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A Study of Sliding Base Isolation System: A Review

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Abstract
Seismic isolation systems are crucial for protecting structures by minimizing the transmission of acceleration during seismic events, and among the various types, the resilient sliding system, which combines restoring springs and sliders, is highly effective in mitigating seismic impacts. This system controls structural responses by balancing stiffness and friction, ensuring safety while maintaining the functionality of buildings. However, optimizing the design of this system requires carefully selecting combinations of stiffness and the coefficient of friction to achieve low acceleration levels, while simultaneously managing the relative displacement within the isolation system to protect both the structure and its occupants. Excessive displacement may compromise the integrity of the isolation system or cause damage to the structure it is meant to protect. The challenge lies in finding the optimal friction and stiffness levels that provide sufficient energy dissipation and restore forces without allowing displacement to exceed acceptable thresholds. Studies show that restoring forces generated by springs help limit excessive displacements, while sliders dissipate seismic energy, and adjustments in these parameters must account for variations in ground motion intensity and frequency. Thus, a balance between flexibility and resistance is essential in sliding systems to ensure maximum structural safety and occupant protection during earthquakes. This paper reviews different sliding isolation systems which fulfils the requirements of controlling the earthquake and functioning accordingly. It include systems such as PF, FPS, VFPI , CFPI,VFPS,PFPE, VCFPS,VFFPI etc.

1. Introduction

Base isolation is one of the seismic protection strategies that is most frequently used and approved. Seismic base isolation (Skinner et al. 1993; Naeim and Kelly 1999) is a technique that mitigates the consequences of an earthquake by basically isolating the structure and its contents from potentially dangerous ground motion, especially in the frequency range where the building is most affected. In Base Isolation system, reducing interstory drifts and floor accelerations is a key aspect of seismic design aimed at minimizing damage to both the structure and its contents. This method decouples a structure from ground motion by inserting flexible materials, thereby altering the building's natural frequency and lengthening its time period, which reduces the force transmitted to the structure during an earthquake. The two main types of base isolation systems are elastomeric isolators and sliding isolators. Elastomeric isolators, typically made of layers of rubber and steel, can withstand substantial axial loads and shear displacements, making them effective in maintaining structural integrity during strong earthquakes. However, they are also prone to buckling under extreme conditions, which remains a challenge in their application. Recent research has focused on improving the resilience and performance of these isolators by optimizing their material composition and design. On the other hand, sliding isolators, which use low-friction materials to allow lateral movement, offer a different approach by dissipating energy and limiting displacement. Advances in sliding isolation technology have aimed at enhancing energy dissipation and reducing wear over time, making them more durable and reliable in long-term applications. Overall, while both systems have their strengths, ongoing research is crucial to address limitations such as buckling in elastomeric bearings and material degradation in sliding isolators, ensuring that base isolation remains a viable and effective strategy for earthquake protection. This paper discusses various devices used to control the response of structures with sliding Isolator, it focuses on PF, FPS, VFPI, CFPI, VFPS, PFPE, VCFPS, VFFPI etc.

2. Sliding Isolation Devices

2.1 Pure Friction (PF)

The basic idea behind a Pure Friction (P-F) base isolator is the sliding friction mechanism (Figure 1a). The horizontal friction force absorbs energy and provides resistance to motion. The type of surface that sliding occurs on determines the coefficient of friction. Figure 1b illustrates the isolator's force-deformation behaviour.

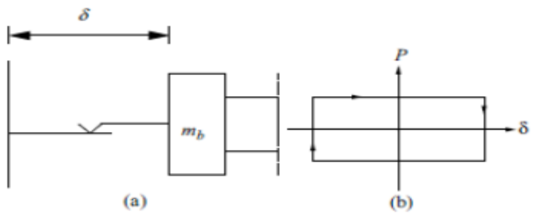

Figure 1 Pure Friction System: (a) Schematic Diagram; and (b) Idealized Force Deformation Behavior (T.K.Datta, 2010)

2.2 Friction-Pendulum System (FPS)

The mechanics of sliding and recentring were established by Zayas et al. in 1987. These are combined into a single device with a spherical sliding surface (Figure 2). Friction-pendulum system (FPS) is all that this isolation system is. Bearings, each consisting of an articulated slider on a spherical, concave chrome surface, support the isolated structure in the friction-pendulum system. The bearing material that faces the slider produces a maximum sliding friction coefficient of 0.1 or less at high sliding velocities and a minimum friction coefficient of 0.05 or less at very slow sliding velocities when it comes into contact with the polished chrome surface. According to Mokha et al. (1988, 1990), Teflon-type materials have this coefficient of friction to velocity dependence. The Friction Pendulum System (FPS) bearing is a widely used seismic isolation device designed to protect structures by allowing controlled movement during an earthquake. It acts like a mechanical fuse, only engaging when earthquake forces exceed the friction threshold that normally keeps it in place. When this happens, the bearing moves and generates lateral forces through two mechanisms: frictional resistance and a restoring force. The frictional resistance originates from the surface interaction, while the restoring force results from the slight vertical displacement of the structure as it moves along the curved surface of the bearing. This displacement causes the structure to lift, which in turn produces a restoring force that opposes the motion. The magnitude of this force is influenced by factors such as the displacement, the weight of the structure, and the radius of the spherical surface. Importantly, a larger radius of curvature reduces the restoring force, allowing for greater displacements under lower restoring forces. This behavior enables the FPS to mitigate seismic forces by allowing for energy dissipation through friction and limiting excessive motion through the gradual buildup of restoring force, thereby enhancing the structure's resilience to earthquakes. This system has important properties:

- Stiffness up to the weight multiplied by the static coefficient of friction.
- Lateral force proportional to the weight supported by the bearing. This important characteristic leads to the development of the resulting lateral force at the centre of mass, hence removing eccentricities. Zayas et al. (1987) have proven this characteristic using shake-table experiments.
- The sliding mode vibration period, which is solely correlated with the spherical surface's

radius of curvature and unaffected by the mass of the structure

- A high degree of stability and minimal susceptibility to the excitation's frequency content

The following relationship is very accurately followed by the lateral force at the isolation level (F_b).

$$F_b = \left(\frac{W}{R}\right) x_b + \mu\,(\dot{x}_b)\, W\, sgn\,(\dot{x}_b) \quad (1)$$

W is the structure's weight, R is the bearings' radius of curvature, μ is the coefficient of friction that is mobilised during sliding, and x_b is the bearing displacement. The stabilising tendency of the FPS bearings' pendulum action is represented by the first term in Eq.1, and the force displacement relationship's slope is denoted by the value W⁄R (Fig. 2). In its rigid body condition, the structure's period of vibration is

$$T = 2\pi \left(\frac{R}{g}\right)^{1/2} \quad (2)$$

where the gravitational acceleration is denoted by g. The fact that T is the natural period of a pendulum of length R indicates that the system's basic idea is founded on pendulum motion principles (Zayas et al., 1978).

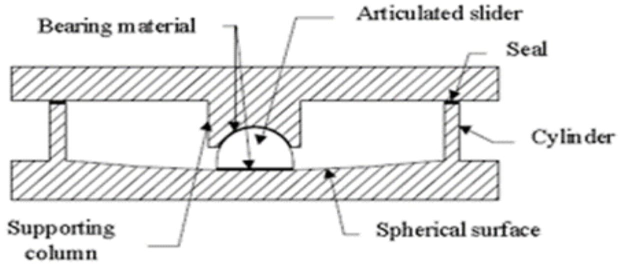

Figure 2 Friction Pendulum System

3. Variable Frequency Pendulum Isolator (VFPI)

The Variable Frequency Pendulum Isolator (VFPI), created by Murnal et al. (2000), employs a sliding surface to regulate vibration [Sinha and Pranesh 1998]. Because of the concave sliding surface in VFPI, the isolator frequency lowers as sliding displacement increases, and its rate can be adjusted by carefully selecting surface characteristics. The Frequency Pendulum System (FPS) and the pure-friction system are both benefited by the VFPI, which also avoids their drawbacks. To obtain the intended starting isolator time-period and the rate of variation of isolator period with sliding displacement, one can select the VFPI parameters. Furthermore, friction along the sliding surface is discovered to offer an efficient energy dissipating mechanism as well, combining isolation and dissipation into one single unit [Sinha and Pranesh 1998]. The Variable Frequency Pendulum Isolator (VFPI) functions incredibly well under a range of excitation and structural conditions. The sliding surface in this isolator has a non-spherical form. Because of its amplitude-dependent time period and softening method of isolator restoring force, this isolation system maintains the benefits of both the pure friction (PF) isolation system and FPS. It is possible to select the isolator's geometry to produce a gradual period shift at various response levels. A mathematical model for the response of structures isolated by VFPI has been devised, which is akin to a PF system. Sliding Isolator Consist of two isolator forces i.e. Restoring force and frictional force. The self-weight component that is tangential to the sliding surface causes restoration because friction force prevents sliding. The self-weight always points in the direction of the starting position and contributes to the restoring mechanism. Frictional force acts in the opposite direction to that of sliding and can either support or oppose the restoring force. One helpful metric to assess a friction isolator's performance is the total isolator force (RF + FF). Thus, there are two key ways in which this isolation system is different from the traditional PF and FPS systems: (Murnal P, 2000).

- VFPI lengthens the time i.e. dependent on sliding displacement.
- VFPI permits softening of restoring force at large displacement.

The geometry is given by:

$$y = b\left[1 - \frac{\sqrt{d^2 + 2dx sgn(x)}}{d + x sgn(x)}\right] \quad (3)$$

The frequency of isolator is derived as:

$$w_b{}^2(x) = \frac{w_i{}^2}{(1+r)^2\sqrt{1+2r}} \quad (4)$$

Where

- $\omega_i = gb/d^2$ = Square of the isolator's initial frequency (at zero displacement)
- VFPI's geometrical parameters are b and d.
- x= is the displacement of the isolator at any given time.
- $r = x\, sgn\,(x)/d$

The frequency variation factor (FVF), which has been specified as the value of 1/d, controls the rate of variation of the isolator frequency. VFPI works over a broad range of structural and isolator characteristics and at all excitation intensities. It behaves similarly to the PF system for high-intensity earthquake excitation and to the FPS for low-intensity excitation. Therefore, VFPI combines the benefits of the PF and FPS systems.

4. Conical Friction Pendulum Isolator (CFPI)

The sliding surface of a CFPI isolator is equal to that of an FPS (with a constant radius R) when the isolator displacement is less than a threshold value, such as db. Once the displacement of the CFPI exceeds db, the sliding surface becomes an inclined plane tangent to the spherical surface (Fig. 3). When determining the geometry of a CFPI isolator, the parameters db and R are crucial.

4.1 Approximate Isolation Frequency

$$\omega_b(x) = \frac{\sqrt{P\, y''(x)}}{m} = \frac{\sqrt{mg\, y''(x)}}{m} = \sqrt{g y''(x)} = \sqrt{gk(x)} \quad (5)$$

$$y(x) = \begin{Bmatrix} R - \sqrt{R^2 - x^2} & \text{for } |x| \leq d_b \\ c_1 + c_2\,(|x| - d_b) & \text{for } d_b < |x| \end{Bmatrix} \quad (6)$$

where,

$$c_1 = R - \sqrt{R^2 - {d_b}^2}\ ,\quad c_2 = d_b \sqrt{R^2 - {d_b}^2}$$

- Following term defines the geometry of the CFPI Isolator:
- For $|x| \leq d_b$ the sliding surface follows a spherical curve
- For $|x| > d_b$ the surface transition to an inclined plane.

One can determine that ω(x) = 0 for x> d_b by substituting y(x) from Eq. (6) in Eq. (5) and taking the second derivative. This suggests that when the isolator displacement is greater than db, the isolation system has no dominant frequency. This outcome suggests:

4.1.1 For Small Displacements ($|x| \leq d_b$)

- The system behaves like a traditional FPS, where the natural frequency depends on the curvature of the sliding surface and the restoring forces.
- The response of the system includes oscillations governed by the natural frequency ω_b

4.1.2 For large displacements ($|x| > d_b$)

- Once the displacement exceeds d_b, the sliding surface becomes an inclined plane.
- The result $\omega(x) = 0$ suggests that for $x > d_b$, the system does not exhibit oscillatory behavior, meaning it does not have predominant natural frequency in this range.
- This behavior might be interpreted as the isolator losing its stiffness or entering a regime where it can slide freely without restoring force, implying a zero frequency.

So, the isolation system has no predominant frequency when $x > d_b$ means that the system enters a non-oscillatory state for large displacements (Figure 3). This is important for understanding how the CFPI works, especially in extreme loading scenarios like during an earthquake. Beyond d_b, the isolator is designed to mitigate forces by allowing the structure to "slide" without oscillation, which can help protect the structure from excessive vibrations or resonant effects.

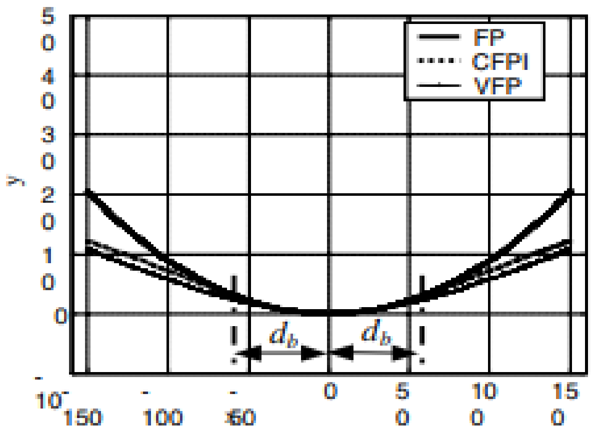

Figure 3 Comparison of Geometric Shapes for Various Isolators

5. VFPS

The Variable Friction Pendulum System (VFPS), is very similar to FPS. The difference in VFPS and FPS is that the friction coefficient varies with the isolator displacement, unlike the FPS where the friction coefficient is constant. This variation in the friction coefficient makes the VFPS a more adaptable isolation system, which can improve its performance in applications like seismic isolation of structures, such as liquid storage tanks. A function of the isolator displacement x_b yields the VFPS's friction coefficient μ:

$$\mu = (\mu_0 + a_1|x_b|)e^{-a_2|x_b|} \quad (7)$$

Where,

- μ_0 - Initial value of the friction coefficient
- a_1 and a_2 - Friction coefficient varies with displacement
- x_b - Isolator displacement

The initial stiffness k_i of the VFPS is expressed as:

$$k_i = \frac{\mu_{max} W}{x_{b,max}} \quad (8)$$

where:

- μ_{max} - Peak friction coefficient of the VFPS,
- $x_{b,max}$ - Displacement at which the peak friction coefficient occurs,
- W= Mg is the effective weight of the isolated structure,

The initial time period of the VFPS is related to its initial stiffness k_i and the mass M:

$$T_i = 2\pi\sqrt{\frac{M}{k_i}} \quad (9)$$

The friction coefficient function can be maximised to determine the displacement x_(b,max), which corresponds to the maximal friction coefficient. The following is the formula for $x_{b,max}$:

$$x_{b,max} = \frac{a_1 - \mu_0 a_2}{a_1 a_2} \quad (10)$$

This gives the value of the displacement at which the friction coefficient reaches its maximum value. The restoring force F_b of the VFPS is composed of two parts: the elastic restoring force (proportional to stiffness) and the frictional force:

$$F_b = k_b x_b + F_x \quad (11)$$

where:

- k_b is the stiffness of the VFPS.
- F_x is the frictional force in the VFPS.

The limiting frictional force Q, which is the maximum force the VFPS can sustain before sliding occurs, is given by:

$$Q = \mu W \quad (12)$$

- Where μ is the current friction coefficient of the VFPS.

The stiffness k_b is designed to achieve a specific isolation period T_b, expressed as:

$$T_b = 2\pi\sqrt{\frac{M}{k_b}} \quad (13)$$

5.1 Modeling the VFPS

To model the VFPS, two key parameters must be specified:

1. Isolation period , T_b
2. Friction coefficient μ, which itself depends on the initial time period T_i and the peak friction coefficient μ_{max}

6. Polynomial Friction Pendulum Isolator (PFPI)

(Lu.L.Y., 2006) proposes the PFPI, which features a uniquely designed sliding surface based on a polynomial function, offering variable isolation frequencies influenced by the isolator's displacement. In contrast to a traditional friction pendulum system (FPS), a PFPI isolator's sliding surface is axially symmetric and has a polynomial function defining its cross-sectional geometry. A novel kind of sliding isolator known as the "Polynomial Friction Pendulum Isolator (PFPI)" is suggested in order to enhance the functionality of a sliding isolation system. To define y′ (x) of the PFPI, the fifth-order polynomial function that follows has been selected:

$$y'(x) = u_r(x)/P = ax^5 + cx^3 + ex \quad (14)$$

One way to think of y' (x) is as a restoring force. It is possible to think of $u_r(x)$ as a normalised restoring force in relation to the vertical load P. Likewise, the normalised isolator stiffness, denoted by y''(x), can be derived as

$$y''(x) = k_r(x)/P = 5ax^4 + 3cx^2 + e \quad (15)$$

The polynomial $y'(x)$ is an odd function, meaning it's symmetric about the origin, and it passes through the origin. There are three retro flexion points (points where the curve changes direction), and one of them is at the origin due to the symmetry.

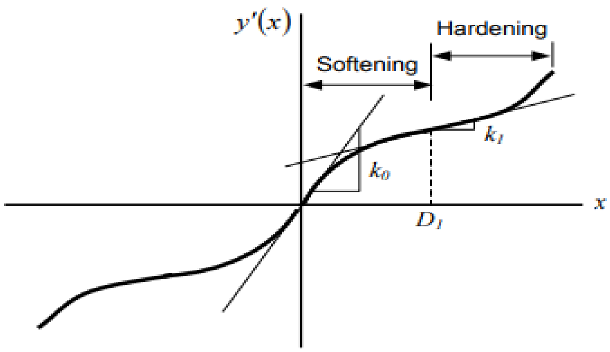

Figure 4 Normalized restoring force $y'(x)$

In the softening section, the stiffness $y''(x)$decreases, helping reduce structural acceleration during smaller earthquakes. In the hardening section, the stiffness $y''(x)$ increases, reducing isolator drift during large earthquakes to maintain stability. Since the polynomial coefficients aaa, ccc, and eee are abstract, they are replaced by three design parameters (Figure 4) for practical engineering purposes:

1. k_o - The initial stiffness at x = 0, which represents the system's starting stiffness, $y''(0) = k_o$
2. D_1 - The critical isolator drift, where the system switches from acceleration control to displacement control. This is a retroflexion point where $y''(D_1) = 0$.
3. k_1 - The stiffness at D_1, i.e., $y''(D_1) = k_1$

The polynomial coefficients a, c, and e can be calculated based on the design parameters as follows:

$$a = \frac{-k_0+k_1}{-5(D_1)^4}, c = \frac{2(-k_0+k_1)}{3(D_1)^2}, e = k_0 \quad (16)$$

This makes it easier for engineers to design and optimize the PFPI by selecting appropriate values for k_0, k_1, D_1. This causes the PFPI's isolation frequency to change and become dependent on the isolator displacement. In this paper, the PFPI's design parameters and hysteretic equation were derived. A parametric study was also used to determine the ideal design parameter values. Numerical modelling results have shown that the PFPI system may successfully suppress the isolator displacement during a strong near-fault earthquake without causing the super-structure to accelerate more quickly.

7. Variable Curvature Friction Pendulum System (VCFPS)

The Variable Curvature Friction Pendulum System (VCFPS), a novel kind of base isolator, is presented in the paper (Tsai et al., 2003). With one significant exception, its mechanical behaviour is comparable to that of the Friction Pendulum System (FPS), created by V. Zayas: The VCFPS has a variable radius of curvature that increases with isolator displacement. In comparison to a structure with conventional FPS isolators, this characteristic helps move the base-isolated structure's fundamental period farther away from the periods of near-fault ground motions, which lowers the amount of earthquake energy communicated to the structure. Pranesh and Sinha devised a similar device called the Variable Frequency Pendulum Isolator (VFPI), in which the sliding surface is based on an ellipse. By subtracting a particular function from the FPS sliding surface equation, the VCFPS, on the other hand, creates its own sliding surface. Structures close to active earthquake faults benefit greatly from the VCFPS, an advanced seismic base isolator that modifies its radius of curvature dependent on the isolator's displacement (Figure 5). By moving the structure's fundamental period away from the times when near-fault ground vibrations are most common, this system lowers the likelihood of resonance.

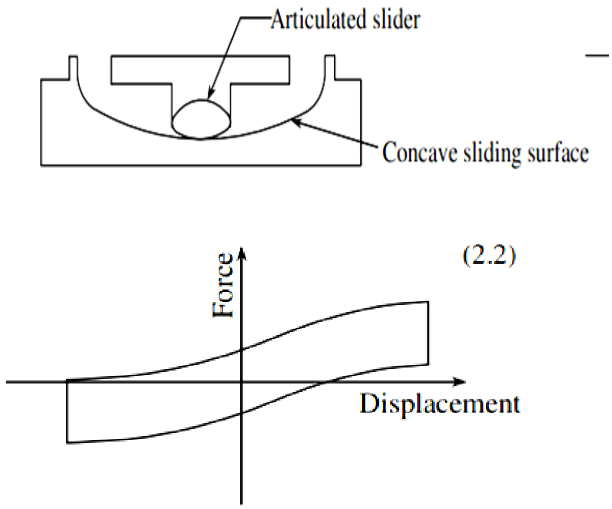

Figure 5 Details of hysteresis loop of VCFPS (Tsai et al. 2003; Tsai et al. 2005)

Variable Radius of Curvature: The radius of curvature of the isolator increases as displacement x_b increases, effectively lengthening the period of the isolated structure and preventing resonance with ground motion frequencies.

Restoring Force: The system's geometric properties ensure that the isolator's slider can return to its initial position within the displacement range x_0. The geometric function describing the VCFPS is given by:

$$y = R - \sqrt{R^2 - {x_b}^2} - f(x_b) \quad (17)$$

Where x_b is the isolator's horizontal displacement, R is the initial radius of curvature at the sliding surface's centre, and $f_{(xb)}$ is a function that characterises how the radius of curvature varies with displacement, it can be written as follows:

$$f(x_b) = Esgn(x_b).{x_b}^3 \quad (18)$$

In this case, the curvature variation is controlled by the parameter E. The parameter E can be found as follows if the restoring force is able to return the slider to its starting position within the sliding displacement x_0 (Tsai et al. 2003; Tsai et al. 2005):

$$E = \frac{\frac{Wx_0}{\sqrt{R^2 - x_0{}^2}} - \frac{T_0}{\cos\theta_0}}{3Wsgn(x_0).x_0{}^2} \quad (19)$$

Where T_0 is the static friction force.

The restoring force depends on the parameter E, which can be determined by ensuring the slider returns to the initial position for a given displacement x_0. The horizontal stiffness of the isolator is given by

$$k\,(x_b) = M.\omega_b{}^2 \quad (20)$$

Where,

ω_b is the frequency of the base isolated structure, defined as:

$$\omega_b{}^2(x_b) = \frac{g}{\sqrt{R^2 - x_0{}^2}} - \frac{sgn(x_b).x_b\left(\frac{gx_0}{\sqrt{R^2 - x_0{}^2}} - \frac{\mu g}{\cos\theta_0}\right)}{sgn(x_0).x_0{}^2} \quad (21)$$

where W = Mg is the weight supported by the isolator, g is the acceleration caused by gravity, and μ is the coefficient of friction at the VCFPS's sliding surface.

- **Dynamic Adjustment:** As displacement increases during an earthquake, the system adjusts its period, reducing the amount of seismic energy transferred to the structure.
- **Improved Performance:** The system's ability to adjust the radius of curvature helps it perform better in near-fault conditions compared to conventional isolators. This makes the VCFPS highly effective in mitigating the effects of strong ground motions by reducing both structural drift and acceleration.

8. Variable Frequency and Variable Friction Pendulum Isolator (VFFPI)

Krishnamoorthy proposed a Variable Frequency Friction Pendulum Isolator (VFFPI)**,** which is designed to vary its radius of curvature exponentially with sliding displacement, making it a system with dynamic curvature adjustment. The goal of this design is to combine the benefits of both the Friction Pendulum System (FPS) and the Polynomial Friction (PF) system by selecting an appropriate constant C.

8.1 Radius of Curvature

The radius of curvature RRR is a function of the sliding displacement xxx, where the variation is governed by an exponential expression:

$$R(x) = R_0.exp(C.x) \quad (22)$$

C is the isolator constant, and its value influences the isolator's behavior. For large C, the isolator behaves more like the PF system with lower base shear, while for small C, it resembles the FPS system with smaller residual displacements.

8.2 Base Shear and Residual Displacement

Increasing C increases the sliding displacement and residual displacement while decreasing the base shear, creating a balance between the characteristics of the PF and FPS systems. The value of C can be selected based on the desired performance of the isolator, achieving similar residual displacement as FPS while reducing base shear to match PF systems. Value of C is given by

$$C = 84(1 + 0.2R) \quad (23)$$

8.3 Coefficient of Friction

To further improve performance, the coefficient of friction μ_x is varied along the sliding surface, as opposed to being constant as in conventional systems. The friction coefficient at displacement x is given by the expression:

$$\mu_x = \sqrt{\left(0.8\mu + 0.1\frac{x}{R}\right)^2} \quad (24)$$

Here, μ is the friction coefficient of a conventional FPS surface, and μ_x decreases slightly as x increases, with a minimum value of 0.8 times the original μ.

8.4 Friction Variations

- For μ = 0.05, the coefficient of friction $\mu_x$varies from 0.04 at x = 0 to 0.05 at x ≥0.12 m.
- For μ = 0.1, $\mu_x$changes from 0.08 at x = 0 to 0.1 at x ≥0.18 m.

The suggested sliding surface's minimum coefficient of friction is just 0.8 times that of a traditional sliding surface. Without creating instability, this slight change in the friction coefficient guarantees that the system stays stable. The variable curvature allows for better control over base shear and displacement, adapting to ground motion demands more effectively than traditional isolators. The slight variation in friction across the sliding surface does not pose stability risks but contributes to reducing earthquake-induced forces on the structure. The VFFPI offers a hybrid approach, combining the strengths of FPS and PF systems to optimize both displacement control and seismic energy dissipation.

Conclusion

The various base isolation systems discussed. The Pure Friction system, relying on sliding friction, is simple but does not inherently provide a restoring mechanism. In contrast, FPS integrates both sliding and reentering mechanisms, utilizing spherical concave surfaces to provide restoring forces proportional to displacement and weight, independent of structural mass, making it effective for seismic isolation. VFPI improves on FPS by allowing the isolation frequency to vary with displacement, effectively handling both low and high-intensity earthquakes. CFPI adds a geometric feature where the sliding surface transitions from spherical to inclined for larger displacements, removing oscillatory behavior and enabling free sliding under extreme conditions. VFPS introduces a displacement-dependent friction coefficient, improving adaptability under seismic conditions. PFPI, using a polynomial sliding surface, provides both hardening and softening behavior, improving control over acceleration and displacement during seismic events. VCFPS adds a dynamically adjustable curvature, enhancing performance in near-fault ground motions by shifting the system's natural period. VFFPI, which varies both curvature and friction, offers a hybrid solution, balancing the low residual displacement of FPS with the lower base shear of PF. These systems show a trend towards combining variable properties—frequency, friction, curvature—to optimize energy dissipation, structural resilience, and adaptability during earthquakes.

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