Seismic Isolation of Three Span Continuous Bridge using Variable Time Period Isolators

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Abstract: Seismic performance of bridges subjected to near-field ground motion can be improved by increasing efficiency of base isolators. Sliding isolators with variable curvature (SIVC) are proved to be more efficient than conventional base isolation systems. The sliding surface is made non-spherical having curvature varying with isolator displacement. The three span continuous bridge isolated with Variable Time Period Isolators (VTPI) such as Polynomial Sliding Isolators having Variable Curvature of order 3 and 5 (PSIVC 3rd and PSIVC 5th) and Variable Curvature Friction Pendulum of order 4 and 6 (VCFP 4th and VCFP 6th) is considered for the study. Bridge deck and piers are considered rigid for modelling purpose. Newmark's linear acceleration method is used to resolve the equation of motion of the structure. The performance of these systems are compared with Variable Radius Friction Pendulum System (VRFPS) for four different near-field ground excitations. From the study, it can be concluded that VRFPS minimizes the pier base shear and deck acceleration compared to other four isolators. In PSIVC 3rd, isolator displacement is effectively reduced. Also, VCFP 6th dissipates more energy among all considered isolators.

***Index Terms* – SIVC, VTPI, PSIVC, VCFP, VRFPS, three span continuous bridge, near-fault ground excitations, base isolation.**

I. INTRODUCTION

Bridges are vital communication links of infrastructure in a road network and should remain operational after an earthquake. From the research, it can be observed that bridges experience more damage due to near-fault earthquake than far-fault. To reduce the devastating effects of earthquake and maximize energy dissipation capacity of structure, base isolation system has been considered as one of the most significant structural vibration control system even for intense earthquake excitations.

Base isolation is a technique of controlling structural response in which structure is decoupled from the foundation by interposing a layer with low stiffness between them. As a result, energy dissipation capacity of structure is increased & structure becomes flexible during earthquake. Generally, in building, isolators are provided between superstructure and foundation whereas in bridge they are installed between deck and substructure. Elastomeric bearing and Sliding bearing are two main form of isolation system.

There have been various parametric studies related to the effectiveness of different isolation systems and it is determined that sliding isolation systems are more beneficial than elastomeric bearings. Friction Pendulum System (FPS) is the basic sliding isolator used to reduce seismic effects on bridges as well as building. FPS has spherical sliding surface i.e., constant radius which introduces constant isolation frequency during earthquake. Therefore, during intense earthquakes, resonance problem is likely to occur. To overcome this limitation, the concept of Variable Time Period Isolator (VTPI) is introduced in which sliding surface is flatter and non-spherical. Also, the curvature of sliding surface is function of isolator displacement. As a result, isolation frequency and time period differ with isolator displacement. Hence the performance of isolator governs by the function of sliding surface.

The purpose of research work is to analyze and compare seismic behavior of three span continuous bridge isolated with five VTPI systems such as PSIVC 3rd, PSIVC 5th, VCFP 4th, VCFP 6th and VRFPS under four different near-fault ground earthquakes. To lessen the computational time, seismic response of bridge is attained by modelling it as a single-degree-of-freedom (SDOF) system i.e., piers and deck are assumed to be rigid from [1]. In bridge with seismic isolation systems, flexibility is primarily focused at isolation arrangements. Therefore, deck and piers of bridge perform nearly as stiff body.

II. EXPLANATION OF PSIVC AND VCFP

Table 1 denotes equations of restoring force and isolator stiffness which are derived from the polynomial functions used to represent the curvature of sliding surface as mentioned in [2] and [3].

Table 1 Polynomial functions used for PSIVC 3rd, PSIVC 5th, VCFP 4th and VCFP 6th

Isolator	Restoring Force $y'(x)$	Isolator Stiffness $y''(x)$	Coefficients
PSIVC 3rd	$ax^3 + cx$	$3ax^2 + c$	$a = (k_1 - k_0)/3D^2, c = k_0$
PSIVC 5th	$ax^5 + cx^3 + ex$	$5ax^4 + 3cx^2 + e$	$a = -(k_1 - k_0)/5D^4, c = 2(k_1 - k_0)/3D^2, e = k_0$
VCFP 4th	$4ax^3 + 2cx$	$12ax^2 + 2c$	$a = (k_1 - k_0)/12D^2, c = k_0/2$
VCFP 6th	$6ax^5 + 4cx^3 + 2ex$	$30ax^4 + 12cx^2 + 2e$	$a = -(k_1 - k_0)/30D^4, c = (k_1 - k_0)/12D^2, e = k_0/2$

Here purely mathematical polynomial coefficient a, c and e can be expressed in terms of some meaningful design parameters such as, k_0, k_1 and D.
where k_0 is defined as initial stiffness at $x = 0$, k_1 is normalized stiffness at $x = D$ and D indicates critical isolator displacement. If $k_1 = k_0$, then isolator stiffness will be constant as FPS. Also, if $k_1 < k_0$, then it can be said that isolator will possess softening behavior. The initial stiffness k_0 can be determined by Eq. (1),

$$k_0 = \left(\frac{2\pi}{T_0}\right)^2 / g \tag{1}$$

where T_0 is initial time period and g stands for gravitational acceleration.
For the present study, isolator time period (T_b) and coefficient of friction (μ) is taken 2.5 sec and 0.08 respectively for all five isolation systems. Other design parameters are assumed as per Table 2.

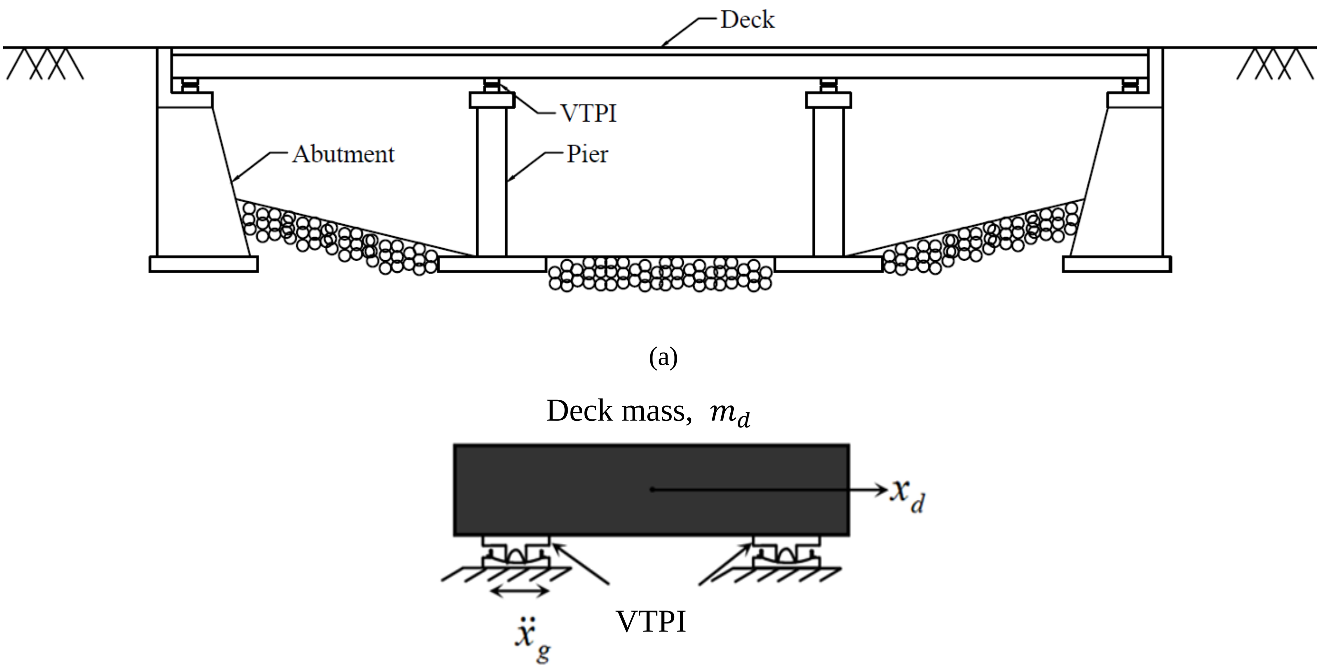
For VRFPS, radius of curvature can be defined as Eq. (2) taken from [4]

$$R(x) = C\,(\exp(x) - 1) + R_0 \tag{2}$$

where C is isolator constant taken 100, x is isolator displacement and R_0 denotes radius of curvature at mid-point (x_b = 0) of isolator which is taken 0.5 m. As isolator displacement increases, radius of curvature increases with it.

III. STRUCTURAL MODELLING

Figure 1 represents three span continuous bridge with VTPI system installed between superstructure (deck) and substructure (abutment and piers).



(a)

(b)

Figure 1 Configuration and mathematical representation of three span continuous bridge with Variable Time Period Isolator

Flowing assumptions are used for analysis taken from [5] :

1. The piers and deck are taken as rigid.
2. The piers of the bridge are fixed at foundation.
3. The bridge is rested on hard soil.

4. The isolators provided above the abutments and piers have the same dynamic characteristics.
5. Contribution of horizontal component of earthquake ground excitations is very much higher than that of vertical component. Hence the effect of vertical component is neglected.

Standard equation of motion of structure is expressed in terms of matrix as per Eq. (3) taken from [6]

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} + [D]\{F\} = -[M]\{r\}(\ddot{x_g}) \tag{3}$$

where $[M]$, $[K]$, $[C]$ are mass, stiffness and damping matrices, respectively, of an order N x N, $\{\ddot{x}\}$, $\{\dot{x}\}$ and $\{x\}$ are vectors representing structural acceleration, velocity and displacement, $[D]$ and $\{F\}$ are location matrix and vector for isolator restoring forces, respectively.

Based on research works, isolator shear force can be expressed as Eq. (4) in sliding state taken from [3]

$$F(x) = F_r(x) + F_f(x) \tag{4}$$

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

$$F_f(x) = \mu W \sin \dot{x} \tag{6}$$

$$k_r(x) = Wy''(x) \tag{7}$$

$$w(x) = \sqrt{gy''(x)} \tag{8}$$

where $F_r(x)$ and $F_f(x)$ are restoring force and friction force respectively, W denotes total weight of superstructure, $y(x)$ is geometric function representing sliding surface of isolator, μ is coefficient of friction for isolator, $k_r(x)$ indicates isolator stiffness and $w(x)$ is isolation freqency. Here, it can be said that isolator freqency, restoring force and isolator striffness all depends on isolator displacement.

The main equation of motion, Eq. (3) is resolved by Newmark's linear acceleration method. The maximum time interval for equation solution is considered 0.001 sec (i.e., Δt = 0.02/20 sec).

IV. NUMERICAL STUDY

This study involves the investigation of seismic behavior of bridge isolated by VRFPS, PSIVC 3rd and PSIVC 5th, VCFP 4th and VCFP 6th for four near-field ground excitations. Damping is assumed to be 5%.

Design assumption for PSIVC and VCFP are as follows taken from [2] and [3]

Table 2 Design assumption for isolators

Isolator	μ	T_b **(sec)**	k_0 (1/m)	k_1 (1/m)	D(m)	g (m/sec^2)
PSIVC 3rd	0.08	2.5	0.650	3.8	0.08	9.81
PSIVC 5th	0.08	2.5	0.650	0	0.08	9.81
VCFP 4th	0.08	2.5	0.643	4.0	0.20	9.81
VCFP 6th	0.08	2.5	0.643	0	0.20	9.81

Table 3 represents properties of three span continuous bridge taken from [5]

Table 3 Properties of bridge

Proerties	**Deck**	**Pier**
Length/Height (cm)	9000	800
Young's modulus of elasticity (N/cm^2)	20.67×10^5	20.67×10^5
Mass Density (kg/cm^3)	2.40×10^{-3}	2.40×10^{-3}
Moment of inertia (cm^4)	2.08×10^8	0.64×10^8
Cross-sectional area (cm^2)	3.57×10^4	4.09×10^4

Details of near-field earthquakes are shown in Table 4 taken from [5]

Table 4 Characteristics of considered near-fault earthquake

Near-Fault Ground Motion	**Normal Component**		
	PGD (cm)	**PGV (cm/sec)**	**PGA (g)**
Imperial Valley,1979 (El Centro Array #5)	76.5	96	0.37
Imperial Valley,1979 (El Centro Array #7)	49.1	113	0.46
Landers, 1992 (Lucerne Valley)	230	136	0.71
Northridge, 1994 (Sylmar)	31.1	122	0.73

V. RESULTS AND COMPARISONS

Table 5 represents peak values of isolator displacement at abutment and pier, deck acceleration and base shear at pier for all five Variable Time Period Isolators (VTPI) under four near-field ground motions.

Table 5 Comparison of peak response quantities

Near-Fault Ground Motion	**Isolator Type**	**Peak Response Quantities**			
		Deck Acceleration (g)	**Isolator Displacement at Pier (mm)**	**Isolator Displacement at Abutment (mm)**	**Pier Base Shear (W)**
Imperial Valley, 1979 (El Centro Array #5)	VRFPS	0.088	749	749	0.022
	PSIVC 3rd	0.607	98	98	0.150
	PSIVC 5th	1.600	161	161	0.257
	VCFP 4th	0.488	154	154	0.121
	VCFP 6th	0.432	258	258	0.108
Imperial Valley, 1979 (El Centro Array #7)	VRFPS	0.088	707	707	0.022
	PSIVC 3rd	2.220	160	160	0.525
	PSIVC 5th	1.580	173	173	0.369
	VCFP 4th	0.676	179	179	0.169
	VCFP 6th	0.460	263	263	0.115
Landers, 1992 (Lucerne Valley)	VRFPS	0.088	807	807	0.022
	PSIVC 3rd	0.895	115	115	0.224
	PSIVC 5th	1.210	165	165	0.301
	VCFP 4th	0.488	154	154	0.121
	VCFP 6th	0.573	277	277	0.143
Northridge, 1994 (Sylmar)	VRFPS	0.088	344	344	0.022
	PSIVC 3rd	1.290	132	132	0.323
	PSIVC 5th	2.800	191	191	0.661
	VCFP 4th	1.910	270	270	0.462
	VCFP 6th	1.550	343	343	0.382

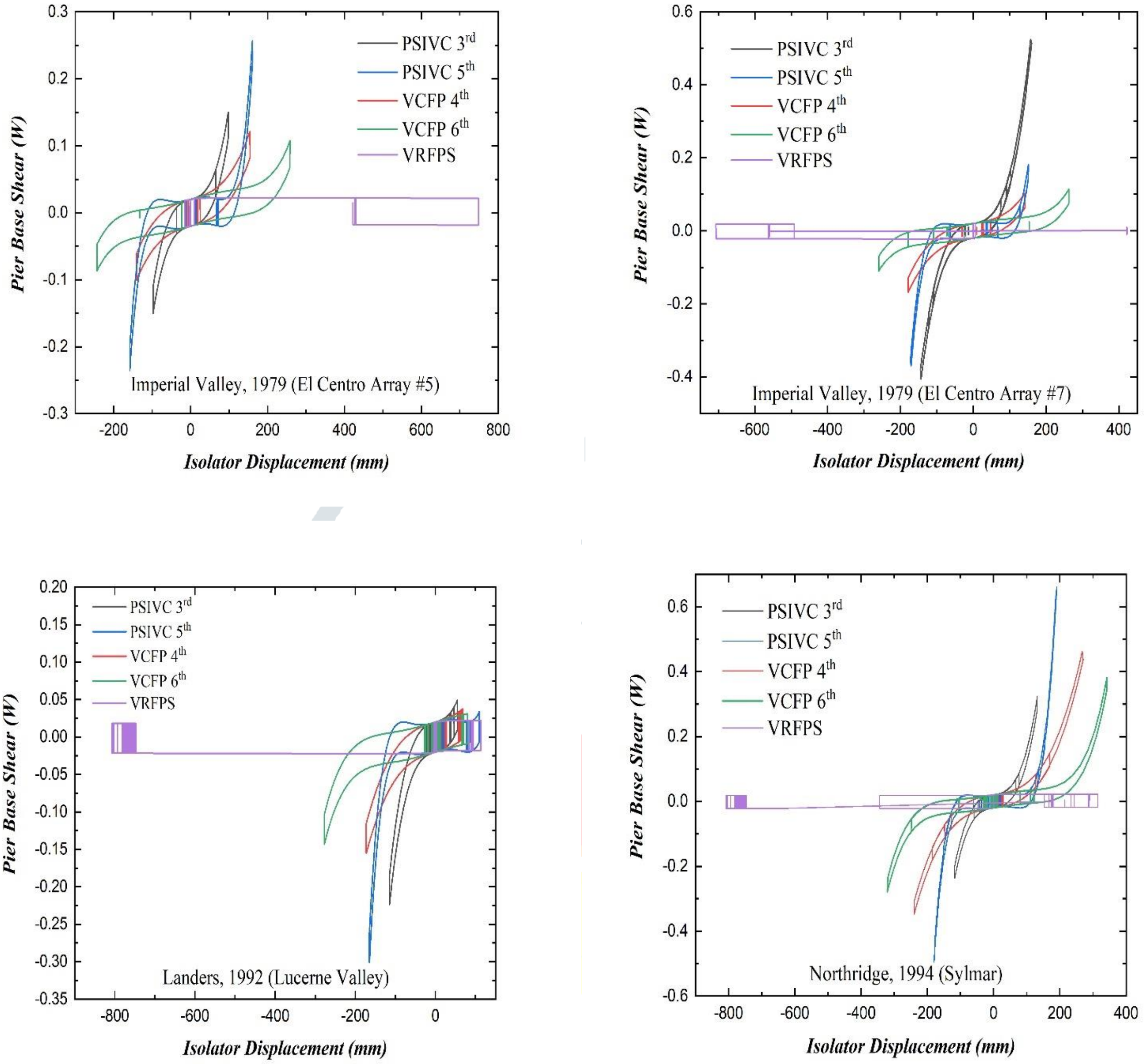


Figure 2 Hysteresis loop of isolators for four different near-field ground motions

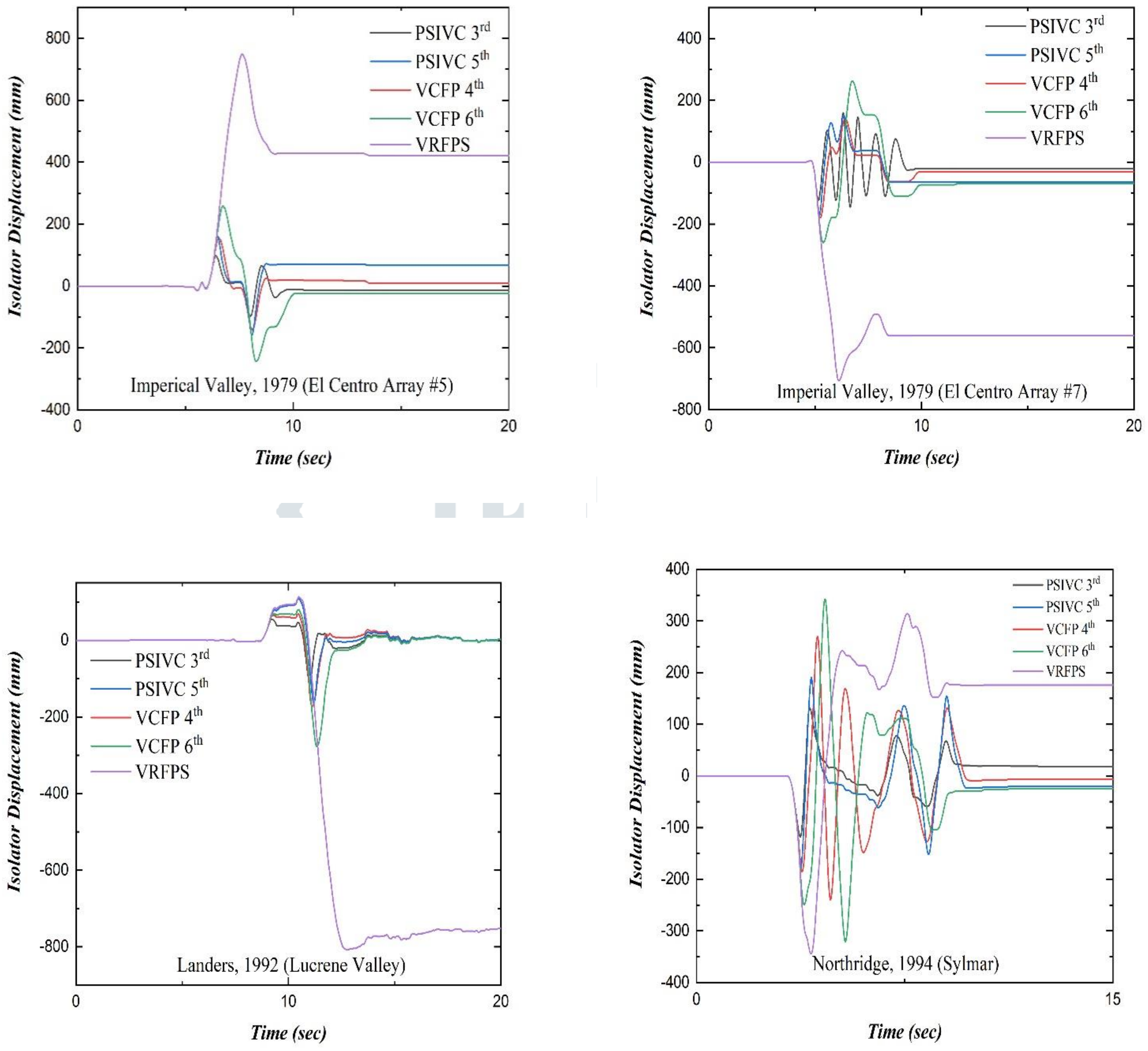


Figure 3 Isolator displacement for four different near-field ground motions

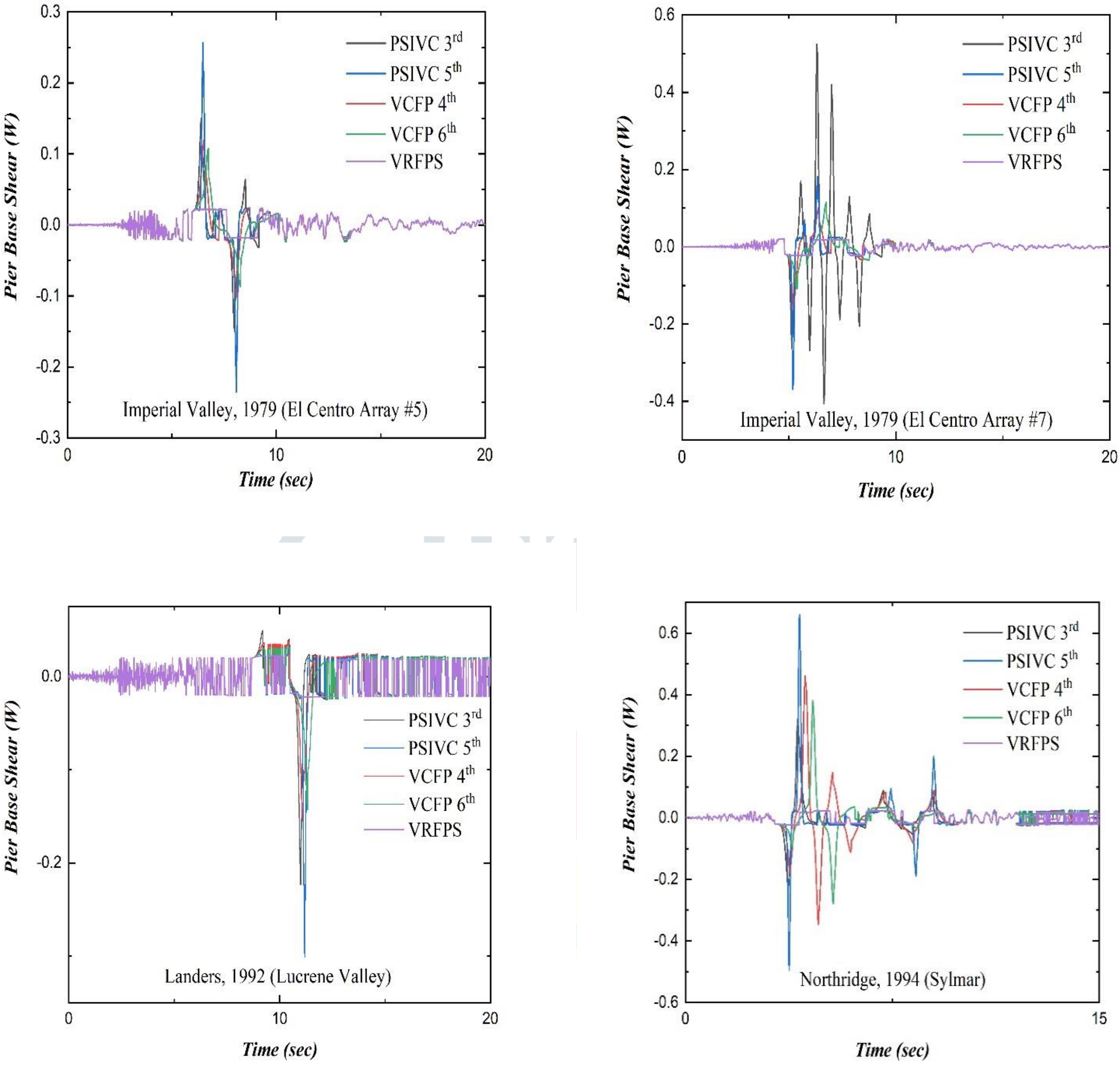


Figure 4 Pier base shear for four different near-field ground motions

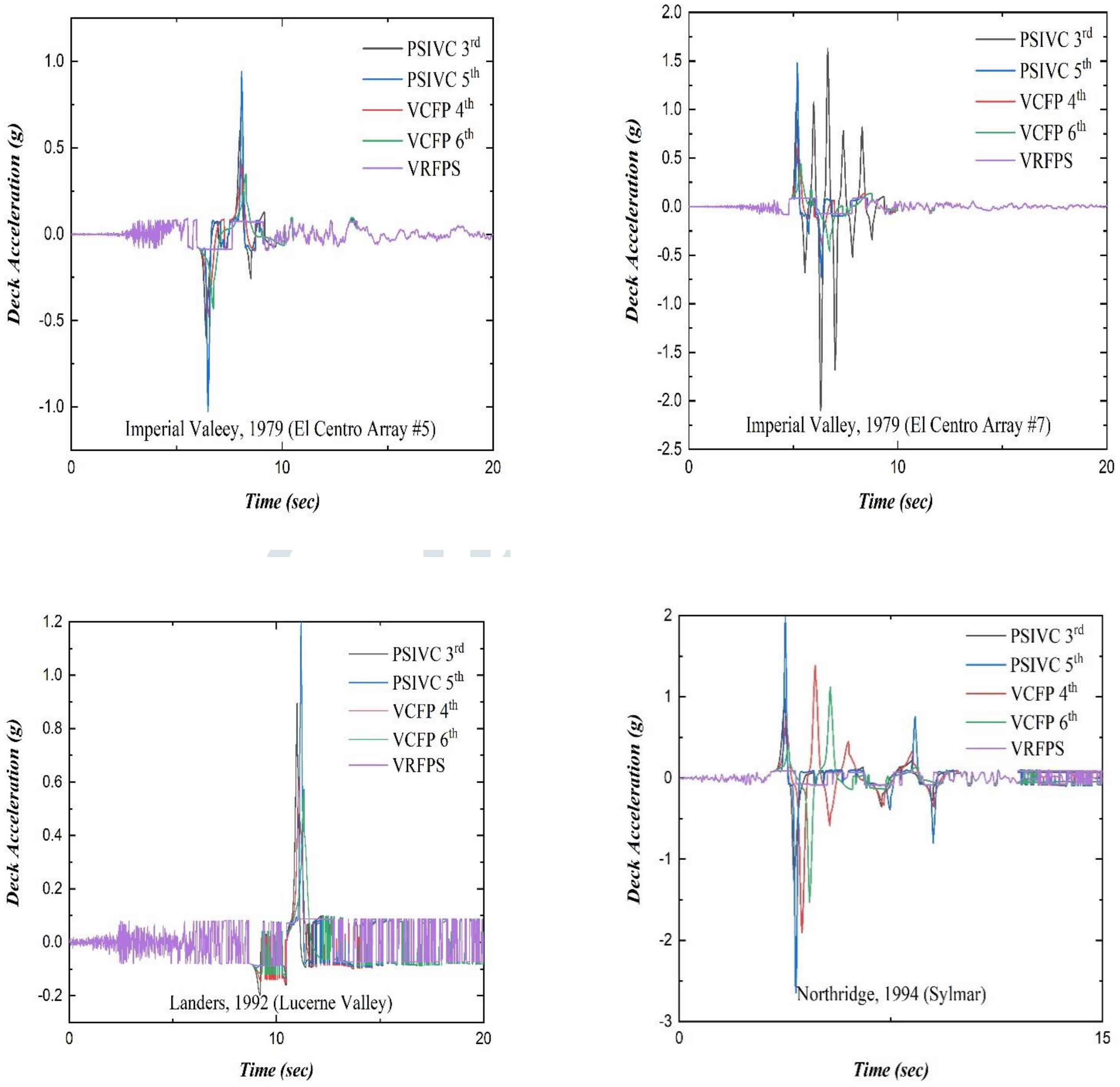


Figure 5 Deck acceleration for four different near-field ground motions

Table 6 represents average peak values of isolator displacement at abutment and pier, deck acceleration and base shear at pier for all five Variable Time Period Isolators (VTPI) under four near-field ground motions.

Table 6 Comparison of average peak response quantities

Isolator Type	**Peak Response Quantities**			
	Deck Acceleration (g)	**Isolator Displacement at Pier (mm)**	**Isolator Displacement at Abutment (mm)**	**Pier Base Shear (W)**
VRFPS	0.088	651.750	651.750	0.022
PSIVC 3rd	1.253	126.250	126.250	0.306
PSIVC 5th	1.798	172.500	172.500	0.397
VCFP 4th	0.891	189.250	189.250	0.218
VCFP 6th	0.754	285.250	285.250	0.187

VI. CONCLUSIONS

Three span continuous bridge is studied for four different near-field earthquakes using five different VTPI systems for the present work. Following conclusions are derived from the comparative study :

1) VCFP 6th isolator increases energy dissipation capacity of bridge compared to other isolators and performance of VRFPS is less efficient in terms of energy dissipation.
2) VRFPS experiences maximum isolator displacement at abutment and pier for near-field ground motions. There is maximum residual displacement observed in VRFPS. On the other hand, PSIVC 3rd undergoes minimum isolator displacement at abutment and pier among all other isolators.
3) Acceleration of deck and base shear at pier are effectively reduced due to VRFPS and there is maximum deck acceleration and pier base shear observed in PSIVC 5th.
4) Hence under near-fault earthquake, bridges with VRFPS perform well in case of deck acceleration and base shear but for displacement and energy dissipation criteria, PSIVC 3rd and VCFP 6th found to be more reliable respectively.

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