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Seismic Isolation of Building-Equipment System Using Modified Variable Friction Pendulum System

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ARTICLE INFORMATION

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ABSTRACT

In this study, building-equipment system with Modified Variable Friction Pendulum System (MVFPS) is investigated under different earthquake ground excitations. Earthquake response of building-equipment system isolated with MVFPS is compared with Variable Friction Pendulum System (VFPS) and Friction Pendulum System (FPS) in order to find efficiency of MVFPS. Newmark's linear acceleration method is used for solving governing equation of motion for building-equipment system. In this investigation, different storey buildings are considered. It is observed that MVFPS is more efficient in reducing the recoverable energy than FPS, but less efficient than VFPS. From the comparative study, it is found that FPS shows robust performance in comparison to MVFPS and VFPS in reducing equipment acceleration and displacement.

1. Introduction

In last few decades, base isolation technique has gained vast adoption because it protects different types of structures, like water tanks, multi-storeyed buildings, bridges etc. against adverse effects of earthquake. The main concept of base isolation technique is that it reduces damages in building by shifting the fundamental time period of building from dominant periods of earthquake. After implementation of base isolation system in building, energy dissipation capability and fundamental time period of building increases. Buildings without base isolation attract more earthquake forces where as buildings which have base isolation attract less amount of earthquake force and protect building against earthquake.

Among different types of base isolation systems, sliding isolators are mostly used for actual implementation as they are insensitive to the frequency content of ground motions. Number of sliding isolators, i.e., Friction pendulum system (FPS), Variable Frequency Pendulum Isolator (VFPI), Variable Curvature Friction Pendulum System (VCFPS), and Triple Friction Pendulum System (TFPS) were examined during last few decades. Mrunal and Sinha [1] supervised study on multi-storey building along with equipment

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with VFPI, PF and FPS; they concluded that VFPI is more effective as compared to FPS and PF system. Lu et al. [2] considered sliding bearings with variable curvatures for near fault ground motions. They showed that CFPI and VFPI is more effective compared to FPS. Joshi et al. [3] studied performance of CFPI and VFPI in multi-storey building with building equipment and concluded that VFPI is more effective than CFPI. Bhayani and Panchal [4] carried out numerical study on multi-storey building with equipment isolated with PFPI and VFPI and demonstrated that VFPI is more effective than PFPI.

In this research work, MVFPS isolated multi-storey building with equal mass at all floor are considered. Here Equipment mass is taken 1% of total mass of building. Different near fault ground excitations are used to determine response of equipment displacement, equipment accelerations and recoverable energy of MVFPS isolated building with view to examine the performance of MVFPS with building equipment. Comparison of MVFPS, VFPS and FPS has been made.

2. Concept of MVFPS

As variation of coefficient of friction is not easy to be attain in case of VFPS, Ali and Abbas [5] suggested MVFPS, which is more advantageous in real practice. The MVFPS system is the variation of VFPS system. The basic difference among FPS, VFPS and MVFPS lies in the variation of friction coefficient with respect to isolator displacement, which is demonstrated in Fig. 1. Variation of friction coefficient in case of MVFPS is similar to that of FPS throughout isolator except in displacement range from $0.5d$ to $1.5d$ (d is the value of isolator displacement with respect to extreme value of friction coefficient of VFPS). In this range, maximum value of friction coefficient of VFPS is considered.

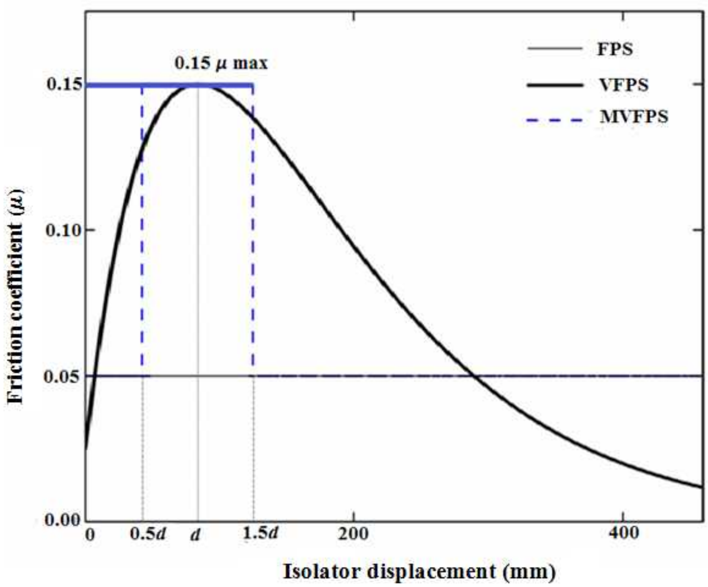

Figure 1: Friction coefficient variation of FPS, VFPS and MVFPS [6]

3. Governing equation of motion

The governing equation of motion for building equipment system is given by Eq. (1).

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = -[M]\{r\}\{\ddot{x}_b + \ddot{x}_g\} \quad (1)$$

Here, [M], [C] and [K] represents mass, damping and stiffness matrices having size of N X N; $\{r\}$ stands for influence coefficient vector and its value is $\{1, 1, \ldots, 1\}^T$; $\{\ddot{x}\}$ and $\{\dot{x}\}$ denotes acceleration and velocity vector, respectively, $\{x\}$ denotes displacement with respect to base mass, $\ddot{x}_g$ indicates earthquake ground acceleration, while $\ddot{x}_b$ denotes base mass acceleration with respect to the ground. The equation of restoring force of MVFPS is given by Eq. (2).

$$F_b = k_b x_b + F_x \quad (2)$$

where F_x denotes frictional force in MVFPS, $k_b = W / R$ represents stiffness of MVFPS; R indicates radius of concave interface of MVFPS.

The MVFPS can be subjected (before sliding) to the limiting frictional force, Q, which is given by Eq. (3).

$$Q = \mu W \quad (3)$$

where μ *and W* indicate coefficient friction of MVFPS and weight of structure. Stiffness k_b, of MVFPS is designed in such a way that certain value of isolation period, T_b, is obtained; which is given by Eq. (4).

$$T_b = 2\pi\sqrt{\frac{M}{k_b}} \quad (4)$$

In above equation M indicate total mass of the MVFPS-isolated building with equipment. The MVFPS has non-linear force deformation behaviour. So, it becomes very tough to solve the equations of governing motion of the building equipment system by classical modal superposition technique. Therefore, the Newmark's linear acceleration method is used to obtain solution of this equation over small time step.

4. Energy balance

Base isolators work as a combination of reducing the energy transferred to the structure and dissipating energy by applicable mechanism. Most of the time it becomes difficult to select convenient trade off among isolator displacements and structural deformations in order to obtain best isolator properties. With the help of energy quantities, it becomes easier to evaluate the isolator performance as it involves all the responsible quantities. Hence, it represents overall response of structure. The equation of energy balance stated by Uang and Bertero [6] for base isolated shown in Eq. (5).

$$\begin{aligned}&\frac{1}{2}\dot{x}_{0_t}^T M_0 \dot{x}_{0_t} + \frac{1}{2} m_b \dot{x}_{b_t}^2 + m_t g y + \frac{1}{2} x_0^T K_0 x_0 + \\ &\int\left[\dot{x}_0^T C_0 \dot{x}_0\right] dt + \int m_t \mu g \, sgn\left(\dot{x}_b\right) dx_b = \int\left[\ddot{x}_0^T M_0 r_0\right] dx_g \\ &+ \int m_b \ddot{x}_{b_t} dx_g\end{aligned} \quad (5)$$

where subscript 't' indicates absolute values of response quantities. Simplified form of Eq. (5) is given by Eq. (6).

$$V_k + V_r + V_s + V_\xi + V_\mu = V_i \quad (6)$$

In above equation, terms V_K, V_r, V_s and Vi stand for to the kinetic energy, potential energy, strain energy and absolute input energy respectively. V_ξ and V_μ indicate the non conservative energies because of structural damping and sliding friction.

The energy balance equation of a equipment resting on the MVFPS isolated building at any instant of time is given by Eq. (7).

$$V_k + V_r = V_i \quad (7)$$

Equation of V_k and V_r are given by (8) and (9)

V_k= ½ X (mass of the equipment) X (absolute velocity of the equipment)^2 (8)

V_k= ½ X (stiffness of the equipment) (relative displacement of the equipment with respect to top floor)^2 (9)

5. Numerical study

In this study, MVFPS isolated one and five storey buildings with equal mass are considered. Also, light equipment with 1% of total floor mass of building is considered at top. In this study, the response of building equipment system is carried out under six different near-fault ground excitations. Fig. 2 & 3 show one & five storey buildings with equipment at top isolated with MVFPS. Table 1 & 2 indicate characteristics of near-fault ground motion and properties of building & equipment.

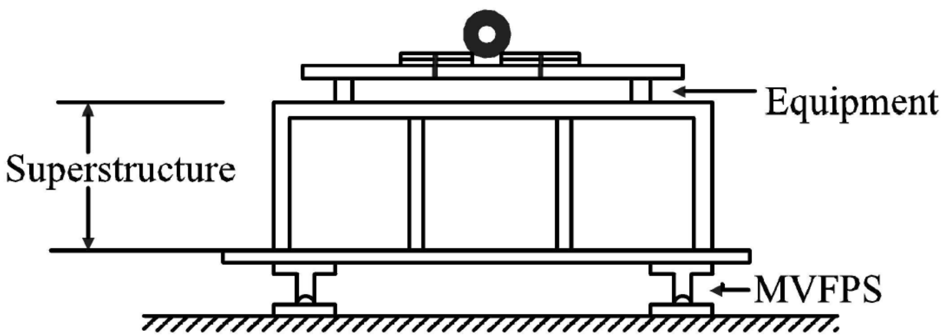

Figure 2: One storey building with equipment isolated using MVFPS

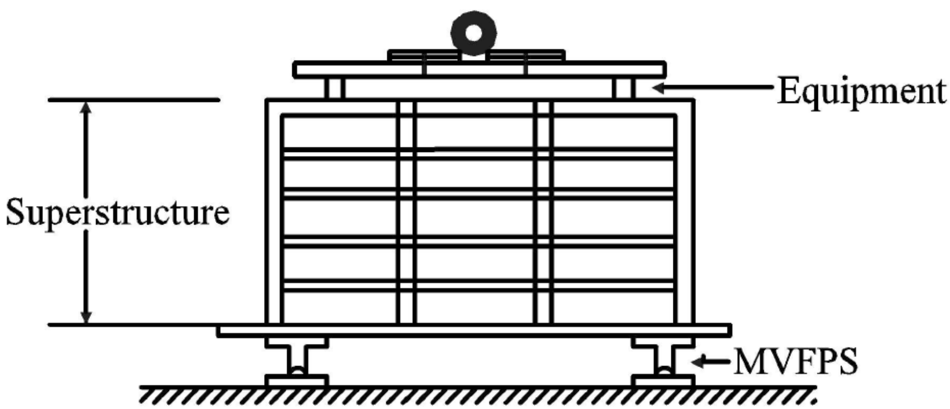

Figure 3: Five storey building with equipment isolated using MVFPS

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Table 1: Characteristics of considered six earthquakes

Near-fault Ground excitation	PGD (cm)	PGV (cm/s)	PGA (g)
1979, Imperial Valley (El Centro Array #5)	76.5	98	0.37
1979, Imperial Valley (E l Centro Array #7)	49.1	113	0.46
1994, Northridge (Newhall)	38.1	119	0.72
1992, Landers (Lucerne Valley)	230	136	0.71
1994, Northridge (Rinaldi)	39.1	175	0.89
1994, Northridge (Sylmar)	31.1	122	0.73

Table 2: Building and equipment properties

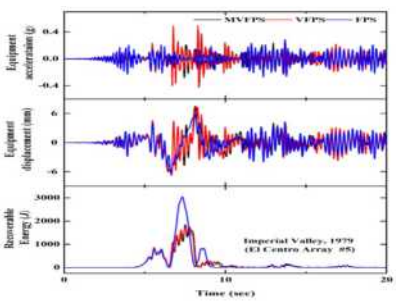
Mass of each floor	60080 kg
Storey stiffness for each floor	11260 kN/m
Equipment mass	1% of floor mass
Damping ratio of building	5%
Damping ratio of equipment	5%
Equipment –frequency	3.85 Hz
Ratio of base mass to floor mass	1.0

6. Results and discussion

Fig. 4 to 6 depict time variation of equipment acceleration, equipment displacement and recoverable energy of building - equipment system of one storey building isolated using MVFPS, VFPS and FPS under near-fault ground motions and Fig. 8 to 10 depict time variation of equipment acceleration, equipment displacement and recoverable energy of building-equipment system of five storey building isolated using MVFPS, VFPS and FPS under near field ground motions.

Fig. 7 and 11 demonstrate the hysteresis loops of MVFPS, VFPS and FPS for various near-fault ground motions for one and five storey buildings with equipment.

Table 3 & 4 shows comparison results of peak response quantities and isolator displacement and base shear under different earthquake ground excitations.



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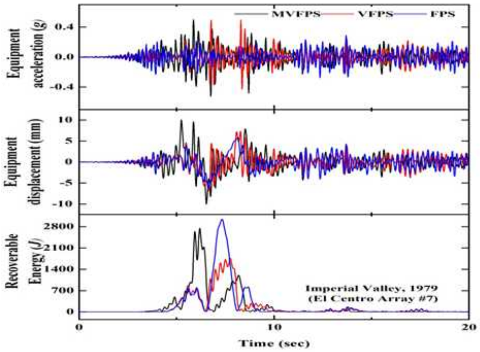
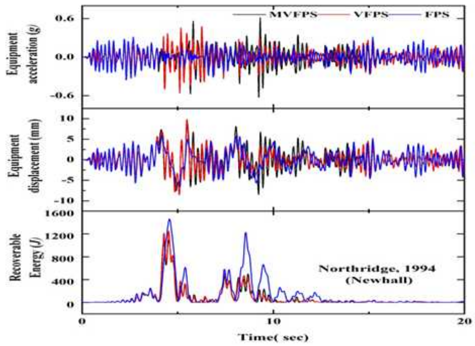


(b)

Figure 4: (a) and (b) Shows time vs. equipment acceleration, equipment displacement and recoverable energy of single storey building-equipment isolated with MVFPS, VFPS and FPS under Imperial Valley (El Centro Array #5) and Imperial Valley (El Centro Arra#7)



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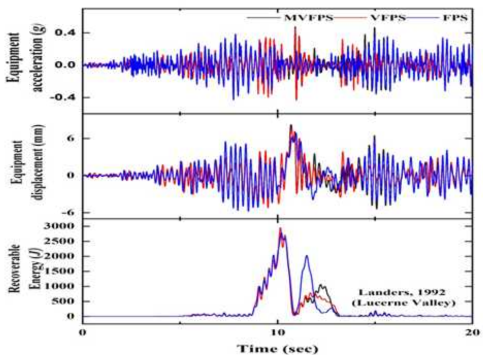
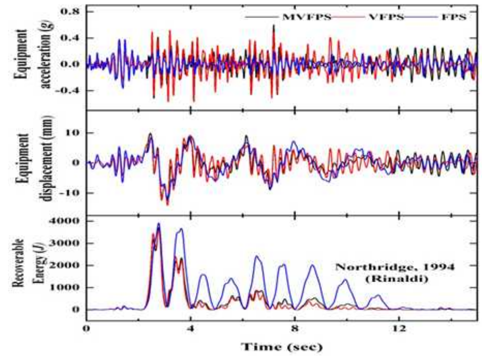


(b)

Figure 5: (a) and (b) Shows time vs. equipment acceleration, equipment displacement and recoverable energy of single storey building-equipment isolated with MVFPS, VFPS and FPS under Northridge, 1994 (Newhall) and Landers, 1992 (Lucerne Valley)



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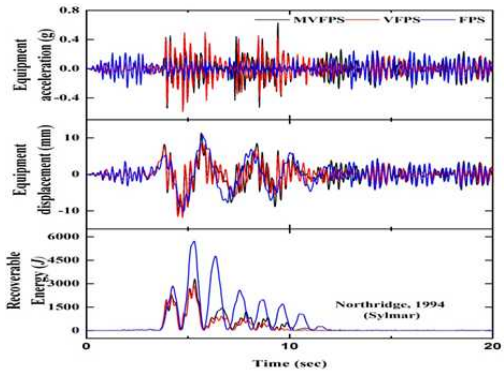

(b)

Figure 6: (a) and (b) Shows time vs. equipment acceleration, equipment displacement and recoverable energy of single storey building-equipment isolated with MVFPS, VFPS and FPS under Northridge,1994 (Rinaldi) and Northridge, 1994 (Sylmar)

Here in above figures, Fig 4 (a) & (b) shows Time vs. equipment acceleration, displacement and recoverable energy of single storey building-equipment isolated with MVFPS, VFPS and FPS under Imperial valley (El Centro Array #5) in this earthquake ground excitations FPS is good compared to MVFPS and VFPS reducing equipment acceleration and equipment displacement But in case of recoverable energy VFPS show better performance compared to MVFPS and VFPS and in Imperial valley (El Centro Array#7) FPS is better in both equipment acceleration and equipment displacement compared to MVFPS and VFPS and in MVFPS recoverable energy is less compared to VFPS and FPS.

In Fig 5 (a) Northridge, 1994 (Newhall) in this earthquake ground excitations equipment acceleration and equipment displacement found less compared to MVFPS and VFPS and MVFPS is better compared to VFPS and FPS in reducing recoverable energy and Fig 5 (b) Landers 1992 (Lucerne Valley) shows that FPS show better in reducing equipment acceleration and equipment displacement and in MVFPS recoverable energy is less compared to VFPS and FPS.

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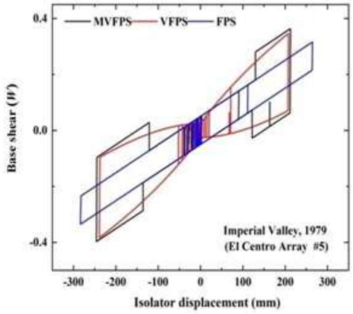
In Fig 6 (a) Northridge 1994 (Rinaldi) in this earthquake ground excitations equipment acceleration and equipment displacement is less in FPS compared to MVFPS and VFPS and recoverable energy is less in VFPS and Fig 6 (b) shows that in Northridge 1994 (Sylmar) earthquake ground excitations FPS shows robust performance compared to MVFPS and VFPS and also it founds that recoverable energy is very less in VFPS.

All the results value of Fig 4 to 6 shows in Table 3.



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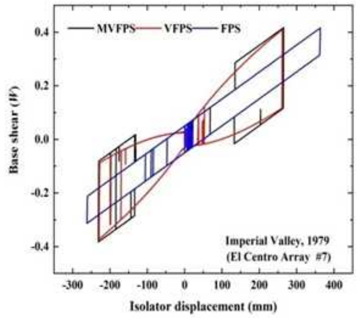

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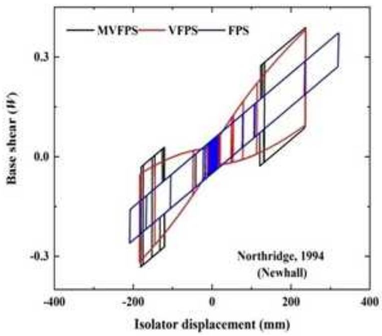

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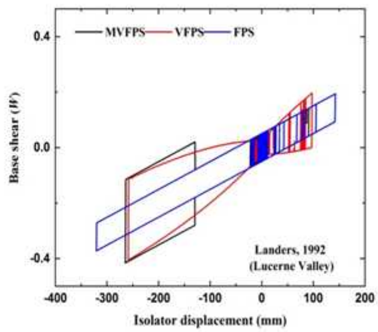

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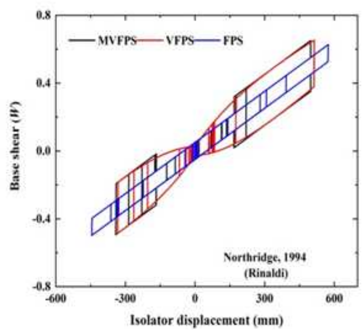

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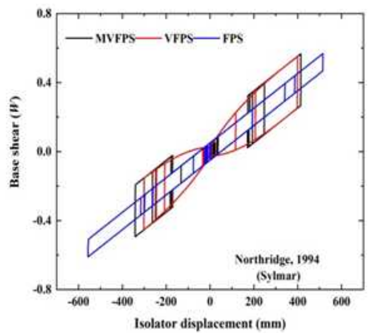
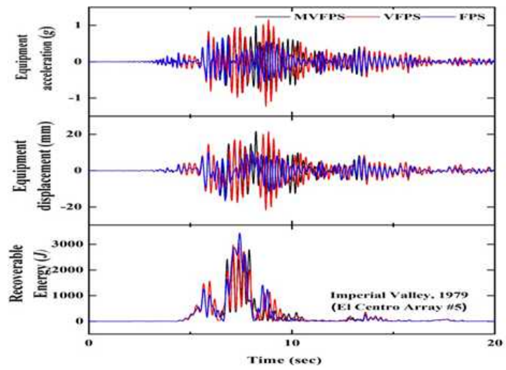
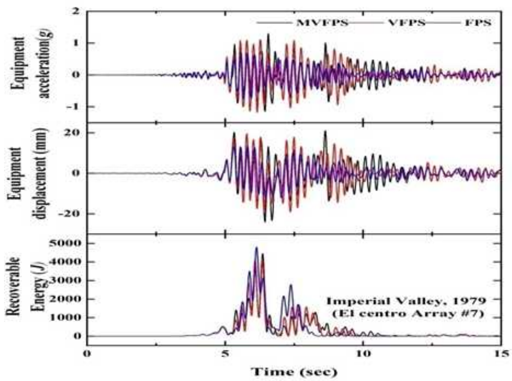


(f)

Figure 7: (a to f) Shows hysteresis loop of MVFPS, VFPS and FPS for single storey building with equipment under different earthquake ground excitations

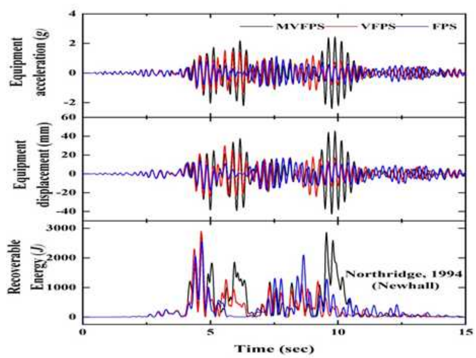


(a)



(b)

Figure 8: (a) and (b) Shows time vs. equipment acceleration, equipment displacement and recoverable energy of five storey building-equipment isolated with MVFPS, VFPS and FPS under different earthquake ground excitations



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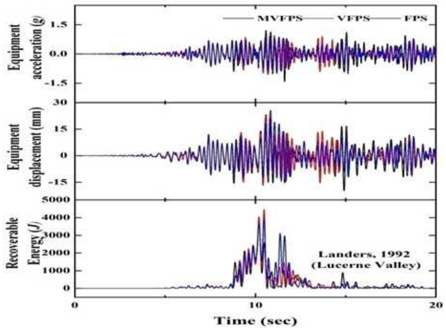
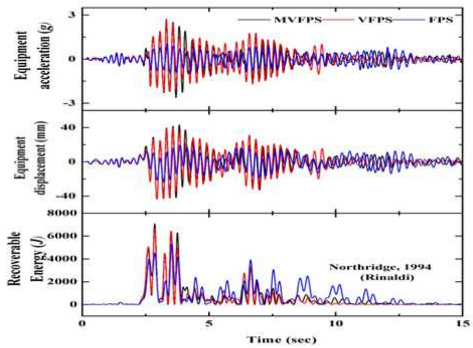


(b)

Figure 9: (a) and (b) Shows time vs. equipment acceleration, equipment displacement and recoverable energy of five storey building-equipment isolated with MVFPS, VFPS and FPS under different earthquake ground excitations



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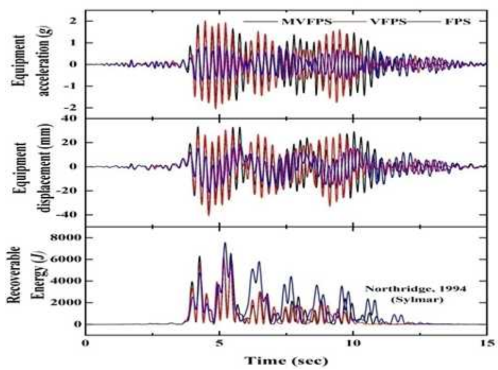


(b)

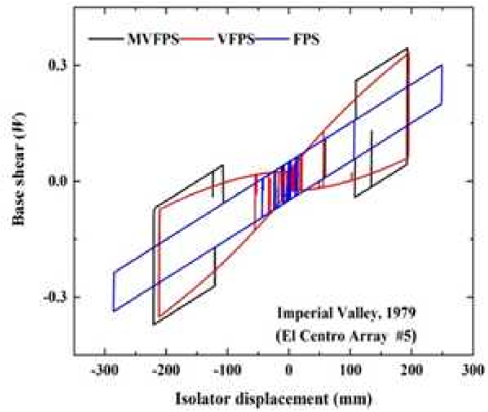
Figure 10: (a) and (b) Shows time vs. equipment acceleration, equipment displacement and recoverable energy of five storey building-equipment isolated with MVFPS, VFPS and FPS under different earthquake ground excitations

From above Figures, Fig. 8 (a) Imperial valley (El Centro Array#5) earthquake ground excitations shows that for five storey building-equipment system equipment acceleration and equipment displacement is less in FPS compared to MVFPS and VFPS and also recoverable energy result less in MVFPS and in Fig 8. (b) Imperial valley (El Centro Array#7) in this earthquake ground excitations FPS is good compared to MVFPS and VFPS. and recoverable energy found less in VFPS,

Both Fig. 9 (a) Northridge 1994 (Newhall) (b) Landers 1992 (Lucerne Valley) shows that equipment acceleration, displacement and recoverable energy is less in FPS compared to MVFPS and VFPS.

Fig. 10 (a) Northridge 1994 (Rinaldi) in this earthquake excitations equipment acceleration, displacement and recoverable energy is less in FPS compared to MVFPS and VFPS and 10 (b) shows that in Northridge 1994 (Sylmar) earthquake excitations equipment acceleration placement is high in VFPS but recoverable energy value is less in VFPS compared to MVFPS and FPS.

Result values of Fig. 8 to 10 Which depict Time vs equipment acceleration, displacement and recoverable energy of five storey building-equipment isolated with MVFPS,VFPS and FPS under different earthquake ground excitations shows in Table 3.



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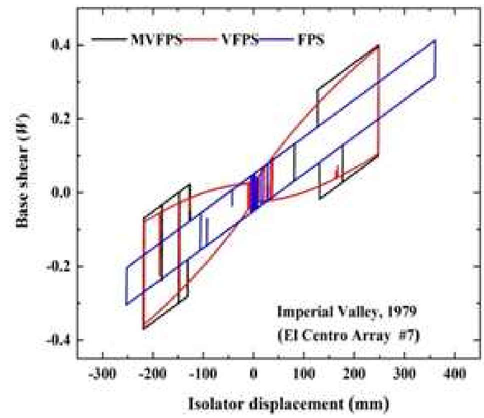

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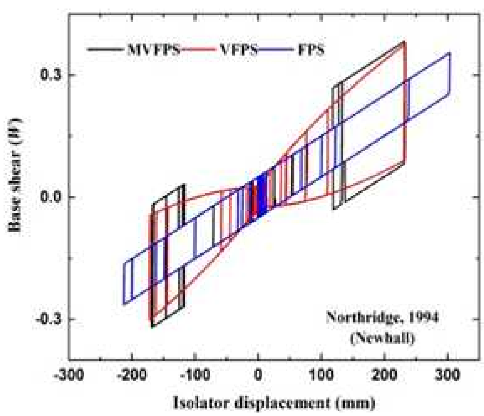

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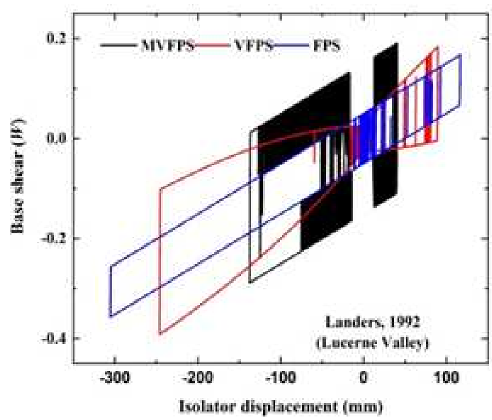

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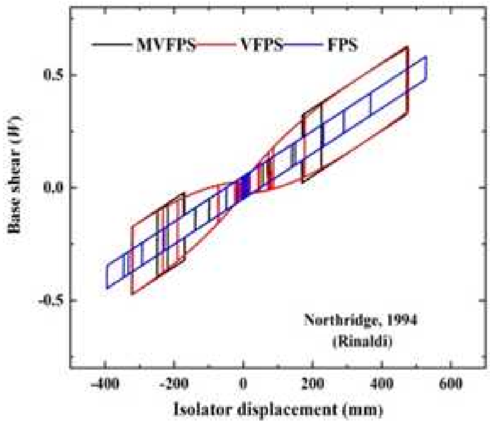

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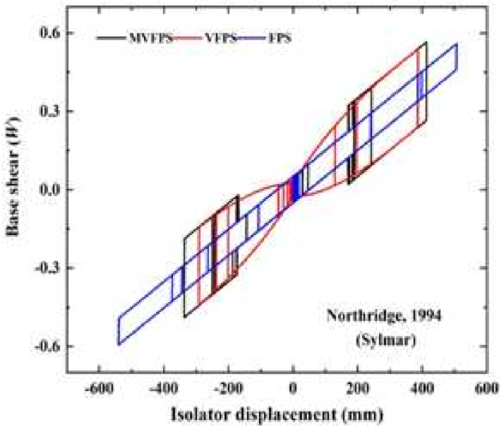

(f)

Figure 11: (a to f) shows Hysteresis loop of MVFPS, VFPS and FPS for five storey building with equipment under different earthquake ground excitations

Table 3: Comparison of peak response quantities under different earthquake ground excitations

Earthquake ground motion	Isolator	N = 1			N = 5		
		Equipment Accelera-tion (g)	Equipment Displace-ment (mm)	Recover-able Energy (J)	Equipment Accelera-tion (g)	Equipment Displace-ment (mm)	Recoverable Energy (J)
Imperial Valley,1979 El Centro (Array #5)	MVFPS	0.48	7.531	1846	0.988	21.527	2794
	VFPS	0.49	7.342	1766	1.151	21.719	3068
	FPS	0.29	6.315	3047	0.6614	16.656	3439
Imperial Valley,1979 El Centro (Array #7)	MVFPS	0.52	10.04	2749	1.1353	22.484	4496
	VFPS	0.57	10.51	2966	1.176	19.536	4167
	FPS	0.28	7.70	3277	0.7621	13.514	4792
Northridge 1994 (Newhall)	MVFPS	0.63	8.68	1118	2.445	45.56	2863
	VFPS	0.56	9.85	1250	1.5456	29.993	2905
	FPS	0.36	6.645	1463	1.148	18.116	2544
Landers 1992 (Lucerne Valley)	MVFPS	0.48	8.23	2798.1	1.417	25.58	3946
	VFPS	0.46	7.59	2957	1.0616	24.717	4451
	FPS	0.43	6.87	2798.3	1.0184	21.697	3939
Northridge 1994 (Rinaldi)	MVFPS	0.6	12.5	3710	2.7115	43.717	7068
	VFPS	0.57	14.1	3590	2.7823	43.584	6629
	FPS	0.38	12.1	3917	1.1105	23.326	5049
Northridge 1994 (Sylmar)	MVFPS	0.63	11.3	3301	1.8339	38.027	6563
	VFPS	0.59	11.9	2867	2.0521	40.685	6265
	FPS	0.28	10.9	5733	0.8669	21.534	7565

Table 4: Comparison results of isolator displacement and base shear under different earthquake ground excitations

Earthquake ground motion	Isolator	N = 1		N = 5	
		Isolator Displacement (mm)	Base shear (W)	Isolator Displacement (mm)	Base shear (W)
Imperial Valley,1979 El Centro (Array #5)	MVFPS	245.68	0.3971	220.43	0.3713
	VFPS	238.71	0.3836	211.61	0.351
	FPS	283.56	0.3352	285.62	0.3372
Imperial Valley,1979 El Centro (Array #7)	MVFPS	265.23	0.4168	248.67	0.3997
	VFPS	262.01	0.41	248.61	0.3949
	FPS	363.44	0.4156	361.21	0.4131
Northridge 1994 (Newhall)	MVFPS	236.99	0.3884	232.26	0.3831
	VFPS	237.87	0.3826	233.13	0.3771
	FPS	321.37	0.3723	303.42	0.3552
Landers 1992 (Lucerne Valley)	MVFPS	264.39	0.4159	137.4	0.2882
	VFPS	258.77	0.4063	246.06	0.392
	FPS	320.62	0.3725	305.43	0.3572
Northridge 1994 (Rinaldi)	MVFPS	513.7	0.651	473.22	0.626
	VFPS	513.43	0.6531	476.88	0.6207
	FPS	573.87	0.6273	528.34	0.5815
Northridge 1994 (Sylmar)	MVFPS	414.32	0.5668	413.47	0.5651
	VFPS	399.6	0.5494	387.18	0.5831
	FPS	557.09	0.611	540.43	0.5931

The above Table 3 shows result of Fig 4. to 6 for one storey building and fig 8 to 9 for five storey building with building equipment. From Table 3 it is clearly shows that increasing number of storey equipment acceleration, displacement and recoverable energy also increased.

Table 4 shows result of Fig. 7 and 11 for different earthquake ground excitations. This table depict result of isolator displacement and base shear for one storey and five storey building.

7. Conclusions

The Base isolated multi-storied building with light weight equipment at top is analyzed to determine its response under near-fault ground excitations with the help of Newmark's linear acceleration method. One and five storey buildings with equipment system isolated with MVFPS are compared with that of FPS and VFPS. The different response quantities examined are equipment displacement, equipment acceleration and recoverable energy. Following conclusions are derived from this comparative study:

From the above study, it is evident that equipment acceleration and equipment displacement increases when studied for five storey building-equipment system as compare to that of a single storey building-equipment system isolated using MVFPS,VFPS and FPS, where there is little increase observed in recoverable energy for five storey building as compared to that of a single storey building. FPS is performing better in reducing equipment acceleration

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and equipment displacement as compared to VFPS and MVFP.

It is found that in MVFPS, base shear and isolator displacement are less as compared to that of VFPS and FPS. The amount of energy dissipation is higher in case of MVFPS than that of FPS and VFPS. From this study it show that MVFPS is more efficient in reducing recoverable energy than FPS, but less efficient than VFPS.

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