SEISMIC ISOLATION OF BRIDGE USING VARIABLE CURVATURE FRICTION PENDULUM SYSTEM

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ABSTRACT :

A conventional numerical study of bridge isolated by the variable curvature friction pendulum system (VCFPS) is carried out. The normal component of recorded near-fault ground motions is used as input ground motions. The selected bridge consists of multi-span continuous deck supported on piers and abutments. In the modeling of the bridge, the deck is considered as rigid whereas the piers are assumed as flexible. The friction coefficient of the VCFPS is assumed to be independent of the relative velocity at the sliding interface. The governing equations of motion of seismically isolated bridge are solved in the incremental form by employing Newmark's step-by-step method assuming linear variation of acceleration over small time interval. In addition, comparison is made between the response of bridge isolated with VCFPS and FPS in order to measure the effectiveness of VCFPS. Furthermore, a parametric study has been carried out to critically examine the influence of important parameters on the seismic response of bridge isolated with VCFPS. From the above investigations, it is concluded that under near-fault ground motions, the VCFPS is quite effective for controlling the seismic response of bridge within the desirable range.

KEYWORDS: Near-fault ground motion, Structural control, VCFPS, Bridge.

1. INTRODUCTION

Recent years have seen a number of occurrences of catastrophic failures of bridges due to severe, impulsive, seismic events such as the 1994 Northridge earthquake in California, the 1995 Kobe earthquake in Japan and 1999 Chi-Chi earthquake in Taiwan. Failure of bridges during such seismic events will seriously hamper the relief and rehabilitation work. To protect bridges from earthquake damages, seismic isolation technology has been applied over the last three decades. This technology is one of the most widely implemented and accepted technologies for seismic hazard mitigation. The fundamental concept in isolation is to reduce the fundamental frequency of structural vibration to a value lower than the predominant energy-containing frequencies of the earthquake. The other purpose of an isolation system is to provide a means of energy dissipation, which dissipates the seismic energy transmitted to the system. Thus, the isolation device, which replaces the conventional bridge bearings, isolate the bridge deck (which alone is responsible for the majority of the pier base shear) from the bridge substructure during the earthquakes, thereby significantly reducing the deck acceleration and the shear forces transmitted to the piers and abutments.

Near-fault ground motion can introduce more devastating response to isolated bridges than an equal or larger (higher peak ground acceleration) far-field ground motion (Loh et al. 2002). This concern profoundly influenced seismic isolation design requirements in the 1997 Uniform Building Code (ICBO 1997). In the earlier code, there were no near-fault effects but in the recent code, near-fault effects viz. source type and distance dependent near-fault factors to the customary design spectrum have been introduced. Further, it is believed that these factors are not sufficient to solve the problem consistently, because they pay little attention to the physical characteristics of near-fault ground motions. Another concern is a lack of data concerning the behaviour of bridges subjected to near-fault ground motions. Consequently, the effects of these motions on bridges are not yet understood fully. Recently, there have been several studies for understanding the dynamic behavior of both isolated and fixed base structures under near-fault motions (Jangid and Kelly 2001; Rao and Jangid 2001; Shen et al. 2004; Jangid 2005; Panchal and Jangid 2008a; Panchal and Jangid 2008b). This review clearly shows that so far, there have not been many attempts to investigate the behaviour of especially bridges isolated with friction base isolators under near-fault ground motions. In view of this, it is necessary to conduct the reliable numerical studies on the behaviour of seismically isolated bridges under near-fault ground motions in order to provide assistance to current research and engineering practice.

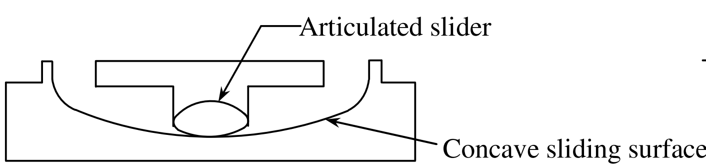
To address above concern, the seismic response of three-span continuous deck bridge seismically isolated with VCFPS is investigated under near-fault ground motions. The specific objectives of the present study may be summarized as: (i) to study the dynamic behaviour of bridge isolated with VCFPS under near-fault ground motions, (ii) to compare the seismic response of bridge isolated with VCFPS and FPS in order to measure the effectiveness of VCFPS and (iii) to investigate the influence of important parameters (i.e., friction coefficient and fundamental period at center of sliding surface of VCFPS) on the response of bridge isolated with VCFPS through a parametric study.

2. VARIABLE CURVATURE FRICTION PENDULUM SYSTEM (VCFPS)

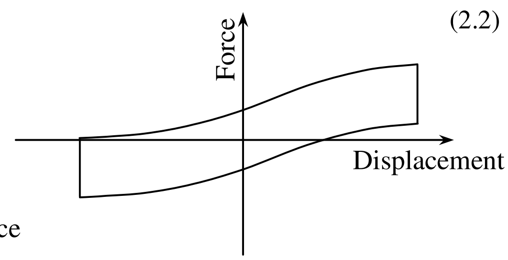
An advanced isolator called variable curvature friction pendulum system (VCFPS) (Tsai et al. 2003; Tsai et al. 2005) is found to be very effective for structures adjacent to active earthquake faults (refer Figure 1). In this isolator, the radius of curvature is lengthened with an increase of the isolator displacement. Hence, the fundamental period of the base-isolated structure can be shifted further away from the predominant periods of near-fault ground motions, and the resonant possibility of the superstructure with earthquakes can be prevented. The geometric function used to describe the VCFPS base isolator can be expressed in the following (Tsai et al. 2003; Tsai et al. 2005):

$$y = R - \sqrt{R^2 - x_b^2} - f\left(x_b\right) \tag{2.1}$$

$$f\left(x_b\right) = E\,\mathrm{sgn}\left(x_b\right) x_b^3 \tag{2.2}$$



(a)



(b)

Figure 1 Details and hysteresis loop of the VCFPS isolator (Tsai et al. 2003; Tsai et al. 2005)

where R is the radius of curvature at the center of the sliding surface of the VCFPS; x_b is the horizontal displacement of the isolator; $f\left(x_b\right)$ is the function to describe the increase of the radius of curvature with an increase of the horizontal displacement; and E is the parameter that describes the variation of curvature of the concave surface. If the restoring force can bring the slider back to the initial position within the sliding displacement x_0, then the parameter E can be determined (Tsai et al. 2003; Tsai et al. 2005) as:

$$\frac{\dfrac{W x_0}{\sqrt{R^2 - x_0^2}} - \dfrac{T_0}{\cos\theta_0}}{3W\,\mathrm{sgn}\left(x_0\right) x_0^2} \tag{2.3}$$

where T_0 is the static friction force.

The horizontal stiffness of the VCFPS can be written (Tsai et al. 2003; Tsai et al. 2005) as

$$k_b(x_b) = M\omega_b^2(x_b) \tag{2.4}$$

$$\omega_b^2(x_b) = \frac{g}{\sqrt{R^2 - x_b^2}} - \frac{\operatorname{sgn}(x_b)\,x_b\left(\dfrac{g x_0}{\sqrt{R^2 - x_0^2}} - \dfrac{\mu g}{\cos\theta_0}\right)}{\operatorname{sgn}(x_0)\,x_0^2} \tag{2.5}$$

where μ is the coefficient of the friction at the sliding surface of the VCFPS; g is the acceleration due to gravity; and $W = Mg$ is the weight supported by the isolator.

3. BRIDGE MODELING AND IDEALIZATION

Figure 2(a) shows the configuration of a bridge that consists of a three-span continuous deck supported by the same number of VCFPS isolators at pier and abutment levels. The following assumptions are made for the earthquake analysis of the isolated bridge model.

1. The bridge deck is considered as rigid whereas the piers are assumed as flexible. The bridge piers are assumed to remain in the elastic state during the earthquake excitation. This is a reasonable assumption, as the isolation attempts to reduce the earthquake response in such a way that the structure remains within the elastic range.
2. The deck of the bridge is straight and is supported at discrete locations along its longitudinal axis by cross diaphragms. The abutments of the bridge are assumed as rigid and the angle of skew is zero.
3. The piers are modeled as a lumped mass system divided into small discrete elements. Each adjacent element is connected by node and at each node single-degree-of-freedom is considered. Masses of each element are assumed to be distributed between two adjacent nodes in the form of point masses.
4. The bridge piers are assumed to be rigidly fixed at the foundation level.
5. The bridge is founded on firm soil or rock and the earthquake excitation is perfectly correlated at all the supports.
6. The VCFPS isolators installed at the piers and abutments have the same dynamic characteristics.
7. The friction coefficient of the VCFPS is assumed to be independent of the relative velocity at the sliding interface. This is based on the findings that such effects do not have noticeable effects on the peak response of the isolated structural system (Fan et al. 1990).
8. The restoring force provided by the VCFPS is considered as nonlinear.
9. The isolated bridge system is subjected to single horizontal component, i.e., normal component of near-fault earthquake ground motion, in its longitudinal direction. The above assumptions will lead to the mathematical model of the isolated bridge system as shown in Figure 2(b) studied earlier by Ghobarah and Ali (1988), Li (1989), Pagnini and Solari (1999) and Kunde and Jangid (2006).

Table 1 Properties of bridge deck and piers

Properties	Deck	Piers
Cross-sectional area (m^2)	3.57	4.09
Moment of inertia (m^4)	2.08	0.64
Young's modulus of elasticity (N/m^2)	20.67×10^9	20.67×10^9
Mass density (kg/m^3)	2.4×10^3	2.4×10^3
Length/height (m)	$3 \times 30 = 90$	8

4. GOVERNING EQUATIONS OF MOTIONS

The governing equations of motion for the isolated bridge system under single horizontal component of near-fault ground motion are expressed in matrix form as

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}+[D]\{F\}=-[M]\{r\}(\ddot{x}_g) \tag{4.1}$$

$$\{x\}=\{x_d, x_1, x_2, ..., x_N\}^T \tag{4.2}$$

where $[M]$, $[C]$ and $[K]$ are mass, damping and stiffness matrices, respectively, of the bridge structure of the order $N \times N$; $\{\ddot{x}\}$, $\{\dot{x}\}$ and $\{x\}$ are structural acceleration, structural velocity and structural displacement vectors, respectively; x_d is the displacement of the bridge deck relative to ground; $x_k\,(k=1,2,.........,N)$ is the displacement of the k^{th} node of bridge pier; $[D]$ is the location matrix for the restoring forces of isolator; $\{F\}$ is vector containing the restoring forces of isolators; $\{r\}=\{1,1,.........,1\}^T$ is influence coefficient vector; $\ddot{x}_g$ is earthquake ground acceleration; and over-dots indicate derivative with respect to time.

The governing equations of motion of the isolated bridge cannot be solved using the classical modal superposition technique due to non-linear force-deformation behaviour of the VCFPS. As a result, the governing equations of motion are solved in the incremental form using Newmark's step-by-step method assuming linear variation of acceleration over small time interval, Δt. The maximum time interval for solving the equations of motion is taken as 0.02/200 sec (i.e., Δt = 0.0001 sec). The response of the bridge system was found to be the invariant for a further decrease in the time interval.

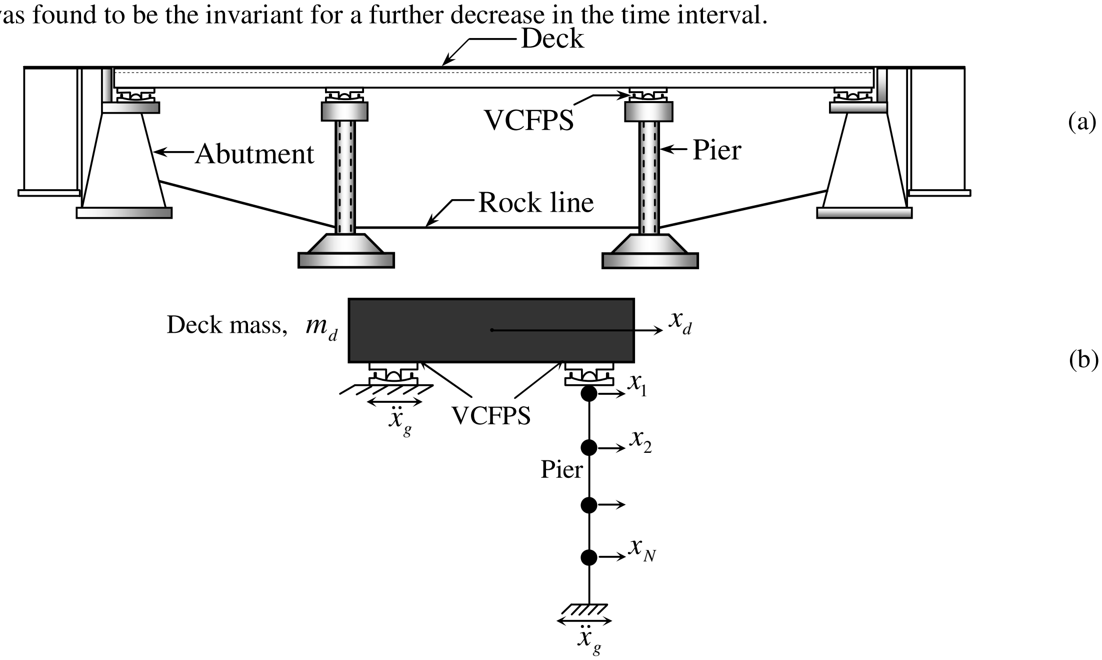


Figure 2 Configuration and mathematical model of three-span continuous deck bridge isolated with the VCFPS

5. NUMERICAL STUDY

The three-span continuous deck with reinforced concrete piers and pre-stressed concrete box girders is considered for the present study. The dynamic properties of this bridge are given in Table 1, taken from Wang et al. (1998) where the seismic response of the same bridge isolated by friction isolators was investigated. The fundamental time period in longitudinal direction of this bridge without isolator is 0.45 sec. The mass matrix has a diagonal form. The stiffness matrix of the piers is constructed separately and then static condensation is carried out to eliminate rotational degrees of freedom. The damping matrix of the pier is not explicitly known, and it is constructed from the assumed modal damping in each mode of vibration using its mode shapes and frequencies. The damping in the piers is taken as 5% of the critical value in all modes of vibration. Four near-fault ground motions are considered for the present study. Some characteristics of these recorded near-fault ground motions are shown in Table 2. The fundamental period at the center of the concave sliding surface of the VCFPS is 2.5 sec, and the desired restoring force can bring the slider back to the center of the isolator when the isolator displacement is less than 0.8 m. For VCFPS, the friction coefficient of 0.05 is chosen for all investigations. For comparison, an example with FPS isolators is also taken with coefficient of sliding friction of 0.05 and fundamental period at the center of concave sliding surface of 2.5 sec.

Table 2 Some characteristics of normal component of near-fault ground motions used in the study

Near-fault motions (Normal component)	Recording station	Duration (sec)	Magnitude (M_w)	PGD (m)	PGV (m/sec)	PGA (g)
Imperial Valley, 1979	El Centro Array #7	36.900	6.4	0.491	1.13	0.46
Kobe, 1995	JMA	60.000	6.9	0.401	1.6	1.088
Landers, 1992	Lucerne Valley	49.284	7.3	2.300	1.36	0.71
Imperial Valley, 1979	El Centro Array #5	39.420	6.4	0.765	0.98	0.37

Note: PGA = Peak Ground Acceleration; PGV = Peak Ground Velocity; PGD = Peak Ground Displacment

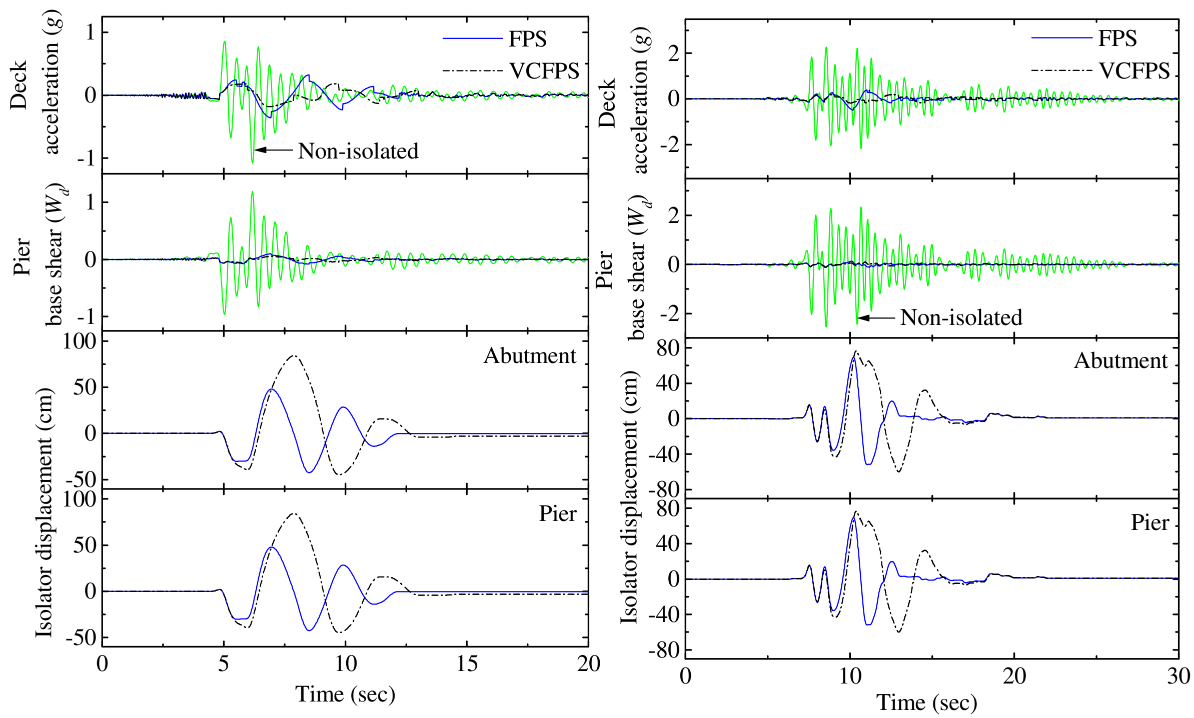


Figure 3 Time variation of the deck acceleration, the pier base shear and isolator displacements of the bridge isolated with the FPS and the VCFPS under Imperial Valley, 1979 recorded at El Centro Array #7 station (Left) and Kobe, 1995 recorded at JMA station (Right)

The response quantities of interest for the bridge system under consideration are the base shear in piers, the absolute acceleration at the centre of bridge deck and the relative displacement of the VCFPS isolators at the abutments and piers. The absolute acceleration of the deck and the pier base shear are directly proportional to the forces exerted in the bridge system due to the earthquake ground motion. On the other hand, the relative displacements of the VCFPS are crucial from the design point of view of isolator and expansion joints.

The time variation of pier base shear, deck acceleration and relative isolator displacements of bridge under Imperial Valley, 1979 recorded at El Centro Array #7 station (Left) is shown in Figure 3. Two types of friction base isolators, i.e., FPS (R = 1.553 m and μ = 0.05) and VCFPS (R = 1.553 m sec and μ = 0.05), are considered for comparison of the seismic response. Figure 3 indicates that there is significant reduction in the pier base shear and deck acceleration of the isolated bridge in comparison with the non-isolated bridge, but the reduction in bridge isolated with VCFPS is more than that of bridge isolated with FPS. The pier base shear is expressed in terms of weight of the deck, W_d, where W_d is equal to $m_d g$ and g is acceleration due to gravity. The peak values of the isolator displacements at abutments and piers for VCFPS and FPS are 841.50 mm and 479.80 mm and 841.10 mm and 479.45 mm, respectively. This implies that with the installation of the VCFPS in bridges, seismic response of the bridge excluding the isolator displacements at abutment and piers can be controlled within desirable range during near-fault ground motions. The figure also reveals that the performance of the VCFPS is quite effective for controlling the deck acceleration and pier base shear than that of the FPS. However, isolator displacements at abutment and piers of the bridge isolated with VCFPS exceeds that of the bridge with FPS. This is expected as the horizontal stiffness of the VCFPS is lower than that of the FPS. Such large isolator displacement of the VCFPS will lead to requirement of very large isolators, costly flexible connections for utilities and extensive and expensive loss of space for a seismic gap. Under near-fault ground motions, this feature of the VCFPS reduces its effectiveness in comparison to the FPS. Similar differences in the response of bridge isolated with VCFPS and FPS are also depicted for Kobe, 1995 earthquake ground motion recorded at JMA station (Right).

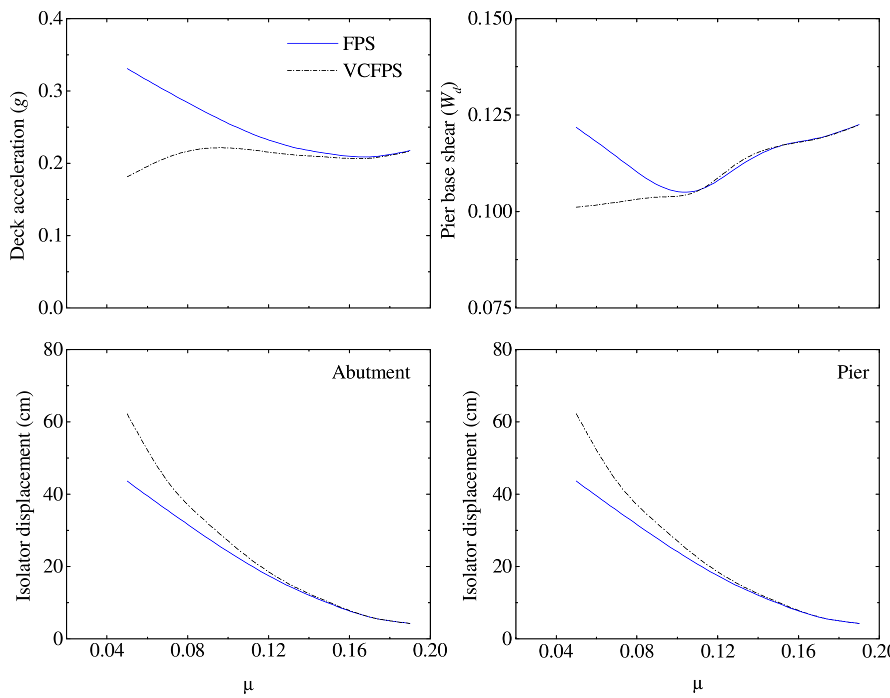


Figure 4 Effects of the friction coefficient on the peak deck acceleration, pier base shear and isolator displacements of bridge isolated with FPS and VCFPS under Landers, 1992 (Lucerne Valley) near-fault ground motion

The variation of peak deck acceleration, pier base shear and isolator displacements of the bridge isolated with FPS and VCFPS against the friction coefficient under Landers, 1992 (Lucerne Valley) near-fault ground motion is shown in Figure 4. The response of the bridge is obtained for different friction coefficient (i.e., 0.05 to 0.19). It is observed from the figure that with the increase in the friction coefficient, the peak isolator displacement decreases. This is due to the fact that for higher values of friction coefficient the isolator becomes relatively stiff; as a result the isolator displacement is reduced. On the other hand, the deck acceleration and pier base shear of bridge isolated with the VCFPS increase with the increase in the friction coefficient whereas the deck acceleration and pier base shear of bridge isolated with FPS first decrease attain the minimum value and then increase with the increase in the friction coefficient.

Figure 5 shows the variation of peak deck acceleration, pier base shear and isolator displacements of the bridge isolated with FPS and VCFPS against the fundamental period at the center of sliding surface under Imperial Valley, 1979 (El Centro Array #5) near-fault ground motion. The response of bridge is plotted for different fundamental period (i.e., 2 to 4.5 sec). Figure 5 illustrates that how the peak deck acceleration and pier base shear in both isolators decrease with the increase in the fundamental period. On the other hand, the isolator displacements of bridge with FPS increase with the increase in the fundamental period whereas there is not much variation in the isolator displacements of bridge isolated with VCFPS.

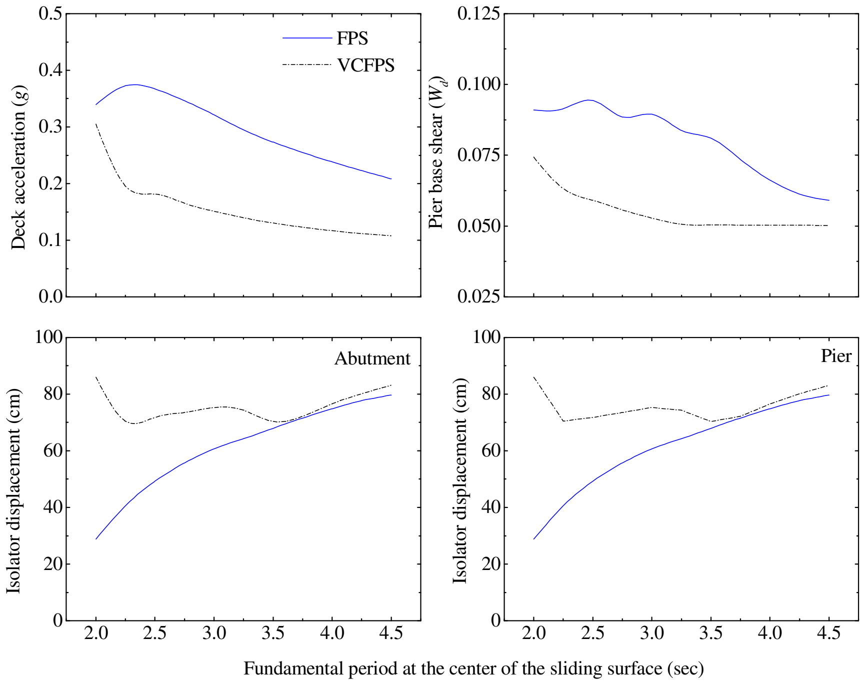


Figure 5 Variation of peak deck acceleration, pier base shear and isolator displacements of bridge isolated with FPS and VCFPS under Imperial Valley, 1979 (El Centro Array #5) near-fault ground motion.

6. CONCLUSIONS

From the trends of the numerical results of the present study, the following conclusions may be drawn:

1. With the installation of the VCFPS in bridges, the deck acceleration and the pier base shear during near-fault ground motions can be controlled within a desirable range. On the other hand, significant increase in the isolator displacements at abutment and piers are observed.
2. The performance of the VCFPS for seismic isolation of the bridges is quite effective in reducing the deck acceleration and pier base shear of the bridges in comparison to the FPS.
3. The peak deck acceleration and the peak pier base shear increase with an increase in the friction coefficient of the VCFPS whereas the isolator displacements at abutment and piers decrease.
4. The peak deck acceleration and the peak pier base shear decrease with an increase in the flexibility of the isolator whereas there is not much variation in the isolator displacements of bridge isolated using VCFPS.

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