EFFECTS OF FLING STEP ON BUILDINGS WITH VARIABLE FRICTION AND VARIABLE FREQUENCY PENDULUM ISOLATOR (VFFPI)

Anjali Desai[1], Dr. V. R. Panchal[2], B. B. Shobhana[3]
[1]Postgraduate Student, M. S. Patel Department of Civil Engineering, Chandubhai S. Patel Institute of Technology, CHARUSAT, Changa, Gujarat, India

[2]Professor and Head of Department, M. S. Patel Department of Civil Engineering, Chandubhai S. Patel Institute of Technology, CHARUSAT, Changa, Gujarat, India

[3]Assistant Professor, M. S. Patel Department of Civil Engineering, Chandubhai S. Patel Institute of Technology, CHARUSAT, Changa, Gujarat, India

ABSTRACT: From literature, it is found that very few attempts have been made to study the behaviour of building with Variable Friction and Variable Frequency Pendulum Isolator (VFFPI) under fling-step ground motions. To address this, a detailed study has been carried out indicating near fault fling step earthquake ground shaking effects on one & five storey buildings isolated with Variable Friction and Variable Frequency Pendulum Isolator (VFFPI). To evaluate the equation of motion of VFFPI isolated building, Newmark's method was used by assuming linear acceleration change over small time interval. Also, a comparison has been made with Variable Frequency Pendulum System (VFPS) with variable frequency to compare the performance of VFFPI. It is found that in VFFPI, base shear (x_b) and the absolute acceleration of top floor ($\ddot{x}_a$) are less than that of VFPS with variable frequency whereas isolator and residual displacement are more than that of VFPS with variable frequency.
Key words: *Base Isolation, VFFPI, VFPS, Fling step ground motions*

I. INTRODUCTION

Base isolation has remained proven technology for protection of buildings from ground shaking (i.e. during an earthquake) since its invention. Many base isolators have been developed like elastomeric bearings system, sliding bearings system and analysed. Much research has been done in order to verify its performance for various structures. The advantage of sliding isolator in reducing seismic response of structure for wide array of frequency has remained its most attractive feature [1].

In recent research, Shah and Panchal [2] compared response of buildings isolated by VFPS with constant frequency, VFPS with variable frequency and VFPI (Variable Frequency Pendulum Isolator) to harmonic motion and concluded that base shear, isolator displacement and absolute acceleration (top floor) in the VFPI are not more than that of VFPS with both constant frequency and variable frequency. Kalkan and Kunnath [3] carried out study on effects of fling step with forward directivity on seismic performance (response) of structures of steel frames designed for moment and determined that fling step ground motions were exciting steel moment frames in the fundamental mode and forward directivity (without fling-step) results in higher modes to be activated. Krishnamoorthy [4] evaluated seismic performance of continuous bridge (three span) isolated by VFFPI (Variable Friction and Variable Frequency Pendulum Isolator), PF (Pure Friction) and FPS (Friction Pendulum System) and concluded that the resonance problem of PF can be eliminated by VFFPI. It includes the benefits of PF and FPS systems. Dhundhiyawala and Panchal [5] compared earthquake performance of isolated slender steel tank for liquid storage with VFFPI and VFPS with Variable frequency under normal near-field ground motions and concluded that VFFPI is found effective in seismic isolation of tanks (liquid storage).

Several studies have concluded that base-isolated structures could be more susceptible to high amplitude (pulse-like) ground motions caused at near fault [3]. Fling step and forward directivity are the primary considerations for near fault earthquakes. Fling step is a higher velocity pulse which originates from the permanent tectonic plate displacement that contributes to the amount of slip for the causative fault. Although, the effects of fling step on the seismic performance of structures has not been studied extensively yet which might be proven to be devastating for structures [7]. Because of the unique nature of these ground motions, seismic performance of structures for such ground motions has obtained much attention recently. Therefore, it is appealing to study the effect of fling step ground motions on the performance of VFFPI-isolated buildings.

In this study, for fling step ground motions, the seismic performance of a multi storey VFFPI isolated building has been evaluated assuming the superstructure as flexible structure. The objectives of the paper are kept as: (i) to evaluate the effects of fling step ground motions on response of a VFFPI isolated building and (ii) to compare the responses of building isolated with VFFPI and VFPS with variable frequency to in order to determine the performance of VFFPI.

2. VARIABLE FRICTION AND VARIABLE FREQUENCY PENDULUM ISOLATOR (VFFPI)

FPS might encounter resonance problem for low frequencies due to constant curvature of an isolator. To solve this problem, VFFPI is proposed by [4] in which sliding surface curvature and coefficient of friction was varied with the slider displacement.

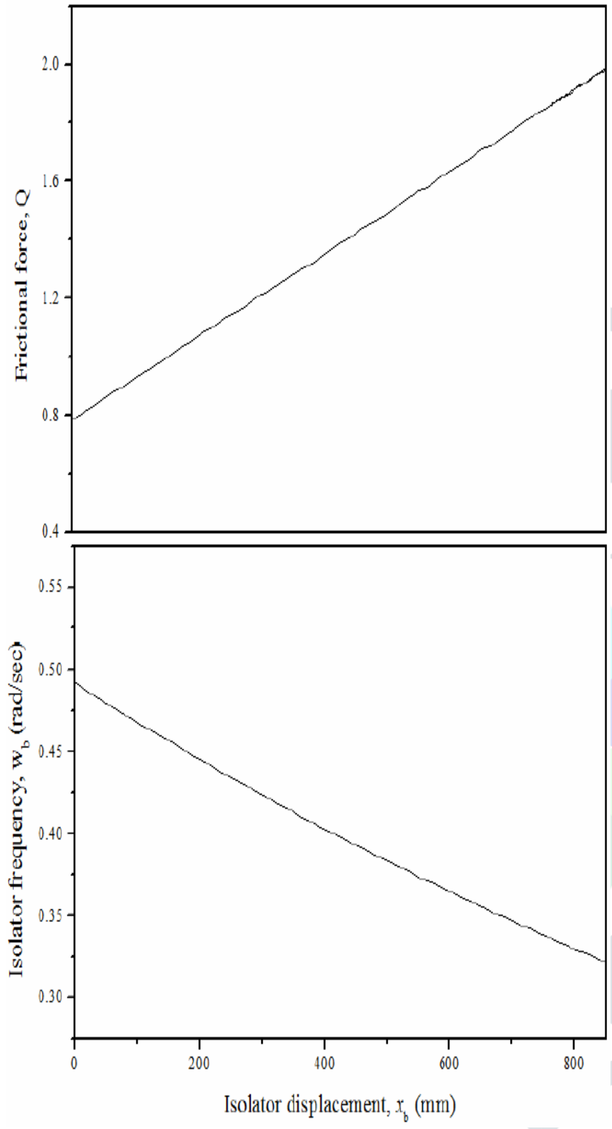

Figure 1 Friction force and isolator frequency vs. isolator displacement

Following empirical relation is used to determine the system geometry and friction coefficient of VFFPI.

$$R(x) = C(\exp(x_b) - 1); \ \mu(x) = \sqrt{\left(0.8\mu + 0.1\frac{x_b}{R}\right)^2} \qquad (1)$$

The value of $C = 84(1 + 0.2R)$. As suggested above, the friction coefficient must not be less than 0.8 times that of conventional sliding surface [4].

Where C = isolator constant, $R(x)$ = Radius of Curvature, $\mu(x)$ = friction coefficient at sliding displacement, x_b, R denotes the radius of sliding surface of FPS and μ is co-efficient of friction of FPS sliding surface.

Figure 1 shows variation of frictional force Q and isolator frequency (ω_b) along with isolator displacement (x_b). This figure is taken from Shah and Panchal [8].

3. VARIABLE FRICTION PENDULUM SYSTEM (VFPS) VARIABLE FREQUECY

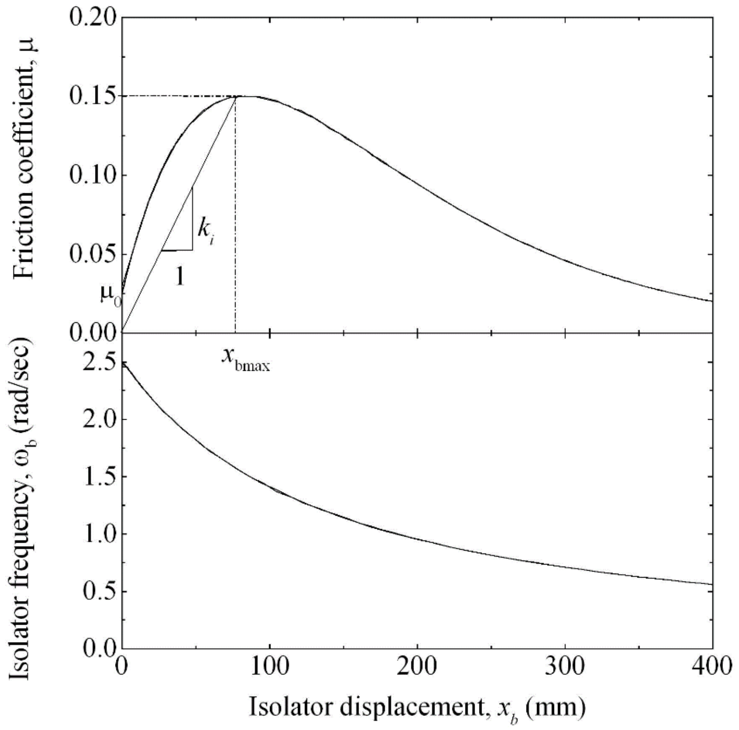

Figure 2. Friction and frequency characteristics of the VFPS with variable frequency.

As the name suggests, VFPS with variable frequency is its variation of frequency in addition to the change (i.e. variation) of friction with respect to sliding displacement at the sliding interface. Figure 2 shows variation of coefficient of frictional (μ) and isolator frequency (ω_b) along with isolator displacement (x_b). This figure is taken from Jasmini et al. [9].

4. FLING STEP GROUND MOTIONS:

Fling step ground motions utilized in the study are given in the Table 1. Data of these ground motions were obtained from [3].

Table 1 Fling step ground motions considered for evaluation

Sr. No.	Fling step earthquake	Station	Component	Magnitude (Mw)	PGD (cm)	PGV (cm/s)	PGA (g)	Fling Displacement (mm)
1	Chi-Chi, 1999	TCU052	NS	7.6	709.09	216.00	0.440	697.12
2	Chi-Chi, 1999	TCU074	EW	7.6	193.22	68.90	0.590	174.56
3	Chi-Chi, 1999	TCU084	NS	7.6	64.91	42.63	0.420	59.43
4	Chi-Chi, 1999	TCU129	NS	7.6	82.70	54.56	0.610	67.54
5	Kocaeli, 1999	Yarimca (YPT)	NS	7.4	184.84	88.83	0.230	145.79

5. VFFPI-ISOLATED BUILDING MODELLING:

Figure 3 indicates the building (shear) under consideration which is joined on the base isolated system. Both VFFPI and VFPS with variable frequency were used for isolation of structure. Assumptions were made for the considered model are [10]:

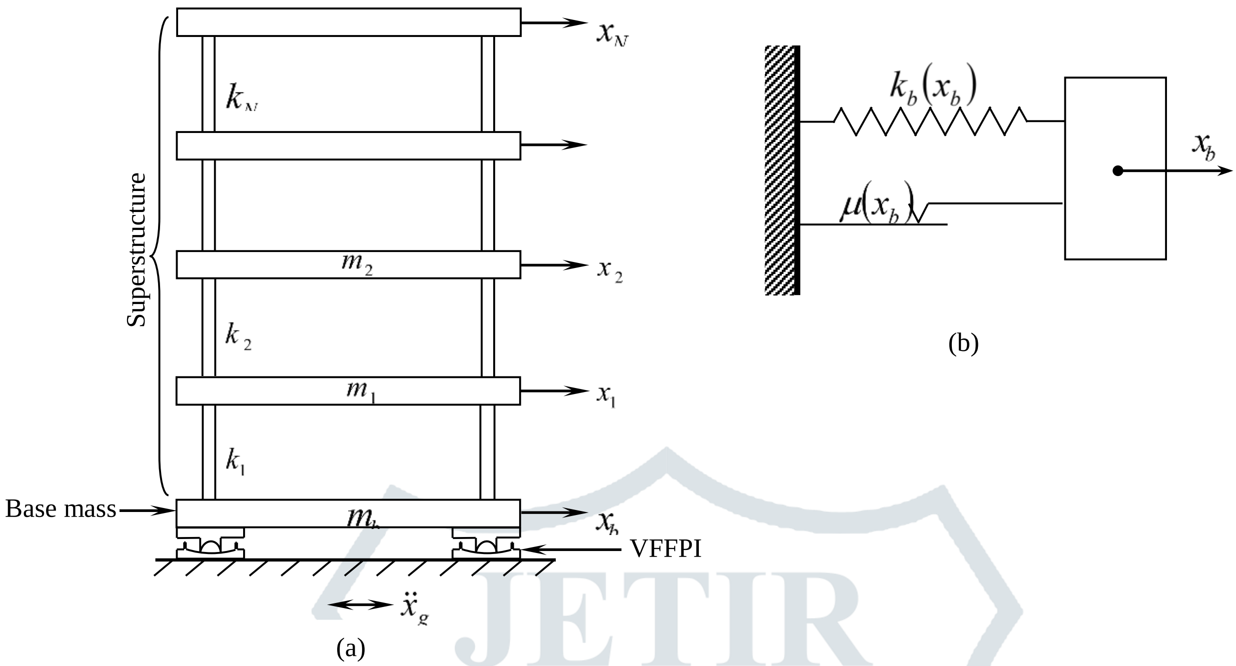

Figure 3: Flexible superstructure with VFFPI and its modelling

1. It is assumed that all the floors of super structure will behave as a rigid floors;
2. Linear force-deformation (Hysteresis) behavior of the superstructure is assumed;
3. The relative velocity at the surface is independent of the co-efficient of friction of isolator at sliding surface. It is assumed such a way because of the conclusions made in [11] that the peak response of structure (isolated) will not be affected by such effects.
4. The restoring force is assumed to be non-linear for both the systems. In addition, the viscous damping was considered other than provided by friction;
5. No tilting or overturning will occur in the structure during the sliding;
6. Vertical component effect on the structure is neglected and it is assumed that structure will be excited only by single component (horizontal) of ground motion.

Lateral dynamic DOF (Degree of freedom) considered at base mass and each floor. Therefore, dynamic DOF are taken as N+1 for the N-storey superstructure. Newmark Method is used to evaluate the equation of motion of VFFPI isolated building by assuming linear acceleration change over small time internal.

6. NUMERICAL STUDY

A programming code has been developed using FORTRAN to calculate the structural response quantities of two different VFFPI isolated buildings (single and five storeys) under fling-step ground motions and response quantities were compared with building isolated with VFPS with variable frequency. For the current study, mass matrix [M] is considered diagonal and is kept constant. Also, stiffness of each and every floor is considered as constant and expressed as k. For getting the time period (fundamental) of superstructure the value of k is taken as fixed base. Damping matrix, [C] is built by assuming constant modal damping ratio The buildings undertaken in the study has one and five storeys with damping ratio, ξ_s = 2% of critical damping, T_s (fundamental time period) = 0.5 sec, mass ratio m_b/m=1 (Jasmini et al., 2009). The base shear, isolator displacement, top floor acceleration, and residual displacement are dominant quantities for base isolated buildings.

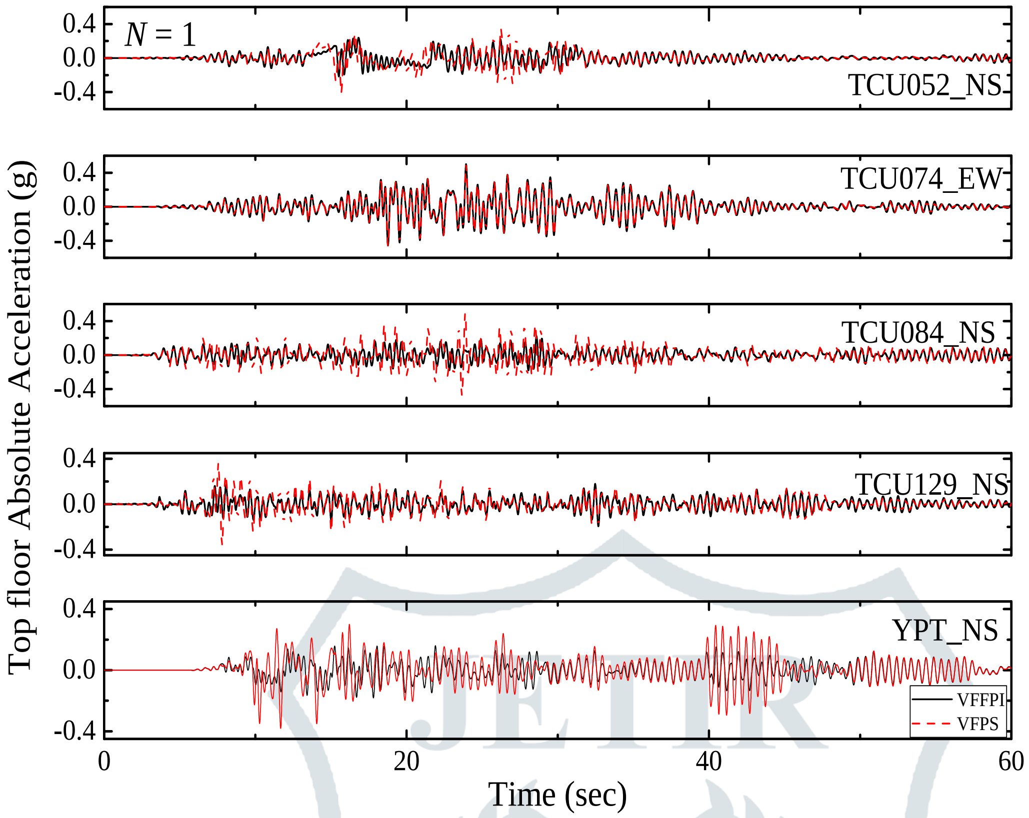

Figure 4 Absolute acceleration of top floor Vs. Time for one-storey building isolated by VFFPI and VFPS with variable frequency under various fling - step ground motions

Using above parameters, response quantities of interest are obtained for one-storey (i.e. for $N = 1$) building isolated by VFFPI and VFPS with variable frequency. Figure 4 demonstrates fluctuation of top floor absolute acceleration with respect to time under different fling-step ground motions. Similarly, isolator displacement vs. time plot is plotted and has been shown in Figure 5. The plot also indicates the residual displacement of both isolators for all considered earthquakes. Also, base shear vs. time plot is plotted and indicated in Figure 6.

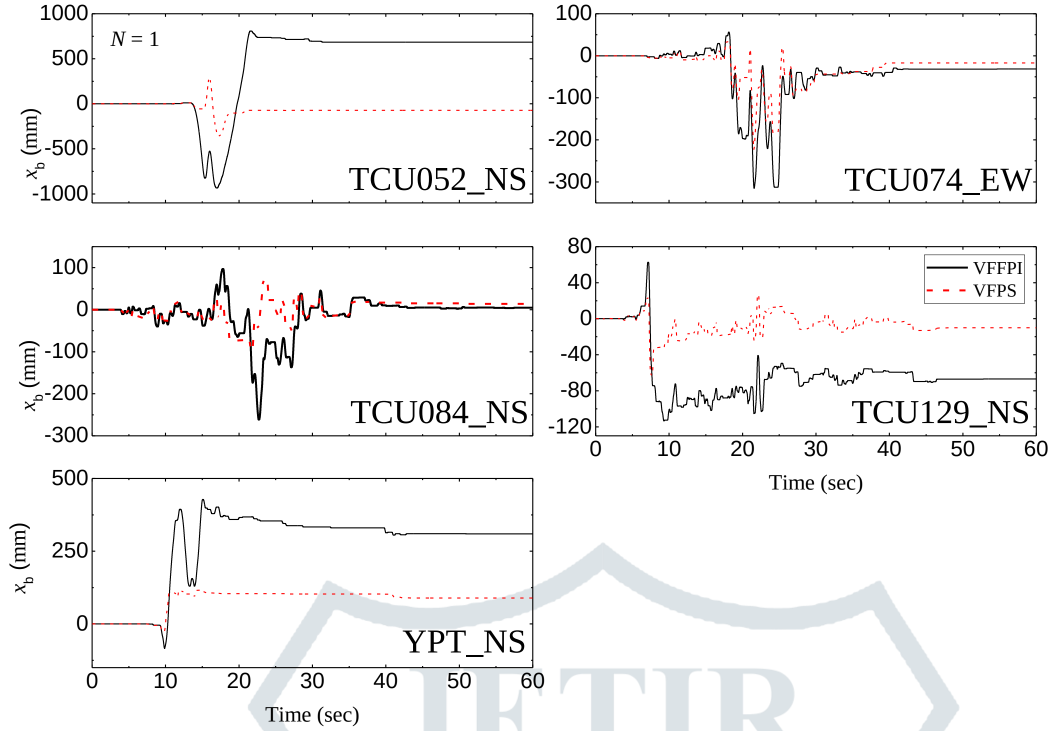

Figure 5 Time fluctuation of isolator displacement of one-storey building isolated by VFFPI and VFPS with variable frequency under various fling - step ground motions.

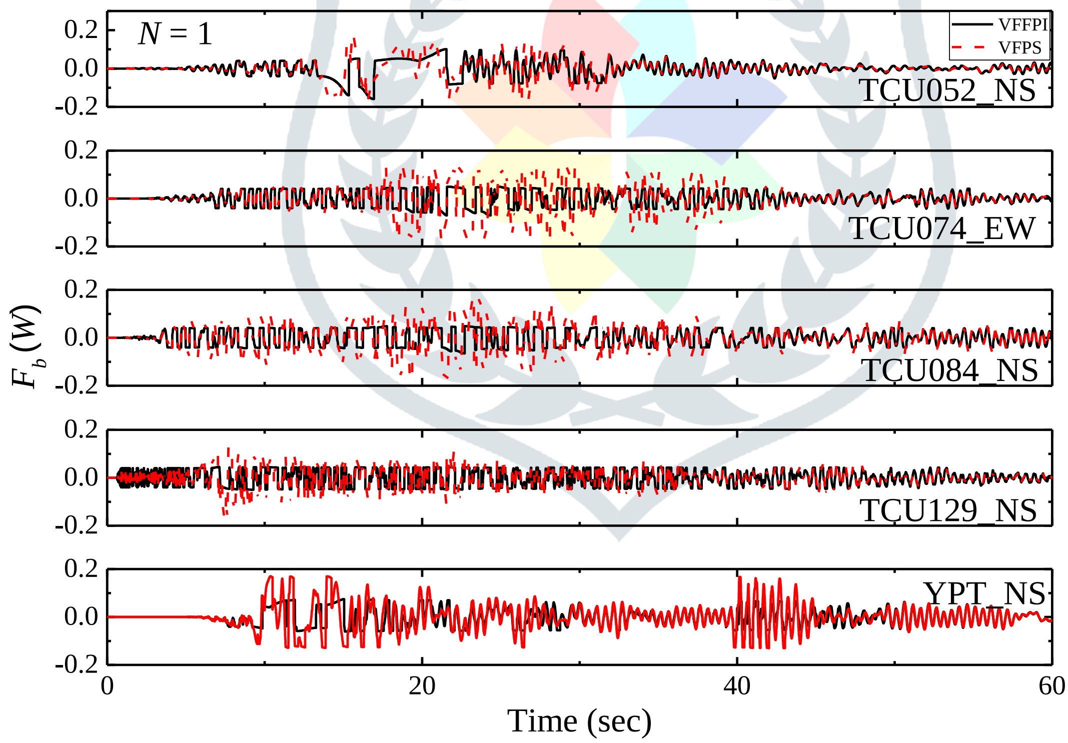

Figure 6 Time fluctuation of base shear of one-storey building isolated by VFFPI and VFPS with variable frequency under various fling - step ground motions.

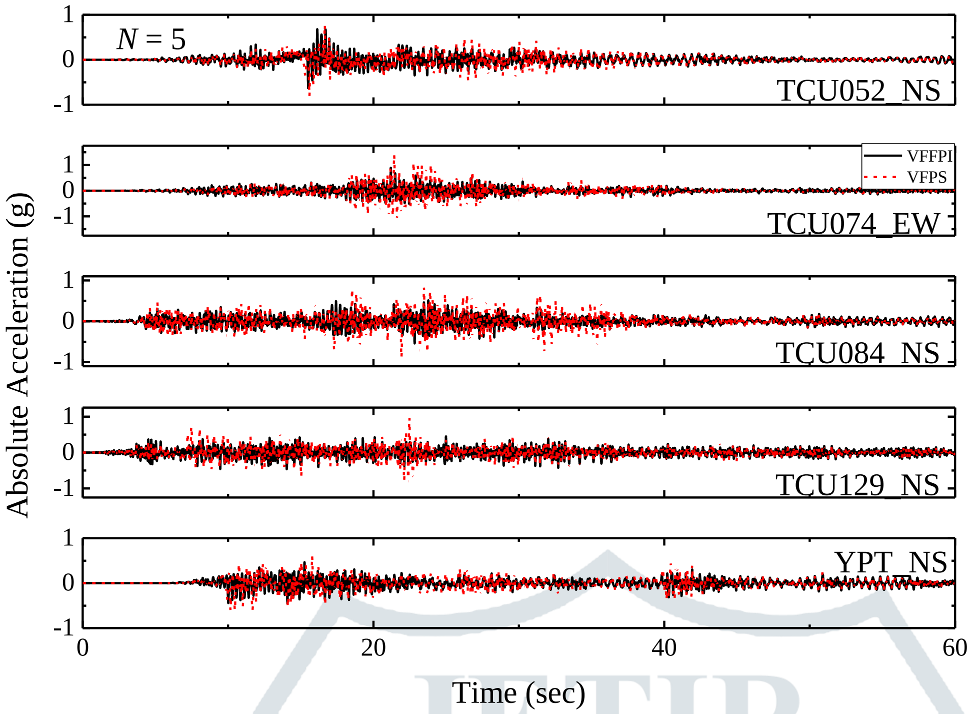

Figure 7 Time fluctuation of absolute acceleration of top floor of five storey building isolated by VFFPI and VFPS with variable frequency under various fling - step ground motions.

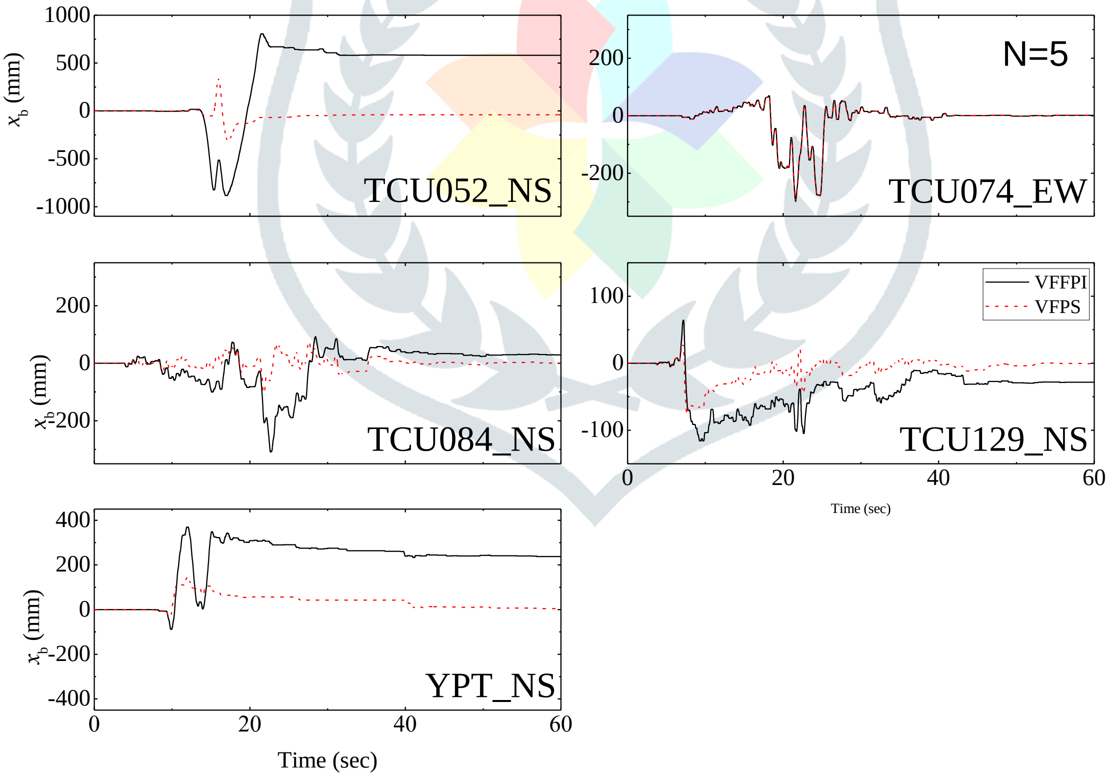

Figure 8: Hysteresis loop for five-storey building isolated by VFFPI under The Imperial Valley, 1979 (El Centro Array #5 station) seismic ground motion

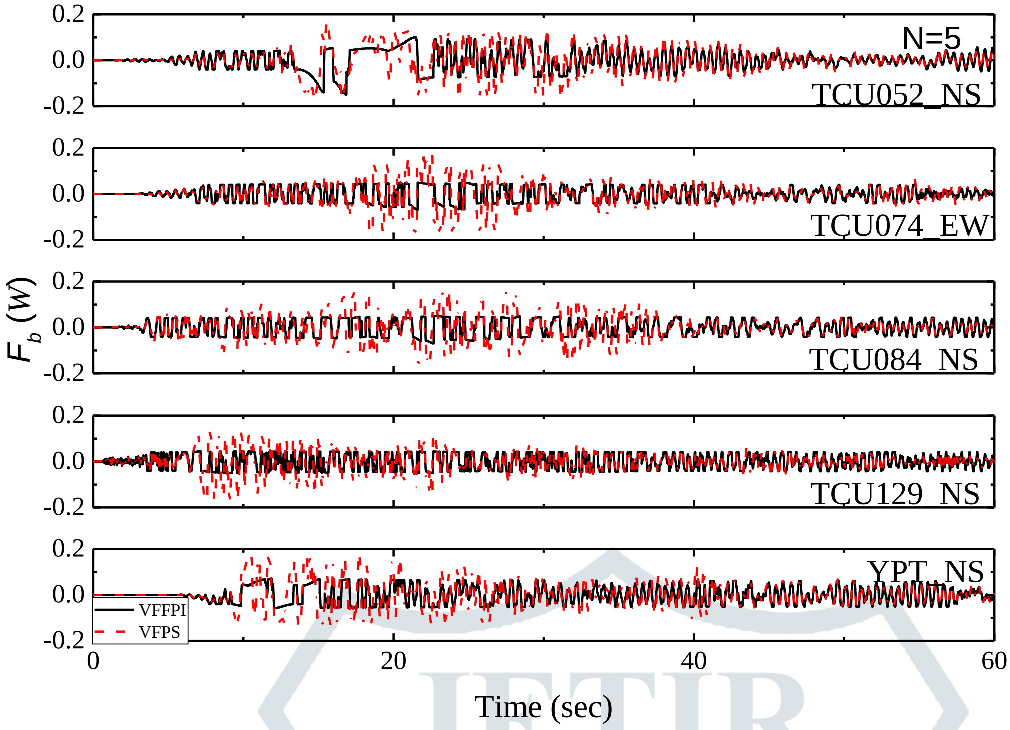

Figure 9 Time fluctuation of base shear of five-storey building isolated by VFFPI and VFPS with variable frequency under various fling - step ground motions.

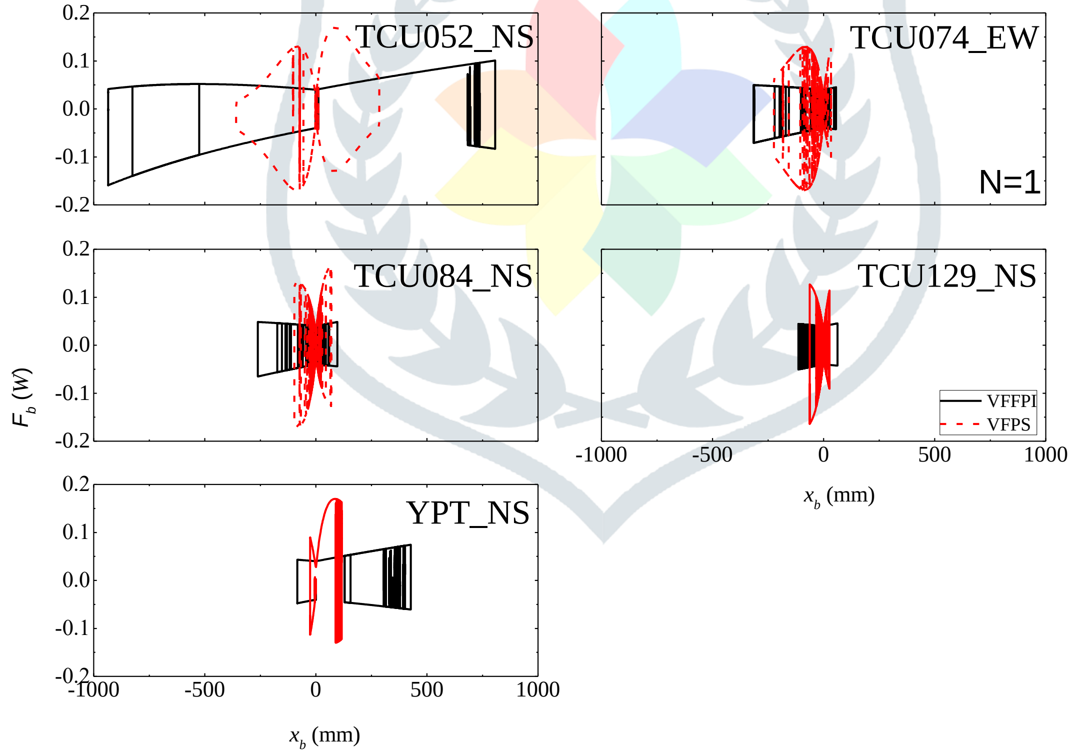

Figure 10 Hysteresis loop for one-storey building isolated by VFFPI by VFFPI and VFPS with variable frequency under various fling - step ground motions.

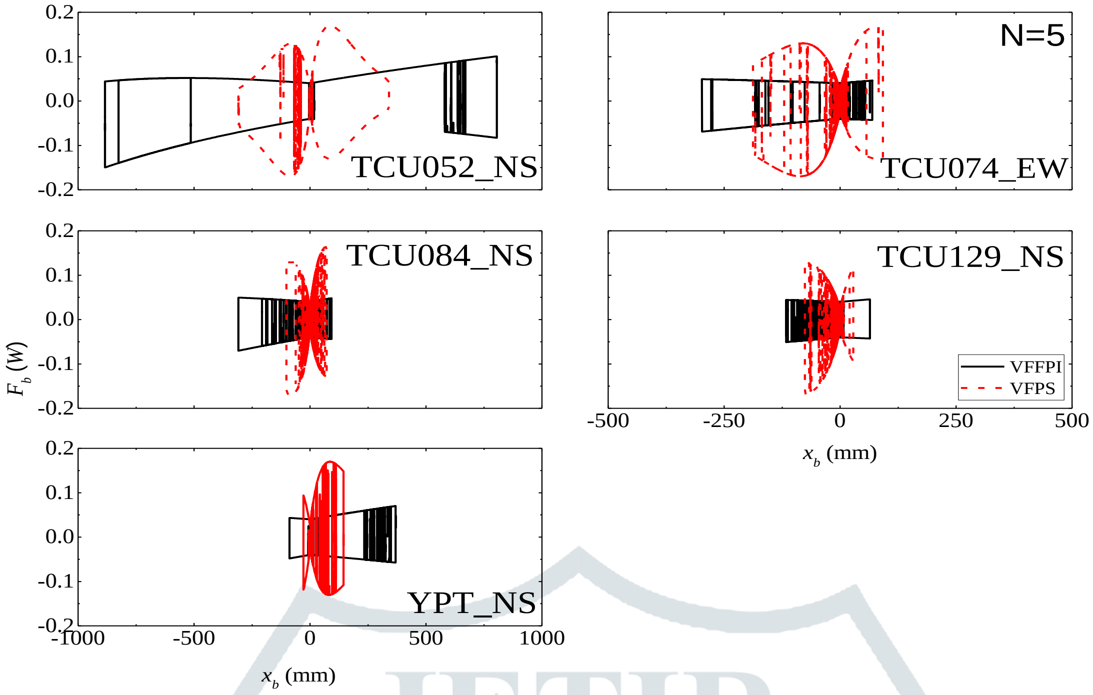

Figure 11 Hysteresis loop for five-storey building isolated by VFFPI by VFFPI and VFPS with variable frequency under various fling - step ground motions.

T_b=2.5 sec, The the initial value of friction coefficient friction coefficient, μ_0=0.05. The parameters of VFFPI are selected as the period of base isolation, T_b=2.5 sec (radius of conventional sliding surface, R=1.553 m), co-efficient of friction of conventional sliding surface, μ=0.05.

Similarly, plots have been generated for five storey building isolated by VFFPI and VFPS with variable frequency under various fling - step ground motions. Figures 7 - 9 show time variation of absolute acceleration the topmost floor (in terms of g), normalized base shear and isolator displacement (mm).

Figures 10 & 11 show hysteresis loops for one- and five-storey buildings isolated by VFFPI by VFFPI and VFPS with variable frequency under various fling - step ground motions.

Tables 2 and 3 show comparison of peak values of response quantities for both isolators (i.e., VFFPI and VFPS with variable frequency)

Table 2: Single storey building Peak response

Fling step ground motion	Condition of building	$\ddot{x}_a$ (g)	x_b (mm)	F_b (W)	Residual displacement (mm)
1999 Chi-Chi (TCU052)	VFPS with variable frequency	0.399	359.14	0.1698	71.490
	VFFPI	0.2386	934.89	0.1589	683.82
1999 Chi-Chi (TCU074)	VFPS with variable frequency	0.5019	223.99	0.1698	17.152
	VFFPI	0.2512	315.42	0.071	31.15
1999 Chi-Chi (TCU084)	VFPS with variable frequency	0.485	97.108	0.1698	13.774
	VFFPI	0.2237	261.43	0.0652	5.0023
1999 Chi-Chi (TCU129)	VFPS with variable frequency	0.359	62.94	0.1636	10.097
	VFFPI	0.195	113.48	0.0504	66.889
1999 Kocaeli (Yarimca YPT)	VFPS with variable frequency	0.3818	116.12	0.1698	89.462
	VFFPI	0.1817	427.73	0.0744	309.34

Table 3 Peak response quantities of five-storey building

Fling step ground motion	Building condition	$\ddot{x}_a$ (g)	x_b (mm)	F_b (W)	Residual displacement (mm)
1999 Chi-Chi (TCU052)	VFPS with variable frequency	0.806	340.860	0.170	39.752
	VFFPI	0.6801	883.87	0.1497	581.92
1999 Chi-Chi (TCU074)	VFPS with variable frequency	1.4	187.91	0.1698	0.0177
	VFFPI	0.8878	279.83	0.06908	0.0177
1999 Chi-Chi (TCU084)	VFPS with variable frequency	0.8824	101.42	0.1698	3.3717
	VFFPI	0.5421	308.73	0.07026	33.403
1999 Chi-Chi (TCU129)	VFPS with variable frequency	0.9725	76.031	0.1688	0.2046
	VFFPI	0.4651	116.03	0.05069	28.463
1999 Kocaeli (Yarimca YPT)	VFPS with variable frequency	0.6018	144.8	0.1698	4.3655
	VFFPI	0.4719	369.1	0.07	237.9

7. CONCLUSION

The earthquake responses of the one and five storey buildings isolated by Variable Friction and Variable Frequency Pendulum Isolator (VFFPI) are examined under different fling step accelerations. The obtained response quantities of focus are isolator displacement, base shear, residual displacement and absolute acceleration of topmost floor. The comparison between seismic responses of one and five storey buildings isolated with VFFPI and Variable Frequency Pendulum System (VFPS) with variable frequency are made to know the effectiveness of VFFPI. The conclusions were drawn from the numerical results of this study are as follows:

1. The base shear and topmost floor absolute acceleration in one and five storey buildings isolated by VFFPI is less than that of building isolated by VFPS with variable frequency.
2. The isolator displacement and residual displacement are quite higher in VFFPI than that of VFPS with variable frequency.

The topmost floor acceleration of five-storey building is more than that of one-storey building whereas residual displacement of one-storey building is more than that of five-storey building. Conversely, the isolator displacement and base shear do not get much affected with the increase in number of storey of multi-storey building.

REFERENCES

[1] Ahmadi, G. (2013), "Stochastic earthquake response of structure on sliding foundation", International Journal of Engineering and Science, Vol. 21, pp. 93–102.

[2] Princy R. Shah and V. R. Panchal "Harmonic response of multi-storey building isolated by VFPS with variable frequency", National Conference on New Horizons in Civil Engineering (NHCE-2017), Surat, 2017.

[3] Erol Kalkan and S. K. Kunnath (2006), "Effects of fling step and forward directivity on seismic response of buildings," Earthquake Spectra, Vol. 22, pp. 367–390.

[4] A. Krishnamoorthy (2010), "Seismic isolation of bridges using variable frequency and variable friction pendulum isolator system," Structural Engineering International, Vol. 20, pp. 178-184.

[5] Hojefa H. Dhundhiyawala and V. R. Panchal, (2018) "Seismic response of liquid storage steel tank isolated with variable frequency and variable friction pendulum isolator", International Journal of Emerging Technology and Advanced Engineering (IJETAE), Vol. 7, pp.166-172.

[6] Mazhar A. Dhankot and Devesh P. Soni (2017), "Behaviour of Triple Friction Pendulum isolator under forward directivity and fling step effect", KSCE Journal of Civil Engineering, Vol. 21, pp 872–881.

[7] H. Hamidi Jamnani A. Karbassi and P. Lestuzz, "Fling-step effect on the seismic behavior of high-rise RC buildings during the Christchurch earthquake", Proceeding of the 2013 NZSEE Conference, Wellington.

[8] Princy R. Shah (2017), "Seismic Response of Multi Storied Building Isolated with Variable Frequency and Variable Friction Pendulum (VFFPI) Isolator", M. Tech Thesis, Civil Engineering Department, Faculty of Technology and Engineering, Charotar University of Science and Technology (CHARUSAT), Changa – 388 421.

[9] Jasmini V. Khatri, V. R. Panchal, Devesh. P. Soni and Kanaiyalal N. Sheth, "Seismic Response of Building Isolated by the VFPS with Variable Frequency" NUCONE 2009, Ahmedabad, 2009.

[10] Jeevan A. Kulkarni and R. S. Jangid (2002), "Rigid body response of base-isolated structures", Journal of Structural Control, Vol. 9, pp. 171–188.