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Response of Pure-Friction Sliding Structures to Three Components of Earthquake Excitation Considering Variations in the Coefficient of Friction

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Abstract. *In the present study, the influence of the coefficient of friction on the seismic response of sliding base isolated structures is investigated. The building is modeled as a simplified single-story structure resting on a group of sliding supports. The frictional forces mobilized at the sliding supports are assumed to have a hysteretic plasticity behavior. Bilateral interaction between the stiffness of the two horizontal orthogonal directions of the isolators has been taken into consideration. The results show that the variations of the coefficient of friction influence the response of a sliding base isolated building. Effects of vertical excitation on the normal and frictional forces are considered too. The influence of the bi-directional interaction of frictional forces and vertical excitation on the response is investigated by comparing the response of the system to mono-directional (excluding vertical component and no interaction between the two horizontal orthogonal directions), bi-directional (excluding vertical component) and tri-directional earthquake excitations. It is demonstrated that the response of the sliding isolated structures is influenced significantly by the bi-directional interaction of frictional forces and by incorporation of the vertical component. Further, the base shear response may be underestimated if the effects of the vertical component are neglected and the sliding structures are designed merely on the basis of single-component or two-component excitation.*

Keywords: *Frictional base isolated structure; Three-component earthquake; Velocity-pressure dependent friction coefficient; Bi-directional interaction; Vertical component.*

INTRODUCTION

Earthquakes have a large potential for disastrous consequences. Apart from the loss of life, they can cause great economic loss through structural damage. The conventional design approach of structures in regions where seismicity is insignificant, aims at the design of structural members in such a way that they can withstand all static and dynamic loads elastically. However, in regions where seismic excitation should be taken into account, this design approach might lead to economically unacceptable design solutions, because structural members might become too large. To prevent this, two alternative design concepts can be employed. In the first alternative design concept, plastic deformation is allowed in special parts of the structure. This strategy is often referred to as the capacity design method. However, plastic deformation still results in damage to the structure and, possibly, its contents. In the second alternative design approach, mechanical devices are added to the conventional superstructure to enhance its seismic response.

In this study, one special type of passive system is considered, namely friction-based base isolation systems. These systems consist of mechanical devices with friction elements that are placed underneath the superstructure to decouple it from the potentially hazardous surrounding ground motion. A significant amount of recent research on base isolation has focused on the use of these elements to concentrate the flexibility of the structural system and to add damping to the isolated structure. The most attractive feature of the frictional base-isolated system is its effectiveness for a wide range of frequency inputs. The other advantage of a frictional type system is that it ensures the maxi-

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mum acceleration transmissibility equal to maximum limiting frictional force. Although it is well-known that these base isolation systems may exhibit (highly) nonlinear behavior, they are often modeled linearly, in engineering practices, as prescribed in recent building codes.

So far, some studies have been performed on the friction characteristics of sliding bearings with Steel-PTFE interfaces. All these experimental observations [1-4] pointed out that the friction coefficient increases more than linearly while increasing sliding velocity, and it decreases with the increase of contact pressure. Temperature and the number of sliding reversals also play a negligible role [5].

Many numerical analyses of the seismic response of structures equipped with sliding isolation systems have been performed [6-9]. In all these studies, as well as in the current design practice, it is assumed that the friction coefficient complies with the Coulomb friction law (i.e. the coefficient of friction remains constant during sliding and friction forces are zero. Furthermore, in almost all these studies, the effects of the vertical component of an earthquake and, in a majority of these studies, the effects of bilateral interaction are neglected and the structure is analyzed with only one horizontal earthquake or harmonic component.

A sliding system with oscillating SDOF superstructures subjected to a harmonic support motion has been studied by Mostaghel et al. [10] and Westermo and Udwadia [11]. Mostaghel and Tanbakuchi [6] also studied a similar sliding system, using a semi-analytical solution procedure to compute the response of the system under earthquake ground motions.

The necessity of considering the vertical component of an earthquake in the design of buildings with a sliding support is pronounced by Liaw et al. [12] during a two-dimensional study. They considered a constant friction coefficient and stated that the frictional stress is a function of the vertical reaction which is produced by the supporting element on the foundation mat. Hence, both vertical and frictional forces vary when there is vertical motion on the sliding system. As an example, they used the El Centro earthquake records on a two-dimensional structural model to verify the effect of the vertical component on the lateral response of the system. Lin and Tadjbakhsh [13] also evaluated the effect of vertical ground motion on the horizontal response of a two-dimensional P-F system. They indicated that the effect of vertical motion is only significant in the cases of harmonically excited foundations. Evaluation of the effect of the vertical component of ground excitation on the response of the resilient friction base isolator (R-FBI) system is studied by Mostaghel and Khodaverdian [14]. They demonstrated that, in the case of the El Centro 1940 earthquake, the contribution of the vertical excitation to the horizontal response quantities was generally less than 1%. However, as they had used a two-dimensional system, they could not incorporate the effect of interaction between the stresses in the principal directions.

The interaction between the orthogonal components of the frictional forces mobilized at the sliding interface is investigated experimentally by Mokha et al. [15]. Jangid [8] also studied the response of a structure with sliding support to bi-directional (i.e. two-horizontal components) earthquake ground motion. He incorporated the coupling effects due to circular interaction between the frictional forces and stated that the design sliding displacement may be underestimated if the bi-directional interaction of frictional forces is neglected.

Vafai et al. [16] investigated the numerical modeling of MDOF structures with sliding supports using a rigid-plastic link. Shakib and Fuladgar [13] studied the effects of a three-component earthquake on the responses of a pure-friction system. They supposed that the sliding base had Coulomb friction characteristics (it was supposed that the sliding base had an almost infinity initial stiffness and a zero post-yield stiffness). The friction force was either zero or its maximum value. The coefficient of friction was assumed to be constant in all cases. The absolute acceleration and base displacement responses were investigated. They stated that the maximum absolute acceleration of the low period superstructures ($Ts < 0.7$ sec) may be underestimated if the three-component earthquake is not considered. However, in moderate and high period superstructures, no significant difference was seen in the maximum absolute acceleration and the maximum base displacement of the sliding system for two and three components of earthquake excitations.

Takahashi et al. [17] and Iemura et al. [18] performed a set of shaking table tests to study the effects of rocking motion and the vertical component of an earthquake on the seismic responses of a two-dimensional (one horizontal and one vertical direction) base isolated rigid deck with a Resilient Sliding Isolation (RSI) system. The isolation system consisted of a number of sliding supports and rubber buffers which were arranged parallel to each other. They stated that the rocking motion contributes to the hysteretic loops of each sliding support, but its effect nullifies when considering total responses. It was also observed that vertical acceleration affects the maximum normal and friction forces of the isolation system, but its affect is negligible on the maximum base displacement.

In the present paper, the response of sliding structures is studied under three components of earthquake excitation. The effects of interaction between the stiffness of two orthogonal directions and vertical acceleration on the seismic responses of sliding base isolated structures are investigated. The isolation system is modeled considering non-Coulomb (hysteretic plasticity) behavior, which is observed in experiments on sliding supports, and makes it possible to introduce phenomenon like stick-slip. Based on recent experiments on the frictional characteristics of sliding bearings, a new formula is proposed which accounts for the effects of sliding velocity and contact pressure on the friction of these bearings. Using this formula, a program for the investigation of sliding isolated structures was developed. The response of the structure in the case of a constant friction coefficient and velocity-dependent friction coefficient is compared with the response when the friction coefficient is a function of sliding velocity and contact pressure in order to evaluate the accuracy of the first two cases.

The new contributions of the present investigation are:

1. Variation of friction coefficient in functions of velocity and pressure simultaneously;
2. Study of wide range of parameters on the seismic behavior of isolated structures considering variation of V and P;
3. Developing a new program for considering variation of friction in function of velocity and pressure simultaneously.

FORMULATION

Consider an elastic one-storey structure with a group of sliding bearings between the base mass and the foundation as shown in Figure 1. This model of a sliding structure has been widely studied under unilateral [10,11,19] support motions and with a constant friction coefficient.

The force-displacement relations of the utilized sliding element is described as:

$$fs_{z_1} = \begin{cases} k_{z_1} u_{z_1} \Leftrightarrow v_{z_1} < 0 \\ 0 \Leftrightarrow v_{z_1} \geq 0 \end{cases} \tag{1}$$

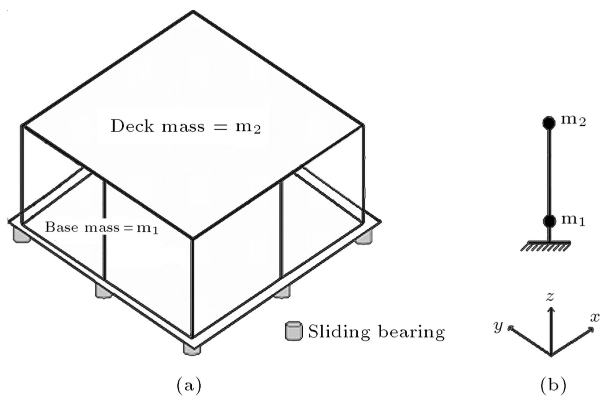

Figure 1. (a) Physical model; (b) Driven mathematical model.

$$fs_{x_1} = |fs_{z_1}\mu| z_x, \tag{2}$$

$$fs_{y_1} = |fs_{z_1}\mu| z_y, \tag{3}$$

in which fs_{z_1} is the normal force; fs_{x_1} and fs_{y_1} are the frictional forces of the sliding element in x and y directions, respectively; u_{z_1} is the displacement of the base mass in the z direction; k_{z_1} is the stiffness of the sliding element in the z direction; μ is the friction coefficient of the sliding interface; and z_x and z_y are dimensionless internal hysteretic variables which can be calculated by the following differential equations:

$$Y\dot{z}_x + \gamma|\dot{u}_{x_1} z_x| z_x + \beta \dot{u}_{x_1} z_x^2 + \gamma |\dot{u}_{x_1} z_y| z_x +$$

$$\beta \dot{u}_{y_1} z_x z_y - A\dot{u}_{x_1} = 0, \tag{4}$$

$$Y\dot{z}_y + \gamma|\dot{u}_{y_1} z_y| z_y + \beta \dot{u}_{y_1} z_y^2 + \gamma |\dot{u}_{y_1} z_x| z_y +$$

$$\beta \dot{u}_{x_1} z_y z_x - A\dot{u}_{y_1} = 0. \tag{5}$$

$\dot{u}_{x_1}$ and $\dot{u}_{y_1}$ are velocities of the base mass in the x and y directions, Y represents the elastic deformation of the frictional element prior to the initiation of sliding, and A, β and γ are dimensionless constants, which must satisfy the condition $A/(\beta+\gamma) = 1$. Constantinou et al. [20] suggested the use of $A = 1$, $\beta = 0.1$, $\gamma = 0.9$, and $Y = 0.25$ mm or less. These values are used in this study too. The relation between the coefficient of friction and the sliding velocity can be expressed by the following equation [15]:

$$\mu = \mu_{\max} - (\mu_{\max} - \mu_{\min}) e^{-\alpha|\dot{u}|}, \tag{6}$$

where $\mu_{\max}$ and $\mu_{\min}$ are the maximum and minimum coefficients of friction in the same order measured on a particular interface under given confining pressure; α is a parameter that controls the intensity of change in the friction coefficient from $\mu_{\min}$ to $\mu_{\max}$; and $\dot{u}$ is the resultant sliding velocity:

$$\dot{u} = \sqrt{\dot{u}_{x_1}^2 + \dot{u}_{y_1}^2}. \tag{7}$$

This coefficient has a minimum value, $\mu_{\min}$, at zero velocity and a maximum value, $\mu_{\max}$, at a very high velocity of sliding. In the present study, the following regressions were obtained, based on the experimental results of Dolce et al. 2005 [4], to describe the variations of the coefficient of friction with the confining pressure:

$$\mu_{\max} = c_1 - (c_1 - c_2) e^{-\beta_1 |p|}, \tag{8}$$

$$\mu_{\min} = c_3 - (c_3 - c_4) e^{-\beta_2 |p|}, \tag{9}$$

$$\alpha = \lambda_1 + \lambda_2 |p|, \tag{10}$$

where c_1 and c_2 are the minimum and maximum values of $\mu_{\max}$, respectively; c_3 and c_4 are the minimum and maximum values of $\mu_{\max}$, respectively; β_1 is a parameter that controls the intensity of change in the $\mu_{\max}$ from c_1 to c_2; and β_2 is a parameter that controls the intensity of change in the $\mu_{\min}$ from c_3 to c_4. λ_1 and λ_2 determine α and, therefore, govern the intensity of change in the friction coefficient and p is the confining interfacial pressure in MPa. Parameters utilized in Equations 8 to 10 were calculated by a regression analysis as given in Table 1. So, the coefficient of friction can be calculated by substituting Equations 8 to 10 into Equation 6. The governing equations are:

$$M\ddot{u} + C\dot{u} + Ku = P. \tag{11}$$

M, C, K: Mass, damping and stiffness matrices, respectively.
$u, \dot{u}, \ddot{u}$: Displacement, velocity and acceleration, related to degree of freedom.

$$\begin{bmatrix} [M_1] & 0 \\ 0 & [M_2] \end{bmatrix}. \tag{12}$$

$[M_i]$: Mass matrix of ith floor, which is equal to:

$$[M_i] = \begin{bmatrix} m_i & 0 & 0 \\ 0 & m_i & 0 \\ 0 & 0 & m_i \end{bmatrix}. \tag{13}$$

K: Stiffness matrix

$$K = \begin{bmatrix} k_1 & -k_1 \\ -k_1 & k_1 + k_2 \end{bmatrix}. \tag{14}$$

k_i: Stiffness matrix of floor

$$[k_i] = \begin{bmatrix} kx_i & 0 & 0 \\ 0 & ky_i & 0 \\ 0 & 0 & kz_i \end{bmatrix}.$$

C: Damping matrix, which could be obtained from the following equation:

$$C = M \sum a[M^{-1}K]^b. \tag{15}$$

P: Force matrix

The previous equation is solved using a constant average acceleration method.

MODEL VERIFICATION

In order to provide validation of the developed program, the comparison of numerical and experimental results on sliding bearings under simultaneous compression and high velocity bi-directional motion is presented in this section. Circular, elliptical and 8-shaped motions (Figure 2) were imposed. Force-displacement loops are considered and the numerical results of the computer program are compared with the experimental results of Mokha et al. [15]. In Table 2 the conditions considered in the experimental tests are listed.

Force-displacement loops of imposed circular motion which are obtained from the developed program and experimental results are shown in Figure 3. It is demonstrated that there is good agreement between the results obtained from the developed program and experimental tests.

Table 1. Calculated constants of friction coefficient.

c_1	c_2	c_3	c_4	β_1 (MPa^{-1})	β_2 (MPa^{-1})	λ_1 (sec/mm)	λ_2 (MPa^{-1}.sec/mm)
8.43e-2	3.17e-1	9.02e-3	1.02e-1	9.06e-2	5.09e-2	1.60e-2	2.14e-4

Table 2. Experimental program conditions.

Test	Motion	Load (KN)	Pressure (MPa)	*x*-Direction Motion			*y*-Direction Motion		
				Maximum Displacement (mm)	Maximum Velocity (mm/s)	Frequency (rad/s)	Maximum Displacement (mm)	Maximum Velocity (mm/s)	Frequency (rad/s)
1	Circular	2 × 45.4	3.58	45.5	22.9	0.5	43.7	21.8	0.50
2	Elliptical	2 × 44.7	3.52	45.5	22.9	0.5	28.9	14.5	0.50
3	8-shaped	2 × 45.8	3.61	45.5	22.9	0.5	43.9	43.9	1.00
4	Circular	2 × 45.8	3.62	45.5	100.8	2.22	43.4	96.5	2.22
5	Elliptical	2 × 46.5	3.67	45.5	100.8	2.22	29.2	64.5	2.22
6	8-shaped	2 × 48.0	3.79	45.2	100.3	2.22	43.9	195.1	4.44

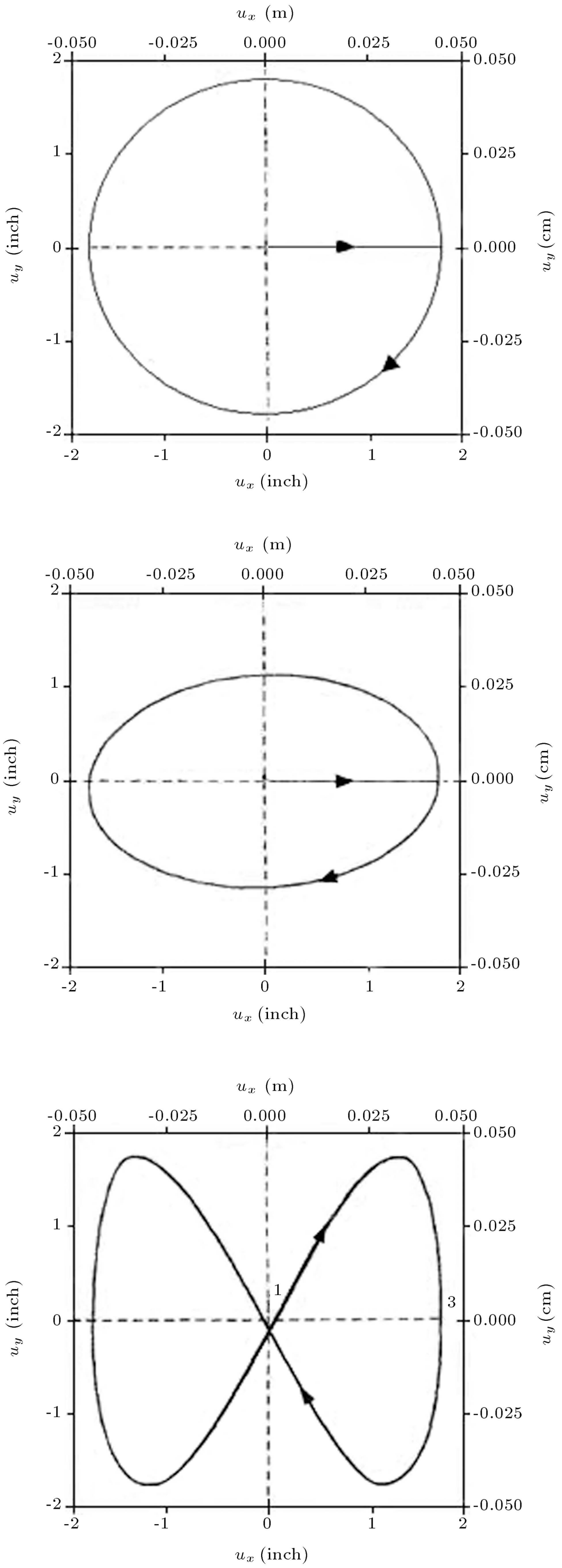

Figure 2. Recorded motion in bi-directional circular, elliptical and 8-shaped tests.

Figure 4 illustrates force-displacement loops of imposed elliptical motion. This figure is different from the previous figure only by the amplitude of displacement in the y-direction. The results validate the developed program too.

Figure 5 shows force-displacement loops of an imposed 8-shaped motion from the developed program and experimental results. There is a good agreement between results obtained from the two methods.

The developed program has also been controlled with the experimental results of Dolce et al. [4].

NUMERICAL STUDY

The response of isolated structures are the structural shears ($R_{sx} = fs_{x_2}$, $R_{sy} = fs_{y_2}$ and $R_s = \sqrt{R_{sx}^2 + R_{sy}^2}$) and the base shears or friction forces ($R_{bx} = fs_{x_1}$, $R_{by} = fs_{y_1}$ and $R_b = \sqrt{R_{bx}^2 + R_{by}^2}$), which are important in the design of superstructure and the components which are connected to the isolation system, respectively, and the relative sliding displacements of the base mass (u_{x_1}, u_{y_1} and $u = \sqrt{u_{x_1}^2 + u_{y_1}^2}$). The latter is displacement between the isolated structure and the ground, which is crucial in the design of sliding systems.

As known, an important duty of a base isolation system is the dissipation of energy exerted on a structure due to an earthquake. So, another parameter on hand is the energy dissipated by the sliding bearings. But, the magnitude of dissipated energy alone cannot show the efficiency of an isolation system. The ratio of the total dissipated energy to the input energy shows the percentage of energy absorbed by the isolation system and energy transmitted through isolators to the structure; thus, giving a more realistic index to show the efficiency or capacity of different isolation systems in controlling structural damage.

In the present study, the natural period of the superstructure as a fixed base is considered to be equal in the x- and y-directions (i.e. $T_s = 2\pi\sqrt{m_2/k_{x_2}} = 2\pi\sqrt{m_2/k_{y_2}}$ where k_{x_2} and k_{y_2} are stiffness of superstructure in x and y directions, respectively; the ratio of the natural period of the superstructure in a z-direction to x- or y-directions is selected as 0.2 ($2\pi\sqrt{m_2/k_{z_2}} = 0.2\ T_s$). The damping ratio of the structure is taken as 5% of the critical, and the mass ratio, m_1/m_2, is assumed to be unity. In the sliding surface, the normal stiffness of the sliding element is taken as $k_{z_1} = 3.5 \times 10^9$ N/m. It is assumed that the building has nine sliding bearings with a radius of 50 mm.

Three cases of friction coefficient are assumed. In the first case, the coefficient of friction is constant, in another case, it is a function of velocity and in

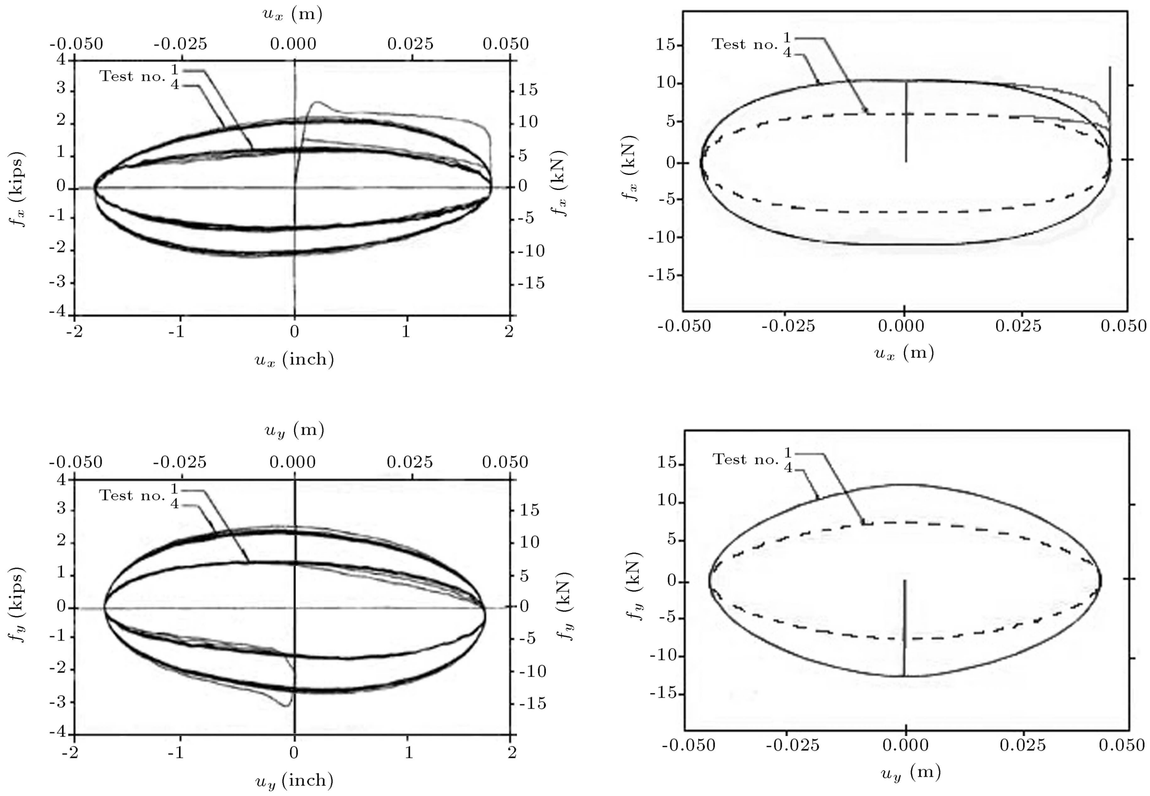

Figure 3. Loops of frictional force and displacement in circular motion case from the developed computer program (right) and from tests (left).

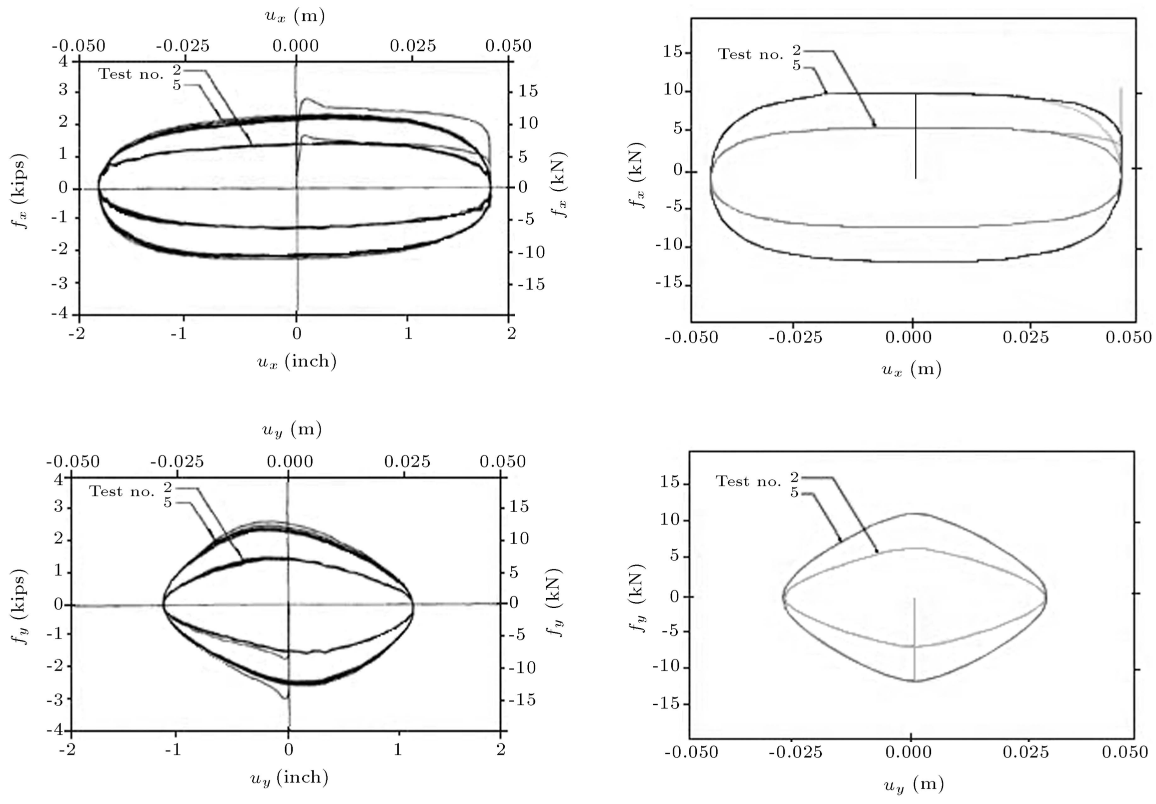

Figure 4. Loops of frictional force and displacement in elliptical motion case from the developed computer program (right) and from tests (left).

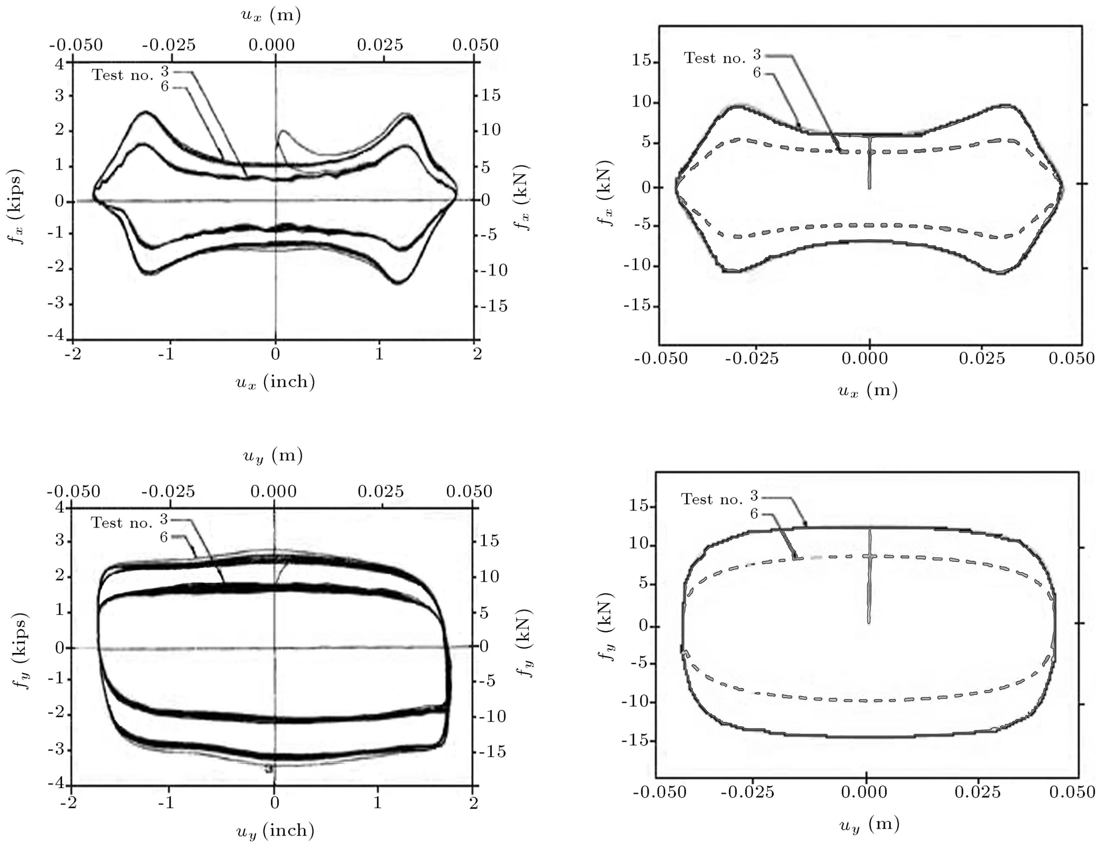

Figure 5. Loops of frictional force and displacement in 8-shaped motion case from the developed computer program (right) and from tests (left).

the last case, it is a function of velocity and pressure. In the cases when the coefficient of friction is constant or is velocity-dependent, it is assumed that the pressure is due to the structural weight. Moreover, for the first case, in order to gain a constant friction coefficient, a zero sliding velocity is substituted in Equation 6.

Also, three combinations of earthquake components are considered; the response of the system with and without vertical components is referred to as the response to three-component and two-component earthquakes, respectively. The response of the system is also obtained for two orthogonal directions (i.e. x- and y-directions) acting independently in each direction. In this case, there is not any interaction between the frictional forces in the two orthogonal directions and this condition can be referred to as a single-component earthquake.

Three earthquake records are considered and applied to the sliding structure. The El Centro 1940 earthquake is chosen, as it has been used widely in previous investigations of pure-friction base-isolated structures. The Tabas 1978 and Northridge 1994 earthquakes are selected as they have a strong vertical component.

EFFECTS OF FRICTION COEFFICIENT

Maximum Structural Shear

Figure 6 shows the maximum structural shear versus the period of the superstructure under Northridge earthquakes. The figure clearly indicates that the sliding support is quite effective in reducing the seismic lateral response of the superstructure subjected to three components of earthquake excitations, simultaneously. Further, the maximum structural shear of the system with a sliding base is less sensitive to the period of the superstructure in comparison with a fixed base system. It also indicates that the maximum structural shear is less for the case of a constant friction coefficient in comparison with a case when the friction coefficient is a function of the sliding velocity and contact pressure. The maximum structural shear in a velocity dependent friction coefficient case, in the majority of periods, is more than in a case when the friction coefficient is a function of the sliding velocity and contact pressure. The maximum difference between these two cases is about 45% under Northridge and Tabas earthquakes and occurs in periods near zero. Note that $T_s = 0$ is a case of a rigid structure with a sliding interface.

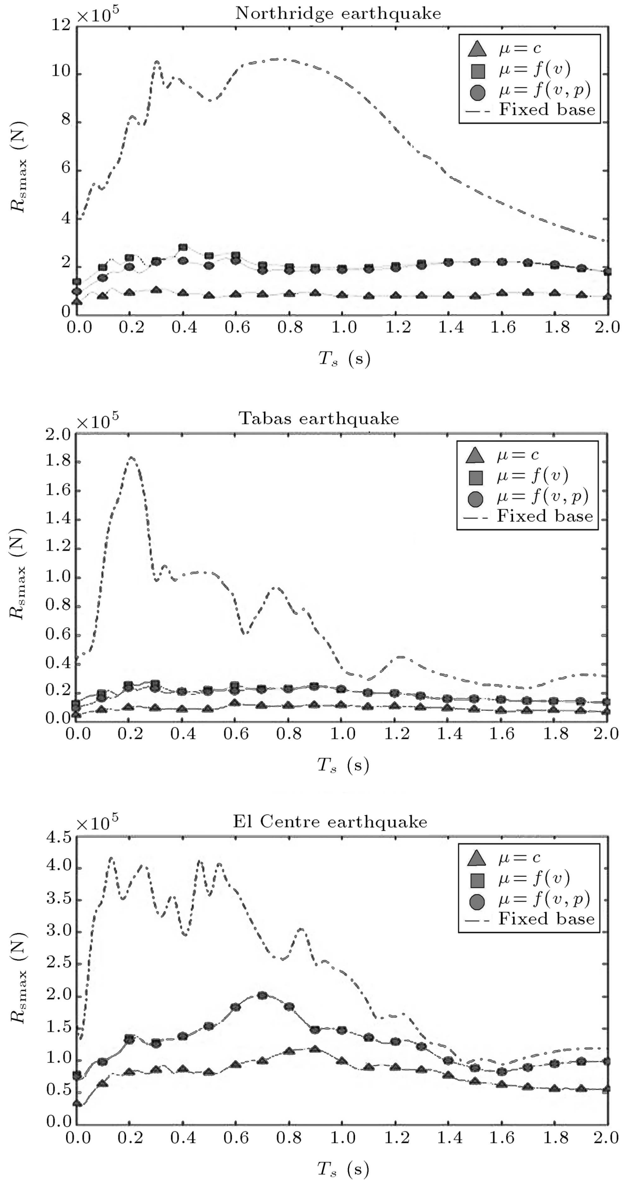

Figure 6. Maximum structural shear versus period of superstructure for different coefficient of friction.

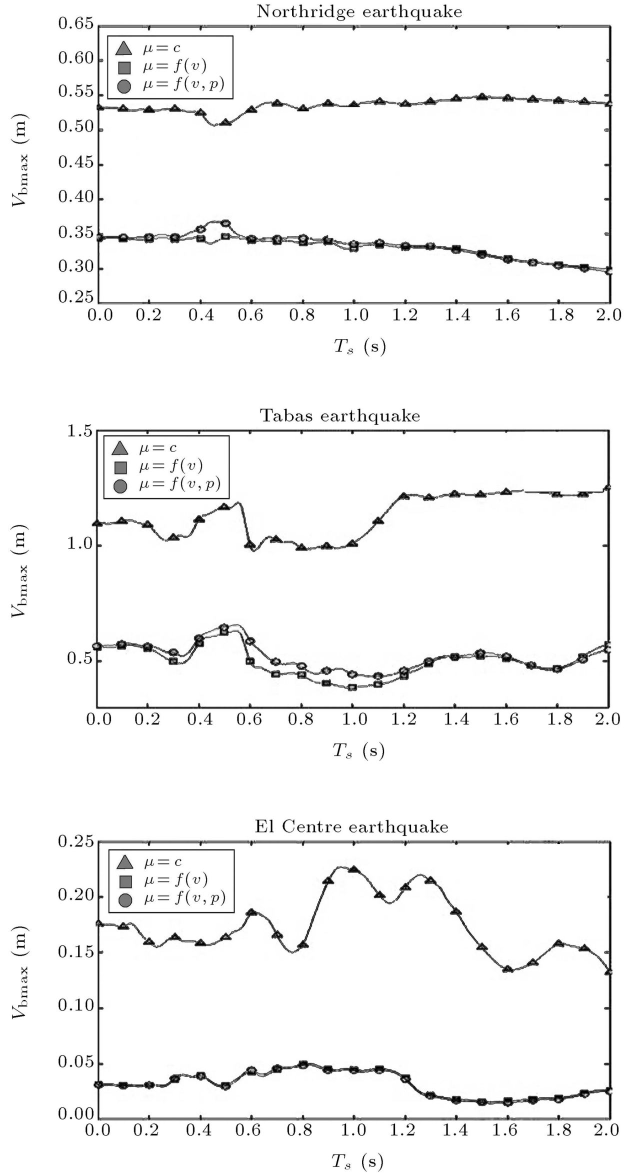

Figure 7. Maximum base displacement versus period of superstructure for different coefficient of friction.

Maximum Base Displacement

Figure 7 illustrates the variation of the maximum base displacement of the sliding system against the structural period for constant velocity dependent and velocity-pressure dependent friction coefficient cases. The figure demonstrates that the maximum base displacement is significantly higher for a constant friction coefficient case, in comparison with a velocity-pressure dependent friction coefficient case. The maximum base displacement of a velocity dependent friction coefficient case, in the majority of periods of a superstructure, is less, in comparison with a case when the friction coefficient is a function of sliding velocity and contact pressure. However, the difference between these two cases is slight (the difference is 16%).

Maximum Base Shear

Figure 8 shows the maximum base shear versus the period of the superstructure under different earthquakes. The constant friction coefficient case has the least value of base shear. It is due to the fact that, in this case, a zero sliding velocity is used to find the friction coefficient and we know that less sliding velocity results in less friction coefficient. So, it is anticipated that, if a much greater value of sliding velocity was used to find the friction coefficient, it would lead to a base shear which would be the greatest. This trading-off phenomenon is commonly observed in other vibration control systems. The velocity dependent friction coefficient case has the greatest maximum base shear. The maximum base shear in a velocity-pressure dependent

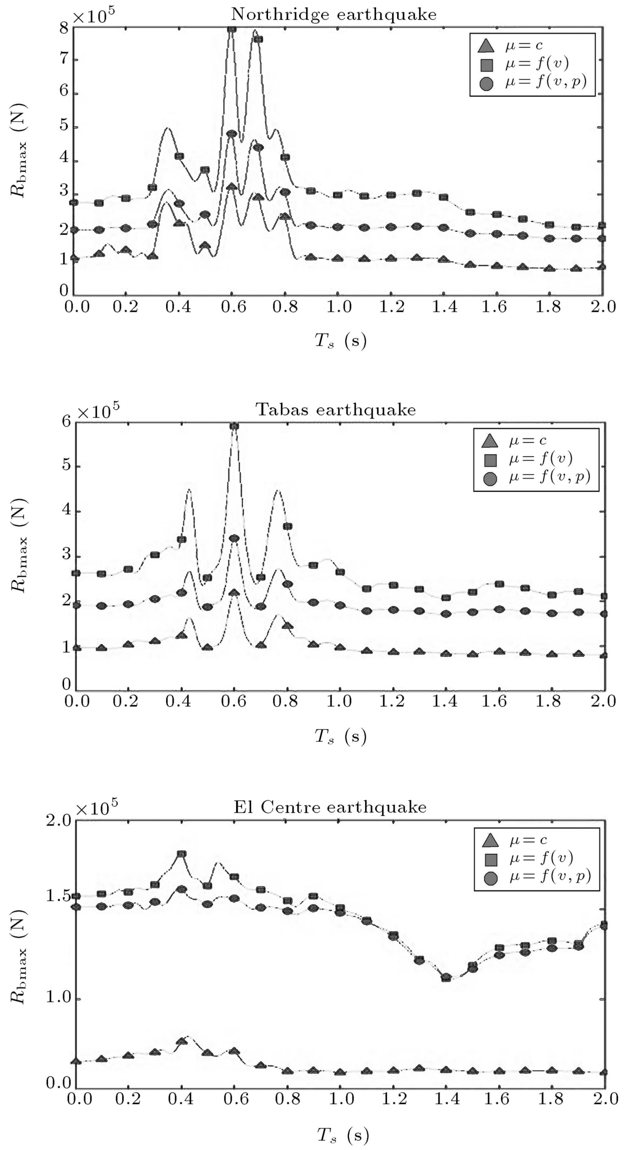

Figure 8. Maximum base shear versus period of superstructure for different coefficient of friction.

friction coefficient case is in between. The base shear (friction force) is equal to a normal force multiplied by the coefficient of friction.

So, it is expected that the maximum value occurs when the normal force is maximum. At this time, because the normal force is maximum, the contact pressure is maximum and, as known, the greater the contact pressure, the less the friction coefficient. On the other hand, the velocity dependent friction coefficient is independent of pressure. So, at the immediate vicinity of the time when the base shear has its maximum value, the velocity dependent friction coefficient is greater than the velocity-pressure dependent coefficient of friction, but the normal forces of these two cases are almost the same. It is the reason why the maximum base shear of the velocity dependent friction coefficient case is greater.

Total Dissipated Energy

Figure 9 shows the ratio of the total dissipated energy to the input energy, versus the period of superstructure under earthquakes. It can be seen that, for all cases with an increase in the period of superstructure, this ratio decreases. It demonstrates that, by increasing the period of the superstructure, the efficiency of the isolation system decreases. For a rigid superstructure, this ratio is almost equal to one. In other words, for a rigid superstructure, the input energy is totally dissipated by the isolation system. In this case, the system coincides with a system with a concentrated mass resting on a frictional interface, and we know that, if someone pulls such a mass, almost all exerted energy will dissipate due to the effect of friction.

The ratio of the total dissipated energy to the

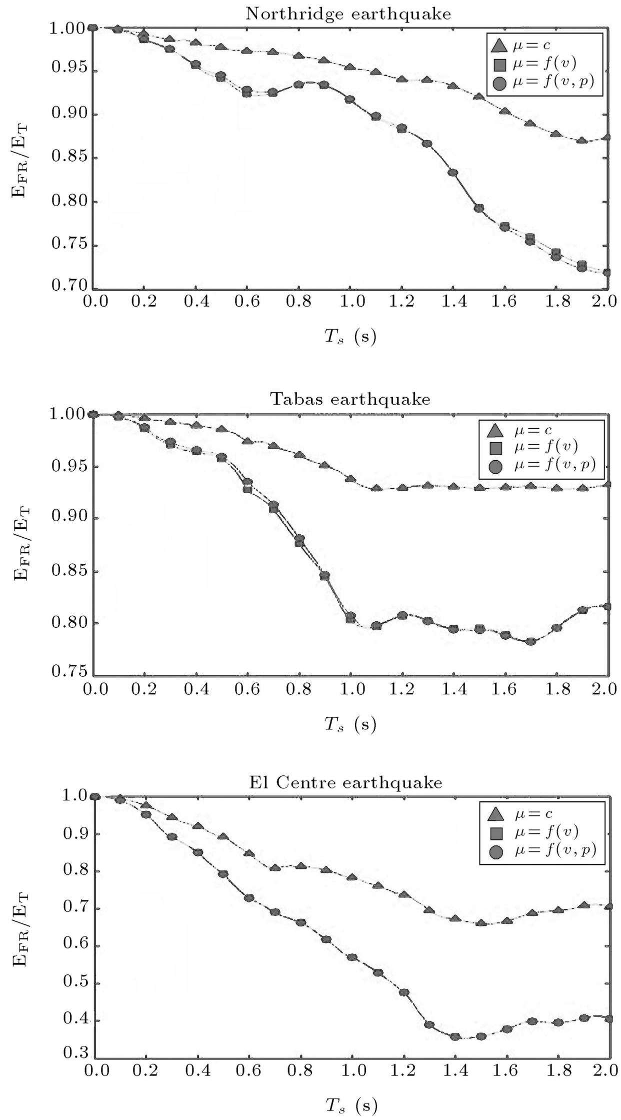

Figure 9. Ratio of the total dissipated energy to the input energy versus period of superstructure for different coefficient of friction.

input energy for the constant friction coefficient case is the greatest at all periods of superstructure and for all earthquake excitations, which shows that this case overestimates the energy dissipated by the isolation system. This ratio is almost the same for velocity dependent and velocity-pressure dependent friction coefficient cases.

EFFECTS OF VERTICAL COMPONENT OF EARTHQUAKE AND BILATERAL INTERACTION

Maximum Structural Shear

Figure 10 shows the maximum structural shear force versus the period of the superstructure under Northridge, Tabas and El Centro earthquakes. The figure clearly indicates that the sliding support is quite effective in reducing the seismic lateral response of the superstructure subjected to three components of the earthquake excitations. In addition, for high-rise buildings, sliding isolation systems are less effective in decreasing the maximum structural shear. Further, the maximum structural shear force of the system with a sliding base in comparison with a fixed base system, is less sensitive to the period of the superstructure.

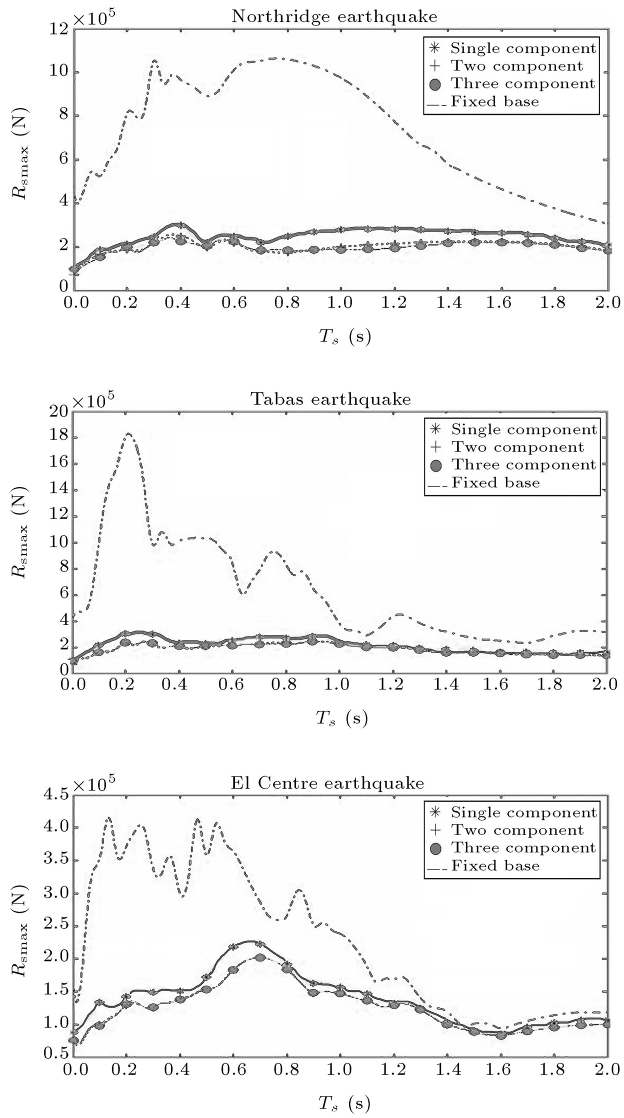

Figure 10. Maximum structural shear versus period of superstructure considering single-, two- and three-components of earthquake.

It also indicates that the maximum structural shear force is higher for the case of a single component excitation, in comparison with cases of two-component and three-component excitations. This is due to the fact that, in the case of a single component earthquake, there is no interaction between the lateral stiffness of the two orthogonal directions of the isolator. So, this system is laterally stiffer than the two other cases and thus has the greatest maximum structural shear. The maximum difference between this case and the two other cases is 50 percent. The maximum structural shear force for the case of two-component excitations is greater or less than three-component excitations, depending on the natural period of the superstructure. Their maximum difference is about 25% under Northridge and Tabas earthquakes.

Maximum Base Displacement

Figure 11 illustrates the variation of the maximum base displacement of the sliding system against the structural period for single-, two- and three-component earthquake excitations. This figure demonstrates that the maximum base displacement is lower for the case of a single-component excitation in comparison with the other two cases. The maximum base displacement of two-component excitation may be greater or less than three-component excitations depending on the period of the superstructure and the input motion. The difference between these two cases is negligible 8%.

Maximum Base Shear

Figure 12 shows the variations of the maximum base shear (friction force) against the period of superstructure under Northridge, Tabas and El Centro earthquakes. For the single- and two-components of Northridge and Tabas earthquake excitations, the maximum base shear remains nearly constant in different natural periods, but they vary under the El Centro earthquake. Under Northridge and Tabas earthquakes, the base shear response of a single-component earthquake may be greater or less than the response in the case of a three-component earthquake excitation, but under the El Centro earthquake, the response of a single-component earthquake excitation is always greater. The variation of the base shear response is

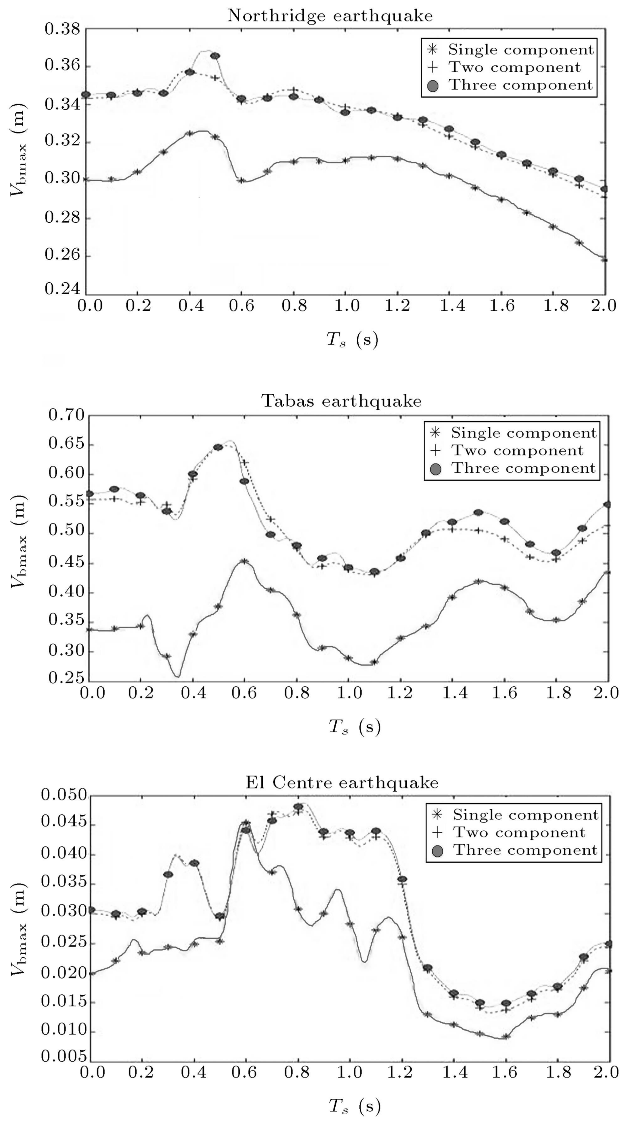

Figure 11. Maximum base displacement versus period of superstructure considering single-, two- and three-components of earthquake.

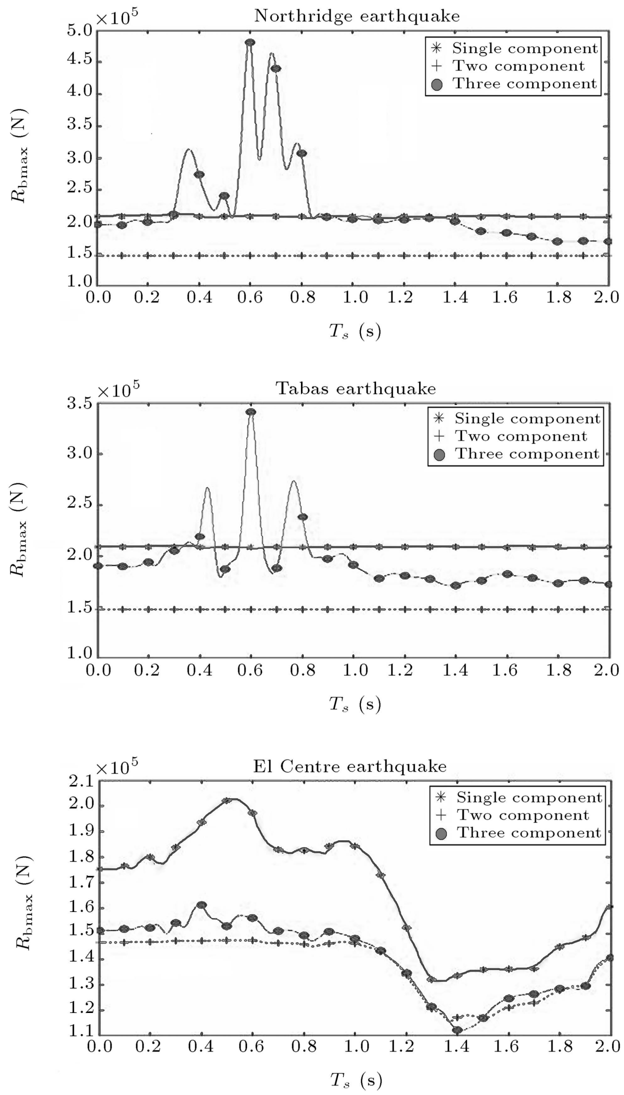

Figure 12. Maximum base shear versus period of superstructure considering single-, two- and three-components of earthquake.

almost the same for all three cases under the El Centro earthquake.

The response of the two-component earthquake excitation is the least. It is due to the fact that, in this case, the interaction between the stiffness of the two orthogonal directions of the sliding plane was considered. So, in the first case, the system has a laterally more flexible sliding element and, therefore, its base shear would be greater. The base shear (friction force) is equal to the normal force multiplied by the coefficient of friction. In both cases of two- and three-component earthquake excitations, the interaction between the stiffness of the two-orthogonal directions is considered, hence, they are not different in this aspect. But, on the other hand, the maximum normal force of the isolated structure under three-component earthquake excitation is greater and the maximum base shear (friction force) occurs in the neighborhood of the time when the maximum normal force response occurs. So, the base shear response of this case would be greater than in the case of a two-component earthquake excitation.

It is mentioned that the base shear of a single-component earthquake excitation may be greater or less than that of three-component earthquake excitations under Northridge and Tabas earthquakes, but under the El Centro earthquake, the response of a single-component earthquake excitation is always greater. The difference between these two cases is that the latter has a greater maximum normal force at the base and because the maximum base shear occurs in the immediate vicinity of the time when the maximum normal force occurs. This increases the base shear response in the case of a three-component earthquake excitation, but on the other hand, in the case of a three-component earthquake excitation, there is interaction between the stiffness of the two-horizontal-orthogonal directions, which in turn decreases the base shear response of this case.

The combination of these two phenomena, in some periods, causes the base shear of a single component earthquake to be greater and, in some periods, to be less for a strong ground motion, such as Northridge and Tabas earthquakes. But, the base shear of a single component earthquake is always greater under the El Centro earthquake. It shows that, for an earthquake with a medium PGA, the difference between the maximum normal forces of these two cases is not so much and, in this case, the interaction factor has the upper hand.

Also, it was mentioned that the base shear (friction force) is equal to the normal force multiplied by the coefficient of friction. For the single-component and two-component systems, the normal force never varies and is always equal to the weight of the system. The contact pressure is constant too, because the normal force is constant. So, the coefficient of friction is only a function of the sliding velocity for these two cases. We know that, as the sliding velocity increases, the friction coefficient increases too, although, after a large sliding velocity (e.g. 0.5 m/s), this increase is negligible and the coefficient of friction remains almost constant. During the occurrence of a strong earthquake, such as Northridge and Tabas earthquakes, the maximum sliding velocity would be high at all periods. So, the maximum friction coefficient would be almost constant at all periods and, therefore, the base shear would be constant. But, for a medium earthquake, like the El Centro earthquake, the maximum sliding velocity is at no time high enough to set the friction coefficient as constant. In fact, for this earthquake excitation, the maximum sliding velocity is never more than 0.3 m/s.

Additionally, it may be noted that, for a rigid structure ($T_s = 0$), the maximum base shear response is exactly twice the structural shear response. The reason is that, for a rigid structure, shear distribution is directly proportional to the cumulative mass distribution, because for such a structure, the absolute acceleration of each mass is exactly the same.

The effects of a vertical component of earthquake excitation can be observed when comparing the results under two-component and three-component earthquake excitations. It can be seen that the effects of a vertical component is far more pronounced on the base shear response, in comparison with other responses (structural shear, base displacement, dissipated energy, etc). The results were obtained by Takahashi et al. [17] and also Iemura et al. [18], using experimental tests. This may be due to the fact that, among all responses, only the base shear (friction force) is directly proportional to the normal force, thus, the effects of normal force is more accentuated.

Total Dissipated Energy

Figure 13 presents the ratio of the total dissipated energy to the input energy versus the period of superstructure under earthquakes. It can be seen that for all cases, by increasing the period, this ratio decreases. It demonstrates that by increasing the period the efficiency of the isolation system decreases. For a rigid structure, this ratio is almost equal to one. In other words, for a rigid structure, the input energy is totally dissipated by the isolation system, because in this case, the superstructure is rigid and the system coincides with a system with a concentrated mass resting on a frictional interface. It is obvious that, if someone pulls the mass, almost all the exerted energy will dissipate due to the effect of friction and will convert to thermal energy.

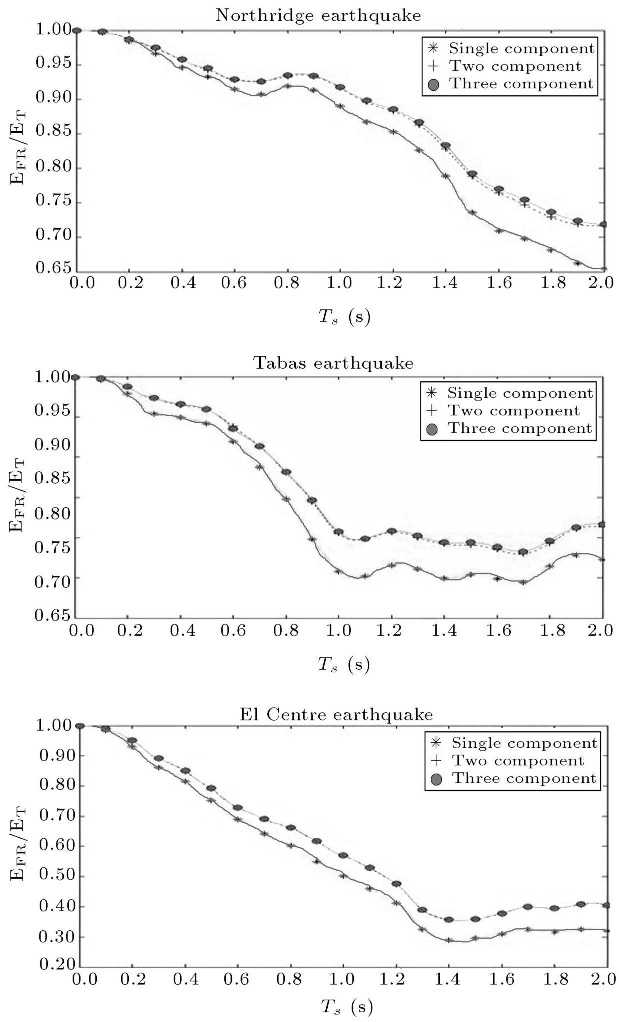

Figure 13. Ratio of the total dissipated energy to the input energy versus period superstructure considering single-, two- and three-components of earthquake.

The ratio of the total dissipated energy to the input energy for two-component earthquake excitations is the least at all periods and for all earthquake excitations, showing that this case underestimates the value of the energy dissipated by the isolation system. This ratio is almost the same for cases of two- and three-component earthquake excitations.

CONCLUSIONS

Symmetric isolated structures with pure friction isolators were studied under single-, two- or three-component earthquakes. Variation of the friction coefficient in the function of velocity and pressure is the main subject of the current paper and, for this purpose, a program was developed. Several important structural parameters were investigated using the developed program. Results of these studies can be expressed in the following conclusions:

1. If the coefficient of friction is assumed constant, responses of the system can be different from real responses (the case of velocity-pressure friction coefficient for a three-component system). The maximum structural shear, the maximum base shear and the energy ratio are less in the case of a constant friction coefficient in comparison with real values. These effects are opposite on the maximum base displacement.
2. When the coefficient of friction is only a function of velocity and the system has been excited by a three component earthquake, the maximum structural shear and maximum base shear responses can be much more than their real values.
3. The vertical component of an earthquake can affect lateral responses considerably.
4. If bilateral interaction between the stiffness of the two orthogonal directions of the isolator is considered, but the vertical component of the earthquake is neglected, depending on the structural period and type of earthquake excitation, structural shear and base shear can be greatly underestimated.
5. There is negligible difference between the maximum base displacements of isolated structures under two-component and three-component earthquakes.
6. If bilateral interaction between the stiffness of the two orthogonal directions of the isolator is neglected (isolated structures under a single component earthquake), structural shear and base shear can be considerably larger and the base displacement can be considerably less than that of two-component systems in which the bilateral interaction between the stiffness of the two orthogonal directions is included.

NOMENCLATURE

fs_{z_1}	normal force,
fs_{x_1}, fs_{y_1}	frictional forces of the sliding element in x and y directions,
u_{z_1}	displacement of the base mass in z direction,
k_{z_1}	stiffness of sliding element in z direction,
μ	friction coefficient of sliding interface,
z_x, z_y	dimensionless internal hysteretic variables in x and y directions,
$\dot{u}_{x_1}, \dot{u}_{y_1}$	velocity of the base mass in x and y directions,
Y	elastic deformation of the frictional element prior to the initiation of sliding,
A, β, γ	dimensionless constants,
$\mu_{\max}, \mu_{\min}$	maximum and minimum coefficients of friction measured on a particular interface under given confining pressure,
α	a parameter which controls the variation rate in the friction coefficient from $\mu_{\min}$ to $\mu_{\max}$,
$\dot{u}$	resultant sliding velocity,
c_1, c_2	minimum and maximum value of $\mu_{\max}$,
c_3, c_4	minimum and maximum value of $\mu_{\min}$,
β_1	a parameter which controls the variation rate in the $\mu_{\max}$ from c_1 to c_2,
β_2	a parameter which controls the variation rate in the $\mu_{\min}$ from c_3 to c_4,
λ_1, λ_2	parameters which determine α,
p	the confining interfacial pressure in MPa.

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