Earthquakes affecting urban areas in the recent past have clearly demonstrated the vulnerability of urban building stock to ground motions. One of the main observations is the damage to large number of engineered buildings designed and constructed using modern techniques. Several modern vibration control techniques using base isolation have been proposed in published literature, some of which have also been implemented successfully. However most of these isolation devices have proved to be of limited effectiveness under near-fault ground motions due to pulse-type characteristics of such excitations. Sliding isolation system, such as PF, FPS, VFPI, CFPI, VFCPI are studied in this paper for near-fault ground motion. Also an attempt had been made to improve the effectiveness of sliding system by varying coefficient of friction at particular distance from centre of isolator during near-fault ground motion. In this paper, behaviour of five storey lumped mass structures isolated using FPS, VFPI and CFPI subjected to near source ground motions has been numerically examined. Comparative study has been carried out to determine most effective sliding isolation system subjected to near-fault ground motion.

1 Introduction

Base isolation has emerged as an effective technique in minimizing the earthquake forces. In this technique, a flexible layer (or isolator) is placed between the super structure and its foundation such that relative deformations are permitted at this level. Due to flexibility of the isolator layer, the time period of motion of the isolator is relatively long; as a result the isolator time period controls the fundamental period of the isolated structure. For properly designed isolation system, the isolator time
period is much longer than those containing significant ground motion energy. As a result, use of isolator shifts the fundamental period of the structure away from the predominant periods of ground excitation. Extensive review of base isolation systems and its applicability is available in literature (Kelly 1986, Buckle and Mayes 1990, Kelly 1993, Naeim and Kelly 1999).

Practical isolation devices typically also include energy dissipating mechanism so as to reduce deformations at the isolator level. For example friction type base isolators, uses a sliding surface for both isolation and energy dissipation, and has been found to be very effective in reducing structural response (Mostaghel et al. 1983). Due to the characteristics of excitation transmitted through sliding surface, the performance of friction isolators is relatively insensitive to severe variations in the frequency content and amplitude of the input excitation, making performance of sliding isolators very robust. The simplest sliding isolator consists of horizontal sliding surface (Pure-Friction or PF system), which may experience large sliding and residual displacements, and are often difficult to incorporate in structural design.

To overcome the difficulty of restoring force an effective mechanism to provide restoring force by gravity has been utilised in Friction Pendulum System (FPS) (Zayas et al. 1987). In this system, the sliding surface takes a concave spherical shape so that the sliding and re-centring mechanisms are integrated in one unit. The FPS isolator has several advantages and has demonstrated acceptable performance for many different structures and excitation characteristics (Mokha et. al. 1991, 1996; Tsopelas et. al. 1996; Tsai 1997; Wang et. al. 1998). Apart from advantages of FPS the main disadvantage of FPS is that it has a constant time period of oscillation due to its spherical surface. As a result FPS isolators can be effectively designed for a specific level (amplitude and frequency characteristics) of ground excitation. Under more severe ground motions, sliding displacement greater than design displacement can occur, which may lead to failure of FPS system. Since in FPS isolator, restoring force is linearly proportional to sliding displacement, the large amount of sliding introduces significant additional energy in the structure. As a result, the maximum intensity of excitation has a strong influence on FPS design. In general, FPS isolator designed for particular level of excitation may not give satisfactory performance during earthquake with much lower or higher intensity. (Sinha and Pranesh 1998)

Variable Frequency Pendulum Isolator (VFPI) incorporates the advantages of both the FPS and PF isolators and overrules disadvantages of FPS and PF isolators (Pranesh and Sinha 1998, Pranesh 2000). The most important properties of this system are: (1) its time period of oscillation depends on sliding displacement, and (2) its restoring force has a bounded value and exhibits softening behaviour for large displacements. The geometry of sliding surface has been defined by second order parametric equation. As a result, the isolator properties can be chosen to achieve progressive period shift with variation in sliding displacement. These properties can be controlled by a set of VFPI parameters, which is otherwise not possible in single parameter systems like FPS.

To overcome the problem of the large amount of sliding which, introduces significant additional energy in the structure, LY Lu et. al. (2004) proposed Conical Friction Pendulum Isolator (CFPI). In this isolator they assumed the sliding surface of CFPI identical to FPS (with constant radius R) when the isolator displacement is within a threshold value, say db (db = 0.1R). Once the displacement of the CFPI exceeds db sliding surface becomes an inclined plane tangent to the spherical surface. As a result CFPI is same as FPS for x < db. Due to tangential portion of CFPI after db the vertical displacement of CFPI is very less as compared to FPS, which reduces the additional energy in the structure.

Lu et. al. (2006) proposed a sliding surface with variable curvature using a polynomial function to define the geometry of the sliding surface. Narasimhan and Nagarajaiah (2006) have proposed a variable friction system to adjust the level of friction in the base isolated structure. Panchal and Jangid (2008) proposed a sliding surface by varying the friction coefficient along the sliding surface in the form of curve of FPS and called isolator as Variable Friction Pendulum Isolator (VFPS). Krishnamoorthy (2010) proposed an isolator, Variable Frequency and variable Friction coefficient Pendulum Isolator (VFFPI). Krishnamoorthy proposed the isolator having radius of curvature varying...
exponentially with sliding displacement and friction coefficient also varying with sliding displacement. These studies shows, that a FPS with either a varying radius of curvature or a varying friction coefficient may be used as an effective isolator for isolating the structure. Variable frequency and variable friction coefficient of isolator experience lower base shear than FPS system. Also residual displacement is much lower and near to FPS system.

2. Near-Fault Ground Motion

The study of structures subjected to near-fault ground motions has a special significance due to the nature of such ground motions. Near-fault ground motions are characterised by pulse type excitations having narrow range of relatively lower frequencies. Near-fault ground motions often contain strong coherent dynamic long period pulses and permanent ground displacements. The dynamic motions are dominated by large long period pulses of motions that occur on the horizontal component perpendicular to strike of fault, caused by rupture directivity effects. This pulse is narrow band pulse which causes the response spectrum to have a peak, such that the response due to near-fault ground motions of moderate magnitude may exceed those of large magnitude at intermediate periods. The radiation pattern of the shear dislocation on the fault causes this large pulse of motion to be oriented in the direction perpendicular to fault plane, causing the strike-normal component of ground motion to be larger than the strike-parallel component. The strike-parallel motion causes permanent ground displacement (fling step) whereas the strike-normal component causes significantly higher dynamic motion (Paul Somerville 1997, Paul G. Somerville 2005). Hence the fling-step usually induces only limited inertial demands on structures due to the long-period nature of the static displacement. On the other hand ground motions that are influenced by forward-directivity effects can be very damaging to structures. During the last two decades, an ever increasing database of recorded ground motions have demonstrated that the kinematic characteristics of the ground motion near the faults of major earthquakes contain large displacement pulses say one or two pulses from 0.5m to more than 1.5m with peak velocity of 0.5m/s or higher. Their period is usually in the range of 1-3s, but it can be as long as 6s.

Structures isolated by most base isolation devices have a long time period which is fairly constant. Since the near fault ground motions have a long period pulse type motions they induce very large displacements at the isolation level. As a result base isolated structures do not perform well under near-fault ground motions. But it has been demonstrated that the VFPI can be effective under both near-fault and far-field ground motions if proper VFPI parameters are adopted in the design (Pranesh and Malu 2007, Malu and Pranesh 2010). However it is difficult to control the large sliding displacements that could occur during near-fault ground motions.

In the present paper it is proposed to use variable coefficients of friction for the VFPI isolator surface so that the effectiveness is maintained for different intensities of earthquake. Panchal and Jangid (2008) and Krishnamoorthy (2010) considered the coefficient of friction changing as a function of sliding displacement. But practically it looks to be quite difficult to change coefficient of friction at every point of sliding surface. Hence in present study coefficient of friction has been changed at a predefined point from centre of isolator say $d_f$ (0.1m, 0.3m and 0.5m). As such in present study only two values of coefficient of friction are considered, viz, initial coefficient of friction ($\mu_1$) and final coefficient of friction ($\mu_2$). The effectiveness of different isolators with and without variable coefficient of friction is examined through a parametric study on MDOF models (6-DOF models when isolated) subjected to near-fault ground motions. Finally the most effective isolator has been proposed for near-fault ground motion by comparative study.

3. Sliding Isolator Geometry

**Mathematical Preliminaries:**
Consider the motion of a rigid block of mass $m$ sliding on a smooth curved surface of defined
geometry, \( y = f(x) \). The restoring force offered by curved sliding surface can be defined as the lateral force required to cause the horizontal displacement \( x \). Assuming point contact the various forces acting on sliding surface when the block is displaced from its original position at the origin of coordinate axes are as shown in Fig. 1. At any instant the horizontal restoring force due to weight of the structure is given by

\[
f_R = mg \frac{dy}{dx}
\]

(1)

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

\[
f_R = k(x)x
\]

(2)

where, \( k(x) \) is the instantaneous spring stiffness, and \( x \) is the sliding displacement of the mass.

If the mass is modelled 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

\[
f_R = ma^2_0(x)x
\]

(3)

Here, \( a^2_0(x) \) is the instantaneous isolator frequency, and depends solely on the geometry of sliding surface. In Friction Pendulum System, which has a spherical sliding surface, this frequency is almost constant and is approximately equal to \( \sqrt{g/R} \), where \( R \) is the radius of curvature of the sliding surface (Zayas et al. 1990).

**Variable Frequency Pendulum Isolator Geometry:**

Sliding surface based on the expression of an ellipse has been used as the basis for developing sliding surface of VFPI (Pranesh 2000). The equation of an ellipse with \( a \) and \( b \) as its semi-major and semi-minor axes, respectively, and with co-ordinate axes as shown in Fig. 1 is given by,

\[
y = b(1 - \sqrt{1 - x^2/a^2})
\]

(4)

Differentiating with respect to \( x \), the slope at any point on the curve is given by

\[
\frac{dy}{dx} = \frac{b}{a^2\sqrt{1-x^2/a^2}}x
\]

(5)

If the equation of sliding surface is represented by Eq. (4), the frequency of oscillation can be determined by substituting Eq. (5) in Eqs. (1) and (3). As a result expression for frequency of elliptical surface is given by

\[
a^2_0(x) = \frac{\omega^2}{1-x^2/a^2}
\]

(6)

where, \( \omega^2 = gb/a^2 \) = square of initial frequency of isolator (at zero sliding displacement).

It can be seen that the frequency of an elliptical curve is fairly constant for small displacements (\( x \ll a \)) and this value depends upon the ratio \( b/a^2 \). From this expression it is observed that the frequency of the surface is inversely proportional to the square of semi-major axis and an increase in its value results in sharp decrease in the isolator frequency. So to get the desired variation of the frequency, the semi-major axis of the ellipse, \( a \), has been taken as a linear function of sliding displacement \( x \) and is expressed as a variable in getting the geometry of VFPI. The semi-major axis
can be expressed as
\[ a = x + d \] (7)

where, \( d \) is a constant.

Substituting in Eq. (4), the expression for geometry of sliding surface of VFPI is expressed as
\[ y = b \left[ 1 - \frac{\sqrt{d^2 + 2dx\text{sgn}(x)}}{d + x\text{sgn}(x)} \right] \] (8)

where, \( \text{sgn}(x) \) is the signum function introduced for maintaining symmetry of sliding surface about the central vertical axis. This assumes a value of +1 for positive sliding displacement and −1 for negative sliding displacement. It is observed from Eq. (8) that the upper bound of vertical displacement is equal to \( b \), and it occurs only at infinitely large horizontal displacement. The slope at any point on this sliding surface is given as
\[ \frac{dy}{dx} = \frac{bd}{(d + x\text{sgn}(x))^2 \sqrt{d^2 + 2dx\text{sgn}(x)}} \] (9)

To simplify the notations, a non-dimensional parameter \( r = x\text{sgn}(x)/d \) is used. By substituting \( r \) and the initial frequency \( \omega_1^2 = gb/d^2 \) in Eq. (9), and combining with Eqs (1) and (2), the isolator frequency at any sliding displacement can be expressed as
\[ \omega_b^2(x) = \frac{\omega_1^2}{(1 + r)^2 \sqrt{1 + 2r}} \] (10)

In the above equations, parameters \( b \) and \( d \) completely define the isolator characteristics. It can be observed that the ratio \( b/d^2 \) governs the initial frequency of the isolator. Similarly, the value of \( 1/d \) determines the rate of variation of isolator frequency, and this factor has been defined as frequency variation factor (FVF). It can also be seen from Eq. (10) that the rate of decrease of isolator frequency is directly proportional to FVF for given initial frequency.

**Conical Friction Pendulum Isolator Geometry:**

The sliding surface of CFPI is basically derived from spherical surface of FPS. The surface is identical to FPS up to \( d_b \), after that it become tangent to the spherical surface. The parameter \( d_b \) and \( R \) are important for defining the geometry of a CFPI isolator, i.e.,

\[ y(x) = \begin{cases} R - \sqrt{R^2 - x^2} & \text{for } |x| \leq d_b \\ c_1 + c_2(\sqrt{|x|} - d_b) & \text{for } d_b < |x| \end{cases} \] (11)

where,
\[ c_1 = R - \sqrt{R^2 - d_b^2} \quad \text{and} \quad c_2 = d_b/\sqrt{R^2 - d_b^2} \] (12)

The frequency of the isolator can be calculated by approximate formula as,
\[ \omega_b = \sqrt{g\ddot{y}(x)} \] (13)

Hence after substituting \( y(x) \) from Eq. (11) in Eq. (13) 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 \( d_b \).

VFPI become softened systems for a larger isolator displacement. 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 $d_b$. Since the value of $d_b$ is small the isolator acts as PF in its major part.

For the comparison purpose the parameters of various isolators are chosen such that the three isolators have the same initial restoring stiffness and same initial period.

Table 1: Parameter values for various isolators for $T_i = 2s$

<table>
<thead>
<tr>
<th>Isolator Type</th>
<th>FPS</th>
<th>VFPI</th>
<th>CFPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter value</td>
<td>$R = 1$ m</td>
<td>$d = 0.3$ m, $b = 0.09$ m</td>
<td>$R = 1$ m, $d_b = 0.1R = 0.1$ m</td>
</tr>
</tbody>
</table>

The geometry of sliding surface of FPS, VFPI and CFPI are as shown in Fig. 2. From Fig. 2 it can be easily observed that the VFPI and CFPI are flatter than FPS, which results in smaller vertical displacement for similar sliding displacement in the structure and hence smaller overturning moment.

4. Mathematical Formulation

Consider an $N$-storey shear structure isolated by sliding type isolator. The motion of the structure can be in either of two phases: non-sliding phase and sliding phase. In non-sliding phase, the structure behaves like a conventional fixed base structure since there is no relative motion at the isolator level. When the frictional force at the sliding surface is overcome, there is relative motion at the sliding surface, and the structure enters sliding phase. The total motion consists of a series of alternating non-sliding and sliding phases.

4.1 Non-sliding Phase

In non-sliding phase the structure behaves as a fixed-base structure, since there is no relative motion between the ground and base mass. The equations of motion in this phase are:

$$M_0 \ddot{x}_b + C_0 \dot{x}_b + K_0 x_b = -M_r \ddot{x}_g$$

and

$$x_b = \text{constant}; \quad \dot{x}_b = \ddot{x}_b = 0$$

where, $M_0$, $C_0$ and $K_0$ are the mass, damping and stiffness matrices of the fixed-base structure, respectively. $x_0 = [x_1, x_2, \ldots, x_N]^T$ is the vector of displacements of the degrees of freedom (DOFs) of the superstructure relative to the base mass (excluding the DOF of base mass), $x_b$ is the displacement of the base mass ($m_b$) relative to the ground, $x_g$ is the ground displacement, $r_b$ is the influence coefficient vector and over-dot indicates derivative with respect to time. Since the base mass does not move relative to the ground, the velocity and acceleration of the base relative to the ground are zero. However the sliding displacement may be non-zero. The structure is classically damped in this phase and hence (14a) can be readily solved by usual modal analysis procedures (Clough and Penzie 1993).

4.2 Initiation of Sliding Phase

When the structure is subjected to base excitation, it will remain in non-sliding phase unless the frictional resistance at the sliding surface is overcome. Therefore the condition for the beginning of sliding phase can be written as

$$\mu \leq \sum_{i=1}^{N} m_i (\ddot{x}_i + \dot{x}_g) + m_0 \ddot{x}_g + m_0 \dot{x}_g$$

$$\geq m_0 \mu g$$

where, $\mu = \mu_1$ or $\mu_2$, is the coefficient of friction at respective isolator position.

4.3 Sliding Phase

Once the inequality (15) is satisfied the structure enters sliding phase and the degree of freedom
(DOF) corresponding to the base mass also experiences motion. The equations of motion are now given by

$$M\ddot{x} + C\dot{x} + Kx = -Mr\ddot{r} - r\mu_f$$

(16)

where, $M$, $C$, $K$ are the modified mass, damping and stiffness matrices of order $N+1$, $r$ is the modified influence coefficient vector and $\mu_f$ is the frictional force as given below.

$$M = \begin{bmatrix} M_0 & M_0r_0 \\ M_0r_0^T & m_f \end{bmatrix} , C = \begin{bmatrix} C_0 & 0 \\ 0 & 0 \end{bmatrix} , K = K_0$$

(17)

$$\mu = \mu_1 \text{ or } \mu_2 \text{, is the coefficient of friction at respective isolator position.}$$

Equations (13) can be solved numerically. But for large size problems the computational effort is large and the analysis does not provide proper insight into the behaviour of the structure. In view of this and the non-classical nature of damping, complex modal analysis is used in the present investigations.

**4.4 Direction of Sliding**

The direction of sliding depends on the signum function that in turn depends on the forces acting on the structure at the end of the previous non-sliding phase. Once inequality (15) is satisfied, the structure starts sliding in a direction opposite to the direction of the sum of total inertia force and restoring force at the isolator level. So, we have

$$\text{sgn}(\dot{x}_b) = \begin{cases} \sum_{i=1}^{N} m_i (\ddot{x}_i + \dot{x}_b + \ddot{x}_g) + m_b (\ddot{x}_b + \ddot{x}_g) + m_i \omega^2 x_b \\ \sum_{i=1}^{N} m_i (\ddot{x}_i + \dot{x}_b + \ddot{x}_g) + m_b (\ddot{x}_b + \ddot{x}_g) + m_i \omega^2 x_b \end{cases}$$

(18)

The signum function remains unchanged in a particular sliding phase. The end of a sliding phase is governed by the condition that the sliding velocity of the base mass is equal to zero, i.e.,

$$\dot{x}_b = 0$$

(19)

Once the sliding velocity is zero, the structure may enter a non-sliding phase, reverse its direction of sliding, or have a momentary stop and then continue in the same direction. To determine the correct state, the solution process needs to continue using equations of non-sliding phase wherein the sliding acceleration is forced to zero and the validity of the inequality (16) is checked. If this inequality is satisfied at the same instant of time when the sliding velocity is zero, it shows that there is a sudden stop at that instant.

**5. Response Of Example Structure**

The effectiveness of VFPI to reduce response of an example MDOF structure subjected to near-field earthquake excitations has been presented in this section. The example structure is a five-storey shear structure. The example building is represented as a lumped mass model with equal lumped mass of 60080 kg and equal storey stiffness of 112600 kN/m for each floor. The frequencies and modal properties for the fixed-base and isolated structures are given in Table 2. Since the natural frequencies of a structure isolated by VFPI change continuously with the isolator sliding displacement, the frequencies shown in Table 2 thus indicate the upper bound on the frequencies when the isolator displacement is zero.

**Table 2: Modal properties of fixed-base and isolated structures**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Isolator</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
</table>

**Girish Malu, Pranesh Murnal: Comparative Study of Sliding Isolation Systems for Near-Fault Ground Motion**
The example structure is analysed for ten near field ground motions. The details of the ground motions are presented in Table 3. These ground motions are derived from historical recordings. The ground motions chosen cover a wide variety of near field ground motions having different peak ground acceleration (PGA), frequency composition and duration. The example structure is also analysed for far-field El Centro 1940 (NS) ground motion.

### Table 3: Details of earthquake records used in this study

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Name of earthquake</th>
<th>Designation</th>
<th>Magnitude</th>
<th>Distance of source (km)</th>
<th>PGA (g)</th>
<th>Duration (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tabas, 1978</td>
<td>NFR-01</td>
<td>7.4</td>
<td>1.2</td>
<td>0.900</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>Loma Prieta, 1989, Los Gatos</td>
<td>NFR-02</td>
<td>7.0</td>
<td>3.5</td>
<td>0.718</td>
<td>25</td>
</tr>
<tr>
<td>3</td>
<td>Loma Prieta, 1989, Lex. Dam</td>
<td>NFR-03</td>
<td>7.0</td>
<td>6.3</td>
<td>0.686</td>
<td>40</td>
</tr>
<tr>
<td>4</td>
<td>C. Mendocino, 1992, Petrolia</td>
<td>NFR-04</td>
<td>7.1</td>
<td>8.5</td>
<td>0.638</td>
<td>60</td>
</tr>
<tr>
<td>5</td>
<td>Erzincan, 1992</td>
<td>NFR-05</td>
<td>6.7</td>
<td>2.0</td>
<td>0.432</td>
<td>21</td>
</tr>
<tr>
<td>6</td>
<td>Landers, 1992</td>
<td>NFR-06</td>
<td>7.3</td>
<td>1.1</td>
<td>0.713</td>
<td>50</td>
</tr>
<tr>
<td>7</td>
<td>Nothridge, 1994, Rinaldi</td>
<td>NFR-07</td>
<td>6.7</td>
<td>7.5</td>
<td>0.890</td>
<td>15</td>
</tr>
<tr>
<td>8</td>
<td>Nothridge, 1994, Olive View</td>
<td>NFR-08</td>
<td>6.7</td>
<td>6.4</td>
<td>0.732</td>
<td>60</td>
</tr>
<tr>
<td>9</td>
<td>Kobe, 1995</td>
<td>NFR-09</td>
<td>6.9</td>
<td>3.4</td>
<td>1.088</td>
<td>60</td>
</tr>
<tr>
<td>10</td>
<td>Kobe, 1995, Takatori</td>
<td>NFR-10</td>
<td>6.9</td>
<td>4.3</td>
<td>0.786</td>
<td>40</td>
</tr>
</tbody>
</table>

The analysis is carried for constant coefficient of friction and variable coefficient of friction. The value of constant coefficient of friction is taken as 0.05. Variable coefficient of friction of initial value of 0.05 and final value of 0.1 has been taken. The coefficient of friction is varied at a distance of 0.1m, 0.3m, and 0.5m from centre of isolator. This will enable larger energy dissipation for larger sliding displacement which may help to control the sliding displacements. The parameter values of isolators are taken as given in Table 1, so that initial period of all isolators is 2s. Further for VFPI, FVF value varied from 1.0 per m to 10.0 per m. The structural damping is assumed as 5% of critical for all modes.

**Time History Response:**

The response quantities are evaluated by solution of the equations of motion as discussed in the preceding sections. The main response quantities of interest are absolute acceleration of top storey and sliding displacement of isolator. To show the effectiveness of VFPI with respect to FPS and CFPI a typical time history response graphs are plotted for NFR-07 as shown in Fig. 3 and Fig. 4.

Fig. 3 shows the storey acceleration time history. The graphs show the control on storey acceleration with VFPI. Storey acceleration due to VFPI and CFPI are close to each other. But acceleration in case of FPS is very high. Therefore it can be seen that both response quantities are effectively controlled by VFPI.

Fig. 4 shows the isolator sliding time history. The graph clearly shows the control on sliding, as well as residual displacement of isolator with VFPI. CFPI sliding is too high. FPS sliding is also comparatively at higher level. CFPI have more residual displacement.

**Effect of Variable Coefficient of Friction:**

Under near-fault excitations, FPS may be able to control sliding displacements, but it may lead to very high level of structural accelerations due to long-period pulse type components in the excitation. On the other hand VFPI can control the accelerations but at the cost of high sliding displacements. So VFPI with variable coefficient of friction is likely to control both accelerations and
sliding displacements. Varying the coefficient of friction may not help in case of FPS as the displacements are already controlled with constant coefficient of friction and accelerations are bound to be high in any case due to the constant time period of FPS.

5. Results And Discussion

For different cases under consideration, time history analyses have been carried out for all the ten near-fault ground motions indicated in Table 3. Since these earthquakes cover a wide variety of near-fault ground motion, the average of the maximum responses under the ten ground motions is considered for discussion. Table 4 and Table 5 show the average response values of VFPI (FVF = 1 to 10), FPS and CFPI isolators with constant and variable coefficient of friction for acceleration and isolator displacement respectively.

Fig. 5 and Fig. 6 show the response of VFPI for different values of FVF with constant and variable coefficient of friction for acceleration and displacement respectively. As expected the accelerations under a lower coefficient of friction of 0.05 are substantially lower than that with a higher coefficient of friction of 0.1. Vice versa sliding displacements are more for $\mu = 0.05$ as compared to $\mu = 0.1$. It is further observed that the accelerations are significantly lower in cases of variable coefficient of friction cases also. It is observed that both accelerations and sliding displacements in all variable coefficient of friction cases (with different values of $d_f$) fall between the values of the two constant coefficients of friction cases, except in $d_f = 0.1m$ for FVF = 4 and 5. In these cases the average sliding displacement is increased due to high sliding values of NFR-01. For all other records the sliding is within controlled limit. Accelerations are reduced for higher value of $d_f$, where as sliding displacement reduces for lower value of $d_f$. This is quite obvious since the higher value of $d_f$ represents lower coefficient of friction in major part of isolator which implies lower acceleration and higher sliding displacement and vice versa.

Fig. 7 and Fig. 8 show the response of VFPI (FVF = 6), FPS and CFPI isolators with constant and variable coefficient of friction for acceleration and displacement respectively. The results show that the variation of FPS and CFPI are not consistent as in case of VFPI. In case of FPS acceleration values are in reverse order than expected, that is acceleration is more for $\mu = 0.05$ and less for $\mu = 0.1$. But displacement is as expected. Also displacement has been controlled for variable coefficient of friction. In case of CFPI the both acceleration and displacement values are random. This is due to the fact that frequency of CFPI suddenly becomes zero after $d_b$.

The results show that acceleration in case of VFPI and CFPI are nearly equal. Again in all cases the acceleration of CFPI is lower than VFPI and FPS. Accelerations of FPS are very high when compared VFPI and CFPI. This will happen due to spherical curvature of FPS which increase the velocity of structure and hence the acceleration.

The results show that displacement in case of VFPI is very close to FPS. Again in all cases the displacement of FPS is lower than VFPI and CFPI. Displacement of CFPI is substantially at higher level. This may be due to the fact that frequency of CFPI suddenly becomes zero after $d_b$.

Also it is observed that as the value of FVF of VFPI increases, acceleration decreases and sliding displacement increases and vice versa. This is quite obvious since increase in FVF make VFPI more and more flat.

6. Conclusions

The effectiveness of isolation system, FPS, CFPI and VFPI for vibration control of multi storied structure (5 storied lumped mass) subjected to near-fault ground motions has been investigated in this paper. For effectiveness of isolation system i.e. for controlling both accelerations and sliding displacements, variable coefficients of friction for the sliding surface has been proposed in this paper.
Based on the investigations the following conclusions can be drawn.

I. Accelerations can be controlled by VFPI and CFPI in both constant and variable coefficient of friction. In case of FPS accelerations are very high for constant, as well as variable coefficient of friction.

II. The sliding displacement of isolator is the minimum in case of FPS for both constant and variable coefficient of friction. In case of VFPI the displacement is nearly equal to FPS for both constant and variable coefficient of friction. But for CFPI it is very high. This may be due to the fact that frequency of CFPI suddenly becomes zero after $d_b$.

III. VFPI has a wide choice of parameters that can be chosen to suit the design requirements.

IV. VFPI is very effective for acceleration reduction under the action of near-fault ground motions with corresponding increase in sliding displacements.

V. It is possible to control both accelerations and sliding displacements by using variable coefficient of friction and by choosing carefully the VFPI parameters.

References


Girish Malu, Pranesh Murnal: Comparative Study of Sliding Isolation Systems for Near-Fault Ground Motion


Figure 1: Free body diagram of sliding surface

Figure 2: Comparison of geometric shapes for various isolators
Girish Malu, Pranesh Murnal: Comparative Study of Sliding Isolation Systems for Near-Fault Ground Motion

Figure 3: Time history of storey acceleration for (NFR-07), $\mu = 0.05$ VFPI (FVF = 6), FPS and CFPI

Fig. 4: Time history of isolator sliding for (NFR-07), $\mu = 0.05$VFPI (FVF = 6), FPS and CFPI
Figure 5: Average absolute acceleration of top storey (m/sec²) for VFPI (Tᵢ = 2s) for constant and variable coefficient of friction.

Figure 6: Average sliding displacement of isolator (m) for VFPI (Tᵢ = 2s) for constant and variable coefficient of friction.
Figure 7: Average absolute acceleration of top storey for VFPI (T_i = 2s), FVF = 6, FPS (T_b = 2s) and CFPI (T_i = 2s) for constant & variable coefficient of friction

Figure 8: Average sliding displacement of isolator for VFPI (T_i = 2s), FVF = 6, FPS (T_b = 2s) and CFPI (T_i = 2s) for constant & variable coefficient of friction
### Table 4: Average absolute acceleration of top story (m/sec²) for VFPI (T₁ = 2s), (FVF = 1 to 10), FPS (T₃ = 2s), CFPI (T₁ = 2s)

<table>
<thead>
<tr>
<th>Isolator →</th>
<th>Coeff. of Frict. ↓</th>
<th>FVF = 1</th>
<th>FVF = 2</th>
<th>FVF = 3</th>
<th>FVF = 4</th>
<th>FVF = 5</th>
<th>FVF = 6</th>
<th>FVF = 7</th>
<th>FVF = 8</th>
<th>FVF = 9</th>
<th>FVF = 10</th>
<th>FPS (T₃ = 2s)</th>
<th>CFPI (T₁ = 2s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>μ = 0.05</td>
<td></td>
<td>3.52</td>
<td>3.58</td>
<td>3.63</td>
<td>3.68</td>
<td>3.63</td>
<td>3.56</td>
<td>3.58</td>
<td>3.52</td>
<td>3.55</td>
<td>3.50</td>
<td>13.82</td>
<td>4.12</td>
</tr>
<tr>
<td>df = 0.1 m</td>
<td></td>
<td>5.14</td>
<td>5.68</td>
<td>5.97</td>
<td>5.85</td>
<td>6.09</td>
<td>6.13</td>
<td>6.12</td>
<td>6.07</td>
<td>6.14</td>
<td>6.17</td>
<td>9.83</td>
<td>5.59</td>
</tr>
<tr>
<td>df = 0.3 m</td>
<td></td>
<td>5.02</td>
<td>5.37</td>
<td>5.58</td>
<td>5.55</td>
<td>5.78</td>
<td>5.83</td>
<td>5.96</td>
<td>5.96</td>
<td>5.97</td>
<td>5.81</td>
<td>12.06</td>
<td>4.97</td>
</tr>
<tr>
<td>df = 0.5 m</td>
<td></td>
<td>4.72</td>
<td>4.79</td>
<td>4.89</td>
<td>4.98</td>
<td>5.02</td>
<td>5.03</td>
<td>5.07</td>
<td>5.02</td>
<td>5.04</td>
<td>5.03</td>
<td>12.01</td>
<td>4.35</td>
</tr>
<tr>
<td>μ = 0.1</td>
<td></td>
<td>5.96</td>
<td>6.00</td>
<td>6.07</td>
<td>6.23</td>
<td>6.14</td>
<td>6.23</td>
<td>6.25</td>
<td>6.23</td>
<td>6.30</td>
<td>6.29</td>
<td>9.32</td>
<td>5.86</td>
</tr>
</tbody>
</table>

### Table 5: Average sliding displacement of isolator (m) for VFPI (T₁ = 2s), (FVF = 1 to 10), FPS (T₃ = 2s), CFPI (T₁ = 2s)

<table>
<thead>
<tr>
<th>Isolator →</th>
<th>Coeff. of Frict. ↓</th>
<th>FVF = 1</th>
<th>FVF = 2</th>
<th>FVF = 3</th>
<th>FVF = 4</th>
<th>FVF = 5</th>
<th>FVF = 6</th>
<th>FVF = 7</th>
<th>FVF = 8</th>
<th>FVF = 9</th>
<th>FVF = 10</th>
<th>FPS (T₃ = 2s)</th>
<th>CFPI (T₁ = 2s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>μ = 0.05</td>
<td></td>
<td>0.689</td>
<td>0.777</td>
<td>0.884</td>
<td>0.948</td>
<td>0.932</td>
<td>0.978</td>
<td>0.983</td>
<td>6.644</td>
<td>12.230</td>
<td>0.929</td>
<td>0.606</td>
<td>2.030</td>
</tr>
<tr>
<td>df = 0.1 m</td>
<td></td>
<td>0.570</td>
<td>0.616</td>
<td>0.677</td>
<td>42.002</td>
<td>57.790</td>
<td>0.706</td>
<td>0.709</td>
<td>0.717</td>
<td>0.715</td>
<td>0.712</td>
<td>0.500</td>
<td>38.709</td>
</tr>
<tr>
<td>df = 0.3 m</td>
<td></td>
<td>0.611</td>
<td>0.678</td>
<td>0.751</td>
<td>0.805</td>
<td>0.760</td>
<td>0.791</td>
<td>0.798</td>
<td>0.801</td>
<td>0.782</td>
<td>0.755</td>
<td>0.561</td>
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</tr>
<tr>
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<td>0.641</td>
<td>0.720</td>
<td>0.751</td>
<td>0.858</td>
<td>0.808</td>
<td>0.838</td>
<td>0.849</td>
<td>0.855</td>
<td>0.836</td>
<td>0.809</td>
<td>0.583</td>
<td>26.719</td>
</tr>
<tr>
<td>μ = 0.1</td>
<td></td>
<td>0.489</td>
<td>0.526</td>
<td>141.742</td>
<td>0.606</td>
<td>0.645</td>
<td>0.649</td>
<td>0.643</td>
<td>0.661</td>
<td>0.651</td>
<td>0.663</td>
<td>0.483</td>
<td>38.434</td>
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</tbody>
</table>