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BEHAVIOR OFSLIDING ISOLATORS WITHVARIABLE FRICTIONUNDER NEAR-FAULTEARTHQUAKES

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ABSTRACT

One of the ways to make FPS adaptable is to make its friction coefficient variable.For a sliding isolator with variable friction (SIVF), the sliding surface may have a constant radius, but the friction coefficient of the isolator is assumed to be a function of the isolator displacement which results in adaptive damping that varies along the isolator displacement.Variable Friction Pendulum System (VFPS) is a kind of SIVF isolator whichis very similar to FPS except that the friction coefficient of FPS is considered to be constant whereas the friction coefficient of VFPS is variedin the form of a curve. However, suchavariation of coefficient of friction is difficult and impractical to be achieved in the real world.The present studyintroduces an alternative isolator, namely, Modified Variable Friction Pendulum System (M-VFPS) with a very simple and practical variation of coefficient of friction. To compare the responses of the two isolators, an idealized 2-DOF shear building with an isolation system modeled by a nonlinear friction element and a variable spring element is simulated by using a general mathematical model. Moreover, a set of seven near-fault earthquake excitations are considered for evaluation purposes with two main aspects governing effectiveness of isolator: (1) base displacement and (2) super-structural acceleration. The results indicate that the seismic behavior of M-VFPS is close to that of VFPS and, thus, it can be considered as an alternative. In addition, in comparison to a conventional FPS isolator, both M-VFPS and VFPS show better behavior in reduction of base displacement while they are not so successful in controlling of the acceleration transmitted to the super-structure.

INTRODUCTION

Seismic base isolation has been used with increasing popularity to protect structures, together with their occupants, secondary systems and internal equipment, from the damaging effects of earthquakes. Seismic isolation is indeed an approach to reduce transmitted earthquake forces to the super-structure by shifting the fundamental period of structure away from the predominant frequencies of ground excitation and minimize the structural damage as a result (Soni D. P. *et al.* 2011).

Among many different types of isolators, friction pendulum system (FPS) is a sliding isolator with a simple geometry that incorporates both energy dissipation and re-centering mechanism into one single unit (Zayas Victor A *et al.* 1987). The effectiveness of FPS isolator has been widely investigated both analytically and experimentally,and it has been found suitable for many different structures and excitation characteristics(Mokha Anoop *et al.* 1991, Tsai CS 1997, Almazán José L *et al.* 1998). The sliding surface of a FPS isolator is made spherical, so that the gravitational load of the structure applied on the slider will provide a restoring stiffness that help reduce residual isolator displacement.However, this restoring stiffness, which is proportional to the curvature of the sliding surface, will inevitably introduce a constant isolation frequency to the isolated structure. Due to the existence of this isolation frequency, a resonance problem may occur when FPS is subjected to strong long-period components of an earthquake, such as near-fault ground motions (Lu Lyan-Yawn *et al.* 2004, Lu Lyan-Ywan *et al.* 2006).

This limitation led researchers to incorporate passive adaptability into FPS. Researchers have recently introduced three types of fully passive-adaptive FPS: (1) sliding isolators with multiple sliding surfaces (SIMSS), (2) sliding isolators with variable friction (SIVF), and (3) sliding isolators with variable curvature (SIVC). Each type is briefly reviewed, below (Lu Lyan-Ywan *et al.* 2011).

(1) In the SIMSS group, the developed isolators usually have more than one spherical sliding surface. By arranging the multiple sliding surfaces of the SIMSS in different ways, the isolator is able to accommodate a larger isolator displacement in a relatively smaller isolator size (Fenz Daniel M 2008). (2) For an SIVF isolator, the sliding surface may have a constant radius, but the friction coefficient of the isolator is assumed to be a function of the isolator displacement which results in adaptive damping that varies along the isolator displacement (Panchal VR and Jangid RS 2008). (3) In the SIVC group, the isolator has a sliding surface of variable curvature rather than a spherical surface with constant radius (Lu Lyan-Ywan *et al.* 2011).

Variable Friction Pendulum Isolator (VFPS) is a kind of SIVF isolator (Panchal VR and Jangid RS 2008). The variation of coefficient of friction in VFPS is based on a curve, which seems difficult to be achieved from a practical point of view. This study introduces Modified Variable Friction Pendulum System (M-VFPS) which uses a very simple and practical variation of coefficient of friction. The behavior of VFPS and its modified version, M-VFPS, together with the conventional FPS are simulated and compared in the present investigation.

Two aspects of seismic responses, namely, base displacement and super-structural acceleration are considered for comparison purposes. Since the behavior of sliding isolators is highly nonlinear, researchers have proposed different friction models to simulate this nonlinearity in numerical simulation (Jangid RS 2005). We have used the modified viscoplasticity friction model which is a continuous model of the frictional force and is based on the Wen equation (Constantinou M. *et al.* 1990).

From the investigations presented herein, it is observed that M-VFPS can be considered as a good alternative for VFPS.

DESCRIPTION OF VFPS AND M-VFPS

Variable Friction Pendulum System (VFPS)

The VFPS is very similar to FPS in regards of details and operation. The difference between FPS and VFPS is that the friction coefficient of FPS is considered to be constant whereas the friction coefficient of VFPS is variedin the form of a curve. Such variation of friction coefficient in VFPS can be achieved by gradually varying the roughness of spherical surface. Figure 1illustrates the comparison between friction coefficient of FPS and VFPS(Panchal VR and Jangid RS 2008).

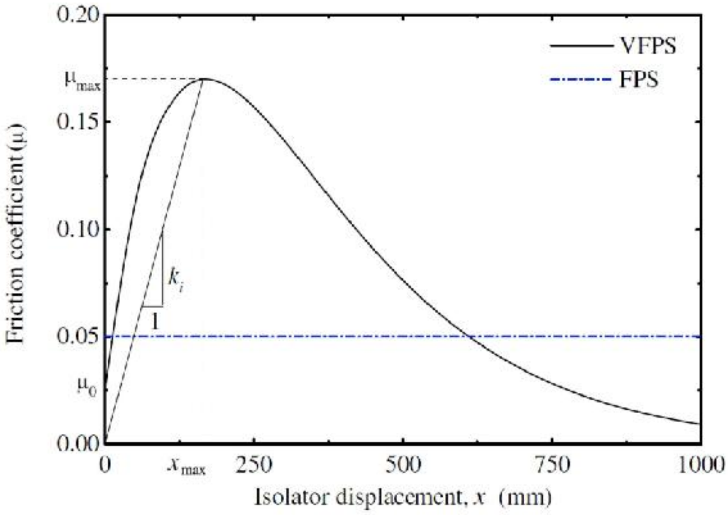

Figure 1. Comparison between friction coefficient of FPS and VFPS(Panchal VR and Jangid RS 2008)

The equation adopted to define the curve for friction coefficient, μ, of theVFPS is as follows (Panchal VR and Jangid RS 2008):

$$\mu(x) = (\mu_0 + a_1|x|)e^{-a_2|x|} \tag{1}$$

Where $\mu_0$is the initial value of friction coefficient; $a_1$and $a_2$are the parameters that describe the variation of friction coefficient along the sliding surface of VFPS; and $x$is the isolator displacement. To find the above parameters, one can approximate the curve by drawing a straight line from the origin up to the peak value of the friction coefficient which is generally kept in the range of 0.15–0.2. The slope of the line gives initial stiffness of the VFPS which controls the initial time period of it.

The initial stiffness, k_i, and initial time period, T_i, of the VFPS are given by

$$k_i = \frac{\mu_{max} W}{x_{max}} \tag{2}$$

$$T_i = 2\pi \sqrt{\frac{M}{k_i}} \tag{3}$$

Where $\mu_{max}$is the peak friction coefficient of the VFPS; $x_{max}$is the isolator displacement corresponding to peak friction coefficient of VFPS; W is as defined before; M is the total mass of the base-isolated building. The value of $x_{max}$is found out by maximizing the friction coefficient of VFPS and it is expressed by

$$x_{max} = \frac{a_1 - \mu_0 a_2}{a_1 a_2} \tag{4}$$

Knowing the initial value of friction coefficient μ_0(usually assumed to be 0.025) and selecting initial time period and peak friction coefficient, the parameters $a_1$and $a_2$can be evaluated by solving equations(1)-(4).

Modified Variable Friction Pendulum System (M-VFPS)

The variation of coefficient of friction in M-VFPS is not based on a curve. Instead a modified variation of coefficient of friction is used as shown in Figure 2. The variation of coefficient of friction in M-VFPS is such that it is identical to FPS all through the isolator except in the displacement range from 0.5x_{max} to 1.5x_{max} (x_{max}as defined before)through which the coefficient of friction is equal to μ_{max} of VFPS.

In mathematical form, variation of μ in M-VFPS is defined as follows:

$$\mu(x) = \begin{cases} \mu_{FPS} & 0 \le x \le 0.5x_{max} \\ \mu_{max\,VFPS} & 0.5x_{max} < x < 1.5x_{max} \\ \mu_{FPS} & x > 1.5x_{max} \end{cases} \tag{5}$$

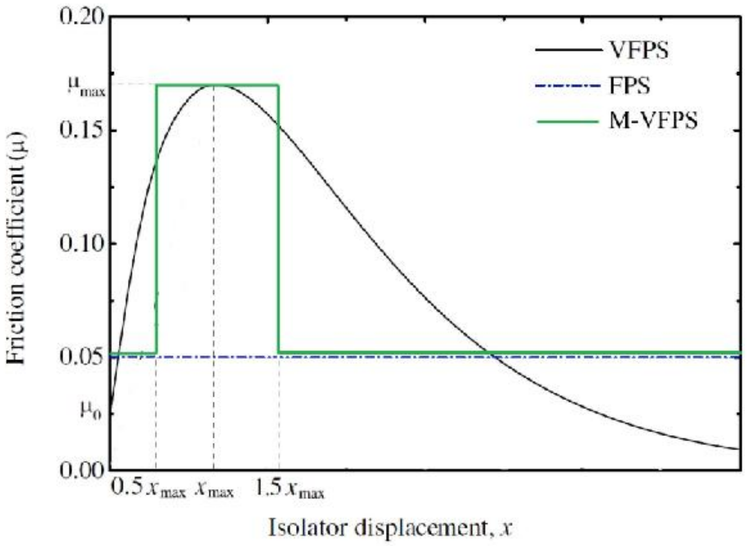

Figure 2. Comparison between friction coefficient of FPS, VFPS and M-VFPS

NUMERICAL SIMULATION

To compare the seismic behavior of the two isolators under study, a SDOF structure atop an isolation system is investigated. The SDOF superstructure chosen to be isolated has the same mass, stiffness, and damping properties as the superstructure in the M. Pranesh and R. Sinha research (Pranesh M. and Sinha Ravi 2000). The mass of the structure and base are taken equal, so that the mass ratio is 0.5. Stiffness of the structure is taken such that the time period of fixed-base structure is 0.5 s, while its damping ratio is taken as 2 percent of critical value.

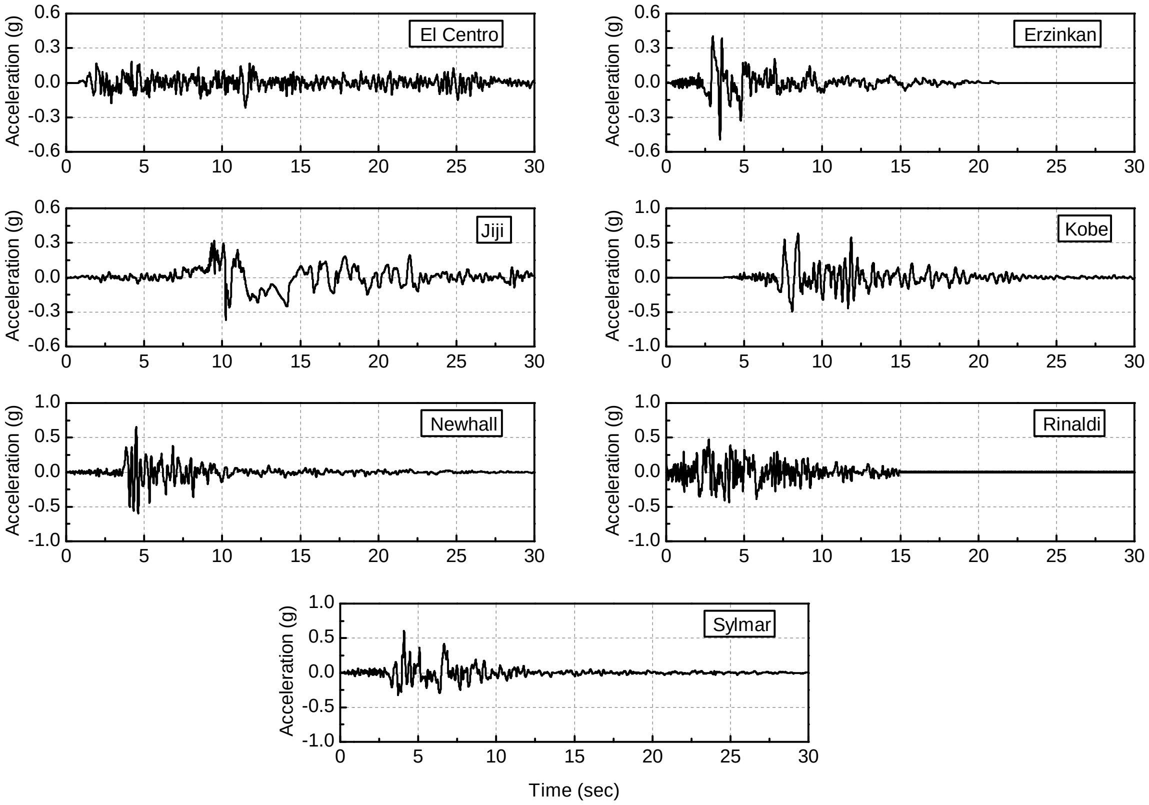

Figure 3.Waveforms of ground accelerations used in the simulation

Table 1.Description of ground motions used in numerical simulation

Earthquake	Year	Station	Magnitude(M_w)	PGA(g)
El Centro	1940	El Centro Array # 9	7.0	0.215
Erzinkan	1992	Erzincan	6.9	0.495
Jiji	1999	TCU068	7.6	0.566
Kobe	1995	KJMA	6.9	0.631
Newhall	1994	Fire Station	6.7	0.583
Rinaldi	1994	Receiving Station	6.7	0.472
Sylmar	1994	Olive View Med FF	6.7	0.604

A set of seven unidirectional near-fault earthquake excitations, recommended for evaluation of smart base isolated building (Narasimhan Sriram *et al.* 2006) are considered for evaluation purposes, waveforms and details of which are shown in Figure 3 and Table 1, respectively.

The idealized structure explained before, is simulated by using a general mathematic model, as shown Figure 4. This model shows a 2-DOF shear building and an isolation system modeled by a nonlinear friction element and a variable spring element. This model implies that the seismic motions of all isolators are assumed to be synchronized and studies have revealed that this assumption is in good consistency with what happens in reality (Lu Lyan-Ywan *et al.* 2011).

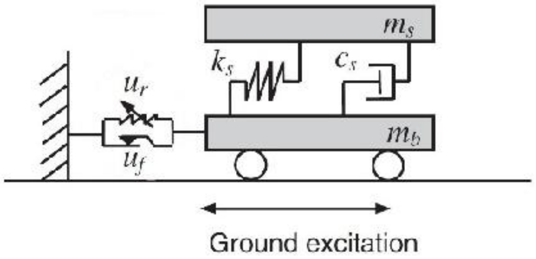

Figure 4.The mathematical model for simulating a SIVF-isolated structure

The dynamic equation of motion of the idealized model in Figure 4 can be expressed in state-space form (Lu L. Y. and Yang Y. B. 1997)

$$\dot{\boldsymbol{z}}(t) = \boldsymbol{A}\boldsymbol{z}(t) + \boldsymbol{E}\ddot{x}_g(t) + \boldsymbol{B}F(t) \tag{6}$$

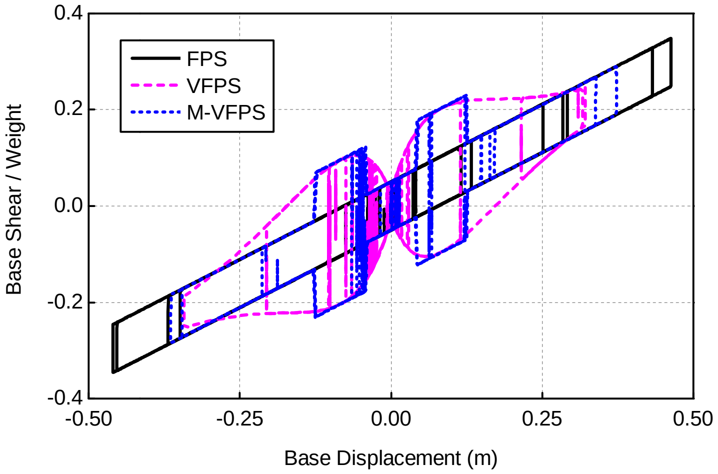

Figure 5. Comparison betweenhysteresis diagrams of FPS, VFPS and M-VFPS

where ***A*** denotes the system matrix; **z**(*t*) is a vector containing the state variables; $\ddot{x}_g(t)$the ground acceleration; ***E*** the excitation distribution matrix; ***B*** the isolator distribution matrix; *F(t)* the total isolator shear force.

The first order ordinary differential equations obtained from state-space formulation of equations of motions can be solved simultaneously using the *ode15s* solver in MATLAB. The *ode15s* solver is a variable order, multi-stepalgorithm that is efficient in solving systems of stiff differential equations (Fenz Daniel M 2008). The system is stiff due to the *Z*variable, which changes very slowly when the bearing is sliding (*Z*variable is continuously either +1 or -1) and changevery rapidly in the region of where the motion reverses direction or sticking occurs(Fenz Daniel M 2008). Inaddition, since the time step in the solution algorithm differs from the time step of thesupplied earthquake acceleration history, the acceleration at each solution time step iscalculated by linearinterpolation of the ground acceleration values.

In this study we have chosen an isolation period of 2.5 s which corresponds to a radius of curvature of 1.55 m for all the isolators. Initial period, T_i, used for VFPS and M-VFPS is 1.5 s. The coefficient offrictionused for FPS is 0.05 at high speed and half of that at low speed with a rate parameter of a = 100 sec/m. Furthermore, for VFPS and M-VFPS a value of 0.15 for $\mu_{max}$and 0.025 for μ_0 are used. Also, the parameters of the plasticity model assigned are u_y= 0.10mm,A =1, η = 2, β = 0.1, andγ = 0.9.

RESULTS

Hysteresis diagrams of the isolators under study are shown in Figure 5. Adaptability of VFPS and M-VFPS along the sliding surface can be observed in their hysteresis diagrams while FPS shows a constant isolation period and thus stiffness.

Figure 6 shows the maximum responses of the isolators under the seven near-fault earthquakes. It is observed that the seismic behavior of M-VFPS is close to that of VFPS under nearly all the earthquakes, except Jiji earthquake which is a very strong near-fault earthquake. Therefore, the M-VFPS isolator is proved to be a good practical alternative to VFPS. Moreover, as shown in Figure 6, in comparison to the seismic behavior of the conventional FPS, both VFPS and M-VFPS behave well in reduction of base displacement while they do not show a good performance in controlling of the transmitted acceleration to the super-structure.

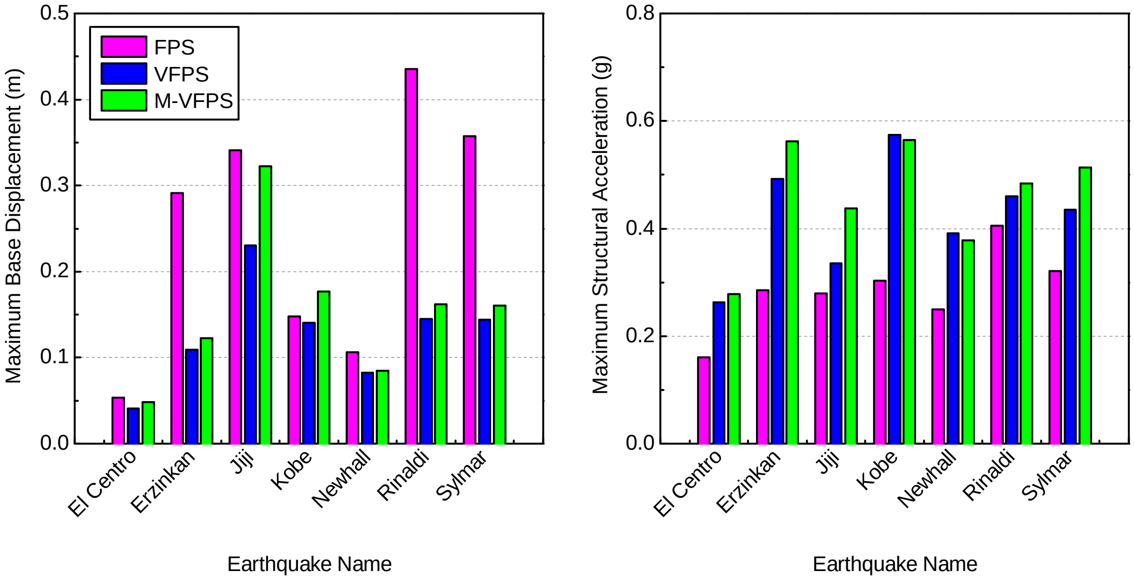

Figure 6. Comparison betweenmaximum responses of FPS, VFPS and M-VFPS under the seven near-fault earthquakes

CONCLUSIONS

Sliding isolators with variable friction (SIVF) are a group of adaptive sliding isolators which have proved to behave better than a conventional FPS isolator in many aspects.In this study, an SIVF isolator, namely, Modified Variable Friction Pendulum System (M-VFPS) is introduced as an alternative for Variable Friction Pendulum System (VFPS). The friction coefficient of VFPS varies based on a curve which is impractical to be achieved while M-VFPS uses a practical variation of coefficient of friction along its sliding surface.

Two main aspects governing effectiveness of isolator has been considered: (1) base displacement and (2) super-structural acceleration.

Based on this investigation the following conclusions can be drawn.

M-VFPS, with a very simple variation of coefficient of friction, can be used as an alternative isolator for VFPS, which uses an impractical variation of coefficient of friction.

Both M-VFPS and VFPS, as two kinds of sliding isolators with variable friction, show a better response in reduction of base displacement than the conventional FPS isolator in near-fault earthquakes.

In comparison to FPS, a poor behavior of M-VFPS and VFPS is observed in controlling of acceleration transmitted to the super-structure.

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