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Seismic Response of Building-Equipment Isolated with Polynomial Friction Pendulum Isolator

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ABSTRACT

Numerical study of multistory building with equipment isolated by the Polynomial Friction Pendulum Isolator (PFPI) is carried out. Six different earthquake ground excitations are used as input ground motions. For this purpose, seismic response of building with equipment isolated with PFPI is obtained under normal component of different ground motions by using Newmark's linear acceleration method. The seismic response of building isolated with PFPI is compared with that of Variable Frequency Pendulum Isolator (VFPI) to examine the effectiveness of PFPI. From the comparative study, it is observed that the VFPI is more efficient in reducing the seismic response of building with equipment as compared to PFPI.

Keywords: Base isolation, PFPI, VFPI, Ground motion data, Building with equipment, Newmark's linear acceleration method

I. INTRODUCTION

Base isolation technique has gained wide acceptance during the last few decades, as it protects different types of structures, like buildings, bridges, nuclear power plants, etc., against the devastating effects of earthquake. In base isolation system, the building is kept away from the surface of the earth, which protects the building from devastating effects of earthquake and increases energy dissipation capacity as well as the fundamental natural time period of building. For this purpose, isolators are provided between the superstructure and foundation. Recent trend of development in base isolation is concentrated on the use of frictional type of base isolation systems as it is effective for a large range of frequency input. Many base isolation systems like Pure Friction (PF), Friction Pendulum System (FPS), Triple Friction Pendulum System (TFPS), Variable Frequency Pendulum Isolator (VFPI) and Polynomial Friction Pendulum Isolator (PFPI).

Murnal and Sinha [1] studied multi-storey building with equipment isolated with FPS, PF and VFPI. From the study they concluded that VFPI is effective as compared to the FPS and PF. Aravintham et al. [2] studied design of different base isolated structure and gave its merits and demerits. Lu et al. [3] conducted the experimental and numerical study of multifunctional floor isolation systems, which consist of several variable stiffness isolators called PFPI and observed that variable stiffness of the PFPI system can reduce displacement and acceleration response of structure. Saha et al. [4] studied seismic response of a highway bridge isolated by PFPI and concluded that PFPI is more effective than FPS for highway bridge.

In this study, PFPI-isolated multi-storey building with equal mass at each floor and top light equipment with 1% of floor mass is considered. Different ground motions are used to investigate the equipment acceleration, equipment displacement and recoverable energy of PFPI-isolated building. Comparison of VFPI and PFPI has been made. Newmark's linear acceleration method is used to solve the equation of motion.

II. CONCEPT OF PFPI

In FPS system, the major problem observed is resonant [5]. PFPI is used to solve this problem of resonant. The only difference in PFPI and FPS is that in PFPI, the sliding surface has been made of an axially symmetric surface with a variable curvature where in FPS, sliding surface has been made of surface with constant curvature.

The advantage of this isolator is that it can handle long period pulse and decrease isolator drift and structural acceleration when compared to FPS. In the PFPI, following polynomial function is used to define the geometry of the sliding surface

$$y'(x) = \frac{U_r(x)}{P} = ax^5 + cx^3 + ex \quad (2.1)$$

$$y''(x) = \frac{k_r(x)}{P} = 5ax^4 + 3cx^2 + e \quad (2.2)$$

$$a = \frac{-k_0 + k_1}{-5(D_1)^4}, \; c = \frac{2(-k_0 + k_1)}{3(D_1)^2}, \; e = k_0 \quad (2.3)$$

In above equation, y'(x) is restoring course function, $U_r(x)$ is the normalized force with respect to the vertical load P and y''(x) is normalized isolator stiffness, $k_r(x)$ is restoring stiffness with respect to the vertical load P, k_o is the normalized initial stiffness, D_1 is defined as critical isolator drift, a, c and e are constants and k_1 is normalized isolated stiffness at x = D_1.

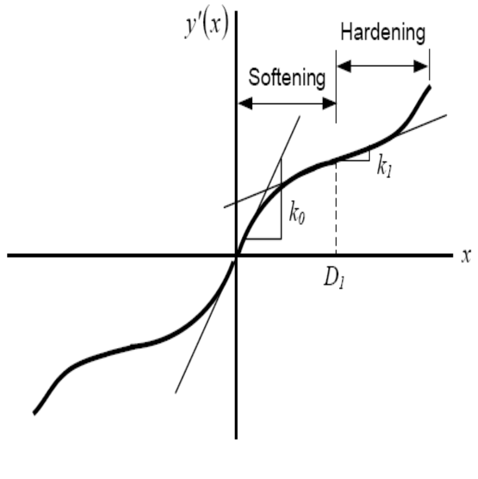

Figure. 1: Normalized restoring force y'(x) [5]

In this type of isolator, there are two process parts in displacement which is shown in Figure 1. The softening and hardening sections were aimed to control the structural acceleration and isolator drift, respectively.

III. GOVERNING EQUATION OF MOTION

The governing equation of motion for building is considered as follows

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = -[M]\{r\}\{\ddot{x}_b + \ddot{x}_g\} \quad (3.1)$$

where [M] is mass, [C] is damping and [K] is stiffness matrix, having size of N X N; $\{r\} = \{1,1,\dots,1\}^T$ is influence coefficient vector; $\ddot{x}_g$ is the ground acceleration; $\ddot{x}_b$ denote acceleration of base mass with respect to the ground.

$$F_b = k_b\, x_b + F_x \quad (3.2)$$

$$k_b = Mgy''(x) \quad (3.3)$$

where F_b is restoring force, F_x is frictional force, y''(x) represents isolator stiffness of PFPI, k_b is isolator stiffness and x_b is isolator displacement, where M is the total mass of the building.

The PFPI can be subjected (before sliding) to the limiting frictional force, Q, which is given by,

$$Q = \mu W \quad (3.4)$$

where μ is the friction coefficient of PFPI. The stiffness, W is the weight of the building.

k_b of PFPI is designed in such a way that certain value of isolation period T_b is obtained; which is given by

$$T_b = 2\pi\sqrt{\frac{M}{k_b}}$$

(3.5)

The maximum time interval for equation solution is taken as 0.02/500 sec i.e., Δt = 0.00004 sec). Following are the equations used for obtaining the seismic response:

$$\Delta\hat{p}_i = \Delta p_i + a\dot{u}_i + b\ddot{u}_i \quad (3.6)$$

where $a = \frac{6}{\Delta t}m + 3c$ and $b = 3m + \frac{\Delta t}{2}c$

$$\Delta u_i = \frac{\Delta \widehat{p_i}}{\hat{k}} \tag{3.7}$$

$$\Delta \dot{u}_i = \frac{3}{\Delta t}\Delta u_i - 3\dot{u}_i - \frac{\Delta t}{2}\ddot{u}_i \tag{3.8}$$

$$\Delta \ddot{u}_i = \frac{6}{(\Delta t)^2}(\Delta u_i - \Delta t \dot{u}_i) - 3\ddot{u}_i \tag{3.9}$$

$$u_{i+1} = u_i + \Delta u_i, \dot{u}_{i+1} = \dot{u}_i + \Delta \dot{u}_i, \ddot{u}_{i+1} = \ddot{u}_i + \Delta \ddot{u}_i \tag{3.10}$$

Once $\Delta\widehat{p_i}$ is known than Δu_i, $\Delta\dot{u}_i$ and $\Delta\ddot{u}_i$ can be computed by using the Equations 3.7-3.9, and u_{i+1}, $\dot{u}_{i+1}$ and $\ddot{u}_{i+1}$ from Equation 3.10.

IV. NUMERICAL STUDY

In this study, PFPI-isolated five-storey building with equal mass is considered. Also, light equipment is with 1% of floor mass is considered at top. Figure 2 shows the building with equipment. Tables I-III show the building properties, isolator properties and different earthquake ground motions respectively. Building with equipment response quantities under consideration are the acceleration of equipment, equipment displacement and recoverable energy.

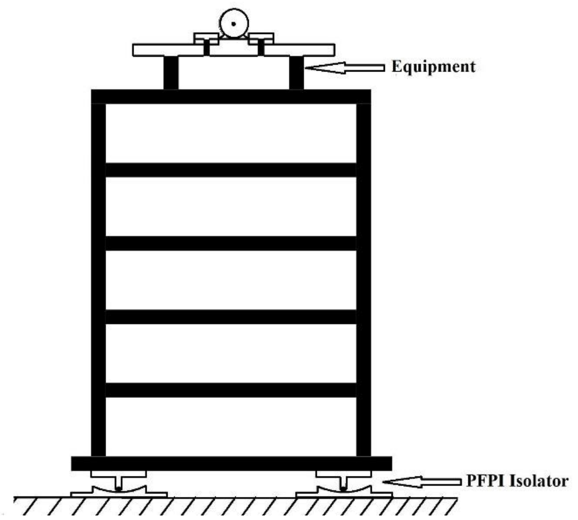

Figure 2: Building with Equipment

Table I
Building and Equipment Properties

Lumped mass for 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%
Fundamental time period of building	0.5 sec
Ratio of mass to base mass	1.0
Equipment frequency	3.85 Hz

Table II
Isolator Properties

Coefficient of friction	0.02
Base isolation time period	2.5 sec
Critical isolator drift (D_1)	0.2
Constant a	81.25
Constant c	-10.83
Constant e	0.65

Table III
Earthquake ground motions

Earthquake ground motion	**PGA (g)**
Imperial Valley, 1940 (EI-Centro)	0.313
Superstition Hills, 1987 (EI-Centro Imperial Court Centre)	0.512
Northridge, 1994 (Topanga-Canyon)	0.477
Northridge, 1994 (Northridge-Saticoy)	0.529
Loma Prieta, 1989 (Capitola)	0.420
EI Centro, 1940 (North-South Component)	0.318

V. RESULTS AND DISCUSSION

Figures 3-8 shows the time variation of equipment acceleration, equipment displacement and recoverable energy of building-equipment isolated with the VFPI and PFPI and Table IV show the peak response value of building-equipment isolated with the VFPI and PFPI.

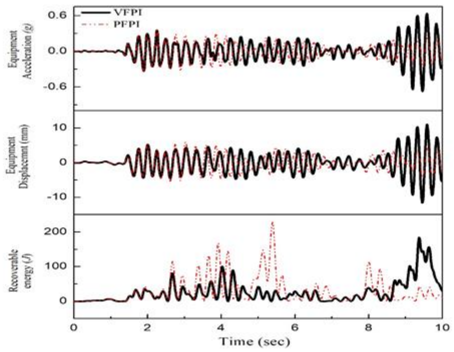

Figure 3: Time variation of equipment acceleration, equipment displacement and recoverable energy of building-equipment isolated with PFPI and VFPI under Imperial Valley, 1940 (El-Centro)

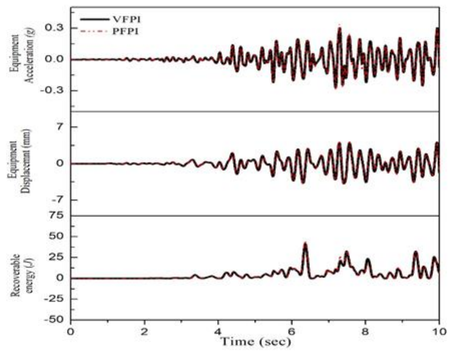

Figure 4: Time variation of equipment acceleration, equipment displacement and recoverable energy of building-equipment isolated with PFPI and VFPI under Superstition Hills, 1987 (El-Centro Imperial Court Center)

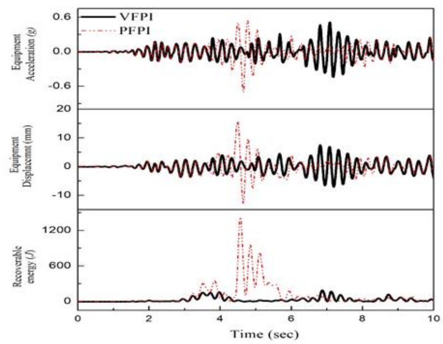

Figure 5: Time variation of equipment acceleration, equipment displacement and recoverable energy of building-equipment isolated with PFPI

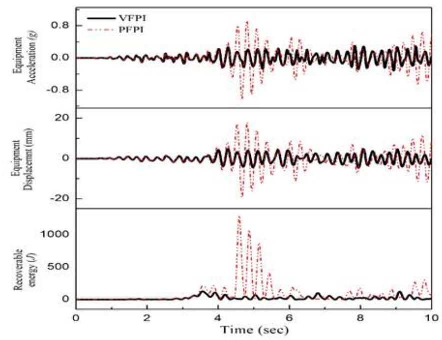

Figure 6: Time variation of equipment acceleration, equipment displacement and recoverable energy of building-equipment isolated with PFPI

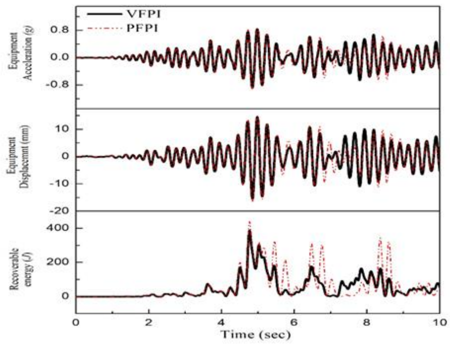

Figure 7: Time variation of equipment acceleration, equipment displacement and recoverable energy of building-equipment isolated with PFPI and VFPI under Loma Prieta, 1989 (Capitola)

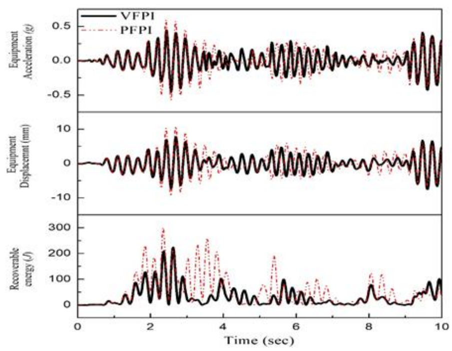

Figure 8: Time variation of equipment acceleration, equipment displacement and recoverable energy of building-equipment isolated with PFPI and VFPI under El-Centro, 1940 (North-South Component)

Table IV
Peak responses quantities of building-equipment isolated by VFPI and PFPI

Earthquake ground motion	Recording station	Isolator	Equipment acceleration (g)	Equipment displacement (mm)	Recoverable energy (J)
Imperial Valley (1940)	El-Centro	PFPI	0.460	7.727	227.800
		VFPI	0.672	11.629	184.280
Superstition Hills (1987)	El-Centro Imperial Court Center	PFPI	0.417	7.302	242.140
		VFPI	0.420	7.088	130.710
Northridge (1994)	Canoga Park - Topanga Canyon	PFPI	0.703	15.795	1424.100
		VFPI	0.515	7.553	190.640
Northridge (1994)	Northridge-Saticoy	PFPI	1.007	19.312	1292.200
		VFPI	0.568	10.171	207.720
Loma Prieta (1989)	Capitola	PFPI	0.927	16.357	438.530
		VFPI	0.884	15.469	388.160
EI-Centro (1940)	North-South component	PFPI	0.597	10.761	299.810
		VFPI	0.459	7.786	223.980

VI. CONCLUSIONS

Conclusions derived from the above study are as follows:

1) In case of VFPI isolated building, equipment acceleration and equipment displacement are less than that of PFPI isolated building under most of the earthquake ground motions.
2) In case of VFPI isolated building, recoverable energy is less than that of PFPI isolated building under most of the earthquake ground
3) From the above results, it is observed that VFPI is more effective than PFPI.

VII. REFERENCES

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