

# Seismic Response of Structures with Sliding Systems

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**ABSTRACT:** *Seismic response of structures supported on the sliding systems to bi-directional (i.e. two horizontal components) earthquake ground motion is investigated. The frictional forces of sliding system are assumed to be dependent on the relative velocity at the sliding interface with bi-directional interaction. Coupled differential equations of motion of the structure with sliding system in two orthogonal directions are derived and solved in the incremental form using step-by-step method with iterations. The iterations are required due to dependence of the frictional forces on the response of the system. The response of the isolated system is analyzed to investigate the effects of velocity dependence and bi-directional interaction of frictional forces of sliding system. These effects are investigated under important parametric variations such as the fundamental time period of superstructure, period, damping and friction coefficient of the sliding system. It is observed that the dependence of friction coefficient on relative velocity of system does not have noticeable effects on the peak response of the isolated system. However, if the effects of bi-directional interaction of frictional forces are neglected then the sliding base displacement will be underestimated which is crucial from the design point of view. Further, the bi-directional interaction effects are found to be more severe for the sliding systems without restoring force (i.e. pure-friction) in comparison to the systems with restoring force.*

**Keywords:** Seismic response; Sliding isolation, Friction; Bi-directional interaction.

## 1. INTRODUCTION

Base isolation is thought of an aseismic design approach in which the building is protected from the hazards of earthquake forces by a mechanism which reduces the transmission of horizontal acceleration into the structure. The main concept in base isolation is to reduce the fundamental frequency of structural vibration to a value lower than the predominant energy-containing frequencies of earthquake ground motions. The other purpose of an isolation system is to provide an additional means of energy dissipation and thereby, reducing the transmitted acceleration into the superstructure. Accordingly, by using base isolation devices in the foundations, the structure is essentially uncoupled from the ground motion during earthquakes. Bukle and Mayes [1] and Jangid and Datta [8] have provided excellent reviews of earlier and recent works on base isolation system.

Several base isolation systems including laminated rubber bearing, frictional bearing and roller bearing have been developed to study the effectiveness of base isolation. A significant amount of the recent research in base isolation has focused on the use of frictional elements to concentrate flexibility of the structural system and to add damping to the isolated structure. The most

attractive feature of the frictional base isolation system is its effectiveness for a wide range of frequency input. The other advantage of a frictional type system is that it ensures maximum acceleration transmissibility equal to maximum limiting frictional force. The simplest friction type device is the pure-friction referred as the P-F system [10, 12]. More advanced devices involve pure-friction elements in combination with a restoring force. The restoring force in the system reduces the base displacements and brings back the system to its original position after an earthquake. Some of the commonly proposed sliding isolation system with restoring force include the resilient-friction base isolator (R-FBI) system [13], Electricite de France (EDF) system [6], Alexisimon isolation system [7], the friction pendulum system (FPS) [16] and the elliptical rolling rods [11]. The sliding systems performs very well under a variety of severe earthquake loading and are quite effective in reducing the large levels of the superstructure's acceleration without inducing large base displacements [13]. Jangid and Datta [9] investigated that the sliding systems are less sensitive to the effects of torsional coupling in asymmetric base-isolated structures. Comparative study of base isolation system has shown that the

response of sliding system does not vary with the frequency content of earthquake ground motion [2, 4, 15]. Most of the above studies on the sliding isolation systems are based on the two-dimensional (2-D) planar model of the isolated structure subjected to uni-directional excitation. Such model of the isolated structures ignores the bi-directional interaction effects of the frictional forces mobilized in the isolation system in two horizontal directions. Experimental study by Mokha et al [14] has shown that there exists interaction between the orthogonal components of the frictional forces mobilized at the sliding interface. These effects were further confirmed by Jangid [10] for the pure-friction sliding system. Analysis of the sliding structures without considering the interaction of the frictional forces generally underestimates the sliding base displacements which can be very crucial from the effective design of the sliding systems. However, there is a need to further investigate the bi-directional interaction effects for different types of sliding systems under parametric variations.

Herein, the response of multi-story structures isolated by the sliding system to two horizontal components of real earthquake ground motion is investigated. The specific objectives of the present study may be summarized as

- (i) To present a method for dynamic analysis of multi-story structures supported on the sliding system to bi-directional earthquake motion which incorporates the bi-directional interaction and velocity dependence effects of the frictional forces
- (ii) To study the effects of bi-directional interaction on the seismic response of the sliding structures (by comparing the response of the system with and

without bi-directional interaction), and

- (iii) To investigate the influence of important parameters on the bi-directional interaction effects of frictional forces. The important parameters considered include the isolator properties (i.e. period, damping and friction coefficient) and the fundamental time period of superstructure.

## 2. MODEL OF SUPERSTRUCTURE AND THE SLIDING SYSTEM

Figure 1 shows the structural system under consideration, which is an idealised  $N$ -story shear type structure mounted on the sliding base isolation system. The sliding system is installed between base mass and the foundation of the structure. Various assumptions made for the structural system under consideration are:

1. Floors of each story of the superstructure are assumed as rigid and symmetric in plan.
2. Superstructure is assumed to remain in the elastic range during the earthquake excitation. This is a reasonable assumption, since the purpose of base isolation is to reduce the earthquake forces in such a way that the system remains within the elastic limits.
3. The friction coefficient of sliding system is assumed to be dependent on the relative velocity of base mass at the sliding interface.
4. Restoring force provided by the sliding systems is linear (i.e. proportional to relative displacement). In addition, the isolation systems also provide a viscous damping.
5. The sliding system is isotropic i.e. there is same coefficient of friction in two orthogonal directions of

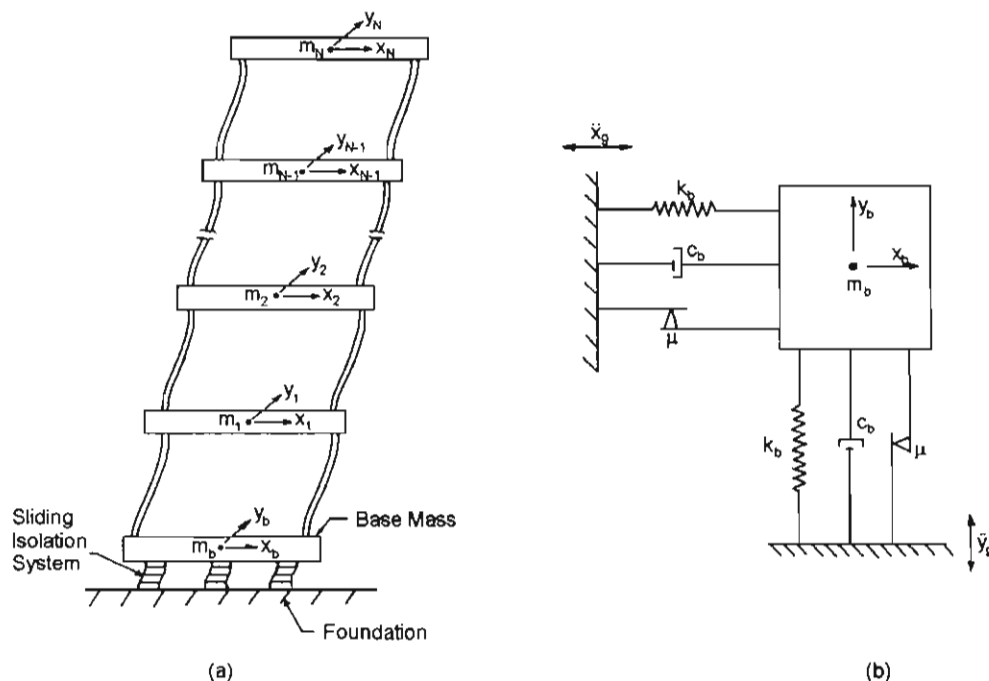


Figure 1. Model of the superstructure and the sliding system.

the motion in the horizontal plane.

6. No overturning or tilting takes place in the superstructure during sliding over the isolation system.
7. The ground accelerations act along both horizontal orthogonal directions (referred as x- and y-directions, respectively) of the structure.

At each floor and base mass two lateral dynamic degrees-of-freedom is considered (both in x- and y-directions). Therefore, for the  $N$ -story isolated superstructure the dynamic degrees-of-freedom are  $2(N+1)$ . The sliding base isolation system is characterised by the parameters namely: the lateral stiffness ( $k_b$ ), the damping constant ( $c_b$ ), and the coefficient of friction. The viscous damping constant of the sliding system is expressed in terms of the damping ratio by

$$c_b = 2\xi_b \left( m_b + \sum_i m_i \right) \omega_b \quad (1)$$

where  $\xi_b$  is the damping ratio of the sliding system;  $m_b$  is the mass of base raft;  $m_i$  is the mass of the  $i^{\text{th}}$  floor of the superstructure,  $\omega_b = 2\pi/T_b$  is the base isolation frequency; and  $T_b$  is the period of base isolation defined as

$$T_b = 2\pi \sqrt{\frac{(m_b + \sum_i m_i)}{k_b}} \quad (2)$$

Note that the isolator parameters are kept the same in both x- and y-directions of the system.

### 2.1. Governing Equations of Motion

The governing equations of motion of the superstructure are expressed in the matrix form as

$$[M]\{\ddot{z}\} + [C]\{\dot{z}\} + [K]\{z\} = -[M]\{I\}(\{\ddot{z}_b\} + \{\ddot{z}_g\}) \quad (3)$$

$$\{z\} = \{x_1, x_2, \dots, x_N, y_1, y_2, y_N\}^T \quad (4)$$

$$\{\ddot{z}_b\} = \left\{ \begin{matrix} \ddot{x}_b \\ \ddot{y}_b \end{matrix} \right\} \quad (5)$$

$$\{\ddot{z}_g\} = \left\{ \begin{matrix} \ddot{x}_g \\ \ddot{y}_g \end{matrix} \right\} \quad (6)$$

where  $[M]$ ,  $[C]$  and  $[K]$  are the mass, damping and stiffness matrix the superstructure of size  $(2N \times 2N)$ ;  $\{z\}$  is the displacement vector of the superstructure;  $\ddot{x}_b$  and  $\ddot{y}_b$  are the acceleration of the base mass relative to the ground in the x- and y-directions, respectively;  $x_i$  and  $y_i$  are the lateral displacement of the  $i^{\text{th}}$  superstructure floor relative to the base mass in the x- and y-directions,  $\{I\}$  is the influence coefficient matrix;  $\ddot{x}_g$  and  $\ddot{y}_g$  are the earthquake ground acceleration in the x- and y-directions, respectively; and  $T$  denotes the transpose.

The governing equations of motion of the base mass

in two orthogonal directions are expressed as

$$m_b \ddot{x}_b + c_b \dot{x}_b + k_b x_b + F_x - c_{x1} \dot{x}_1 - k_{x1} x_1 = -m_b \ddot{x}_g \quad (7a)$$

$$m_b \ddot{y}_b + c_b \dot{y}_b + k_b y_b + F_y - c_{y1} \dot{y}_1 - k_{y1} y_1 = -m_b \ddot{y}_g \quad (7b)$$

where  $m_b$  is the mass of base raft;  $c_b$  and  $k_b$  are the damping and stiffness of the sliding isolation system, respectively;  $F_x$  and  $F_y$  are the mobilized frictional forces in the system, respectively;  $k_{x1}$ ,  $k_{y1}$ ,  $c_{x1}$ , and  $c_{y1}$  are the stiffness and damping of the first story, respectively in the x- and y- directions of the system.

The limiting value of the frictional force,  $F_s$  to which the sliding system can be subjected in a particular direction is expressed as

$$F_s = \mu \left( m_b + \sum_i m_i \right) g \quad (8)$$

where  $\mu$  is the friction coefficient of the sliding system; and  $g$  is the acceleration due to gravity.

The coefficient of sliding friction  $\mu$  at a sliding velocity,  $\dot{z}_b = \sqrt{\dot{x}_b^2 + \dot{y}_b^2}$  may be approximated from Reference [3] by the following equation:

$$\mu = \mu_{max} - (\Delta\mu) \exp(-a|\dot{z}_b|) \quad (9)$$

where  $\mu_{max}$  is the coefficient of friction at large velocity of sliding (after leveling off);  $\Delta\mu$  is the difference between the friction coefficient at large and zero velocity of the system; and  $a$  is constant for a given bearing pressure and condition of interface, its value is taken as 0.2sec/cm.

### 2.2. Criteria for Sliding and Non-Sliding Phases

In a non-sliding phase ( $\ddot{x}_b = \ddot{y}_b = 0$  and  $\dot{x}_b = \dot{y}_b = 0$ ) the resultant of the frictional forces mobilized at the interface of sliding system is less than the limiting frictional force (i.e.  $\sqrt{F_x^2 + F_y^2} < F_s$ ). The system starts sliding ( $\ddot{x}_b \neq \ddot{y}_b \neq 0$  and  $\dot{x}_b \neq \dot{y}_b \neq 0$ ) as soon as the resultant of the frictional forces attains the limiting frictional force. Thus, the sliding of the system takes place if

$$F_x^2 + F_y^2 = F_s^2 \quad (10)$$

Note that the Eq. (10) indicates a circular interaction between the frictional forces mobilized at the interface of the sliding system as shown in Figure 2a. The system remains in the non-sliding phase inside the interaction curve. Further, the governing equations of motion in two orthogonal directions of the structures supported on the sliding isolators are coupled during the sliding phases due to interaction between the frictional forces. However, this interaction effect is ignored if the structural system is modeled as a 2-D system. In such cases the corresponding curve which separates the sliding and non-sliding phases is a square as shown in Figure 2a by dashed line.

Since the frictional forces oppose the motion of the

system, the direction of the sliding of the system with respect to the x-direction is expressed as

$$\theta = \tan^{-1}\left(\frac{\dot{y}_b}{\dot{x}_b}\right) \quad (11)$$

where  $\dot{x}_b$  and  $\dot{y}_b$  are the velocities of the base mass relative the ground in x- and y-directions, respectively.

**2.3. Solution of Equations of Motion**

The frictional forces mobilized in the sliding system are non-linear functions of the displacement and velocity of the system in two orthogonal directions. Also, during the sliding phase of motion, the mobilized frictional forces are coupled with each other by the circular interaction curve (Reference Eq. (10)). As a result, the equations of motion are solved in the incremental form. Network's method has been chosen for the solution of governing differential equations, assuming linear variation of acceleration over the small time interval,  $\delta t$ . The incremental equations of motion in terms of unknown incremental displacements are expressed as

$$[K_{eff}]\{\delta z\} = \{P_{eff}\} + \{\delta F\} \quad (12)$$

where  $[K_{eff}]$  is the effective stiffness matrix;  $\{P_{eff}\}$  is the effective excitation vector;  $\{\delta z\} = \{\delta x_1, \delta x_2, \dots, \delta x_N, \delta x_b, \delta y_1, \delta y_2, \dots, \delta y_N, \delta y_b\}^T$  is the incremental displacement vector;  $\{\delta F\}$  is the incremental frictional force vector containing  $\delta F_x$ ,  $\delta F_y$ ,  $\delta F_x$ , and  $\delta F_y$  are the incremental frictional forces in the x- and y-directions, respectively.

In order to determine the incremental frictional forces, consider the Figure 2b. Let at time  $t$  the frictional forces are at point A on the interaction curve and moves to point B at time  $t + \delta t$ . Therefore, the incremental frictional forces are expressed as

$$\delta F_x = F_s^{t+\delta t} \cos(\theta^{t+\delta t}) - F_x^t \quad (12a)$$

$$\delta F_y = F_s^{t+\delta t} \sin(\theta^{t+\delta t}) - F_y^t \quad (12b)$$

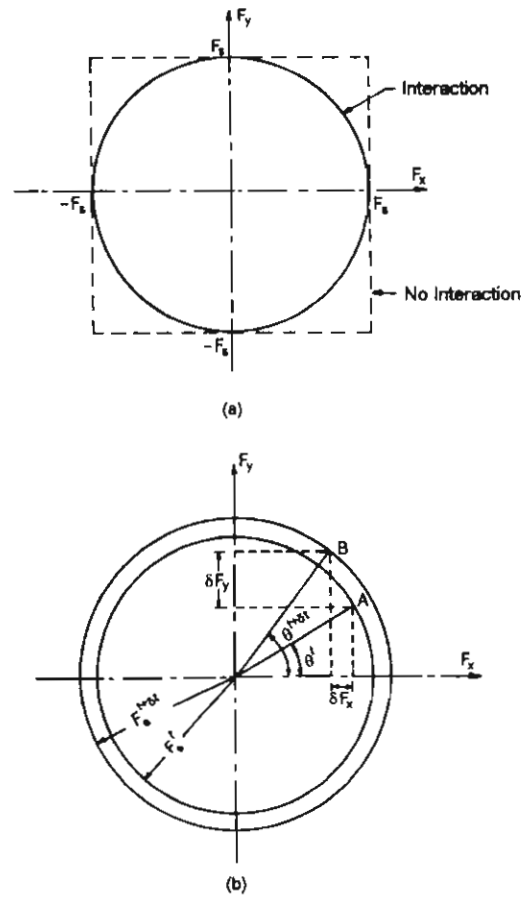
The superscript denotes the time. Since the frictional forces are opposite to the motion of the system, therefore, the angle  $\theta^{t+\delta t}$  is the expressed in terms of the relative velocities of the system at time  $t + \delta t$  by

$$\theta^{t+\delta t} = \tan^{-1}\left(\frac{\dot{y}_b^{t+\delta t}}{\dot{x}_b^{t+\delta t}}\right) \quad (13)$$

Substituting for  $\theta^{t+\delta t}$  in Eq. (12), the incremental frictional forces are expressed as

$$\delta F_x = F_s^{t+\delta t} \frac{\dot{x}_b^{t+\delta t}}{\sqrt{(\dot{x}_b^{t+\delta t})^2 + (\dot{y}_b^{t+\delta t})^2}} - F_x^t \quad (14a)$$

$$\delta F_y = F_s^{t+\delta t} \frac{\dot{y}_b^{t+\delta t}}{\sqrt{(\dot{x}_b^{t+\delta t})^2 + (\dot{y}_b^{t+\delta t})^2}} - F_y^t \quad (14b)$$



**Figure 2.** Interaction curve between frictional force and the incremental frictional forces during the sliding phase.

In order to solve the incremental matrix Eq. (12), the incremental frictional forces ( $\delta F_x$  and  $\delta F_y$ ) should be known at any time interval. The incremental frictional forces involve the system velocities at time  $t + \delta t$  (Reference Eq. (14)) which in turn depend on the incremental displacements ( $\delta x_b$  and  $\delta y_b$ ) at the current time step. As a result, an iterative procedure is required to obtain the required incremental solution. The steps of the procedure considered are as follows:

1. Assume  $\delta F_x = \delta F_y = 0$  for iteration,  $j=1$  in the Eq. (12) and solve for  $\{\delta z\}$ .
2. Calculate the incremental velocity  $\delta \dot{y}_b$  using the  $\delta x_b$  and  $\delta y_b$  from the vector  $\{\delta z\}$ .
3. Calculated the velocities at time  $t + \delta t$  using incremental velocities (i.e.  $\dot{x}_b^{t+\delta t} = \dot{x}_b^t + \delta \dot{x}_b$  and  $\dot{y}_b^{t+\delta t} = \dot{y}_b^t + \delta \dot{y}_b$ ) and compute the revised incremental frictional forces  $\delta F_x$  and  $\delta F_y$  from Eq. (14).
4. Iterate further, until the following convergence criteria are satisfied for both incremental frictional forces i.e.

$$\frac{|(\delta F_x)^{j+1}| - |(\delta F_x)^j|}{|(\delta F_x)^j|} \leq \epsilon \quad (15a)$$

$$\frac{|(\delta F_y)^{j+1}| - |(\delta F_y)^j|}{|(\delta F_y)^j|} \leq \epsilon \quad (15b)$$

where  $\epsilon$  is a small threshold parameter. The superscript to the incremental forces denotes the iteration number.

When the convergence criteria is satisfied, the velocity of the sliding structure at time  $t + \delta t$  is calculated using incremental velocity. In order to avoid the unbalance forces, the acceleration of the system at time  $t + \delta t$  is evaluated directly from the equilibrium of system Eqs. (3) and (7). At the end of each time step the phase of the motion of the system should be checked. The response of the sliding structures is quite sensitive to the time interval,  $\delta t$  and initial conditions at the beginning of sliding and non-sliding phases. For the present study, the results are obtained with time interval,  $\delta t = 0.0001s$ . The number of interactions in each time step is taken as 10 to determine the incremental frictional forces.

### 3. NUMERICAL STUDY

For the present study, the mass matrix of the superstructure,  $[M]$  is diagonal and characterized by the mass of each floor which is kept constant (i.e.  $m_i = m$  for  $i = 1, 2, \dots, N$ ). Also, for simplicity the stiffness of all the floors is taken as constant expressed by the parameter  $k$  in both the directions. The value of  $k$  is selected to provide the required fundamental time period of superstructure as a fixed base. The damping matrix of the superstructure,  $[C]$  is not known explicitly. It is constructed by assuming the modal damping ratio which is kept constant in each mode of vibration. The model of the isolated structural system under consideration can be completely characterised by the parameters namely, the fundamental time period of the superstructure with fixed base ( $T_s$ ), damping ratio of the superstructure ( $\xi_s$ ), number of stories in the superstructure ( $N$ ), the ratio of base mass to the superstructure floor mass ( $m_b/m$ ) the period of base isolation ( $T_b$ ), the damping ratio of the sliding system ( $\xi_b$ ) and the coefficient of friction of the sliding system ( $\mu_{max}$  and  $\Delta\mu$ ). However, to restrict the number of parameters the values of the some of the parameters are held constant. These are  $\xi_s = 0.05$ ,  $m_b/m = 1$  and  $N = 5$ .

The seismic response of isolated system is investigated for the two real earthquake motion, namely the El-Centro, 1940 and Northridge, 1994 (recorded at Pacoima dam site). The components N00E and S05W of El-Centro and Northridge earthquake, respectively are applied in the x-direction of the system (with the orthogonal component applied in the y-direction). Response quantities of interest for the system under consideration are the absolute acceleration of the superstructure (in x-direction,  $\ddot{x}_a = \ddot{x}_N + \ddot{x}_b + \ddot{x}_g$  and in y-direction  $\ddot{y}_a = \ddot{y}_N + \ddot{y}_b + \ddot{y}_g$ ) and the relative sliding base displacement ( $x_b$  and  $y_b$ ). The absolute acceleration is directly proportional to the forces exerted in the superstructure due to earthquake ground motion. On the other hand, the relative sliding base displacement is crucial from the design point of view of

sliding system.

Figures 3 and 4 show the time variation of the top floor absolute acceleration and the sliding base displacement in the x- and y-directions of the system, respectively under the El-Centro, 1940 earthquake excitation. The sliding system considered is the FPS isolator with the parameters considered as  $T_b = 2s$  and  $\mu_{max} = 0.05$  taken from Reference [16]. The response is plotted for both considering and ignoring the bi-directional interaction effects of the frictional forces. Figures indicate that the nature of variation of the absolute acceleration is almost the same for both the cases. The absolute acceleration of the superstructure is relatively less for considering the interaction as compared to those without interaction. On the other hand, there is a significant difference in the base displacement for two cases. The base displacements are relatively higher when the interaction is considered (peak base displacement with interaction in x- and y-directions are 1.615 and 1.174 times more than the corresponding peak displacement without interaction, respectively). This is due

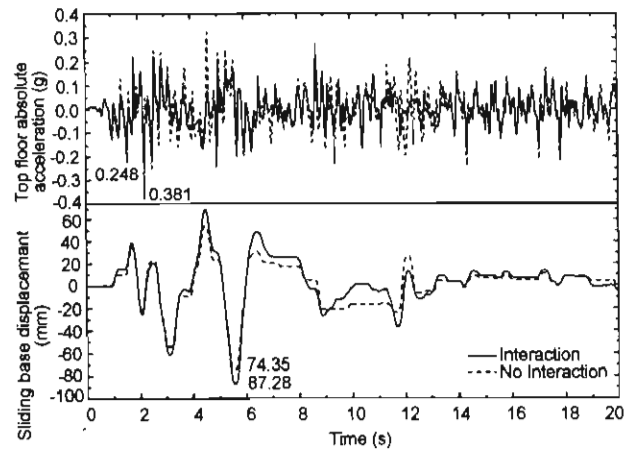


Figure 3. Time variation of top floor absolute acceleration and sliding displacement of the system in x-direction for the FPS isolation system to El-Centro, 1940 excitation ( $T_s = 0.5s$ ,  $T_b = 2s$ ,  $\xi_b = 0$ ,  $\Delta\mu = 0$  and  $\mu_{max} = 0.05$ ).

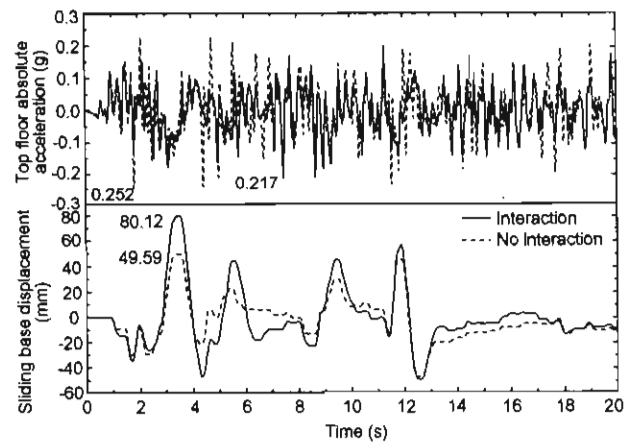


Figure 4. Time variation of top floor absolute acceleration and sliding displacement of the system in y-direction for the FPS isolation system to El-Centro, 1940 excitation ( $T_s = 0.5s$ ,  $T_b = 2s$ ,  $\xi_b = 0$ ,  $\Delta\mu = 0$  and  $\mu_{max} = 0.05$ ).

to the fact that when the interaction is considered, the system starts sliding at a relatively lower values of the frictional forces mobilized at the sliding isolation interface (see the interaction Eq. (9)), as a result, there is more sliding displacement taking place in the system. Thus, the sliding base displacements may be underestimated if the effects of bi-directional interaction of frictional forces are not considered simultaneously for designing the sliding isolation systems.

Figure 5 shows the variation of the resultant peak top floor absolute acceleration of the superstructure (i.e.  $\sqrt{(\ddot{x}_a)_{max}^2 + (\ddot{y}_a)_{max}^2}$ ) and resultant sliding base displacement ( $\sqrt{(\dot{x}_h)_{max}^2 + (\dot{y}_h)_{max}^2}$ ) against the time period of the

superstructure,  $T_s$ . The sliding isolation system considered is the P-F system with  $\mu_{max} = 0.1$ . The figure indicates that the resultant absolute acceleration of the superstructure is less when considering the interaction in comparison to that without interaction. The absolute acceleration spectra of the superstructure without isolation system (referred as fixed base) are also shown in order to study the effectiveness of the isolation system. Figure indicates clearly that the sliding system is quite effective in reducing the earthquake response of the superstructure. Further, the absolute acceleration of the isolated system is less sensitive to the time period of the superstructure in comparison to the fixed base system. The resultant peak sliding base displacement is significantly higher for the case with considering the interaction in comparison to that without interaction implying that there is a need to consider the bi-directional interaction effects of frictional forces for effective design of the sliding isolation systems. Similar effects of bi-directional interaction on the resultant response of the system are depicted in Figures 6 and 7 for the FPS and R-FBI sliding isolation systems, respectively.

So far the effects of bi-directional interaction of frictional forces are investigated for the fixed parameters typically recommended for various proposed isolation systems. However, it will be interesting to study the influence of isolator parameters (such as period, damping and friction coefficient) on the bi-directional interaction effects. In Figure 8, variation of the resultant response of the system is plotted against the friction coefficient of the sliding system. The responses of the sliding system with restoring force (i.e.  $T_b = 3s$  and  $\xi_b = 0.1$ ) are compared with the corresponding P-F system (without any restoring force having limiting value of  $T_b$  and  $\infty$ ). Figure 8 indicates the similar effects of bi-directional interaction effects for the two types of isolation systems for all values of friction coefficient. However, the effects of bi-directional interaction are relatively more pronounced for the P-F system in comparison to that of the system with restoring force. Thus, the presence of restoring force in the isolation system reduces the effects of bi-directional interaction of friction forces. In addition, the figure also indicates that the effects of bi-directional interaction are relatively less significant for the low values of friction coefficient of the sliding system. This is due to fact that for lower value of friction coefficient, the isolation system remains most of the time in the sliding phase for both the cases (i.e. with and without interaction). As a result, the difference in the response of the system obtained by considering or ignoring the interaction effects does not differ.

In Figure 9, effects of bi-directional interaction of frictional forces are shown against the time period of the sliding system  $T_b$ , for  $\mu_{max} = 0.05$  and  $0.1$ . The damping ratio of the sliding system,  $\xi_b$  is taken as  $0.1$ . It is observed from the figure that the effects of bi-directional

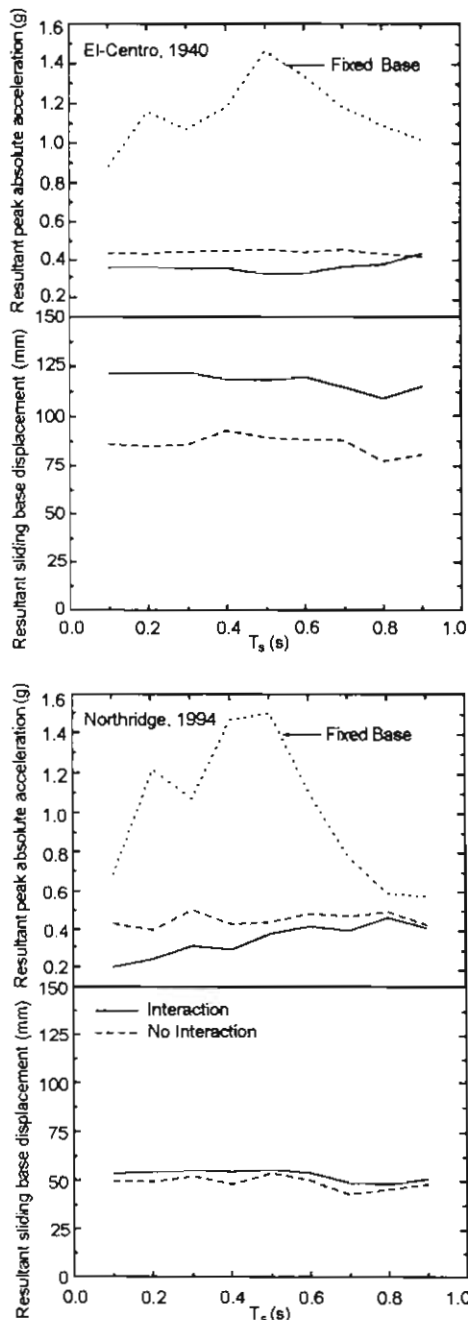
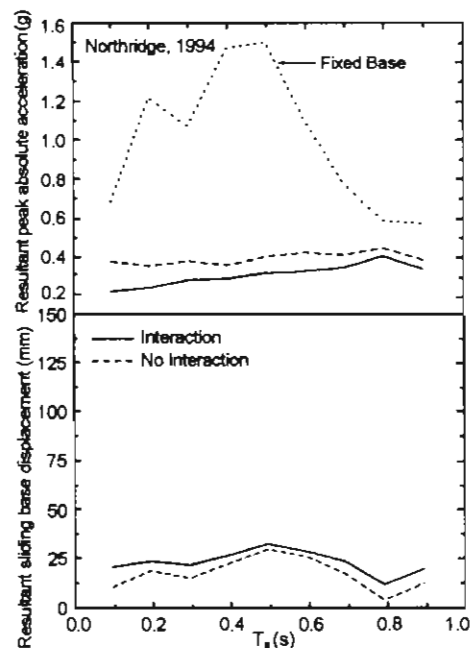
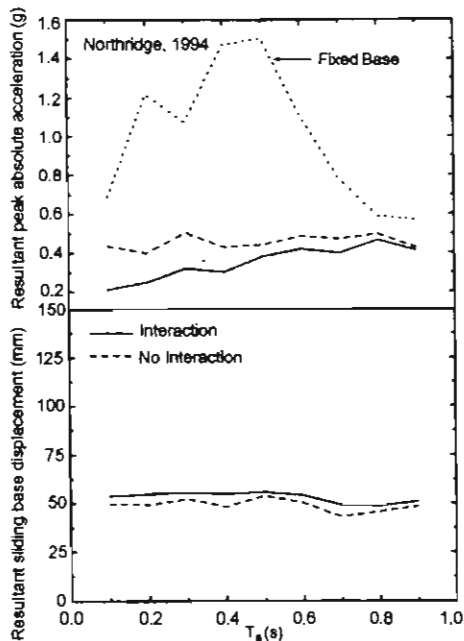
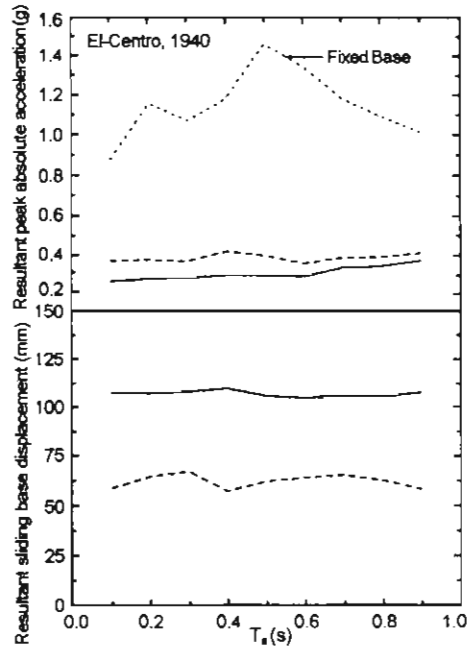
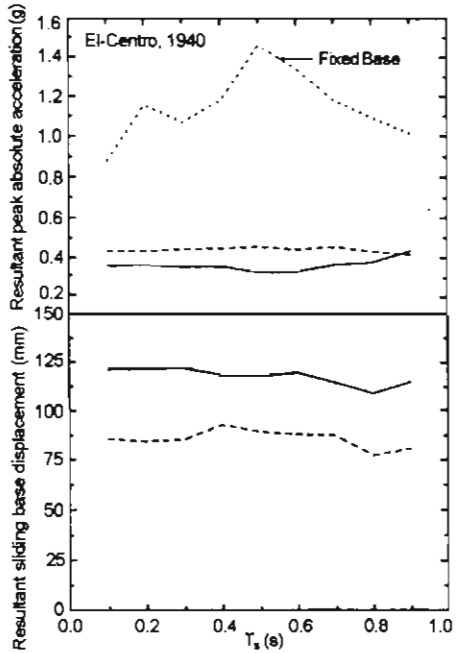


Figure 5. Plot of the resultant top floor absolute acceleration and base displacement against the time period of superstructure for P-F isolation system ( $\Delta\mu = 0, \mu_{max} = 0.1$ ).



**Figure 6.** Plot of the resultant top floor acceleration and base displacement against the time period of superstructure for FPS isolation system ( $T_b = 2s, \xi_b = 0, \Delta\mu = 0$  and  $\mu_{max} = 0.05$ ).

**Figure 7.** Plot of the resultant top floor acceleration and base displacement against the time period of superstructure for R-FBI isolation system ( $T_b = 4s, \xi_b = 0.1, \Delta\mu = 0$  and  $\mu_{max} = 0.04$ ).

interaction become quite significant with the increase of the time period indicating that the interaction effects are less pronounced for the system with strong restoring force in comparison to that with a weak restoring force. This happens due to fact that the restoring force dominates the sliding base displacement in comparison to friction in the systems having strong restoring force. As a result, the effects of bi-directional interaction are not quiet significant for the sliding system with strong restoring force.

Figure 10 shows the variation of the resultant response of the system against the damping ratio of the isolation system,  $\xi_b$ . Figure 10 indicates that the bi-directional

interaction effects are not much influenced by the damping of the isolation system. This might happen because in the sliding isolation system the response is more controlled by the friction damping with less effect from the additional viscous damping. Thus, the bi-directional interaction effects are not much influenced by the variation of additional viscous damping of the sliding isolation system.

The friction coefficient of various sliding isolation systems is typically dependent on the relative velocity at the sliding interface. For the present study, the velocity dependence of friction coefficient is modeled by Eq. (9)

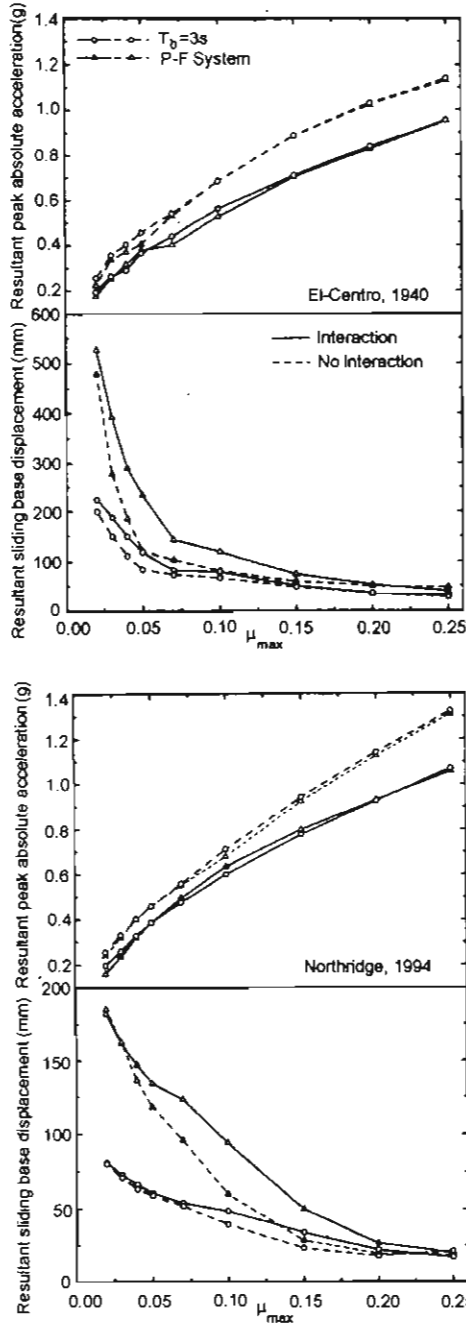


Figure 8. Effects of friction coefficient of the sliding system on the bi-directional interaction effects ( $T_s = 0.5s$ ,  $\Delta\mu = 0$  and  $\xi_b = 0.1$ ).

and it will be interesting to study these effects on the peak response of sliding isolation systems. Figure 11 shows the variation of the resultant response of the system against the coefficient of friction of the isolation system. The response is shown for three values of  $\Delta\mu$  i.e. 0, 0.15  $\mu_{max}$  and 0.3  $\mu_{max}$ . Note that  $\Delta\mu = 0$  denotes that the friction coefficient of sliding isolation system is independent of velocity at sliding interface (i.e. Coulomb-friction idealization). It is observed from Figure 11 that the dependence of friction coefficient on the relative sliding velocity does not have noticeable effects on the peak response of sliding systems for both earthquake ground motions. This confirms to the similar observation made by

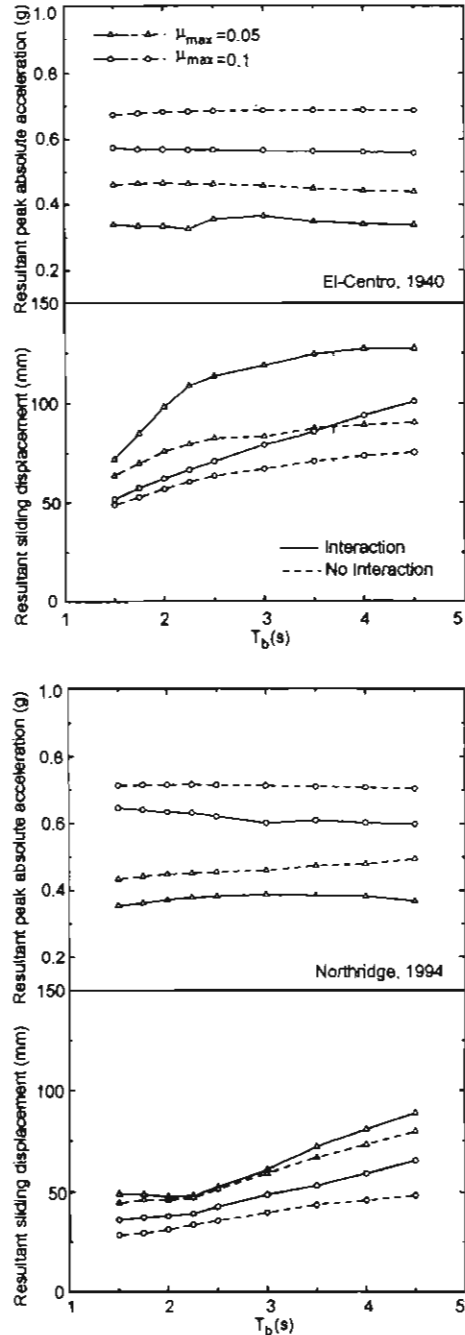


Figure 9. Effects of period of isolation of the sliding system on the bi-directional interaction effects ( $T_s = 0.5s$ ,  $\Delta\mu = 0$  and  $\xi_b = 0.1$ ).

Fan and Ahmadi [5]. Thus, the effects of dependence of friction coefficient on sliding velocity may be ignored for finding out the peak response of the system.

#### 4. CONCLUSIONS

A method for finding the seismic response of multi-story superstructures supported on the sliding isolation system to bi-directional earthquake excitation is presented. The velocity dependence and bi-directional interaction of the frictional forces of sliding system are duly considered in the analysis. The response of system is analyzed to study the effects of velocity dependence and bi-directional interaction of frictional forces of sliding system. A



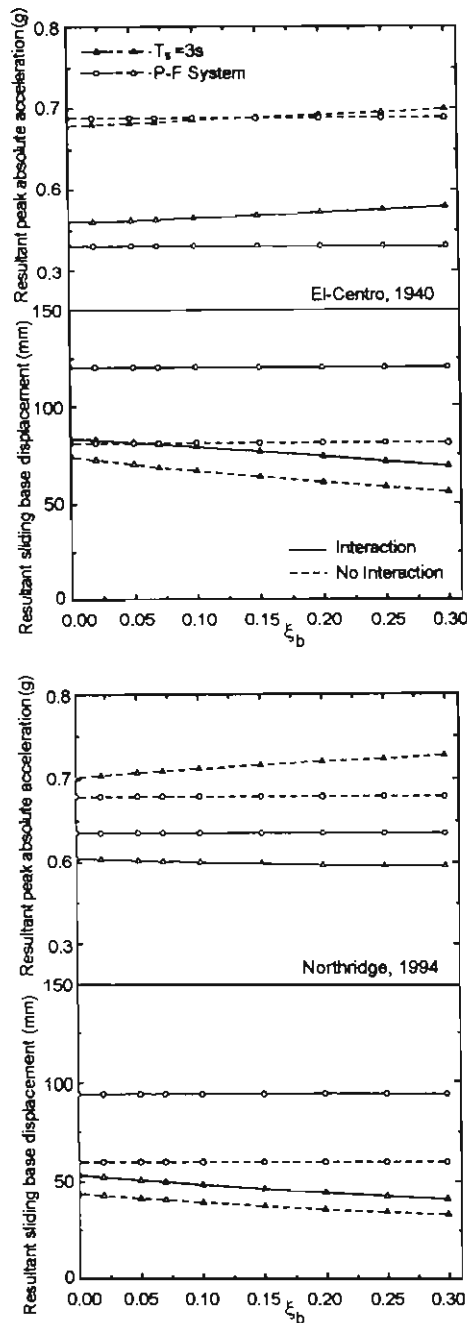


Figure 10. Effects of damping ratio of the sliding system on the bi-directional interaction effects ( $T_s = 0.5s, \Delta\mu = 0$  and  $\mu_{max} = 0.1$ ).

parametric study is conducted to investigate the effects of important parameters on the bi-directional interaction effects of frictional forces. The important parameters considered include the isolator properties (i.e. period, damping and friction coefficient) and the fundamental time period of superstructure. From the trends of the results of present study, following conclusions may be drawn:

- ❖ Seismic response of the structure supported on the sliding isolation systems are significantly influenced by the bi-directional interaction effects of frictional forces. These effects must be considered for the effective design of the sliding systems.
- ❖ There is significant underestimation of the sliding

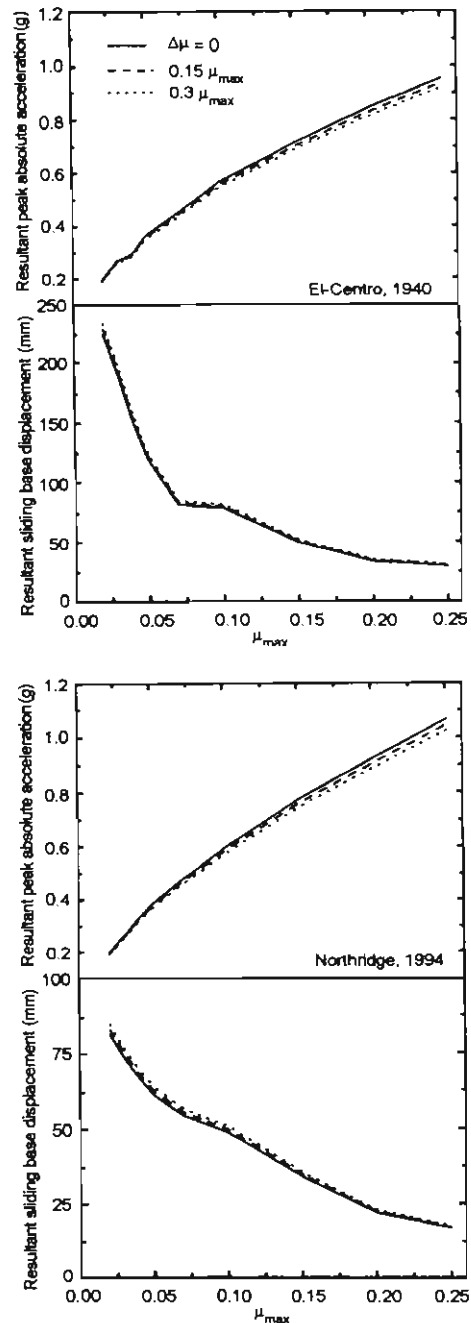


Figure 11. Effects of velocity dependence of friction coefficient on the peak response of the sliding system with bi-directional interaction effects ( $T_s = 0.5s, T_b = 3s$  and  $\xi_b = 0.1$ ).

base displacement and overestimation of the superstructure acceleration if the bi-directional interaction effects are ignored and the system is idealized as a 2-D system.

- ❖ The effects of bi-directional interaction are found to be more pronounced for the P-F sliding systems as compared to the sliding system with restoring force (such as FPS and R-FBI systems).
- ❖ In general, the effects of bi-directional interaction are found to be relatively severe for the isolation systems having higher friction coefficient and weak restoring force as compared to corresponding isolation system with lower value of friction coefficient and strong

restoring force.

- ❖ The bi-directional interaction effects are not much influenced by the variation of additional viscous damping of the sliding isolation systems.
- ❖ The dependence of friction coefficient on the relative velocity of the system does not have noticeable effects on the peak response of the isolated systems. Therefore, these effects may be ignored for finding out the peak response of the system.

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