Earthquakes and Structures, Vol. 3, No. 2 (2012) 169-180
DOI: http://dx.doi.org/10.12989/eas.2012.3.2.169

Effect of ground motion characteristics on the pure friction isolation system

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(Received September 9, 2011, Revised November 21, 2011, Accepted December 4, 2011)

Abstract. The performance of pure friction isolation system with respect to the frequency bandwidth of excitation and the predominant frequency is investigated. A set of earthquake ground motions (artificial as well as recorded [with different combinations of magnitude-distance and local site geology]) is considered for investigating effectiveness of pure friction isolators. The results indicate the performance of pure friction base isolated system does not only depend upon coefficient of friction and mass ratio but the stick-slip behaviour depends upon the frequency content of the excitation as well. Slippage prevails if the excitation frequency lies in a suitable frequency range. This range widens with increasing mass ratio. For larger mass ratios, the sliding effect is more pronounced and the maximum acceleration response is further reduced in the neighbourhood of frequency ratio (ω/ω_n) of unity. The pure friction isolation system is effective in the case of broadband excitations only and that too, in the acceleration sensitive range of periods. The pure friction system is not effective for protection against narrow band motions for which the system response is quasi-periodic.

Keywords: band-limited excitation; earthquake; ground motion characteristics; friction isolation; frequency content; shape factor

1. Introduction

Earthquake protection by passive control can be classified into two broad categories namely, base isolation and the use of supplemental dampers for energy dissipation (Soong and Dargush 1997, Hanson and Soong 2001, Christopoulos and Filiatrault 2006, Takewaki 2009). In the base isolation technique, the super-structure is decoupled from the sub-structure by means of seismic isolation bearings, which check the transmission of seismic waves to the super-structure thereby limiting the deformations (Naeim and Kelly 1999). Most of the base isolation devices employ some kind of re-centering mechanism, which minimizes the possibility of any residual drift after an earthquake. These base isolation devices, however, tend to be rather large and heavy in addition to being expensive. A sliding system without any re-centering mechanism, for example, pure friction base isolation system, however, does not require any sophisticated manufacturing process and is the simplest among all base isolation devices. A typical pure friction system consists of decoupling the super-structure from its foundation at the plinth level by means of a pure friction interface. The

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smaller the coefficient of friction the lesser is response acceleration and base shear. There is no restoring force provided by any type of external horizontal spring or damping elements, which causes residual displacement at the sliding interface at the end of the earthquake. Special attention needs to be given to keep these displacements within acceptable limits. Since a lower friction coefficient leads to larger sliding displacement, a usable range of friction coefficient has been suggested by Nikolic-Brzev (1993) to be in the range (0.05-0.15).

The performance of pure friction sliding system under harmonic and earthquake type excitation has been under scrutiny for a long time (e.g. see Mostaghel and Tanbakuchi 1983, Mostaghel *et al.* 1983, Masashi *et al.* 1992, Jangid 1996, Shakib and Fuladgar 2003, Jangid 2005, Qamaruddin and Ahmad 2007, Ahmad *et al.* 2009, Ozbulut and Hurlebaus 2010, Oliveto *et al.* 2008, Nanda *et al.* 2010, 2011). While these studies explored the feasibility of pure friction systems for mitigating the effects of earthquakes, little attention has been paid to the effect of ground motion characteristics on the performance of pure friction isolation system. We address this aspect of the problem in this study. The purpose of this paper is to study the effect of ground motion characteristics on the effectiveness of pure friction isolation system under harmonic excitations, recorded earthquake ground motions for different combinations of magnitude-distance and local site geology, as well a design spectrum compatible synthetic accelerogram.

2. Mathematical idealization

A lumped two-mass model, as shown in Fig. 1, is used to describe the seismic behavior of a single story building with a sliding interface (Westermo and Udwadia 1983, Mostaghel *et al.* 1983). The structure above the sliding joint is assumed to remain elastic as the purpose of base isolation is to reduce the earthquake forces in such a way that the system remains within elastic limit. The mass of the roof in addition to one half the mass of the wall is lumped at the roof (M_t) while the rest is lumped at the base with the mass of the bond beam (M_b). The base mass is assumed to rest on a

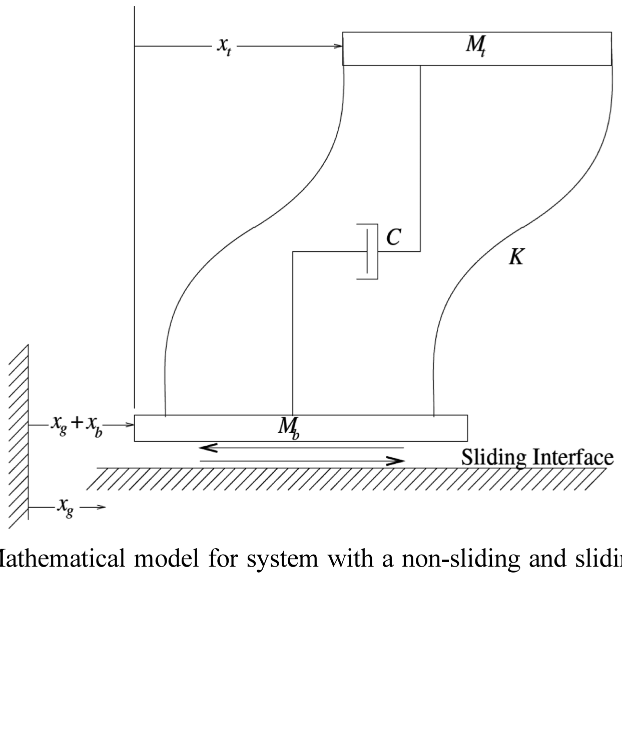


Fig. 1 Mathematical model for system with a non-sliding and sliding mode

plane with dry friction damping of coulomb type to permit sliding of the system. The possibility of rocking is neglected because of low height of the building.

Let the ground acceleration be denoted by $\ddot{x}_g$; x_t and x_b represent the relative displacement of top mass with respect to bottom mass and relative displacement of the bottom mass with respect to ground respectively; and θ (= M_t/M_b) be the mass ratio (MR). The natural frequency of the non-sliding system (ω_n) is related to the stiffness (K) and the top mass as $\omega_n = \sqrt{K/M_t}$, and ξ (= $C/2\omega_n M_t$) is the fraction of critical damping, where C is the damping coefficient. The coefficient of friction (μ) for the sliding interface governs the dynamic response of pure friction base isolation system. The friction characteristics of several sliding interfaces were examined experimentally (Nanda *et al.* 2011). For the range of velocities considered in the tests, the dynamic coefficient of friction was found to be only marginally lower than the static coefficient. Hence, a constant value of the coefficient of friction is considered to apply for both static as well as dynamic conditions. The effect of vertical component of earthquake ground motion can be easily accounted by considering an effective instantaneous coefficient of friction $\mu' = \mu(1+\ddot{z}_g/g)$, where $\ddot{z}_g$ denotes the instantaneous vertical component of ground acceleration and g is the acceleration due to gravity. The effect of vertical component on the acceleration response, however, has been reported to be negligible (Tsopelas *et al.* 1996) and hence not considered in this study.

2.1 Non-sliding condition

The governing differential equation for non-sliding condition can be obtained from equilibrium considerations as

$$M_t(\ddot{x}_g+\ddot{x}_t)+C\dot{x}_t+Kx_t = 0 \tag{1}$$

Eq. (1) may be rearranged as

$$\ddot{x}_t+2\xi\omega_n\dot{x}_t+\omega_n^2x_t = -\ddot{x}_g \tag{2}$$

The above equation governing the dynamic response of the system to base excitation during non-sliding condition is exactly same as that for a fixed base system.

2.2 Sliding condition

The sliding of bottom mass begins when the sliding force overcomes the frictional resistance at the plinth level. The building now acts as two degree of freedom system and governing differential equation of motion of top mass can be derived from equilibrium considerations

$$M_t(\ddot{x}_g+\ddot{x}_b+\ddot{x}_t)+C\dot{x}_t+Kx_t = 0 \tag{3}$$

Eq. (3) may be rearranged as

$$\ddot{x}_t+\ddot{x}_b+2\xi\omega_n\dot{x}_t+\omega_n^2x_t = -\ddot{x}_g \tag{4}$$

while the motion of the bottom mass may be described by

$$M_b(\ddot{x}_g+\ddot{x}_b)-C\dot{x}_t-Kx_t+(M_t+M_b)g\ \ \mathrm{sgn}(\dot{x}_b) = 0 \tag{5}$$

which may be rearranged as

$$\ddot{x}_b-2\xi\omega_n\theta\dot{x}_t-\omega_n^2\theta x_t+\mu(1+\theta)g\ \ \mathrm{sgn}(\dot{x}_b) = -\ddot{x}_g \tag{6}$$

where, $\mathrm{sgn}(x) = \begin{cases} 1, x>0 \\ -1, x<0 \end{cases}$ denotes the signum function.

The non-sliding condition prevails when the horizontal inertia force of bottom mass does not exceed the opposing friction force at plinth level, *i.e.*

$$|C\dot{x}_t+Kx_t-M_b(\ddot{x}_g+\ddot{x}_b)|<\mu(M_t+M_b)g \tag{7}$$

$$|2\xi\omega_n\dot{x}_t+\omega_n^2x_t-(\ddot{x}_g+\ddot{x}_b)/\theta|<\mu(1+1/\theta)g \tag{8}$$

As long as the dynamic lateral force does not exceed the frictional resistance at the sliding interface, there is no relative movement between the bottom mass and the base/ground, *i.e.* $x_b = 0$. The sliding initiates whenever the force acting at the base exceeds the frictional resistance and stops whenever the non-slip condition (Eq. (8)) holds. Thus at any time instant response of the building can be obtained by solving either Eq. (2) when the non-sliding condition (Eq. (8)) holds, or two coupled differential equations (Eqs. (4) and (6)) during the sliding phase. These equations are solved by using Runge-Kutta 4th order solver in MATLAB-SIMULINK environment (Moler 2004).

3. Response to harmonic excitation

For a rigid block sliding motion is initiated when horizontal inertia force, which depends only the ground acceleration, exceeds the opposing frictional force. But from sliding condition it is seen that bottom mass of the system experiences the time dependent elastic and (viscous) damping forces, which promote slippage. To investigate the performance of pure friction system to the excitation frequency, a finite duration harmonic base excitation is assumed as

$$\ddot{x}_g = \begin{cases} A\sin(\omega t); 0 \le t < 30s \\ \quad 0;\ \ \text{otherwise} \end{cases} \tag{9}$$

with ω, the harmonic frequency, being varied to cover a wide range of frequency ratio (FR = ω/ω_n) by keeping natural frequency of the super structure 50 pi rad/s approximately (Nanda *et al.* 2010). The amplitude (A) of the sinusoid is considered to correspond to the most severe zone with the effective peak ground acceleration (PGA) of 0.36g for maximum considered earthquake (MCE) condition (IS: 1893 (Part 1) 2002). Ariga *et al.* (2006) and Takewaki (2008) also recommend the use of frequency ratios to study the dynamic response of base isolated buildings to resonant excitation. Further, they have highlighted the vulnerability of base isolated high-rise buildings to long-period waves.

Following parameters are chosen for evaluating the effect of frequency content on the response of single story masonry buildings with pure friction sliding interface.

The frequency ratio ($FR = \omega/\omega_n$) is varied from 0.05 to 10 to cover a large range of structural systems; mass ratio (MR) = 1, 2 and 5; and friction coefficient (μ) = 0.075, 0.10 and 0.15. The maximum absolute acceleration of the roof mass is the response quantity of interest for its direct

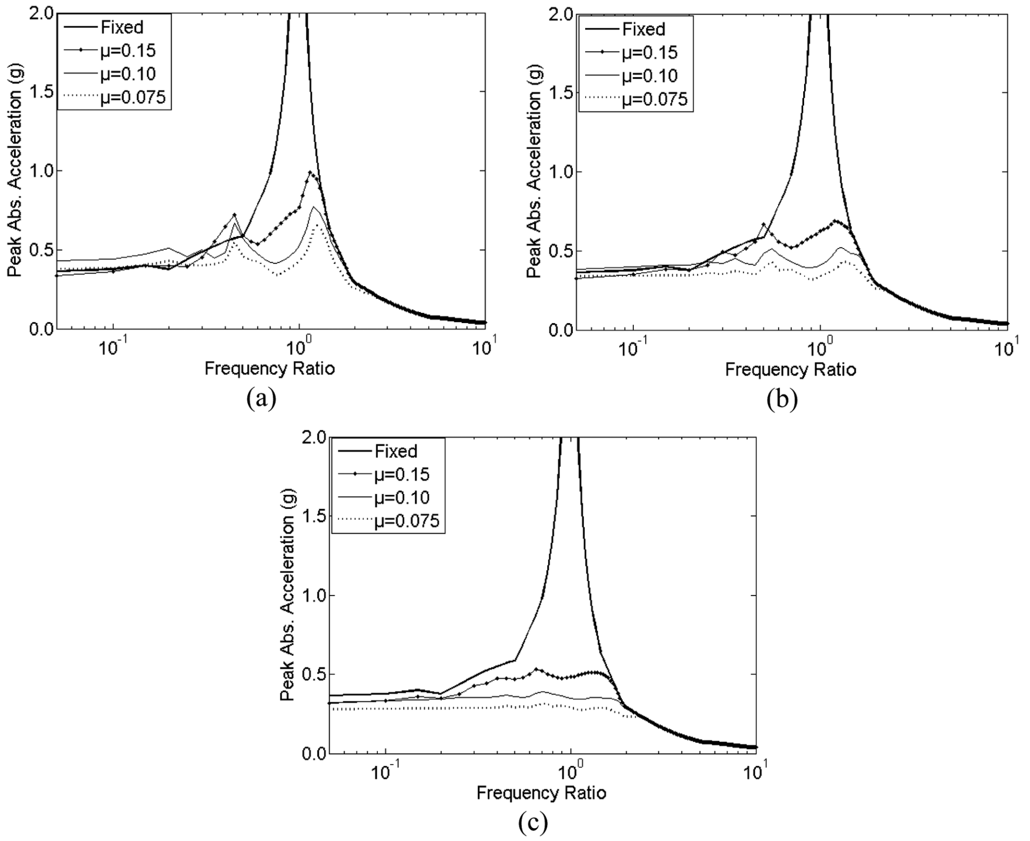


Fig. 2 Peak absolute acceleration response of the roof mass versus frequency ratio for MR=1 (a), MR=2 (b) and (c) MR=5

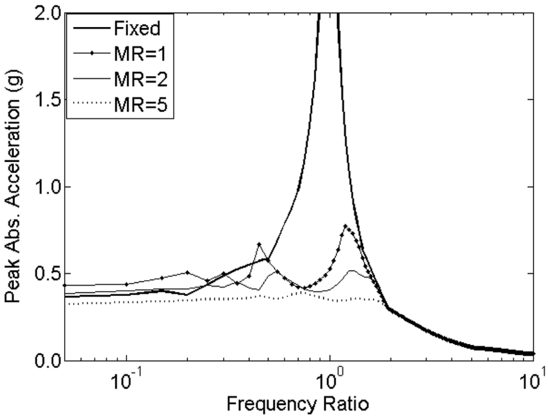


Fig. 3 Peak absolute acceleration response of the roof mass versus frequency ratio for different mass ratios ($\mu = 0.1$)

relationship with the maximum base shear and maximum bending moment at the base.

Fig. 2 shows the maximum absolute acceleration response of top mass versus frequency ratio for different mass ratios (MR = 1, 2 and 5) with different coefficients of friction and 5% viscous damping. For mass ratio of 1, there is a reduction in maximum top mass acceleration in the range of frequency ratio from 0.3 to 1.5 for sliding interface model vis-a-vis the fixed base model. For larger mass ratios the sliding effect is more pronounced and the maximum acceleration response is further reduced in the neighbourhood of FR = 1. For FR >> 1 the inertia force at bottom mass, M_b will be greater than the force on M_b due to oscillation of mass M_t and the net force along the interface is too small to cause sliding and the system will behave as fixed base. Hence, for frequencies larger than ω_n the sliding system response equals to that of the fixed base system.

Fig. 3 shows maximum absolute acceleration response of top mass versus FR for different mass ratios with coefficient of friction, $\mu = 0.1$ and 5% damping. For harmonic excitations, the friction isolation system response exhibits multiple poles. Due to these multiple resonant peaks, the maximum response of pure friction isolation system may be greater than the response of fixed base system to harmonic excitation (Westermo and Udwadia 1983). This effect is more pronounced for smaller mass ratios (Fig. 3).

4. Effect of excitation bandwidth

Since the presence of sub-harmonic peaks in the response of pure friction sliding system to harmonic excitation causes and increase in the absolute acceleration response of the top mass for certain range of frequency ratio, it is important to investigate the effect of excitation bandwidth on the computed response. Several excitation time histories are generated by the superposition of sinusoids for studying the effect of the spectral bandwidth of excitation on performance of pure friction isolation system as

$$\ddot{x}_g = \begin{cases} A \sum_{k=-m}^{m} sin(\omega + k\Delta\omega)t; 0 \le t < 30s \\ \quad 0;\text{otherwise} \end{cases} \tag{10}$$

where, m is a parameter controlling the number of components in the summation thereby controlling the bandwidth of excitation, and $\Delta\omega$ is a fixed increment to the central frequency ($\omega = 5$ pi rad/s), which is considered as 0.2 pi rad/s with PGA scaled to $0.36g$. The bandwidth of excitation is

Table 1 The number of wave components and corresponding shape factor

Number of components (m)	Shape factor(δ)
3	0.09
6	0.18
9	0.25
12	0.32
15	0.37
20	0.46

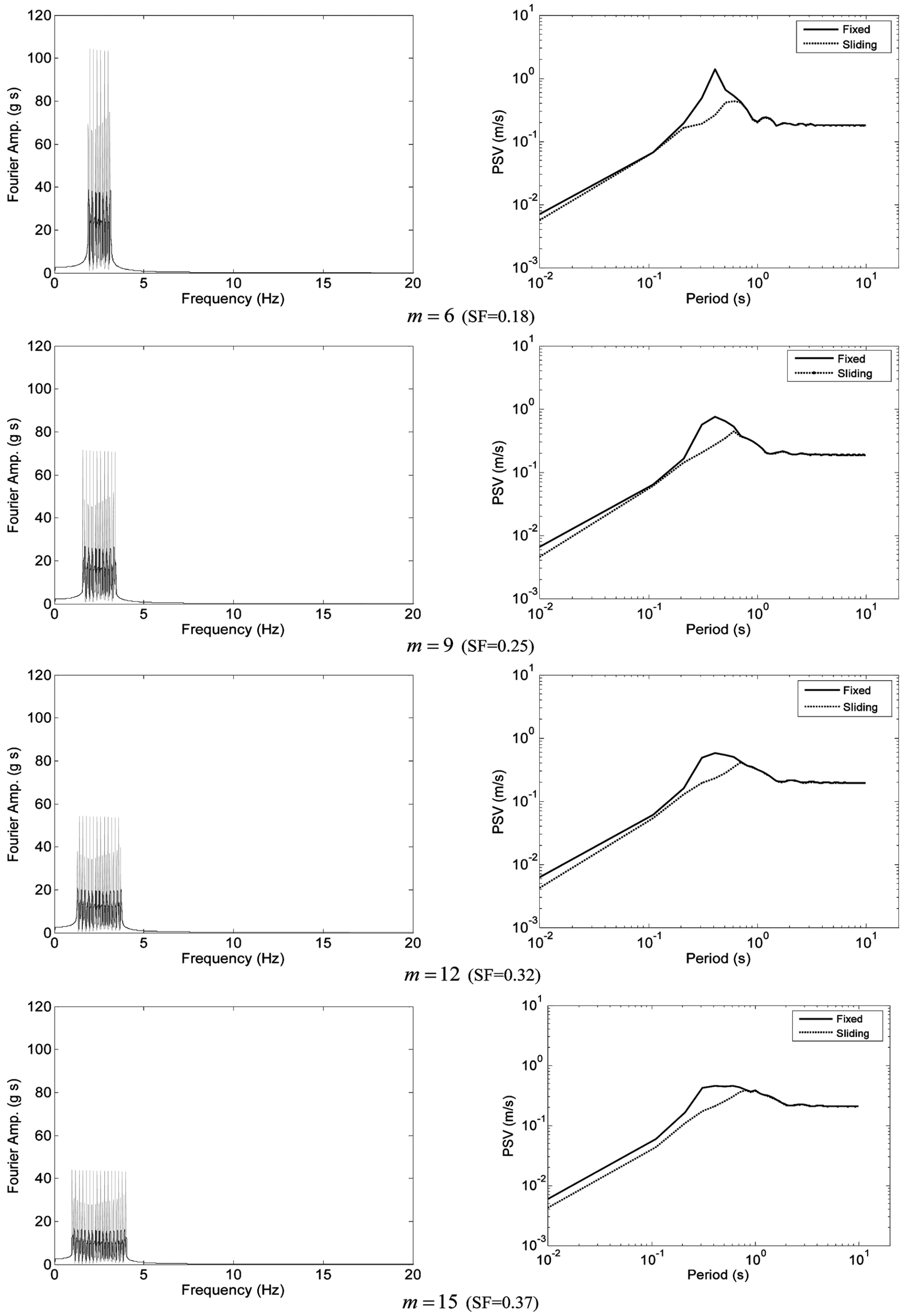


Fig. 4 Smooth Fourier amplitude spectra of different shape factor ground excitation and corresponding 5% damped PSV response for fixed and isolated model

characterized by a dimensionless parameter, known as the shape factor (δ), which is defined in terms of first three spectral moments as (Vanmarcke 1976)

$$\delta = \sqrt{1-\lambda_1^2/\lambda_0\lambda_2} \tag{11}$$

where, λ_0, λ_1 and λ_2 are respectively the zeroth, first and second spectral moments defined by (Kramer 2004)

$$\lambda_i = \int_0^{\omega_n} \omega^i G(\omega)\mathrm{d}\omega; i = 0, 1, 2 \tag{12}$$

where, ω_N denotes the Nyquist frequency, and $G(\omega)$ is the one-sided power spectrum of the time series. This shape factor has limiting values of 0 for single harmonic signal and 1 for a broad-band signal (high frequency waves dithering on a low frequency carrier wave), while a value of 0.5 corresponds to a band-limited white noise.

These time histories of different shape factors are used as the horizontal excitation for studying the effectiveness of isolation system. Table 1 shows number of wave components and the corresponding shape factor.

Fig. 4 shows Smooth Fourier amplitude spectra of excitation time histories of different band widths and the Pseudo-Spectral Velocity (PSV) response for fixed and isolated model of mass ratio 2, damping coefficient 5% and coefficient of friction of sliding interface 0.1 for these excitation time histories. Though the maximum absolute acceleration response is directly proportional to the maximum design forces, we consider the PSV response spectrum, which provides an idea of the distribution of seismic energy with respect to frequencies. For an undamped oscillator, the PSV spectrum provides an upper bound for the Fourier amplitude spectrum of the excitation. The pseudo- acceleration spectrum can be readily derived from the PSV spectrum. It can be seen that for narrow band excitations, where the response is more like periodic in nature, the response reduction in pure friction isolation system is not significant, except in a narrow band of intermediate natural frequencies in the neighbourhood of the central frequency of excitation. As the excitation bandwidth increases, the pure friction isolation system gets more effective in suppressing the response at short periods whereas practically ineffective in reducing the response of long period systems.

5. Response to earthquake time histories

Several recorded accelerograms as well as an artificial accelerogram that is compatible with design spectrum of Indian standard (IS 1893 (Part 1) 2002) corresponding to the level of maximum considered earthquake in the most severe seismic zone (PGA = 0.36*g*) are considered for studying the effectiveness of the pure friction isolator. The average coefficient of friction of 0.1 with mass ratio 2 is considered. The recorded accelerograms used in this study are: (1) transverse component with 0.113*g* PGA, Central Chile Earthquake of March 3, 1985 recorded at Cauquenes, Chile; (2) S-E component with 0.358*g* PGA, California earthquake of May 18, 1940 recorded at Imperial Valley Irrigation Project, EL Centro, 8.8 km from the fault and (3) N 75 E component with 0.346*g* PGA, Uttarkashi earthquake of October 20, 1991 recorded at Uttarkashi, India, 32.4 km from fault, and are shown in Fig. 5. All accelerograms are scaled to have PGA of 0.36*g*.

Fig. 6 shows Smooth Fourier amplitude versus frequency of different recorded and artificial accelerogram and the corresponding PSV response for fixed and isolated model. The shape factors for spectral bandwidth are found to be 0.30, 0.56, 0.48 and 0.66 for Chile earthquake, El Centro earthquake, Uttarkashi earthquake and spectrum compatible artificial accelerogram respectively. For Chile earthquake, a relatively narrow-band excitation, it has been observed that the isolation is not effective with less reduction in the response curve of sliding model over fixed response. At a few periods, the response of sliding model even exceeds the fixed-base response. This is due to quasi-periodic nature of response to narrow-band excitation. The critical nature of narrowband excitation has also been established by Takewaki and co-workers (Takewaki 2001, 2006, Moustafa *et al.* 2010). For all other broadband excitations, the pure friction isolation system is quite effective in reducing the seismic response in the short period range or, the acceleration sensitive region. At long periods, the pure friction isolation system is practically ineffective in controlling seismic response.

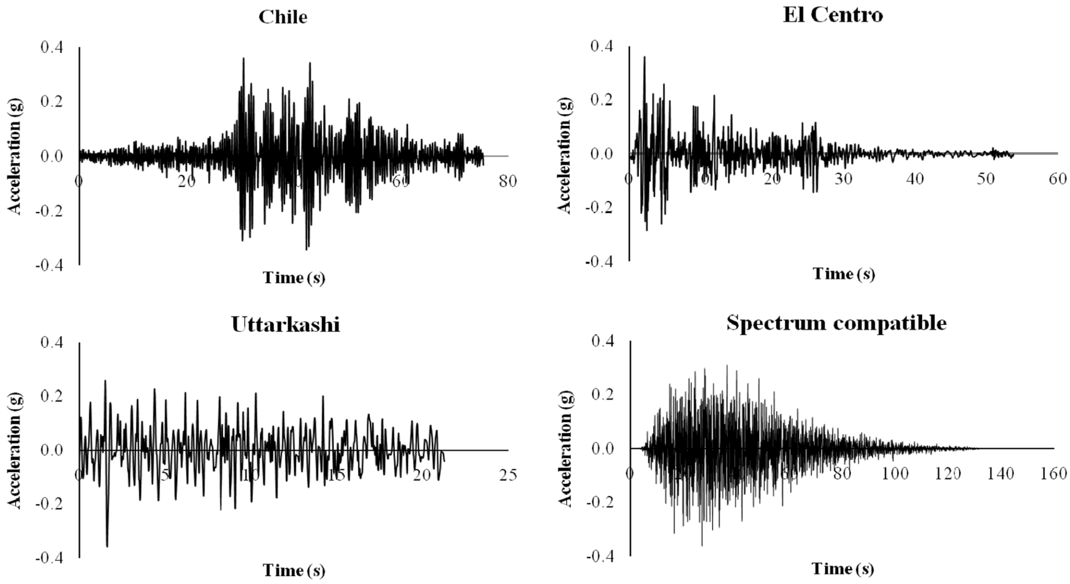
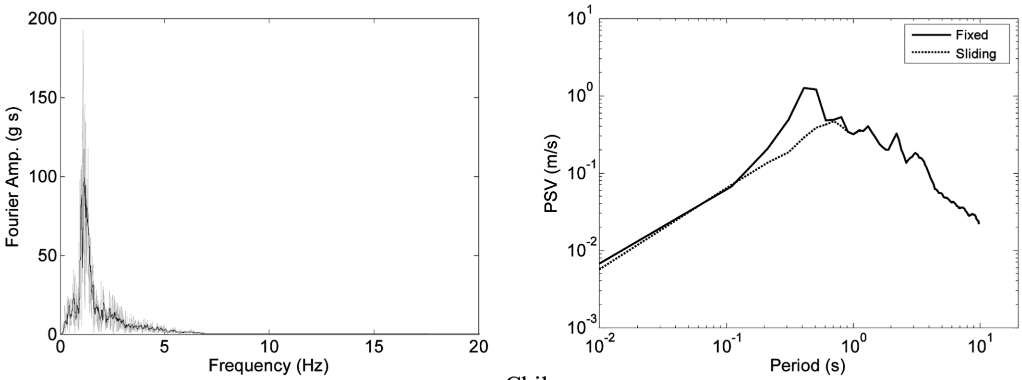


Fig. 5 Time histories of recorded and artificial earthquake



Chile

Fig. 6 Smooth Fourier amplitude spectra of different recorded and artificial accelerogram and corresponding PSV response for fixed and isolated model

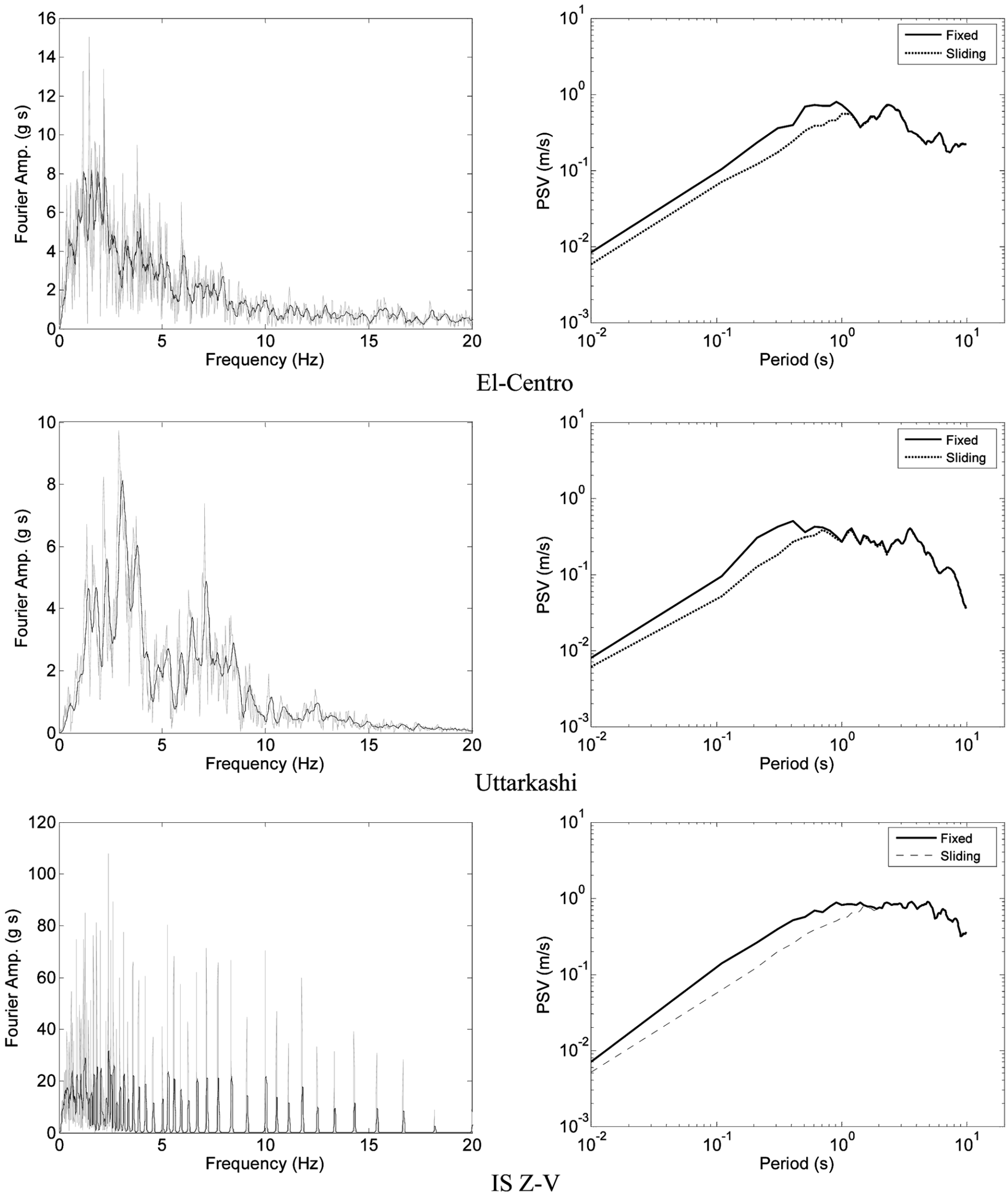


Fig. 6 Continued

6. Conclusions

The performance of pure friction base isolated system does not only depend upon coefficient of friction and mass ratio but the condition of slippage depends upon frequency content of the excitation as well. The frequency response function indicates that slippage prevails if the excitation frequency lies in a suitable frequency range. This range increases with higher mass ratio. For mass ratio of 1 in the range of frequency ratios from 0.3 to 1.5 there is a reduction in maximum top mass acceleration for sliding interface model vis-a-vis the fixed base model. For larger mass ratios the sliding effect is more pronounced and the maximum acceleration response is further reduced in the neighbourhood of FR = 1. The response for harmonic excitation shows several sub harmonic resonant frequencies so that the peak response of such system may not be necessary less than that of fixed response. The pure friction isolation system is effective in the case of broadband excitations only and that too, in the acceleration sensitive range of periods. The pure friction system is not effective for protection against narrow band motions like Chile earthquake for which the system response is quasi-periodic.

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