Chapter 4

Performance of Sliding Isolation Systems Subjected to Far field Ground Motions – Single Storey and Multi Storied Structure

4.1 INTRODUCTION

In this chapter the performance of sliding isolation systems subjected to far field ground motion has been investigated. An attempt has been made to confirm that VFPI is effective in reducing the response values in case of far field ground motion. The period of FPS isolator is considered as 2 s (R = 1.0 m). For a given coefficient of friction, the main parameters of VFPI affecting the response are (i) initial time period and (ii) Frequency Variation Factor (FVF). For the present analysis FVF has been varied from 1.0 per m to 10.0 per m for VFPI with two values of initial time period, 1 s and 2 s. The response quantities are evaluated by solution of the equations of motion as discussed in the previous chapter. The main response quantities of interest are sliding displacement of isolator, absolute acceleration of top storey and residual displacement.

4.2 DETAILS OF FAR FIELD GROUND MOTION

4.2.1 Characteristics of Far Field Ground Motion

The far field ground motion is a motion when site is at large distance from fault (generally more than 10 km). Due to large distance from fault the earthquake excitation contains higher frequencies. Due to higher frequencies the isolator displacement is comparatively less than near-field and low frequency ground motions. To understand the characteristics of far field earthquake the time history of ground motion and response spectrum of El Centro 1940, N-S component is shown in Figures 4.1 and 4.2 respectively. From time history of ground motion it is found that PGA is 0.318g and duration of earthquake is 31.18 s. From response spectrum it can be observed that the ground motion is of broad band nature. The predominant period is 0.16 s to 0.66 s. Hence in present study for SDOF system a system with period of 0.5 s has been considered for analysis.

4.2.2 Details of Far Field Ground Motion Used in this Research Work

The detail of the ground motion used in this study is presented in Table 4.1. This ground motion is from historical recordings.

4.3 PERFORMANCE OF SLIDING ISOLATION SYSTEMS SINGLE STOREY STRUCTURE

The behavior of various isolators has been studied through time history analysis for El centro 1940 N-S component ground motion. This analysis is carried out to confirm the performance of isolator during far field earthquake which is already well-established in literature (Mostaghel and Tanbakuchi 1983; Constantinou et. al. 1990; Lin et. al. 1990; Zayas 1990; Pranesh and Sinha 1998; Lu et. al. 2004). Therefore a representative analysis for only one ground motion for SDOF and MDOF system is carried out for various isolators with constant coefficient of friction. The single-storey shear structure is represented as a lumped mass model. The mass and stiffness of the structure are chosen such that the period of structure will be 0.5 s, which typically represent a medium rise structure. The mass of structure and base are taken equal, so that the mass ratio, $\alpha = 0.5$. The mass ratio is so chosen because it is observed from literature that larger the mass ratio, more effective the sliding supports in cutting down the level of acceleration response (Mostaghel et. al. 1983). The response values are tabulated in Tables 4.2 and 4.3. The results of normalized (normalized with respect to FPS values) response values of far field record (FFR, SDOF) are presented graphically in Figures 4.3 and 4.4.

4.3.1 Results and Discussion: SDOF Systems

In this section performance of various isolators has been discussed when subjected to far-field ground motion. The main parameters affecting the response are, (i) Geometry of isolator and (ii) Coefficient of friction. To have comparative analysis, the responses of isolator are normalized with respect to the corresponding values of a FPS isolator having a time period of 2 s, which is a normally adopted FPS time period.

4.3.1.1 Effect of geometry:

Among the various isolators considered PF has no geometrical parameter and FPS is the single parameter system defined by its radius, which defines the time period of isolator. VFPI is multi parameter system having initial time period and FVF as its parameters in addition to coefficient of friction.

From figures [Figure 4.3 and 4.4] it is observed that the acceleration of structure isolated with VFPI reduces with increase in FVF for both values of initial time period. However the acceleration for $T_i = 1$ s are greater than FPS. This is because the initial time period defines initial stiffness which tends to increase acceleration. However accelerations for VFPI with $T_i = 2$ s are lower than those with FPS.

On the other hand it is observed that there is increase in sliding displacement with increase in FVF and they are lower for lower initial time period. So it can be seen that it is possible to decide VFPI parameters for having the desired control over acceleration and displacement when subjected to far-field ground motion.

As PF has flat geometry the sliding and residual displacements are higher. But at the same time, as it has no predominant frequency the acceleration is controlled. Due to higher initial stiffness of FPS the sliding and residual displacements are lower, but storey accelerations are higher.

Further since the magnitude of sliding displacement is relatively small, CFPI and FPS geometry remain same for all practical purposes for small sliding displacement.

4.3.1.2 Effect of coefficient of friction

As expected an increase in coefficient of friction leads to an increase in acceleration and reduces sliding displacements. From figures [Figure 4.3 and 4.4] it is observed that with increase in coefficient of friction the effect of change in geometry reduces. As the ground motion does not contain pulse type excitation, sliding of isolator is lower. Hence the sliding is nearly equal for both values of coefficient of friction. But as acceleration is well controlled by lower value of coefficient of friction, $\mu = 0.05$ is found to be more effective for all the isolators.

4.3.1.3 Remarks

From above discussion it can be concluded that $\mu = 0.05$ is most effective for all isolators. Again it is found that there is marginal difference in all response values of VFPI ($T_i = 2$ s), PF and FPS at $\mu = 0.05$. Hence **all isolators found equally effective at $\mu = 0.05$** in case of far field record.

4.4 PERFORMANCE OF SLIDING ISOLATION SYSTEMS MULTI STORIED STRUCTURE

The behavior of various isolators has been studied through time history analysis for El centro 1940 N-S component ground motion which is also used for single storey structure.

The analysis is carried out for constant coefficient of friction. The example structure is a five-storey shear structure. The example building is represented as a lumped mass model with 60080 kg of equal lumped mass and 112600 kN/m of equal storey stiffness for each floor. The frequencies and modal properties for the fixed-base and isolated structures are as given in Table 4.4. Since the natural frequencies of a structure isolated by VFPI change continuously with the isolator sliding displacement, the frequencies shown in Table 4.4 thus indicate the upper bound on the frequencies when the isolator displacement is zero. (Murnal and Malu 2007)

The response values are tabulated in Tables 4.5 and 4.6. The results of normalized (normalized with respect to FPS values) response values of far field record (FFR, MDOF) are presented graphically in Figures 4.5 and 4.6.

4.4.1 Results and Discussion: MDOF Systems

In this section the performance of MDOF system of various isolators has been discussed with respect to (i) Geometry of isolator (ii) Coefficient of friction and (iii) Modal participation

4.4.1.1 Effect of geometry

From figures [Figure 4.5(a) and 4.6(a)] it is observed that the acceleration is lower for lower value of FVF for both values of initial time period. However the acceleration for $T_i = 1$ s are slightly less than FPS and $T_i = 2$ s. Acceleration of $T_i = 2$ s and FPS are nearly equal. Although the difference in acceleration values of all isolators is very less.

On the other hand it is observed that there is increase in sliding displacement with increase in FVF and they are lower for lower initial time period. [Figure 4.5(b) and 4.6(b)] Again residual displacement of $T_i = 1$ s is substantially less than FPS and $T_i =$ 2s, as $T_i = 1$ s have high initial stiffness it leads to very less residual displacement. Residual displacement of FPS and $T_i = 2$ s are almost same as both are equally spherical. Due to lack of restoring force residual displacement of PF is too high. [Figure 4.5(c) and 4.6(c)]

Further since the magnitude of sliding displacement is relatively small, CFPI and FPS geometry remain same for all practical purposes for small sliding displacement.

4.4.1.2 Effect of coefficient of friction

As expected an increase in coefficient of friction leads to an increase in acceleration and reduces sliding displacements. From figures [Figure 4.5 and 4.6] it is observed that with increase in coefficient of friction the effect of change in geometry reduces. It is observed that coefficient of friction has marginal effect on sliding and residual displacement of isolator. But storey accelerations are lower for lower value of coefficient of friction.

4.4.1.3 Effect of modal participation

Table 4.7 to Table 4.9 shows the cumulative response of MDOF structure with respect to modes. Typical cases are considered for the discussion, where sliding displacement and storey acceleration are comparatively higher. From the table it is observed that the storey acceleration and residual displacement have higher contribution for higher modes. Hence it can be concluded that the higher mode contribution is significant.

4.4.1.4 Remarks

From above discussion it can be concluded that $\mu = 0.05$ is **more effective for all isolators.** Again it is found that sliding, residual displacement and acceleration of VFPI (T_i = 1 s) are less or slightly higher than PF and FPS. Overall it is found that all isolators are equally effective for structure subjected to far field ground motion. However VFPI being multi parameter system provides a variety of choices for design depending on the requirements.

Table 4.1: Details of far field earthquake record used in this research work

Sr. No.	Name of earthquake	Designation	Distance of source (km)	PGA (g)	Duration (s)
1	El centro 1940 N-S Component	FFR-01	> 10	0.318	31.18

Table 4.2: Peak response values, (FFR, SDOF), (μ = 0.05, μ = 0.1), {VFPI (T_i = 1 s, T_i = 2 s, FVF = 1 to 10)}

FVF	Sliding Disp. of Isolator (m)				Residual Disp. of Isolator (x 10^{-2} m)				Abs. Acc. of Top Storey (m/s^2)			
	μ = 0.05		μ = 0.1		μ = 0.05		μ = 0.1		μ = 0.05		μ = 0.1	
	T_i=1s	T_i=2s	T_i=1s	T_i=2s	T_i=1s	T_i=2s	T_i=1s	T_i=2s	T_i=1s	T_i=2s	T_i=1s	T_i=2s
1	0.047	0.061	0.032	0.030	0.121	1.023	0.639	0.977	2.81	1.80	2.90	2.95
2	0.049	0.061	0.033	0.032	0.152	1.020	0.656	0.967	2.75	1.79	2.90	2.95
3	0.050	0.064	0.033	0.032	0.179	1.380	0.672	0.962	2.58	1.86	2.90	2.95
4	0.043	0.066	0.034	0.033	0.201	1.018	0.689	0.950	2.33	1.85	2.90	2.95
5	0.044	0.069	0.034	0.034	0.231	1.017	0.706	0.949	2.17	1.90	2.90	2.95
6	0.044	0.068	0.034	0.035	0.252	1.015	0.723	0.950	2.32	1.90	2.90	2.95
7	0.045	0.069	0.035	0.035	0.289	1.016	0.739	0.954	2.07	1.89	2.90	2.95
8	0.045	0.071	0.035	0.036	0.307	1.005	0.755	0.967	1.96	1.88	2.90	2.95
9	0.046	0.067	0.035	0.035	0.350	1.001	0.771	0.937	2.01	1.88	2.90	2.95
10	0.046	0.067	0.036	0.037	0.375	1.010	0.786	0.833	1.96	1.87	2.90	2.95

Table 4.3: Peak response values, (FFR, SDOF), (μ = 0.05, μ = 0.1), {PF; FPS (T_b = 2 s)}

Sliding Disp. of Isolator (m)				Residual Disp. of Isolator (x 10^{-2} m)				Abs. Acc. of Top Storey (m/s^2)			
μ = 0.05		μ = 0.1		μ = 0.05		μ = 0.1		μ = 0.05		μ = 0.1	
PF	FPS	PF	FPS	PF	FPS	PF	FPS	PF	FPS	PF	FPS
0.096	0.054	0.078	0.030	0.149	1.022	4.126	0.990	1.76	1.63	2.96	2.94

Table 4.4: Modal properties of fixed-base and isolated structures.

Mode	Isolator	1	2	3	4	5
Fixed – Freq. (Hz)	-	1.96	5.72	9.02	11.59	13.22
Eff. Modal Mass (%)	-	87.95	8.72	2.42	0.75	0.16
Isolated – Freq. (Hz)	0.49	3.64	6.92	9.76	11.93	13.31
Eff. Modal Mass (%)	99.93	0.07	0.00	0.00	0.00	0.00

Table 4.5: Peak response values, (FFR, MDOF), (μ = 0.05, μ = 0.1), {VFPI (T_i = 1 s, T_i = 2 s, FVF = 1 to 10)}

FVF	Sliding Disp. of Isolator (m)				Residual Disp. of Isolator (x 10^{-2} m)				Abs. Acc. of Top Storey (m/s^2)			
	μ = 0.05		μ = 0.1		μ = 0.05		μ = 0.1		μ = 0.05		μ = 0.1	
	T_i=1s	T_i=2s	T_i=1s	T_i=2s	T_i=1s	T_i=2s	T_i=1s	T_i=2s	T_i=1s	T_i=2s	T_i=1s	T_i=2s
1	0.043	0.071	0.033	0.032	0.060	0.289	0.680	1.001	2.82	3.36	4.32	4.78
2	0.045	0.074	0.034	0.042	0.061	0.291	0.712	0.985	2.77	3.37	4.32	4.78
3	0.046	0.073	0.029	0.043	0.023	0.285	0.743	0.972	3.06	3.38	4.56	4.78
4	0.047	0.075	0.029	0.045	0.020	0.286	0.774	0.963	3.10	3.87	4.55	4.79
5	0.048	0.075	0.029	0.046	0.014	0.287	0.805	0.969	3.12	3.39	4.54	4.79
6	0.211	0.076	0.029	0.046	0.003	0.288	0.835	0.933	3.17	3.40	4.53	4.58
7	0.038	0.072	0.028	0.047	0.021	0.288	0.864	0.947	3.20	3.40	4.52	4.57
8	0.043	0.072	0.029	0.049	0.012	0.287	0.900	0.930	3.18	3.40	4.61	4.57
9	0.042	0.072	0.029	0.050	0.004	0.289	0.927	0.882	3.23	3.41	5.59	4.57
10	0.039	0.067	0.029	0.052	0.033	0.297	0.964	0.863	3.19	3.41	4.75	4.57

Table 4.6: Peak response values, (FFR, MDOF), (μ = 0.05, μ = 0.1), {PF; FPS (T_b = 2 s)}

Sliding Disp. of Isolator (m)				Residual Disp. of Isolator (x 10^{-2} m)				Abs. Acc. of Top Storey (m/s^2)			
μ = 0.05		μ = 0.1		μ = 0.05		μ = 0.1		μ = 0.05		μ = 0.1	
PF	FPS	PF	FPS	PF	FPS	PF	FPS	PF	FPS	PF	FPS
0.131	0.065	0.091	0.031	8.969	0.287	4.711	1.009	3.11	3.34	4.73	4.77

Table 4.7: Mode wise cumulative storey acceleration (m/s^2), (FFR, MDOF), (μ = 0.05)

Isolator	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
PF	1.97	2.98	3.00	3.07	3.11
FPS (T_b = 2s)	2.20	3.11	3.38	3.47	3.34
VFPI (T_i = 2s, FVF = 6)	2.20	3.19	3.36	3.46	3.40

Table 4.8: Mode wise cumulative sliding displacement (m), (FFR, MDOF), (μ = 0.05)

Isolator	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
PF	0.112	0.122	0.119	0.120	0.131
FPS (T_b = 2s)	0.070	0.068	0.068	0.068	0.065
VFPI (T_i = 2s, FVF = 6)	0.086	0.075	0.076	0.076	0.076

Table 4.9: Mode wise cumulative residual displacement (x 10^{-2} m), (FFR, MDOF), (μ = 0.05)

Isolator	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
PF	6.438	8.561	8.083	8.197	8.969
FPS (T_b = 2s)	0.003	0.308	0.279	0.284	0.287
VFPI (T_i = 2s, FVF = 6)	0.038	0.337	0.302	0.308	0.288

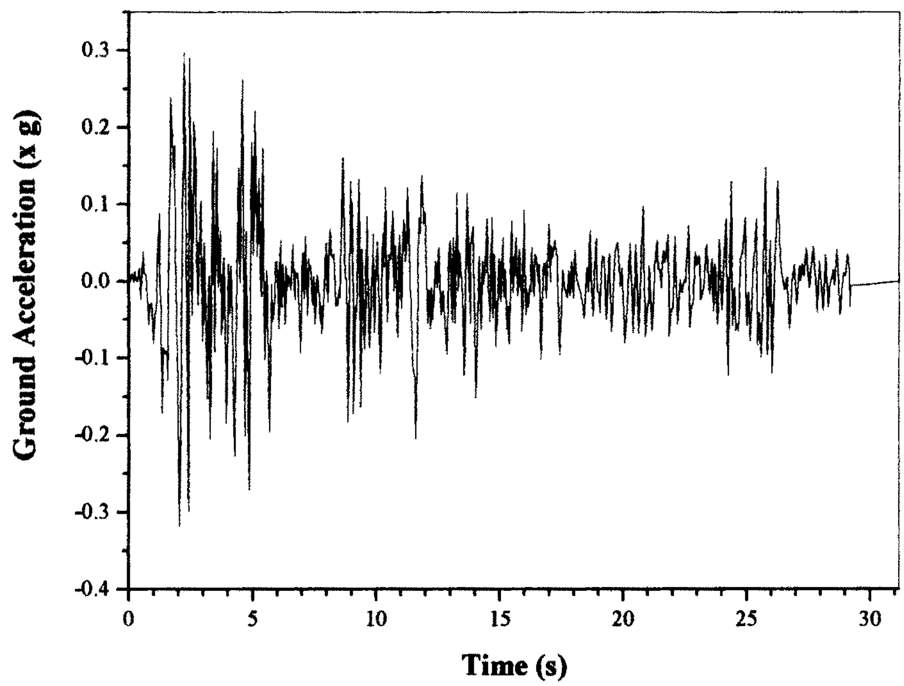

Figure 4.1: Time history of El Centro 1940, N-S component ground motion

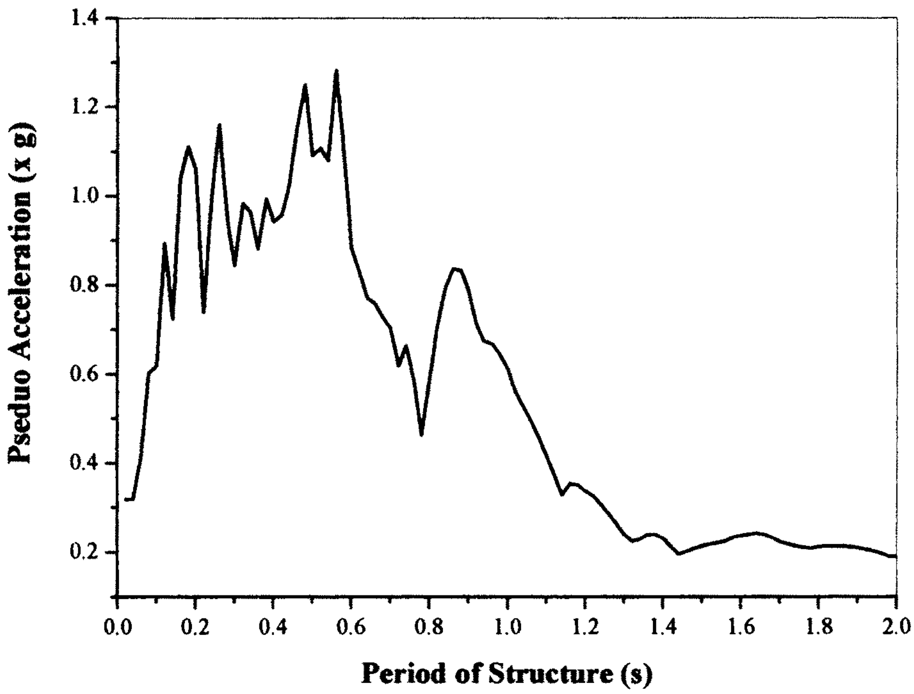

Figure 4.2: Response spectra for El Centro 1940, N-S component ground motion

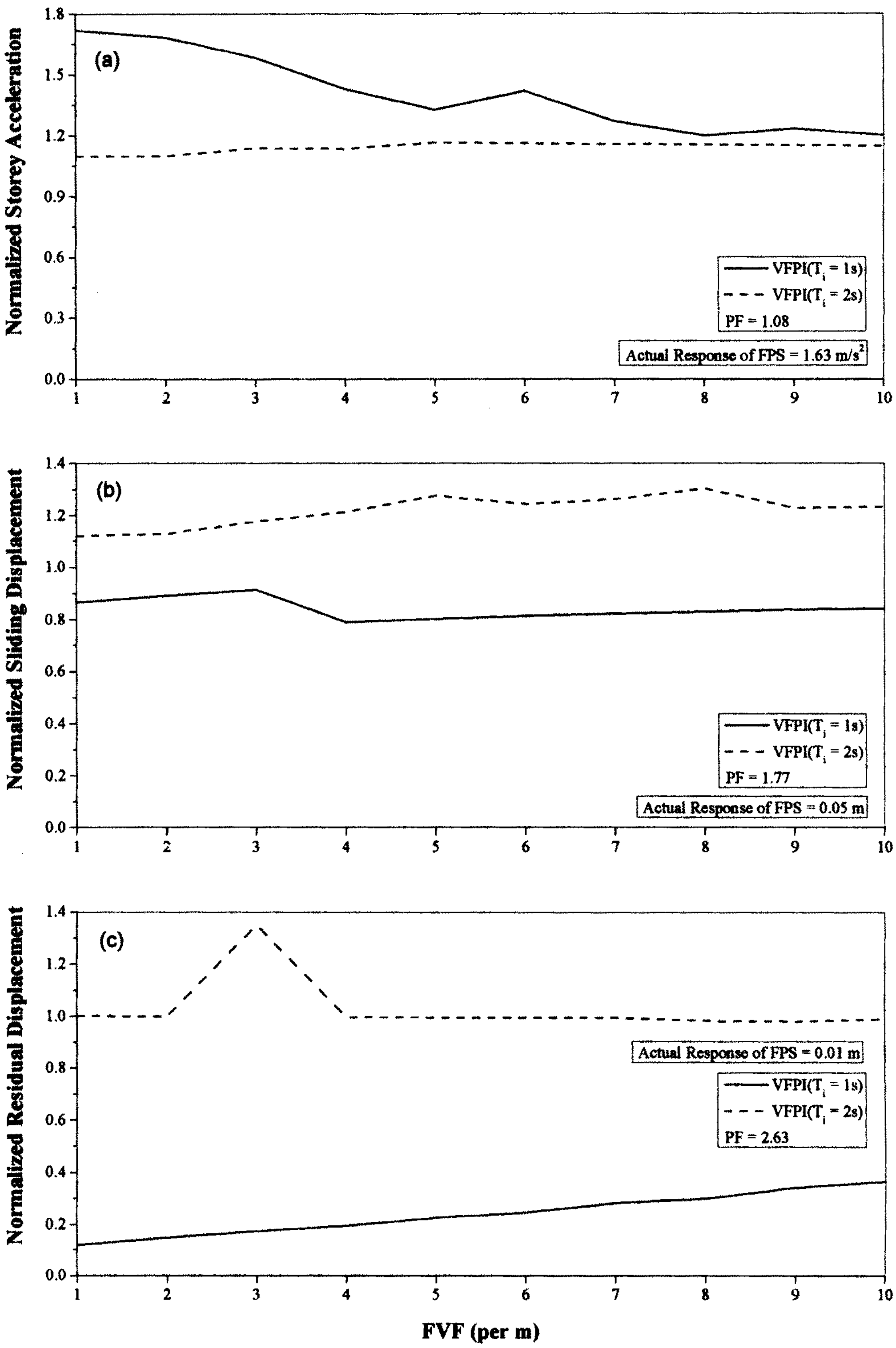

Figure 4.3: Responses normalized with that of FPS ($T_b = 2$ s) for SDOF system subjected to El Centro 1940 (N-S) earthquake, ($\mu = 0.05$)
(a): Absolute acceleration of top storey (b): Sliding displacement of isolator
(c): Residual displacement of isolator

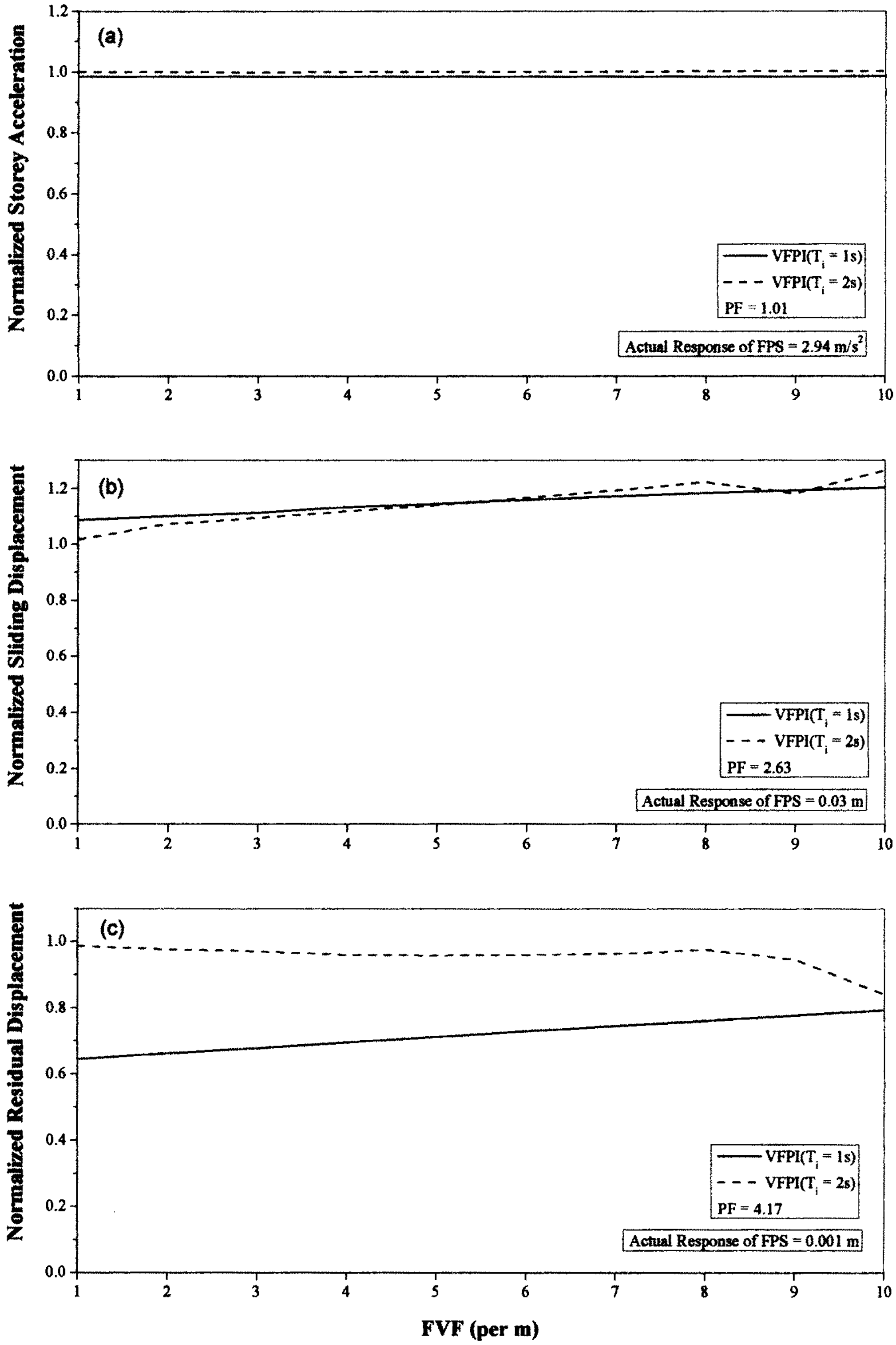

Figure 4.4: Responses normalized with that of FPS ($T_b = 2$ s) for SDOF system subjected to El Centro 1940 (N-S) earthquake, ($\mu = 0.1$)
(a): Absolute acceleration of top storey (b): Sliding displacement of isolator (c): Residual displacement of isolator

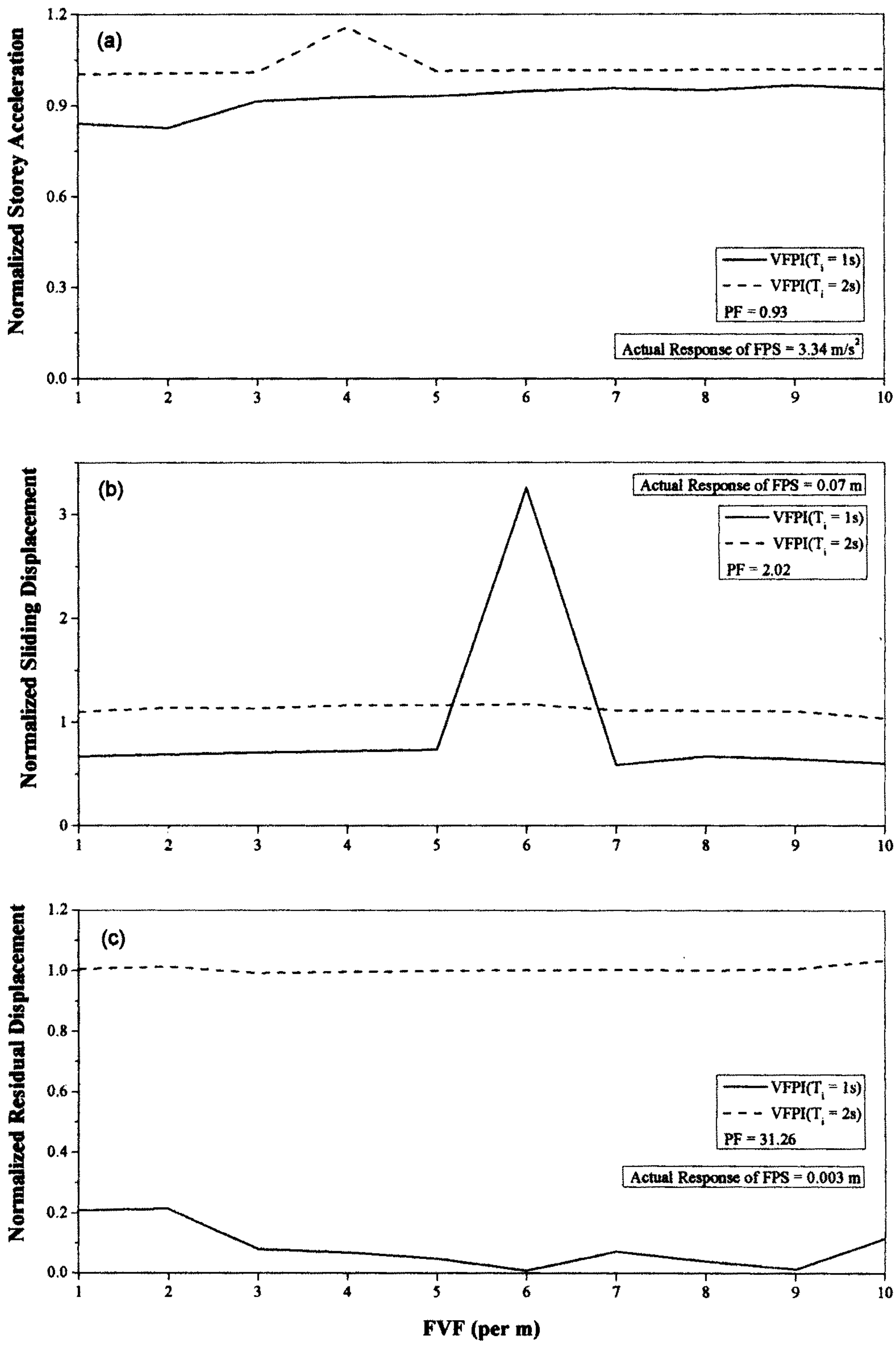

Figure 4.5: Responses normalized with that of FPS ($T_b = 2$ s) for MDOF system subjected to El Centro 1940 (N-S) earthquake, ($\mu = 0.05$)
(a): Absolute acceleration of top storey (b): Sliding displacement of isolator
(c): Residual displacement of isolator

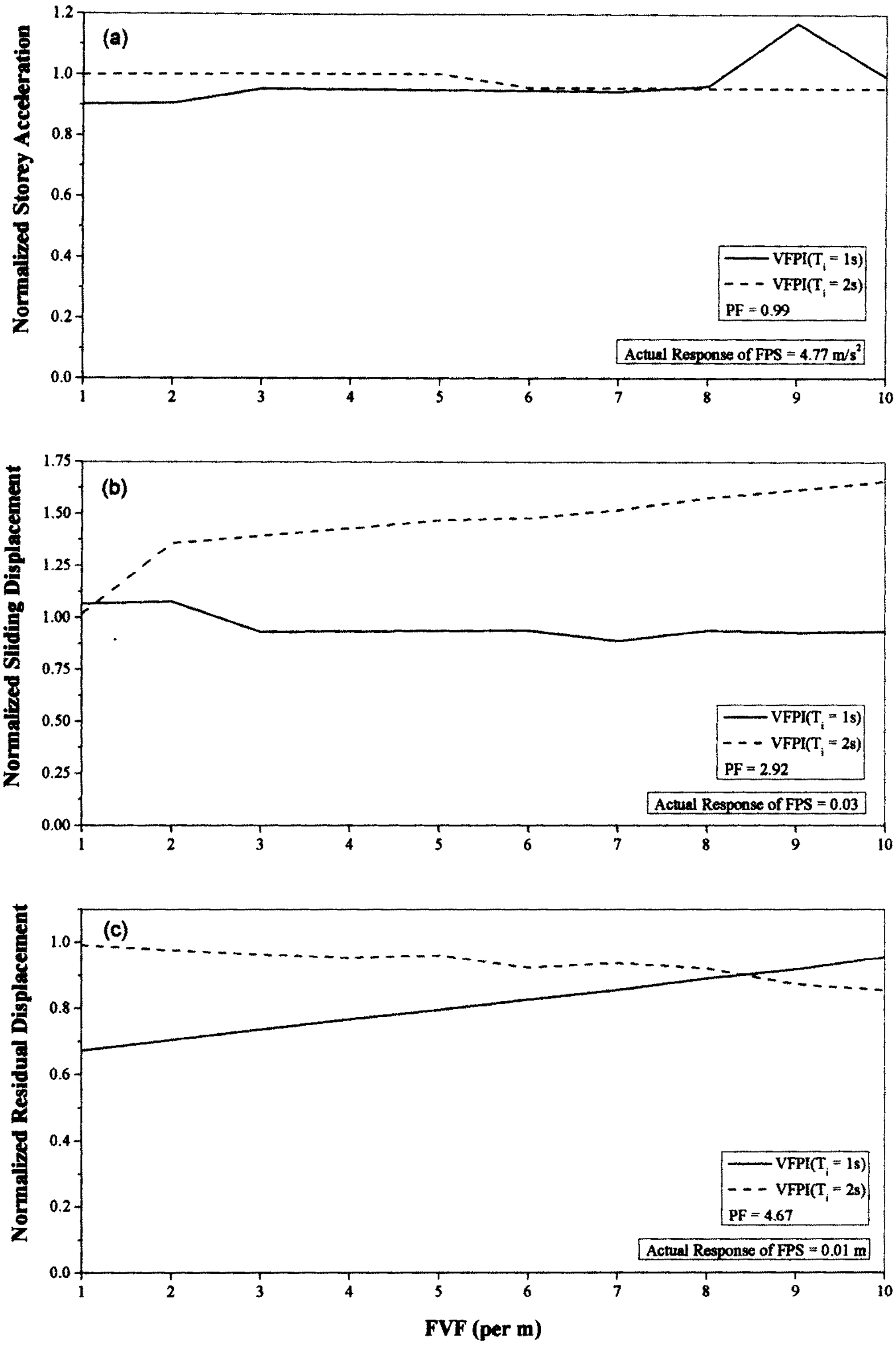

Figure 4.6: Responses normalized with that of FPS ($T_b = 2$ s) for MDOF system subjected to El Centro 1940 (N-S) earthquake, ($\mu = 0.1$)
(a): Absolute acceleration of top storey (b): Sliding displacement of isolator
(c): Residual displacement of isolator