient μ. The latter parameter can be defined by two parameters, viz, initial time period T_i and peak friction coefficient $\mu_{\max}$

9. VARIABLE FREQUENCY AND VARIABLE FRICTION PENDULUM ISOLATOR (VFFPI)

Krishnamoorthy [10] proposed VFFPI. For the proposed isolator, radius of curvature is varied exponentially with sliding displacement to develop the isolator with varying curvature. The radius of curvature is a function of sliding displacement *x* and is in by the expression, $R(x) = C(\exp(x) - 1)$ (15)

In the above equation, *C* is an isolator constant. Sliding and residual displacement increases and base shear decreases as the value of *C* increases and the behavior of isolator approaches the behavior of PF system for large values of *C*. Value of *C* may be selected considering the advantages of both the FPS and PF system. Thereby the residual displacement of VFFPI is similar to the FPS and the base shear of VFFPI is similar to PF system. Value of *C* is given by the equation $C = 84(1 + 0.2R)$ is found to be satisfactory to meet the above requirement. In this equation, R is the radius of the conventional FPS sliding surface in meters.

To improve the performance of the proposed isolator further, coefficient of friction is also varied along the sliding surface. If μ is the value of friction coefficient which is constant along the conventional sliding surface, then for the proposed surface, it is varied along the surface using the equation:

$$\mu_x = \sqrt{\left(0.8\mu + 0.1\frac{x}{R}\right)^2} \tag{16}$$

where, μ_x is the coefficient of friction at sliding displacement, *x*. however the maximum value of μ_x is limited to that of μ. It can be noted from “equation 16” that variation of μ_x along the sliding surface is marginal, that is, μ_x varies from 0.04 at $x = 0$ to 0.05 at $x \geq 0.12$ m for $\mu = 0.05$ and for $\mu = 0.1$, it varies from 0.08 at $x = 0$ to 0.1 at $x \geq 0.18$ m. Minimum coefficient of friction of the proposed sliding surface is only 0.8 times the coefficient of friction of conventional sliding surface. This small variation of coefficient of friction, along the sliding surface does not produce any stability problems.

10. VARIABLE FRICTION ISOLATOR (VFI)

Malu and Murnal [11], [12] proposed variable friction isolator. Practically a sliding surface with a continuous variable coefficient of friction may be difficult to achieve as suggested for VFPS and VFFPI. Hence Malu and Murnal proposed to change the coefficient of friction at predefined point from centre of isolator so that it is practical to achieve such an isolator. For large displacements during high intensity earthquakes higher coefficient of friction in the peripheral portion is likely to control the sliding displacements. Hence it is proposed to have a lower coefficient of friction in the central portion and higher value in the peripheral region with a predetermined location of change in coefficient of friction. The coefficient of friction can be changed at d_f = 0.1m, 0.2m, 0.3m, and so on from centre of isolator. They worked on near-fault and low frequency ground motions and compared the PF, FPS, CFPI and VFPI systems with constant and variable coefficient of friction. Malu and Murnal concluded that variable friction isolator found to be effective isolator where both major responses such as storey acceleration as well as sliding and residual displacement of isolator are effectively controlled for all isolators. But from comparative study they concluded that VFPI with variable coefficient of friction is found to most effective. Also they concluded that VFPI T_i = 2s, FVF = 2, d_f = 0.4 to 0.6 m is the most effective isolator to control the near-fault ground motion for both SDOF and MDOF system. Again they concluded that VFPI T_i = 2s, FVF = 6 and 7, d_f = 0.3 and 0.4 m is the most effective isolator to control the low frequency ground motion for both SDOF and MDOF system.

11. CONCLUSION

The sliding isolation systems are passive control system. PF has infinite time period, hence can be used for all kinds of sites. But it has a problem of large sliding and residual displacement. FPS has spherical geometry. Due to spherical geometry, FPS restores the structure at its original position and hence residual displacements will be minimized. But FPS has a constant time period, due to which FPS may face the problem of resonance, particularly under the action of near-fault and low frequency ground motions. VFPI has progressive period shift and will not face the problem of resonance. The geometry of VFPI is derived from elliptical shape. To improve the performance of sliding systems under the action of near-fault and low frequency ground motion CFPI, PFPI, VFPS, VFFPI, VFI system has been developed.

The surface of CFPI is identical to FPS up to d_b, after that it becomes tangential to the spherical surface. For CFPI, the restoring force becomes a constant when the isolator displacement exceeds d_b. CFPI has zero frequency after d_b. A polynomial function has been employed to define the geometry of the PFPI. PFPI will possess a softening section followed by a hardening section. The softening and hardening sections aim to control the structural acceleration and isolator drift, respectively. VFPS is similar to FPS except for the fact that the friction coefficient of VFPS is varied in form of curve and is an exponential function. For the VFFPI isolator, radius of curvature is varied exponentially with sliding displacement to develop the isolator with varying curvature. In addition coefficient of friction is also varied along the sliding surface of VFFPI. In VFI it is proposed to change the coefficient of friction at predefined point from centre of isolator so that it is practical to achieve such an isolator. It is proposed to have a lower coefficient of friction in the central portion and higher value in the peripheral region for VFI.

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