STUDY OF PLAIN FRICTION (P-F) ISOLATION SYSTEM IN SEISMIC CONTROL OF STRUCTURES

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Abstract*—This paper introduces a recent seismic isolation system, named Pure or Plain Friction (P-F) isolator, for efficient protection of Structures against destructive earthquakes. One of the simplest system which uses friction is pure friction system. This system is quite effective in reducing the forces transferred to the structure but has no restoring capability. There are several structural and isolator properties which affect the response of the structure. The structural properties affecting the response include structural fixed base time period, mass ratio (ratio of superstructure mass to the total mass) and damping ratio. The isolator property affecting the response is the coefficient of sliding friction. In this investigation, parametric studies on structures isolated by pure friction isolation system subjected to base excitation are carried out. The objective of this experimental study is to critically assess the influencing parameters that control the behaviour of structures isolated by the PF isolators.

***Index Terms*—Plain Friction, Seismically Structure, Structural Control**

I. INTRODUCTION

Base Isolation is a very effective way for controlling seismic response of civil engineering structures. This technique is based on the principle that it is more efficient to reduce seismic demand on a structure rather than increasing its earthquake resistance capacity. The main idea behind the Base Isolation is based on minimizing the earthquake induced forces transferred to the superstructure. The earthquake energy is prevented from entering the structure by decoupling the later from the ground motion, thereby reducing both the ductility demand and inter-storey drifts. This uncoupling is done by interposing the structural elements with low horizontal stiffness between foundation and superstructure which reduce the fundamental frequency of structural vibration to a lower value than the predominant energy containing frequencies of earthquake ground motions and it also provides a means of energy dissipation which reduces the transmitted acceleration to the superstructure.

Seismic isolation is the separation of the structure from the harmful motions of the ground by providing flexibility and energy dissipation capability through the insertion of the socalled isolators between the foundation and the superstructure. It is not a long time since the first application of the isolators as the first base-isolated building in the USA was built in 1985 [1], although the idea is more than a century years old.

Friction force is a natural and powerful energy dissipation device, which reduces the acceleration, experienced by the structure and associated equipment during an earthquake. The simplest of these is pure friction (PF) system. In the pure-friction isolation systems the isolation mechanism is sliding friction. A schematic diagram of a pure-friction base isolator is shown in the Figure 2.3. These base isolators are the simplest base isolation systems of all.

II. SINGLE DEGREE OF FREEDOM STRUCTURE

A single degree of freedom structure supported on pure friction isolation system is taken for the study (Figure 1). Considering a damping ratio ξ of 5% of critical, normalized response spectra (normalized with respect to the corresponding peaks of the input excitations) are calculated and plotted for absolute accelerations, relative displacements, and sliding displacements relative to ground displacements for different values of coefficients of friction, and mass ratios, α . The response has been obtained for μ = 0.05, 0.10, 0.15, 0.20 for three mass ratio α = 0.75, 0.50, 0.25 (implying m/m_b = 3, 1 and 1/3) where m is the mass of the structure and m_b is the base mass.

We are primarily interested in the maximum response quantities of the structure for design purposes. So the parametric study can be best carried out by studying the response spectra that represent the variation in the maximum responses for a given parametric variation, therefore, to display the effectiveness of sliding supports in reducing the maximum level of response acceleration, and to show the variations of the maximum sliding displacements, the normalized absolute acceleration response and the normalized sliding displacement response are plotted.

Figure 1 shows a single degree of freedom structure of mass m, damping c and stiffness k supported by a base mass that can slide horizontally. X is the total displacement of mass m, x is the displacement of the mass relative to base, X is the total displacement of the base mass and F is the interface force between the foundation raft and its support. X_s is the sliding displacement and X_s is the sliding velocity. The coefficient of sliding friction is μ . a is the peak excitation acceleration and D is the peak excitation displacement. The response for different coefficients of friction and mass ratios is evaluated and presented graphically.

Structure Subjected to Harmonic Support Motion

The structure is subjected to sinusoidal excitation $X = a\sin\Omega t$. The maxima of x_r , $\ddot{x}$ and X_s are determined for the structural period from T = 0.05 to T = 1.0 s at period intervals of 0.05 s and for a single value of excitation period (Mostaghel 1983)

$$T_g = \frac{2\pi}{\Omega} = 0.5\text{s}$$

The duration of excitation is taken to be 10 times the excitation period T_g, i.e.

$$t_d = 10\, T_g$$

Assuming the period of excitation T_g to be 0.5s, this yields excitation duration of 5s. This duration is used in all calculations. The non-dimensionalized responses are defined as:

Normalised Absolute Acceleration = $\dfrac{\ddot{x}(T,\xi,\mu)}{a}$

Normalised Relative Displacement = $\dfrac{x_r(T,\xi,\mu)}{D}$

Normalised Sliding Displacement = $\dfrac{X_S(T,\xi,\mu)}{D}$

Where,

$$\ddot{x}(T,\xi,\mu) = \max\left|\ddot{x}(t,T,\xi,\mu)\right|$$

$$x_r(T,\xi,\mu) = \max\left|x_r(t,T,\xi,\mu)\right|$$

$$X_s(T,\xi,\mu) = \max\left|X_s(t,T,\xi,\mu)\right|$$

$D = a/\Omega^2$ is the steady-state peak ground displacement and a is the peak ground acceleration. To display effectiveness of sliding supports in reducing the structural response, various response quantities are plotted against the frequency ratio,

$$\beta = \frac{\Omega}{\omega} = \frac{T}{T_g}$$

Excitation amplitudes of a = 0.3g, 0.5g (where g is the acceleration of gravity) are considered for study. Typical time history plots for sinusoidal excitation for structures isolated by PF system are shown in Figure 2. The plot clearly shows the effectiveness of the PF system in reducing the forces transmitted to the structure. There is substantial reduction in the absolute acceleration and relative displacement of the structure. The structure displaces itself to an offset from the initial position and starts oscillating about the displaced position.

Effect of Coefficient of Friction – Figure 4 represents the normalized acceleration spectrum in which the mass of the structure is three times the mass of the foundation raft and the peak support acceleration is 0.5g. As expected the sliding displacement response is larger for smaller coefficient of friction. It is observed that;

1. The spectral response of isolated structures appears to be independent of frequency.
2. The level of response depends only on the coefficient of friction of base surface. As expected the smaller the coefficient of friction, the lower the response.
3. The level of response of isolated structures is considerably lower than the level of response of corresponding fixed base structures

Effect of Mass Ratio – Figures 4 and 6 are the acceleration response spectra. The level of support excitation is 0.5g in all the three cases. However, the mass ratio is 0.75 in Figure 4, 1 in Figure 6 and 0.25 in Figure 6. The observations made for Figure 4 hold except that the response becomes somewhat frequency dependent for the frequency ratios above 1.0, especially for large coefficient of friction. Comparing Figures 4 and 6, it may be concluded that the larger the mass of the superstructure as compared to the mass of the foundation raft, the lower the level of acceleration response.

Figure 5 and Figure 7 are the sliding displacement response spectra. The level of support excitation is 0.5g in all the three cases. However, the mass ratio is 0.75 in the Figure 5, 1 in Figure 7 and 0.25 in Figure 7. Comparing Figures 5 and 7, it may be concluded that, for the same frequency ratio, variations in mass ratio do not affect the level of sliding displacement significantly. Also, lower the mass ratio, the less variation in sliding displacement with frequency ratio.

Effect of Amplitude of Excitation – Figure 4 and 8 represents acceleration response for the support excitation of 0.5g and 0.3g respectively. Observations made for Figure 4 apply for Figure 8 as well. Comparing 4 and 8 it may be concluded, that higher the level of excitation, the more effective is the sliding support in reducing the normalized acceleration response. It can also be concluded that reduction in the level of support acceleration reduces the sliding displacement response. However, this reduction is not uniform over the frequencies considered.

Structure Subjected to Earthquake Support Motion

The P-F isolated SDOF structure is subjected to earthquake excitation. The ground motion record used for the NS component of El Centro 1940 has a data at a time interval of $0.02s$ and peak acceleration (PGA) of 0.34g and peak ground displacement of 10.9cm. Time duration of the earthquake excitation is $30s$ (Mostaghel 1983). Normalized responses are defined as:

Absolute Acceleration = $\dfrac{\ddot{x}(T,\xi,\mu)}{a}$

Relative Displacement = $\dfrac{x_r(T,\xi,\mu)}{D}$

Sliding Displacement = $\dfrac{X_s(T,\xi,\mu)}{D}$

Relative-to-ground displacement = $\dfrac{X_{rg}(T,\xi,\mu)}{D}$

Residual sliding displacement = $\dfrac{X_{rs}(T,\xi,\mu)}{D}$

where,

$$\ddot{x}(T,\xi,\mu) = \max\left|\ddot{x}(t,T,\xi,\mu)\right|$$

$$x_r(T,\xi,\mu) = \max\left|x_r(t,T,\xi,\mu)\right|$$

$$X_s(T,\xi,\mu) = \max\left|X_s(t,T,\xi,\mu)\right|$$

$$X_{rg}(T,\xi,\mu) = \max\left|x_r(t,T,\xi,\mu) + X_s(t,T,\xi,\mu)\right|$$

$$X_{rs}(T,\xi,\mu) = \left|X_s(t_d,T,\xi,\mu)\right|$$

The response is obtained for the total duration t_d of ground acceleration, and the maxima of different response quantities are evaluated for different structural periods from T = 0.05 to T = 2.0*s* at period intervals of 0.05*s*. *D* is the peak ground displacement, *A* is the peak ground acceleration and t_d is the duration of ground motion. The normalized responses are plotted against period *T* in Figures 10-14. The results obtained have been discussed in the following section.

Effect of Coefficient of Friction - Figure 10 represents the normalized acceleration spectrum for structures in which the mass of the structure is three times the mass of the foundation raft. The observations are same as in the case of sinusoidal excitation.

Effect of Mass ratio

1. Absolute Acceleration - Figures 10 represent the normalized acceleration spectra for structures in which the mass ratio is 0.75, 0.50 and 0.25 respectively. The observations made for Figure 10 hold, except that the response tends to be more frequency dependent, especially for larger coefficients of friction. Comparing Figures 10, it may be concluded that the larger the mass of the structure as compared to the mass of the foundation raft, the lower the level of acceleration response. For low coefficients of friction, the acceleration response does not vary with the frequency content of the ground motion. This implies that sliding supports can be effectively used for all kinds of sites.

2. Sliding Displacement - Figure 11 represents the normalized sliding displacement spectrum for structures in which the mass ratio is 0.75. Contrary to expectations that were substantiated by harmonic excitations, for some structures the maximum sliding displacement is lower for lower coefficients of friction. This is due to the disorderly arrangement of pulses in earthquake ground motion, which controls the direction of sliding.

To study the effects of mass ratio on sliding displacement, sliding displacement spectra for mass ratios of α =0.5 and 0.25 are presented in Figures 11 respectively. By comparing Figures 11 it may be observed that in general the lighter the superstructure, as compared to the weight of the foundation raft; the less is the maximum sliding amplitude. As may be noted from these figures, the maximum sliding even for the lowest coefficient of friction (0.05) considered is of the order of 1.25 times the peak ground displacement. There is a theoretical limit to the amount of sliding as the coefficient of friction is reduced to zero. For zero coefficient of friction, theoretically, no acceleration is transferred to the superstructure. That is, the structure remains stationary.

3. Relative Displacement - The normalized relative displacement spectrum for the mass ratio α = 0.75 is given in Figure 12. As expected, the relative displacement of mass *m* is much lower than the fixed base response. This is expected; because, according to Figure 10, the lower mass is subjected to much lower accelerations than if the base of the structure was fixed. The lower levels of relative displacements imply lower levels of deformations in the structures. The same conclusion may be drawn from Figures 12 which are for mass ratio α = 0.75 and 1.

4. Relative to ground displacement - Relative to ground displacement is of interest in structures which have elements such as piping's connected to the ground. Normalized spectra for relative-to-ground displacements for three different mass ratios are given in Figures 13. These figures suggest that, in general, for the ground motion, the structures and the coefficients of friction considered, the maximum of the relative-to-ground displacement is of the order of 1.25 times the peak ground displacement.

5. Residual Sliding Displacement - The residual sliding displacement, that is, the displacement due to sliding which remains when the ground motion is over, is of practical interest for any later re-centring operation. The normalized residual sliding displacement spectra for the three mass ratios are given in Figures 14. From these figures it may be observed that for the ground motion, the structures and the coefficients of friction considered, the maximum residual displacement is of the order of 1.25 times the peak ground displacement.

The large reduction in the level of response acceleration and the relatively small relative to ground displacements, sliding displacement and residual sliding displacement suggest that sliding supports have the potential of being a very effective and inexpensive isolation system. The above results based on earthquake excitation are also supported by the results from harmonic excitations.

Response to Magnified El Centro Earthquake

To understand the behaviour of various base isolation systems under different intensity earthquakes, the accelerogram of the El Centro 1940 earthquake scaled by a factor of 0.5, 1 and 2 is used as the ground excitation. The other objective here is to study the sensitivity of the PF isolation system to increase in intensity of the earthquake excitation, while its frequency contents remain unchanged. The results of these studies are described in this section.

Figure 15-17 shows the variation of responses of the structure subjected to different scaled intensities of El Centro earthquake. As expected the relative displacement and sliding displacement are maximum in the case of high intensity earthquake whereas the absolute acceleration is less as compared to the less intensity earthquakes. It can be concluded that pure friction system are quite effective in reducing the forces transmitted to the structure in case of high intensity earthquake.

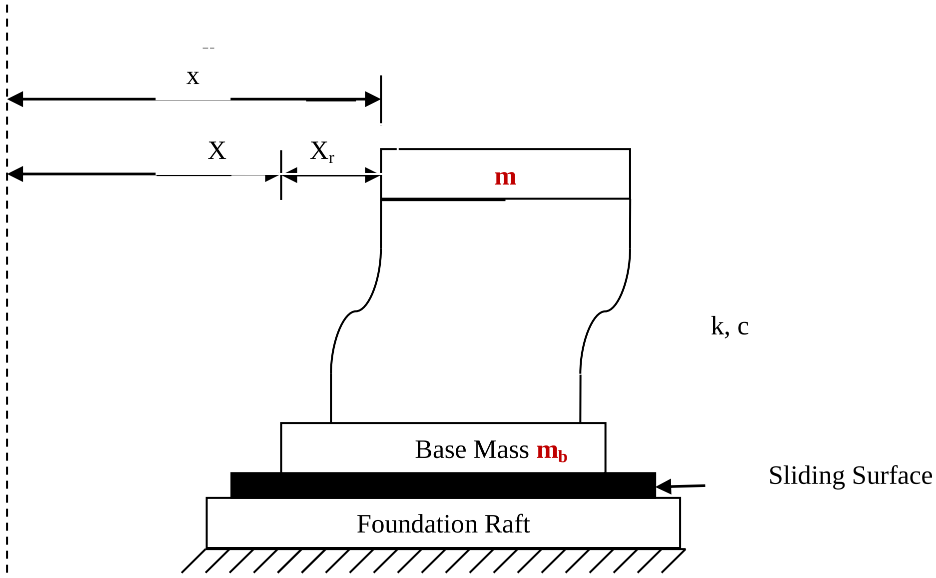
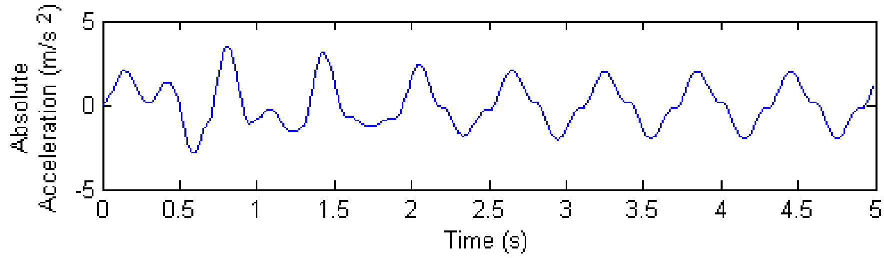
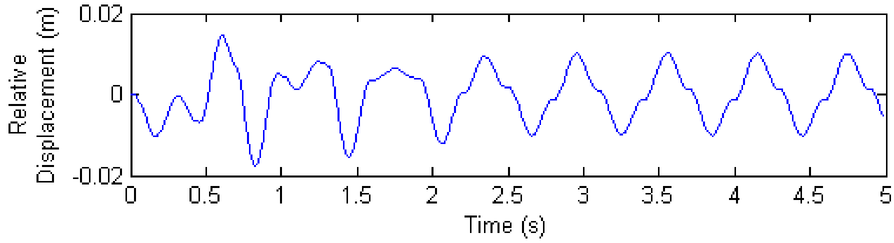


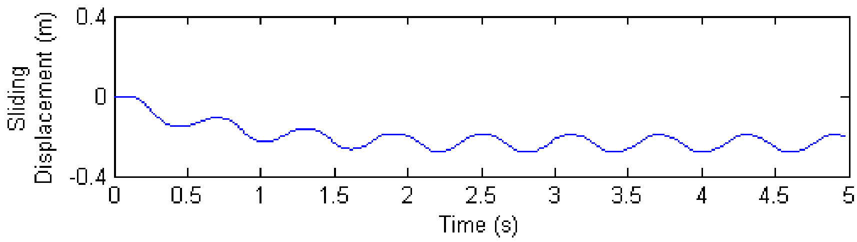
Figure 1 Pure friction isolated structure (Mostaghel 1983)



(a) Absolute acceleration of the structure

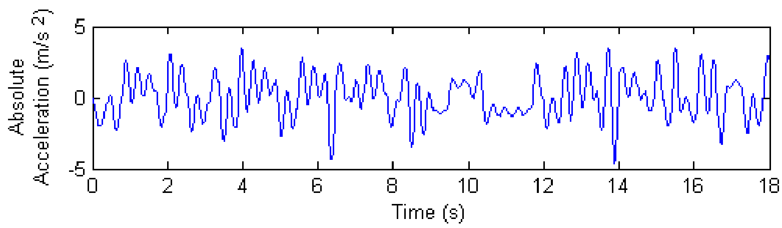


(b) Displacement of the structure relative to base mass

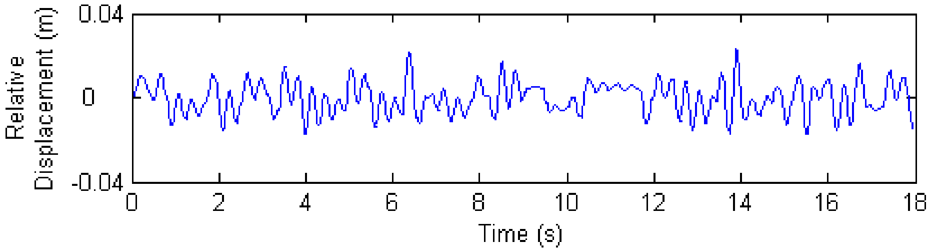


(c) Sliding displacement of the base mass

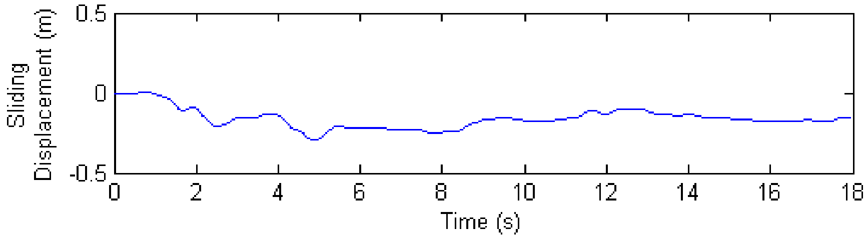
Figure 2 Typical time-history of SDOF structure isolated by PF system subjected to sinusoidal excitation



(a) Absolute acceleration of the structure



(b) Displacement of the structure relative to base mass



(c) Sliding displacement of the base mass

Figure 3 Typical time-history of SDOF structure isolated by PF system subjected to El Centro 1940(NS) ground motion

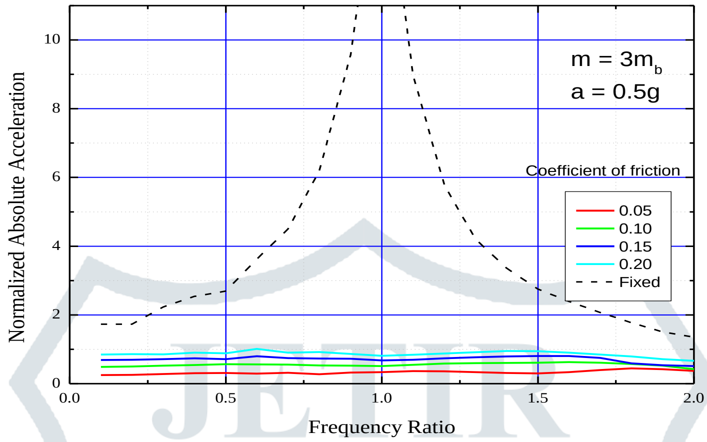


Figure 4 Variation of Acceleration with frequency ratio for harmonic excitation

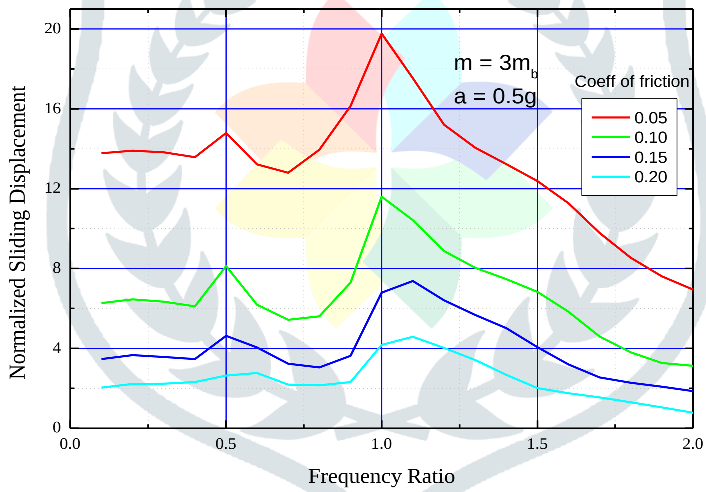


Figure 5 Variation of Sliding displacements with frequency ratio for harmonic excitation

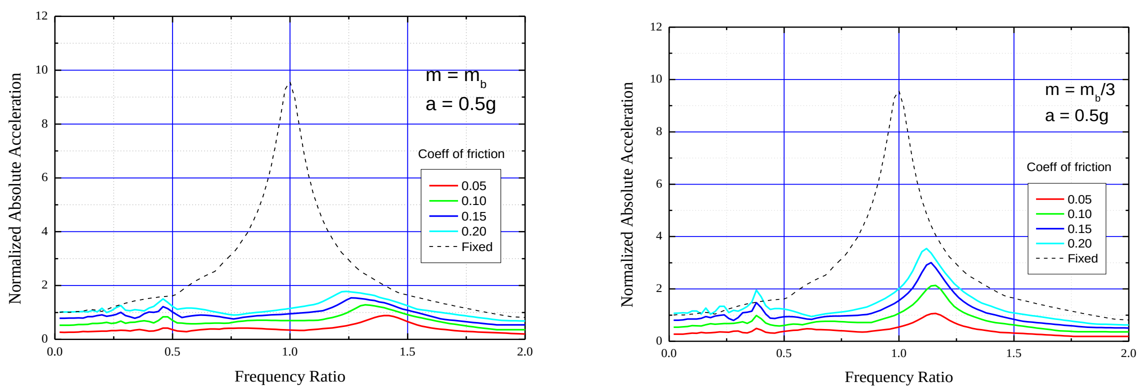


Figure 6 Variation of Acceleration with frequency ratio for harmonic excitation

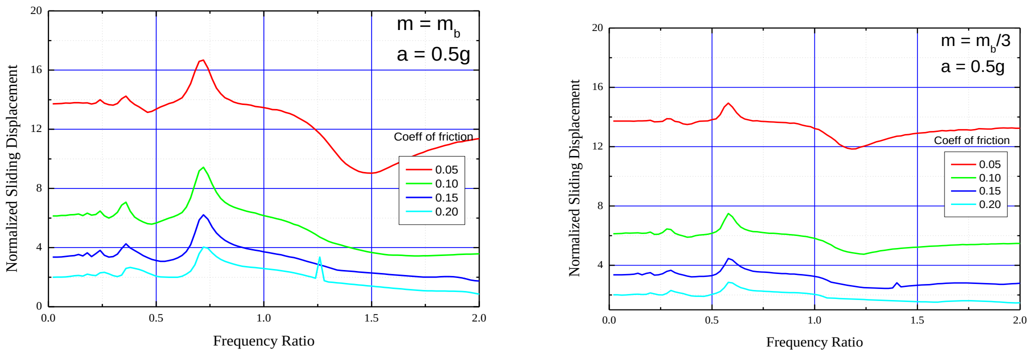


Figure 7 Variation of Sliding displacements with frequency ratio for harmonic excitation

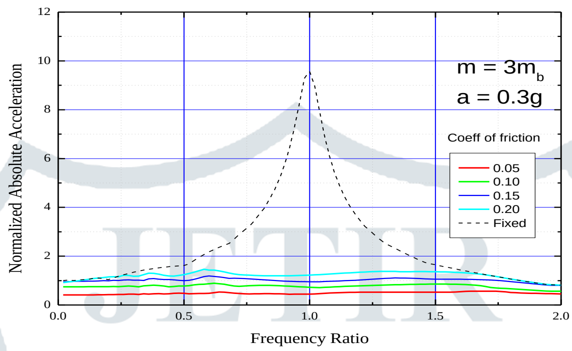


Figure 8 Variation of Acceleration with frequency ratio for harmonic excitation

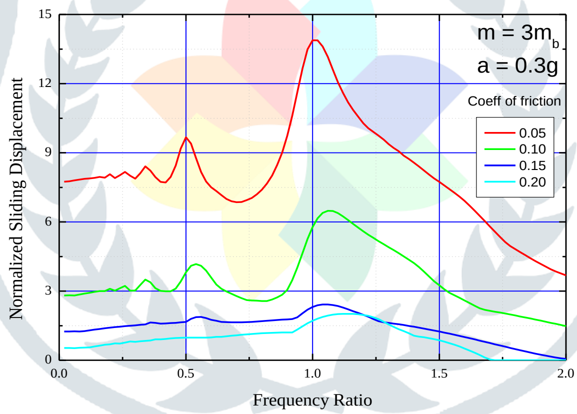


Figure 9 Variation of Sliding displacements with frequency ratio for harmonic excitation

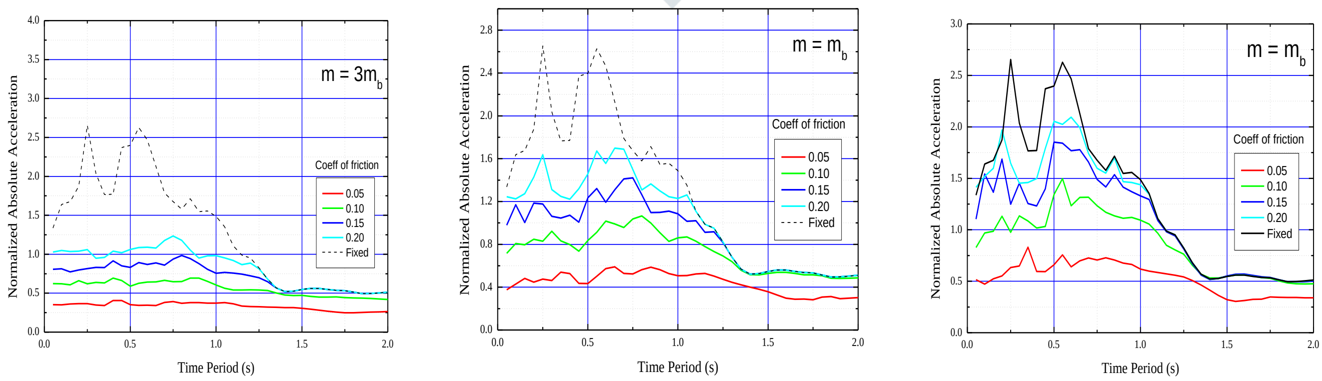


Figure 10 Acceleration responses for El Centro 1940 earthquake

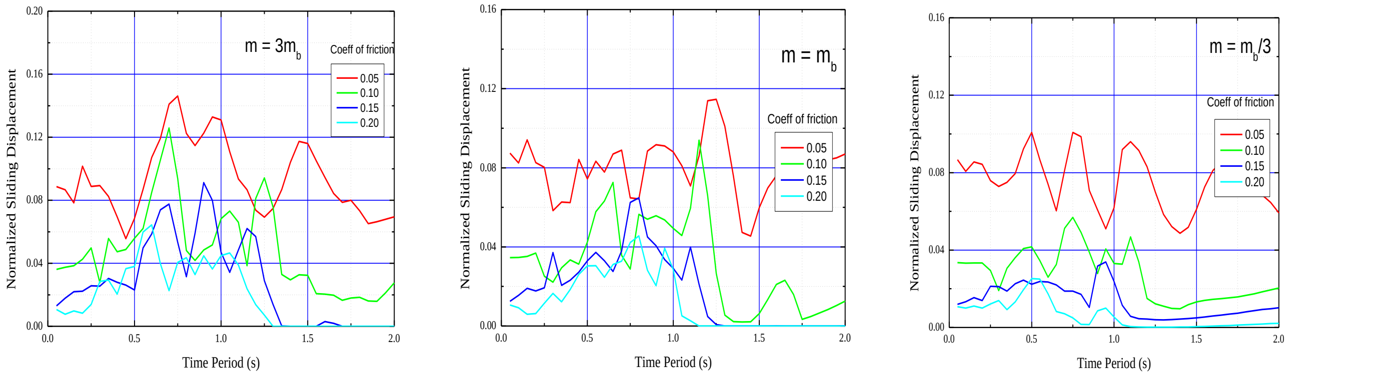


Figure 11 Sliding displacement responses for El Centro 1940 earthquake

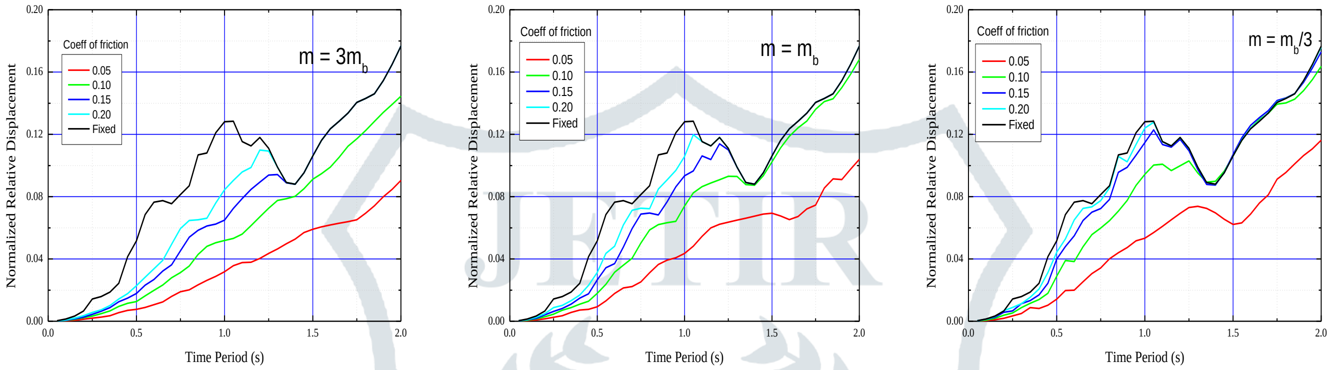


Figure 12 Relative displacement responses for El Centro 1940 earthquake

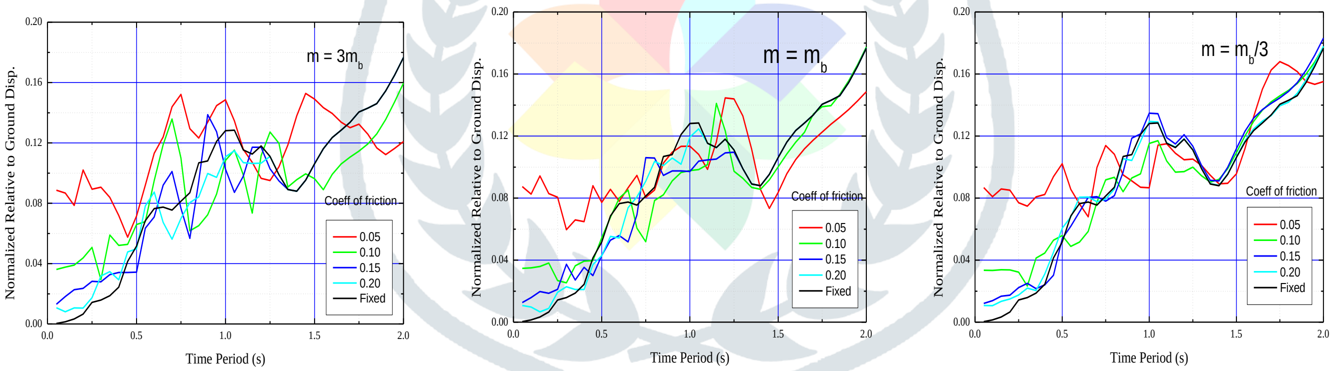


Figure 13 Relative to ground displacement response for El Centro 1940

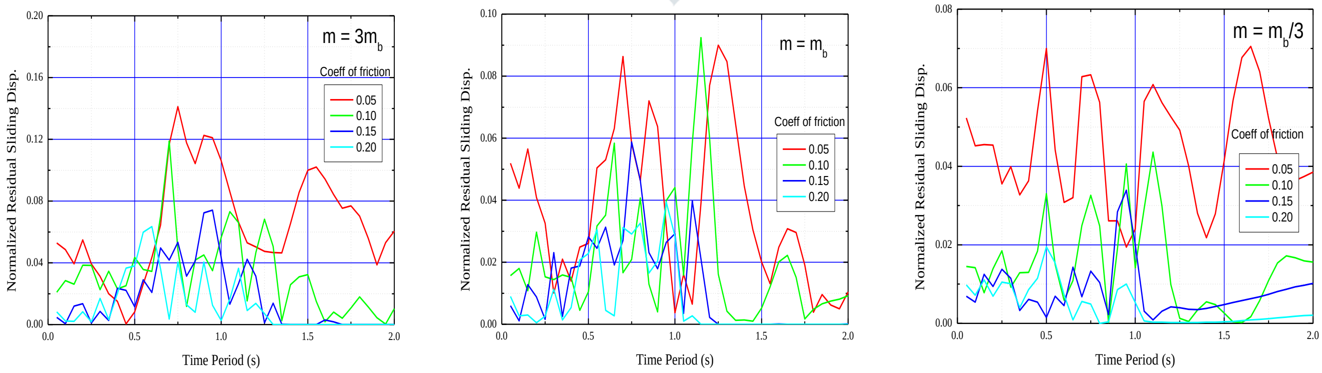


Figure 14 Residual sliding displacement responses for El Centro 1940

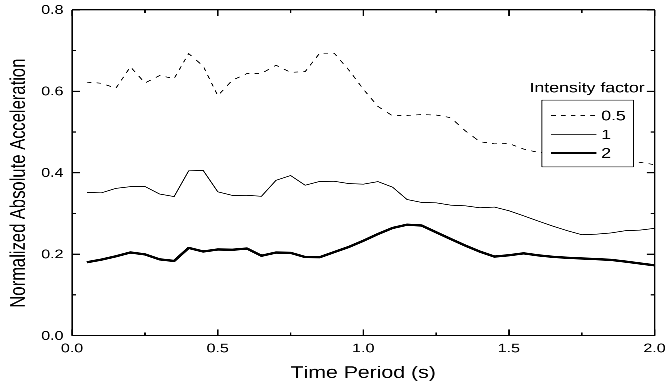


Figure 15 Acceleration response for scaled El Centro intensities

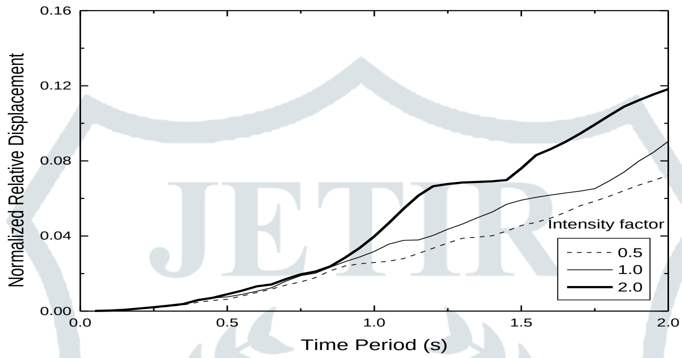


Figure 16 Displacement response for scaled El Centro intensities

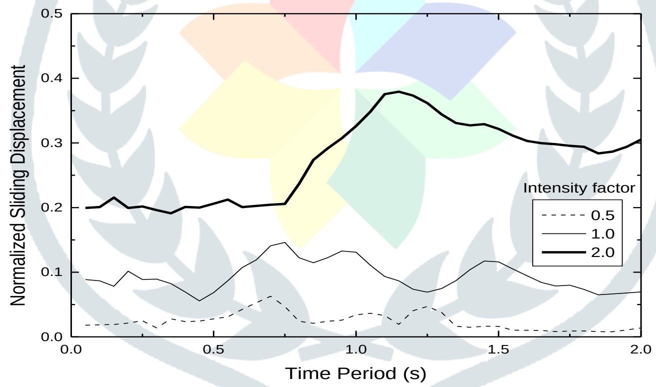


Figure 17 Sliding displacement response for scaled El Centro intensities

III. CONCLUSIONS

In this investigation, SDOF and MDOF structure isolated using pure friction isolation system were studied in detail. These systems were subjected to harmonic and earthquake excitation. Since the first mode participates maximum in the response of the structure, therefore, a two DOF model was considered. To ascertain the effectiveness of pure friction system in restricting the forces transferred to the structure, shear beam structure was taken for study. Based on the results obtained for different systems, and for different parametric studies following conclusions can be made:

1. The results obtained show that the pure friction was quite effective in restricting the forces transferred to the structure, when the structure was subjected to harmonic and earthquake excitations.

2. Since most of the real life structures are MDOF system, a MDOF system was chosen for study and it was found that pure friction isolation system equally effective in reducing the forces transmitted to the structure during earthquakes. The only disadvantage of sliding systems is the large sliding displacement during excitations.

3. Since first few modes contribute maximum to the response of the structure, the structure can be modelled as 2 DOF systems. The sliding systems are quite effective in reducing the peak responses of MDOF structures under both harmonic and earthquake excitations. Practically good results can be obtained for the MDOF structure treating the superstructure as SDOF system.

4. The PF system was found to be quite effective in the case of shear beam structure.

5. It has been established that sliding supports can be quite effective in controlling the level of acceleration response of structures; therefore, the sliding supports can effectively isolate structures from support excitations and are practical.

6. It was observed that the level of acceleration response of sliding structures especially for larger mass ratios is almost independent of the period of the input excitations and depends only on the base's coefficient of friction. It can be reduced considerably by reducing the base's coefficient of friction.

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