COMPARISON OF VARIOUS SLIDING BEARINGS UNDER NEAR FAULT GROUND MOTIONS

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ABSTRACT

In recent years, the damages to the well-designed structures, caused by earthquakes, has attracted the attention of engineers to use seismic isolation systems such as sliding bearings. The seismic responses of conventional fixed base and isolated systems will be amplified in near fault ground motion due to its long period. Herein, the behaviour of a seismically isolated structure mounted on various sliding bearings is investigated under real ground motions, then the effects of isolation’s period on seismic responses of structure is studied. The numerical results show that the normalized base shear and superstructure’s acceleration are reduced significantly and can be controlled within a desirable rang with the installation of sliding bearings. It is also found that the VFPI has better performance compared to other sliding bearings. In addition, increasing the isolation’s period leads to decreasing the normalized base shear.

INTRODUCTION

Base isolation is one the most effective methods of reducing the induced damages and responses of structures during earthquake. Among different types of seismic isolation devices, the friction-type base isolator are highly popular and used specially in vital structures such as bridges and liquid storage tanks since its period does not depend on the weight of the mounted structure during earthquake. This type of isolator is also relatively insensitive to variations in the frequency content and amplitude of the input excitation (Mostaghel and Tanbakuchi, 1983).

The first generation of Friction Pendulum System (FPS) was introduced by Zayas et al. in 1987 (Zayas et al., 1987). FPS uses the gravity action to supply restoring force, containing of a spherical stainless steel surface to dissipate energy and re-centring the isolator after occurred movement during earthquake.Fig. 1 shows the cross section of FPS.Since the sliding surface of FPS isolator is spherical, its time period of oscillation remains constant.

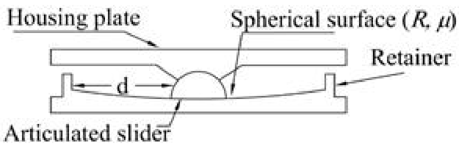

Figure 1. Cross section of FPS

Unfortunately, the uses of spherical sliding surface results in several practical disadvantages. One of these disadvantages is that FPS needs to be designed for a specific level of ground excitation amplitude which leads to reduce its efficiency under broad range of ground motions(Pranesh and Sinha, 2000).

In recent years, several studies and experimental researches have been done to improve the seismic performance of FPS isolators and provide fully adaptive devices.Pranesh and Sinha,introduced variable frequency pendulum isolator (VFPI) to overcome the limitations of usage of FPS.The VFPI is a kind of variable curvature friction pendulum system whose its sliding surface has an elliptical shape that its major axis extends as the slider takes away from the center point of sliding surface. VFPI has oscillation frequency decreasing with sliding displacement, and the restoring force has an upper bound so that the force transmitted to the structure is limited (Pranesh and Sinha, 2000). They also describe the mathematical formulations for a base isolated single degree of freedom (SDOF) structure and energy balance. Later on, in 2003, Tsai et al., proposed the variable curvature friction pendulum systems (VCFPS). The radius of the curvature of VCFPS is lengthened with an increase of the isolator displacement. Therefore, the fundamental period of the base-isolated structures can be shifted further away from the predominant period of ground motions (Tsai et al., 2003). Sincethe near fault ground motions have long period component, they may affect the structures which have long period. Therefore the VCFPS has better performance due to its adaptability with ground motions (Tsai et al., 2003).

Theoretical and experimental study for sliding isolator with variable curvatures have been done by Lu et al (Lu et al., 2011). They define sliding surfaces with 4^{th}-order and 6^{th}-order polynomial function for the curvature of isolator. The results demonstrated that the proposed VCFP is able to effectively reduce the isolator drift in a near-fault earthquake with strong long-period component, compared to FPS with same friction coefficient (Lu et al., 2011).

The aim of this paper is to scrutinize the seismic behaviour of various sliding bearings such as FPS, VCFP with 4^{th} and 6^{th} order polynomial function andVFPI under near fault ground motions. For this purpose, a single degree of freedom system is considered and the responses are compared with fixed base conditions. The parametric study is also conducted out to investigate the effects of isolation's period on responses.

MATHEMATICAL MODEL

In this section a mathematical formula is derived to describe the force-displacement behaviour of a general VCFP. The isolator force of a sliding isolator consists of two main parameters, namely, the restoring force due to the component of the weight of the system above the isolator, and the frictional force opposing the sliding. In FPS the restoring force varies linearly with sliding displacement, so that the isolator force increases with sliding displacement (Pranesh and Sinha, 2000). However, unlike the FPS whose sliding surfaces are spherical with a constant radius, the sliding surface of the VCFP has variable curvature, therefore, the restoring force and isolation frequency becomes adaptive to the isolator displacement (Lu et al. 2004). To simulate the behaviour of VCFP, the free body diagram of a variable curvature friction pendulum isolator shown in Fig.2 is used. The radiant cross section of the sliding surface is defined by a geometric function *y(x)* in the $x - y$ coordinates.

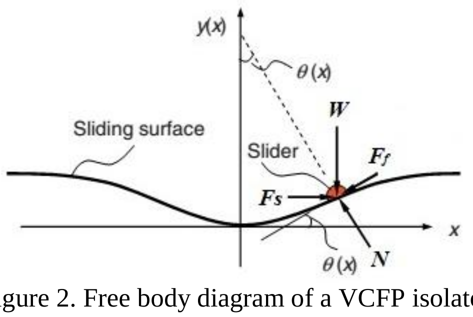

Figure 2. Free body diagram of a VCFP isolator

The isolator shear force of the sliding surface with variable curvature can be expressed as (Lu et al., 2011):

$$F_s(x) = F_r(x) + F_f(x) \tag{1}$$

$$F_r(x) = W y'(x) \tag{2}$$

$$F_f(x) \approx \mu W sign(\dot{x}) \tag{3}$$

Where $F_r(x)$ and $F_f(x)$represent the restoring and friction force, respectively.$W$is the total weight of the superstructure, $y'(x)$ is the first derivative of geometric function,μ is the velocity dependent coefficient of friction which is described by Mokha et al. (Mokha et al., 1991):

$$\text{«} = f_{\max} - (f_{\max} - f_{\min})\exp(-a|\dot{x}_b|) \tag{4}$$

Furthermore, $\dot{x}_b$ is the sliding velocity, f_{max} and f_{min} are the maximum and minimum mobilized coefficients of friction, a is a parameter which controls the friction coefficient with velocity, respectively. The isolator stiffness $k_r(x)$, which may be defined as the rate of change of the restoring force $F_r(x)$, and the tangential isolation frequency $\omega_b(x)$ of the isolation system can be computed by:

$$k_r(x) = Wy''(x) \tag{5}$$

$$\mu_b = \sqrt{gy''(x)} \tag{6}$$

Eq. (2) to Eq. (6) have shown that the restoring force $F_r(x)$, the isolator stiffness $k_r(x)$ and the isolation frequency $\omega_b(x)$ are all explicit functions of the geometric function $y(x)$and its derivatives. Furthermore, the isolator stiffness and isolation frequency are variable and depend on slider displacement x.

DEFINING SLIDING SURFACE

According to Eq. (2), restoring force $F_r(x)$ is an explicit function of $y'(x)$. So if an increasing restoring force is needed, we need to select a mathematical function which its first derivate increases with displacement. Order 4 and order 6 polynomial function can afford hardening behaviour. The VFPI isolator, has elliptical function with a seismic behaviour softer than FPS isolator. Table 1 shows the geometric functions of three considered VCFP. The order 4, order 6 and elliptical VCFP are shown by VCFP-O4, VCFP-O6 and VCFP-ELL, respectively.

Table 1.Geometric function used for VCFP isolators with their first derivatives

Function	VCFP-ELL	VCFP-O4	VCFP-O6
$y(x)$	$b(1-\sqrt{1-\frac{x^2}{a^2}})$	$\frac{1}{4}ax^4+\frac{1}{2}cx^2$	$\frac{1}{6}ax^6+\frac{1}{4}cx^4+\frac{1}{2}ex^2$
$y'(x)$	$bx\ /\ (a^2\times\sqrt{1-\frac{x^2}{a^2}})$	ax^3+cx	ax^5+cx^3+ex

As it has been shown in Table 1, the design parameters that the geometric function and exact shape of sliding surface, are "*a*" and "*b*" for VCFP-ELL, "*a*" and "*c*" for VCFP-O4 and "*a*", "*c*" and "*e*" for VCFP-O6. Becase the mentioned parameters are purly mathematical, they have to convert into some parameters that are phisically and meaningful. The normalized initial stiffness is represented by *k0*. The isolator displacement at the retroflexion point is shown by *D1*, and *k1* is the normalized stiffness at the retroflextion point. The initial stiffness *k0*is evaluated by:

$$k0 = (\frac{2\text{®}}{T_0})^2 / g \tag{7}$$

In Eq. (7)T_0 and$g$are initial period of isolation and the acceleration due to gravity, respectively. The relation between "*a*", "*c*" and "*e*" and "*k0*", "*k1*" and "*D1*" and their assumed values are tabulated in Table 2.

Table 2. Assumed values of design parameters

Funtion	Isolator	Assumptions	Design parameter
Elliptical	VCFP-ELL	a = 0.09	$b = \frac{a^2}{g}(\frac{2\text{®}}{T_0})^2$
Order 4 polynomial	VCFP-O4	k_0 = 1 (1/m), k_1= 0 (1/m), D = 0.1 (m)	$a = \frac{k_1 - k_0}{3D^2}$ $c = k_0$
Order 6 polunomial	VCFP-O6	k_0 = 1(1/m), k_1 = 0 (1/m), D = 0.1 (m)	$a = \frac{k_0 - k_1}{5D^4}$ $e = k_0$

The "a" parameter in VCFP-ELL isolator helps the isolator to keep servicing under severe earthquake and do not fail when it possesses slight friction coefficient. In order to make a meaningful comparison between the results of FPS, VCFP with elliptical surface, order 4 and order 6 polynomial VCFP, the period of FPS and the initial period of VCFP-ELL, VCFP-O4 and VCFP-O6 is kept constant at T_b = 2 sec.The maximum and minimum friction coefficient of all base isolation are considered f_{max} = 0.06 and f_{min} = 0.03 (Fenz and Constantinou, 2008). The rate parameter "a" is assumed 100 s/m.

NUMERICAL STUDY

In order to compare the efficiency of considered isolators, a SDOF structure is considered (Fenz and Constantinou, 2008). The total weight of the structure, damping, stiffness and damping are W = 116,800 KN, k_s = 283 KN/mm and c_s = 2.07 KN-sec/mm.For the nonlinear time history analysis of both fixed and isolated structures,two different types of ground motions with different PGA were used. The properties and station names of considered near fault ground motions are tabulated in Table 3 and time history of considered ground motions are shown in Fig. 3. In order to analyse the SDOF structure under considered ground motions, after deriving the equation of motions, the MATLAB programming is employed to obtain the seismic responses using state space formulation.

Table 3. Properties of considered ground motions

Record No.	Earthquake	Station	Distance to fault (km)	PGA(g)
SN-10	Loma Prieta	Gilroy - Gavilan Coll.	9.96	0.29
SN-23	Kobe	Takarazuka	0.27	0.645

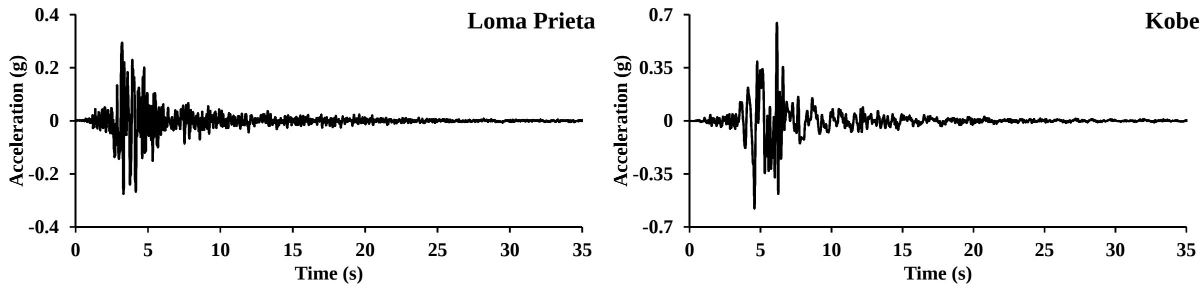

Figure 3.Time history of two considered ground motions (a) Loma Prieta (b) Kobe

RESULTS AND DISCUSSIONS

To investigate the isolation performance the obtained peak in both fixed base and isolated conditions are compared. The main considered responses are structure's acceleration (s_{acc}), structure's displacement (u_s), isolator displacement (u_b) and base shear normalized by weight of the structure (V_s/W). The time history of normalized base shear of considered structure subjected to Kobe ground motion in both fixed base condition and isolated with variousisolator are shown in Figure 4, and the force-displacement loop of isolators are shown in Fig. 5.

It is observed that as a results of shifting period of isolated structure the transmitted acceleration to the superstructure is significantly reduced,therefore the base shear will be reduced. Furthermore using isolators caused to reduce the structure's displacement. Such reductions will lead to better performance of the structures during earthquake events. Table 4 shows the peak responses of considered structure in both fixed base and isolated conditions. The results show that compared to FPS, VCFP can control the responses, in a way that if the purpose is to control the base shear the VCFP-ELL can be choose, else if the controlling of base isolation displacement is required the VCFP-O6 may be use.

Fig. 6 shows the relative reduction percentages of various responses under Loma Prieta and Kobe ground motions, respectively .Although, Table 4 shows that as the PGA increases the structure in fixed condition gets more excited,it is observed that the performance of isolators in reducing the responses get increased, in a way that the maximum relative reduction percentage of normalized base shear under Loma Prieta ground motion is 78.95% but the maximum relative reduction percentage of mentioned response under Kobe ground motion is 87.70%.

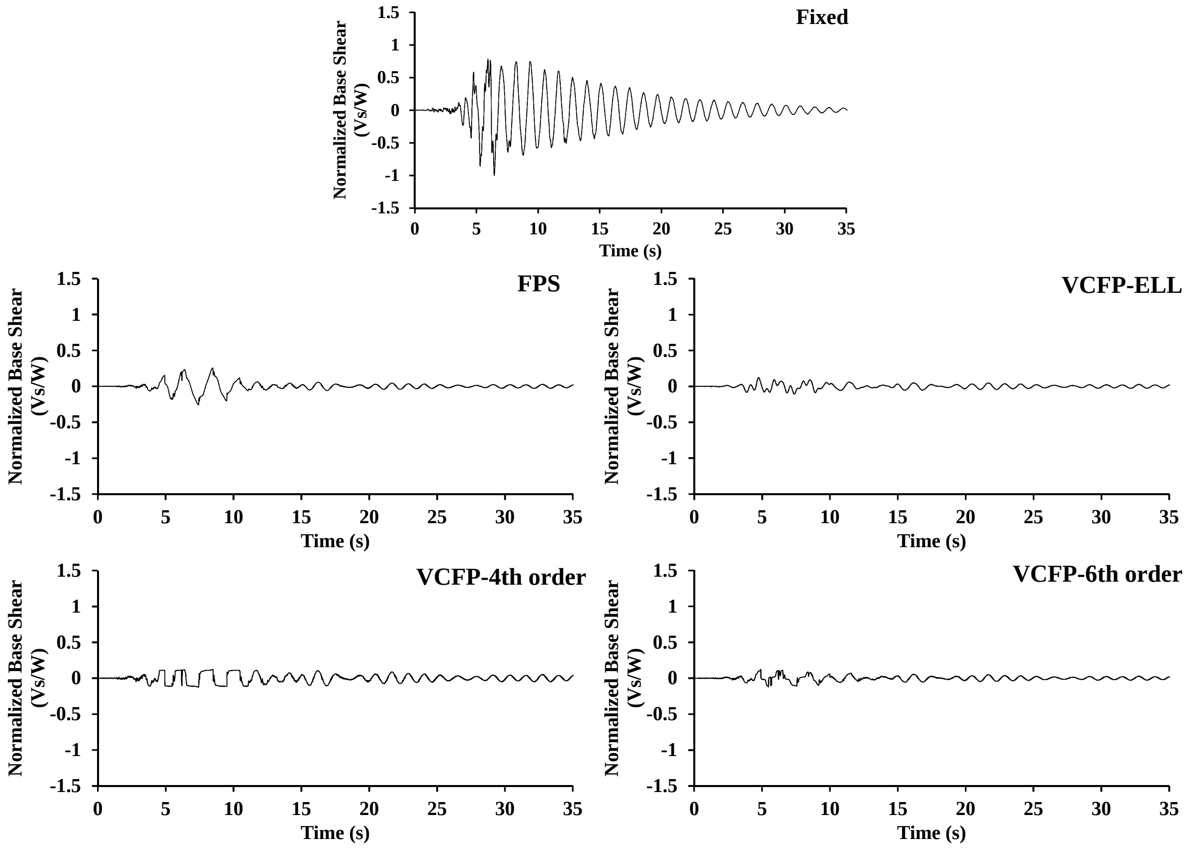

Figure 4. Time history of normalized base shear subjected to the Kobe ground motion in non-isolated and isolated condition

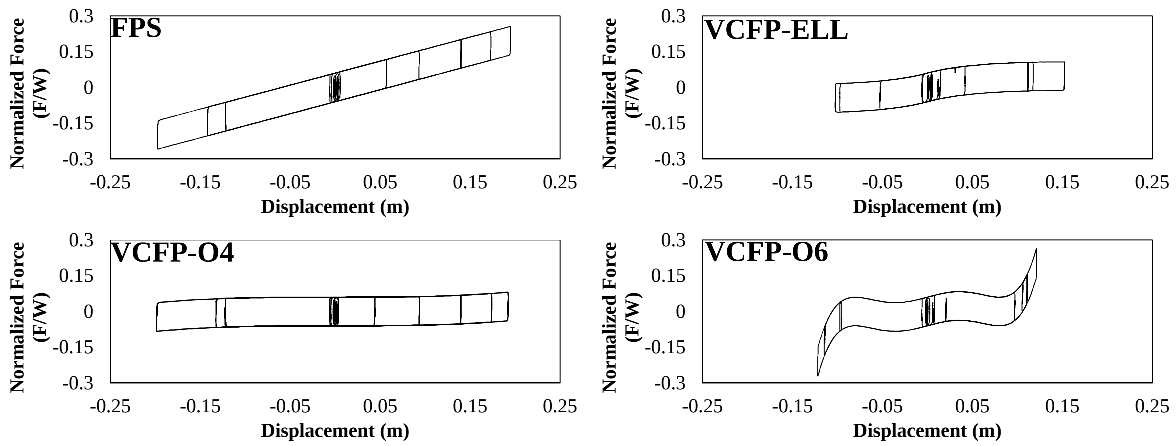

Figure 5. Force-displacement of various base isolations under Kobe ground motions

Table 4. Peak responses of considered structure under Loma Prieta and Kobe ground motions in fixed and isolated conditions

Earthquake	Condition	s_{aac}(m/sec^2)	u_s(m)	u_b(m)	V_s/W
Loma Prieta	Fixed Base	3.9119	0.06842	-------	0.31677
	FPS	0.8434	0.02823	0.02666	0.08625
	VCFP-ELL	0.84311	0.02822	0.02780	0.06667
	VCFP-O4	0.84339	0.02822	0.02573	0.0698
	VCFP-O6	0.8433	0.02822	0.02741	0.08487
Kobe	Fixed Base	12.2327	0.3186	-------	1.0004
	FPS	2.5984	0.08695	0.1974	0.2581
	VCFP-ELL	1.7466	0.05842	0.1526	0.1230
	VCFP-O4	2.3520	0.08627	0.1971	0.1235
	VCFP-O6	1.7332	0.05793	0.1216	0.1235

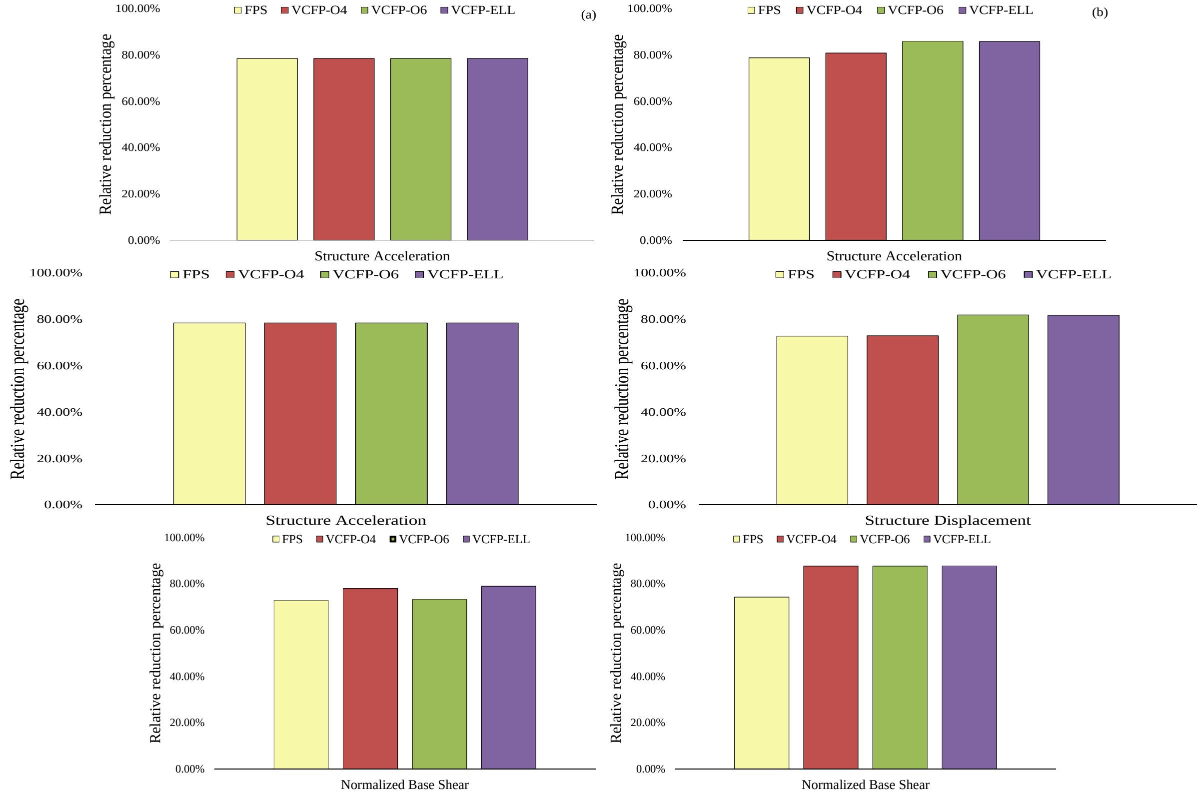

Figure 6. Relative reduction percentages under Loma Prieta ground motion

The other important that must be considered is displacement of base isolation. Several researches have illustrated that the near fault ground motions can cause excessive displacement in base isolator compared to far fault ground motions (Tavakoli et al. 2014). This excessive displacement may cause the slider will come into contact with displacement retainer and base isolated structure behaves like fixed ones. The results show that as the PGA increases the displacement of base isolator increases, therefore the impact would be occurred.

Fig.7 shows the effects of initial period of isolation on base isolation displacement (u_b), structure displacement (u_s) and normalized base shear (V_s/W) subjected to Loma Prieta ground motion. Generally speaking as the initial period increases the isolator become more flexible therefore the base isolator displacement increases. On the other hand, as the period of isolation increases the structure's displacement and normalized base shear are decreased, but for period over $T_b = 4$ sec. the effect of isolation's period is insignificantly.

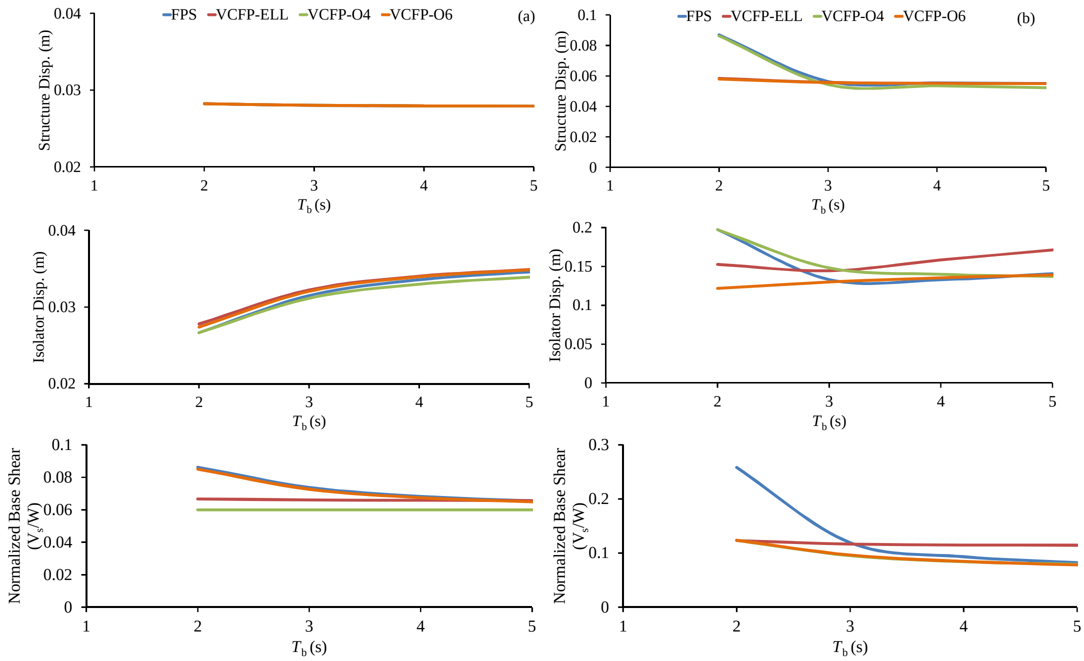

Figure 7. Effect of initial time period on seismic responses of considered base isolated structure subjected to (a) Loma Prieta (b) Kobe ground motion

CONCLUSIONS

The seismic response of base isolated structures using sliding isolators is investigated in this paper. It was shown that base isolation is a one of the most effective methods to reduce the responses induced to the structure during the earthquake. It is concluded that variable curvature friction pendulum isolators as a kind of passive adaptive system behave differently based on chosen function of sliding surface. It is shown that the hysteresis loop of VCFP is different with that of FPS based on its restoring force defining by sliding surface geometric function. Since near fault ground motions may excite the base isolator more than far fault ones due to its strong long-period components, the possibility of using VCFP was scrutinized in this paper, and found that the VCFP-ELL has better performance compared to FPS. It is shown that the VCFP can control structural acceleration or isolator displacement or both of them simultaneously, to minimize the structural damage during severe ground motions.It is also found that, although increasing the isolation period leads to increasing the isolator’s displacement, the normalized base shear reduced.

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