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SEISMIC ISOLATION OF SLENDER LIQUID STORAGE TANK ISOLATED BY VARIABLE RADIUS FRICTION PENDULUM SYSTEM

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Abstract

The effectiveness of Variable Radius Friction Pendulum System (VRFPS) is examined in this study. For this purpose, seismic response of slender liquid storage tank isolated with VRFPS are obtained for normal component of different near-fault, far-fault and fling step ground motions. The liquid mass of the tank is demonstrated as lumped masses known as impulsive, convective and rigid masses. Governing equation of motion of slender liquid storage tank is solved using Newmark's linear acceleration method. Seismic response of slender liquid storage tanks isolated with VRFPS is compared with the seismic response of tanks isolated with FPS in order to find the effectiveness of VRFPS isolator. From this study, it is observed that the VRFPS is effective in controlling the seismic response of slender liquid storage tanks compared to FPS under far-field, forward directivity and fling-step effect. It is observed that base shear, impulsive displacement and convective displacement are reduced in VRFPS as compared to that of FPS. There is increase in Isolator displacement in VRFPS as compared to that of FPS. The response of tank isolated with VRFPS is less sensitive to far-field ground motions compared to near-fault ground motions because of inherent large velocity pulse and permanent ground deformation.

Keywords: VRFPS; base isolation; near-fault ground motions; far-fault ground motions; fling step ground motions.

1. Introduction

The liquid storage tanks are important as well as most commonly used structure since they have wide applications in certain fields such as industries, water serving systems and nuclear plants. Major failures of liquid storage tanks seen in Taiwan's Chi-Chi earthquake (1999), Japan's Kobe earthquake (1995) and California's Northridge earthquake (1994). Such failure causes major destruction. This destruction follows the economic loss as well as spreading of diseases due to contamination of fluid which is harmful to human and makes surrounding and environment polluted. Hence, the wellbeing of fluid tanks has become a prime worry against the serious earthquakes. Consistently, base-isolation has been seen as perhaps the best alternative passive system of tanks for ground motions.

Base-isolation is passive earthquake protective system in which tank is separated from the surface of earth by providing isolators between the foundation and superstructure by introducing a suspension system between them that allows structure to minimize the transmission of earthquake excitation from the foundation.

Numbers of researchers have acquired the usefulness of seismic isolation for analysis of tanks using different types of sliding isolator. Among different base-isolation systems, sliding isolators are mostly used for actual implementation as they are unaffected to frequency content of earthquake excitations. Number of sliding isolators, i.e., FPS, Variable Curvature Friction Pendulum System (VCFPS), Variable Friction Pendulum System (VFPS), Variable Frequency Pendulum Isolator (VFPI) and Variable Frequency and Variable Friction Pendulum Isolator (VFFPI) were suggested and examined by Panchal et al. [11], Panchal and Jangid [10-12], Krishnamoorthy [7], etc. during last few decades. According to few investigators, base isolated structures situated at close to epicenter are more susceptible to the large pulse-like ground motions. Malhotra [9] studied seismic demand of base isolated tanks and concluded, isolation was helpful in reduction in the response of the tanks without any important modification in sloshing displacement compared to fixed base tank. Tejani and Panchal [13] investigated seismic response of tank equipped with MVFPS which is Modified Variable Friction Pendulum System and compared with the tank isolated with FPS and found that MVFPS is found quite effective in base isolation of slender liquid storage tanks as compared to FPS but less efficient than

VFPS. Dhundhiyawala and Panchal [1] investigated response of liquid storage tank isolated with VFFPI and compared with same tank isolated with VFPS with variable frequency and observed that VFFPI is found quite operative in seismic isolation of liquid storage tank VFPS with changing frequency. Faldu et al. [14] investigated response of liquid storage tank isolated with VRFPS and compared with same tank isolated with FPS and observed that VRFPS is found quite operative in seismic isolation of liquid storage tank than FPS. Present investigation is conducted on response of isolated liquid storage slender steel tank with VRFPS under eighteen earthquake excitations as listed in Table 1 to Table 3. The time history of these ground accelerations is presented in Figure 2. The specific aim of this research is to inspect the efficiency of tank isolated with VRFPS and response comparison of VRFPS and FPS was done.

2. Concept of VRFPS

The curvature radius of isolator (R) is constant in FPS. Because of this, it may create a low frequency resonance problem. To solve this problem, VRFPS is proposed by Krishnamoorthy [8]. This isolator is similar to VFPI and VCFPS. At the center of sliding surface radius of FPS is same as radii of VRFPS system which increases becomes infinite at a higher sliding displacement [8]. For the VRFPS, the radii of the curvature is function of isolator displacement (xb), and it's shown in Equation 1.

$$R(x) = C(\exp(x_b) - 1) + R \tag{1}$$

$$y(x) = \int \frac{x_b dx}{C(\exp(x_b) - 1) + R} \tag{2}$$

where $x_b$denotes the isolator displacement, C denotes the variation of curvature of concave surface and R is radii of curvature, at center of VRFPS (at x_b = 0).

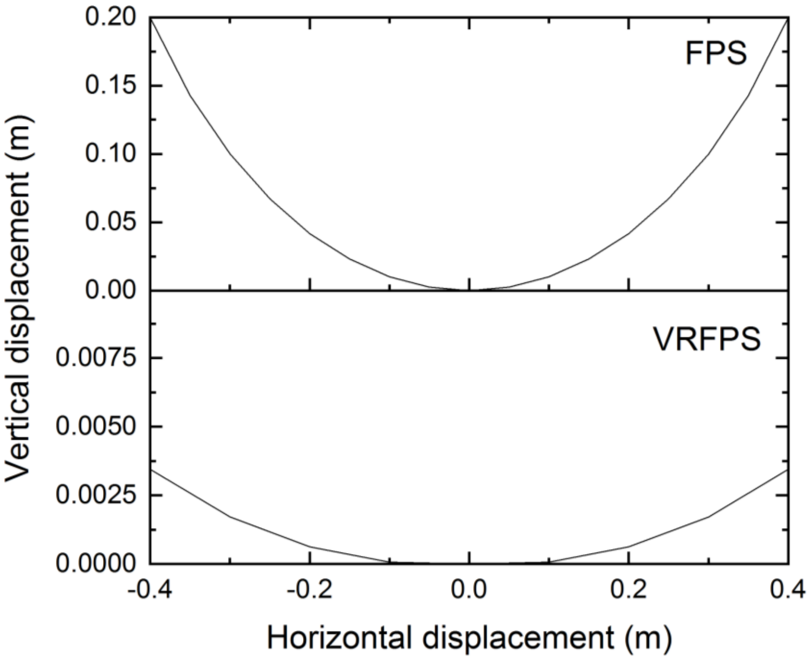

Fig. 1 – Geometry of FPS and VRFPS isolators

The vertical displacement, $y(x)$, at isolator displacement, x_b, can be obtained by numerical integrating of Equation 2. Figure 1. shows the sliding surface of FPS with a constant radius R = 0.5 m and VRFPS with a constant radii R = 0.5 m and C = 100. The radii of curvature is increasing in VRFPS while increasing the isolator displacement.

Table 1 – Characteristics of Near-field Excitations

Near-Fault Ground Motions	**Normal component**		
	PGD (cm)	**PGV (cm/s)**	**PGA (g)**
Imperial Valley, 1979 (El Centro #5) (EQ 11)	76.5	98	0.37
Imperial Valley, 1979 (El Centro #7) (EQ 21)	49.1	113	0.46
Northridge, 1994 (Newhall) (EQ 31)	38.1	119	0.72
Landers, 1992 (Lucerne Valley) (EQ 41)	230	136	0.71
Northridge, 1994 (Rinaldi) (EQ 51)	39.1	175	0.89
Northridge, 1994 (Sylmar) (EQ 61)	31.1	122	0.73

Table 2 – Characteristics of Far-field Excitations

Normal component of Far-field Ground excitation	**Station**	**Magnitude (Mw)**	**PGA (g)**
Loma Prieta, 1989 (CAPX)	Capitola	6.90	0.420
Chamoli, 1999 (CHAMOLI)	Chamoli	6.40	0.359
Superstition Hill, 1987(ICCX)	El Centro Imp. Co.	6.70	0.512
Imperial Valley, 1940 (ELCX)	El Centro	6.95	0.313
Northridge, 1994 (CNPX)	Canoga Park-Topanga Canyon	6.70	0.477
Northridge, 1994 (STCX)	Northridge-Saticoy	6.70	0.529

Table 3 – Characteristics of Fling Step Excitations

Name and Designation of earthquakes	**Station**	**Magnitude (Mw)**	**PGA (g)**	**Fling Displacement (m)**
Chi-Chi, 1999	TCU052_NS	7.6	0.440	6.97
Chi-Chi, 1999	TCU074_EW	7.6	0.590	1.74
Chi-Chi, 1999	TCU084_NS	7.6	0.420	0.594
Chi-Chi, 1999	TCU129_NS	7.6	0.610	0.675
Chi-Chi, 1999	TCU068_EW	7.6	0.500	6.01
Kocaeli, 1999	YPT_NS	7.4	0.230	1.45

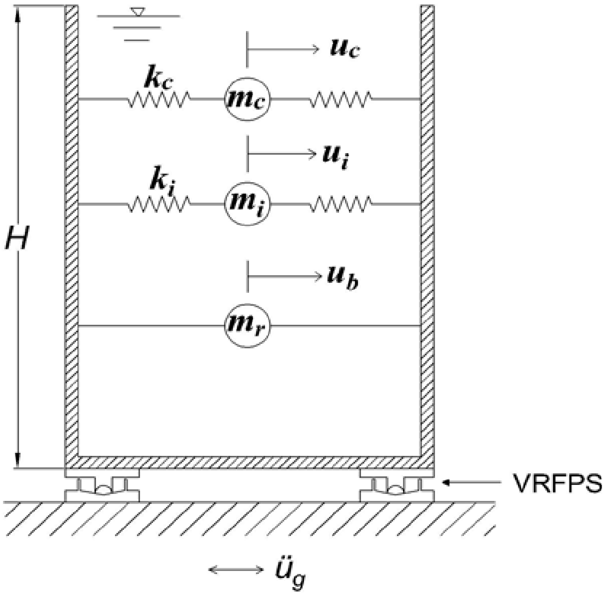

Fig. 2 – Mathematical modelling of liquid storage tank isolated with VRFPS

3. Modeling and Idealizing

The prototypical of the base-isolated liquid storage steel tank taken for present investigation is shown in Figure 3. VRFPS is provided between foundation and base of tank. Tank containing liquid is assumed to have irrotational flow, incompressible and also has no-viscosity. Throughout the earthquake, the whole liquid mass of the tank shakes in three specific forms and demonstrated by lumped masses such as convective mass (mc), impulsive mass (mi) and rigid mass (mr) which is recommended by Haroun [9]. Vibration of convective and impulsive mass is described by the numerous modes. However, the response is predicated by taking initial convective mode and initial impulsive mode as detected mathematically by Malhotra [9] and experimentally by Kim and Lee [6]. Hence, the tank structure isolated at the base is considered as three-degrees freedom system for one-directional ground motion. And, those are referred as xc, xi and xb which indicate the relative convective, impulsive and bearing movement, respectively.

The several assumptions created for the system taken into account are: (a) The self-weight of tank is ignored due to the fact that it is very less; (b) The damping ratio is assumed for the calculation of damping constant corresponding to the motion of impulsive mass and convective mass; (c) The friction coefficient of the VRFPS does not rely on relative velocity at the concave surface. Because, that consideration does not considerably affect the maximum value of earthquake response of isolated structure [2]; (d) The force needed for re-centering the articulated slider, which is delivered by the VRFPS is assumed to be non-linear; (e) Involvement of parallel element is neglected and only the normal element of far-field ground motion is assumed to be excited on the system as the resultant peak isolator movement is largely affected by the normal element of the far-field ground excitations.

Convective, impulsive and rigid masses in relation to liquid mass, m and various mass ratios for th/R = 0.004 [4] are introduced as:

$$m_c = Y_c m \tag{3}$$

$$m_i = Y_i m \tag{4}$$

$$m_r = Y_r m \tag{5}$$

$$m_r = Y_r m \tag{6}$$

$$m = \pi R^2 H \rho_w \tag{7}$$

$$Y_c = 1.01327 - 0.87578S + 0.35708S^2 - 0.06692S^3 + 0.00439S^4 \tag{8}$$

$$Y_i = -0.15467 + 1.21716S - 0.62839S^2 + 0.14434S^3 - 0.0125S^4 \tag{9}$$

$$Y_r = -0.01599 + 0.86356S - 0.30941S^2 + 0.04083S^3 \tag{10}$$

where, Y_c, Y_i, and Y_r are denoted as mass ratios, which depends on the aspect ratio of tank respectively, S = H/R; ρ_w is symbolized as the mass density of containing liquid; R is the tank radius; and H is liquid height.

Following equation shows fundamental frequency of convective and impulsive mass, ω_c, and ω_i, respectively:

$$\omega_i = \frac{P}{H}\sqrt{\frac{E}{\rho_s}} \tag{11}$$

$$\omega_c = \sqrt{1.84\left(\frac{g}{R}\right)\tanh(1.84S)} \tag{12}$$

Where, g denotes acceleration due to gravity; E denotes elastic modulus and ρ_s denotes tank wall density; and P is given by:

$$P = 0.037085 + 0.084302S - 0.05088S^2 + 0.012523S^3 - 0.0012S^4 \tag{13}$$

Equations used (Equations 3-12) for modelling of the tank and for value of th/R = 0.004 are selected from Panchal and Jangid [10]. For different ratios of th/R, similar equations can be resolved. The damping and stiffness, equivalent with the convective and impulsive masses are introduced as:

$$k_c = m_c \omega_c^2 \tag{14}$$

$$k_i = m_i \omega_i^2 \tag{15}$$

$$c_c = 2\xi_c m_c \omega_c \tag{16}$$

$$c_i = 2\xi_i m_i \omega_i \tag{17}$$

where, ξ_c and ξ_i denotes ratio of damping corresponding to convective and impulsive masse, respectively.

Governing equation of motion is expressed as given below in matrix form for liquid storage tank with isolation:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} + \{F\} = -[M]\{r\}\ddot{u}_g \tag{18}$$

where [K], [M] and [C] are stiffness matrix, mass matrix and damping matrix; {x} = {x_c, xi, xb} T is the relative displacement; {F}= {0, 0, Fx} is the friction force vectors; {r}= {0, 0, 1} T is the influence constant vector; $x_c = u_c - u_b$ is the displacement of sloshing mass related to bearing displacement; $x_i = u_i - u_b$is the displacement of impulsive mass related to bearing displacement; $x_b = u_b - u_g$ is the displacement of bearing related to ground; Fx is the frictional force in the VRFPS; T denotes transpose; is the earthquake ground acceleration and over dots indicate derivative with respect to time.

Force-deformation behaviour of VRFPS is non-linear and also superstructure and isolator damping are different, therefore it does not possible to solve governing equation of motion using classical modal superposition technique. Hence, to obtained the solution of governing equation of motion, Newmark's method with the assumption that the variation of acceleration is linear through small time interval is utilized.

The response of slender tanks isolated with VRFPS for six different far-field ground excitations is examined. The various essential parameters required to define slender liquid storage tank system are as follows which is taken from Panchal and Jangid [12].

1. Aspect ratio, S is 1.85;

2. Height, H is 11.3 m;
3. The natural frequency of ωi and ωc is 5.963 and 0.273 Hz, respectively;
4. Ratio of damping of ξc and ξi is 0.5% and 2%, respectively;
5. Elastic modulus, E is 200 GPa;
6. Density of mass, ρs is 7900 kg/m3 and
7. Thickness of wall of tank to radius ratio, th/R is 0.004.

The different response quantities are base-shear (F_b), displacement of isolator (x_b), impulsive displacement (x_i) and convective displacement (x_c). Two types of isolator are used for comparison of seismic response, (i) VRFPS (Tb = 1.418 sec and μ = 0.036) and (ii) FPS (Tb = 1.418 sec and μ = 0.036).

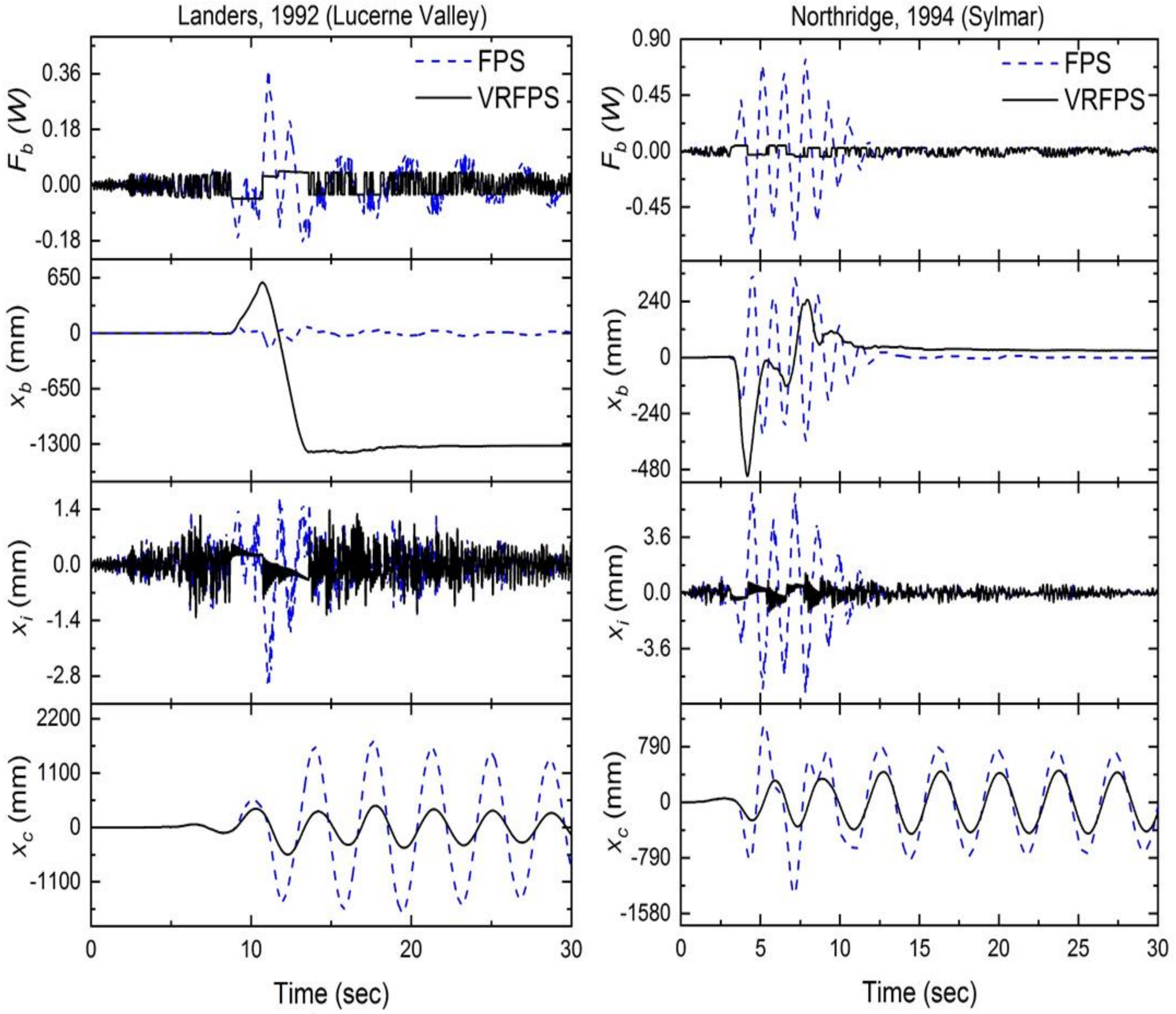

Fig. 3 – Response quantities of slender tank under Near-Fault ground motions

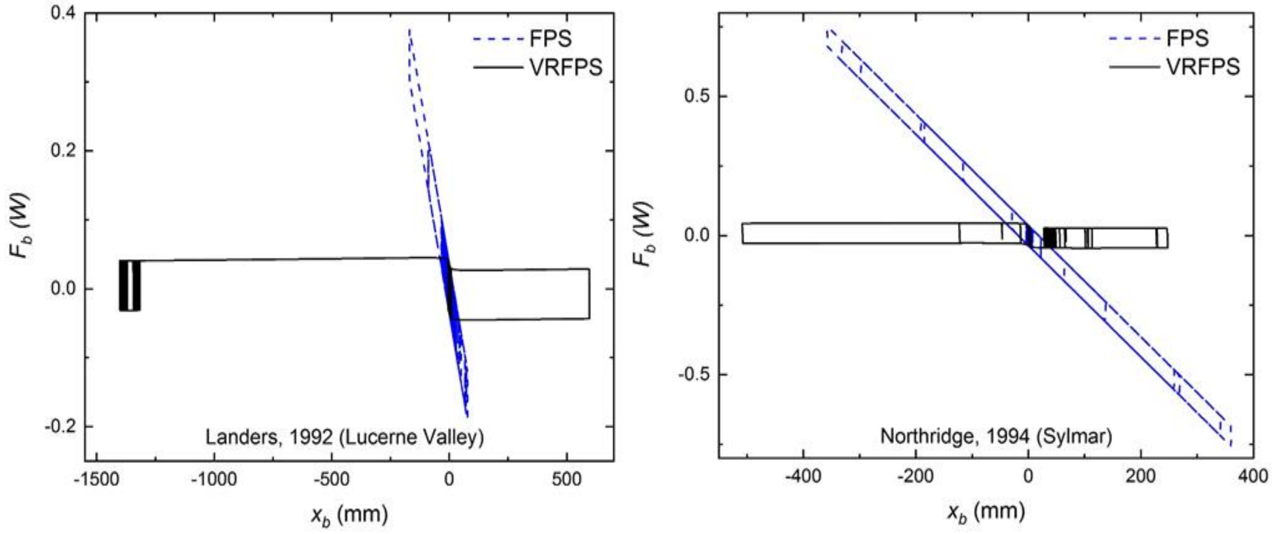

Fig. 4 – Hysteresis loop of slender tank isolated under Near-Fault ground motions

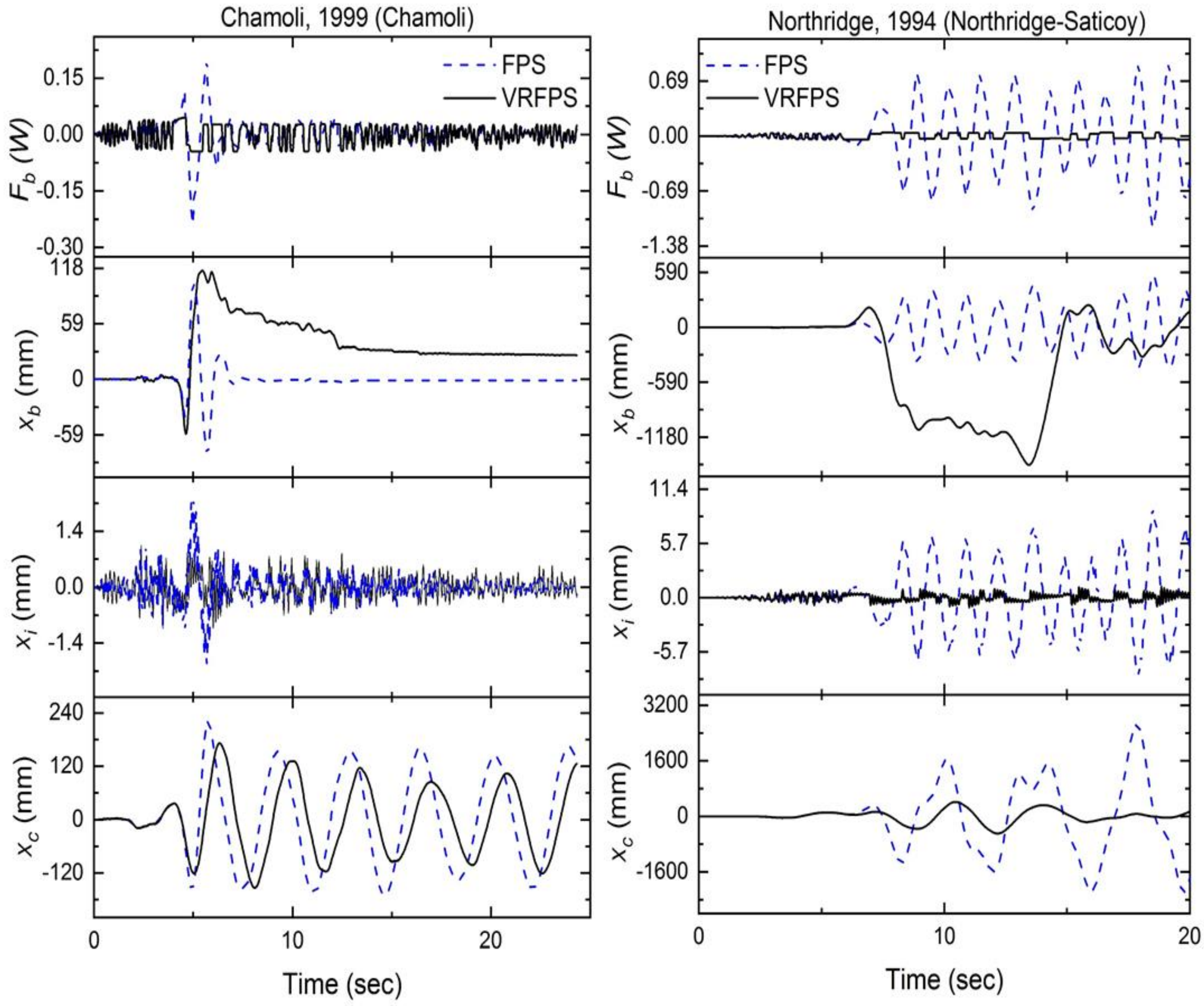

Fig. 5 – Response quantities of slender tank under Far-Fault ground motions

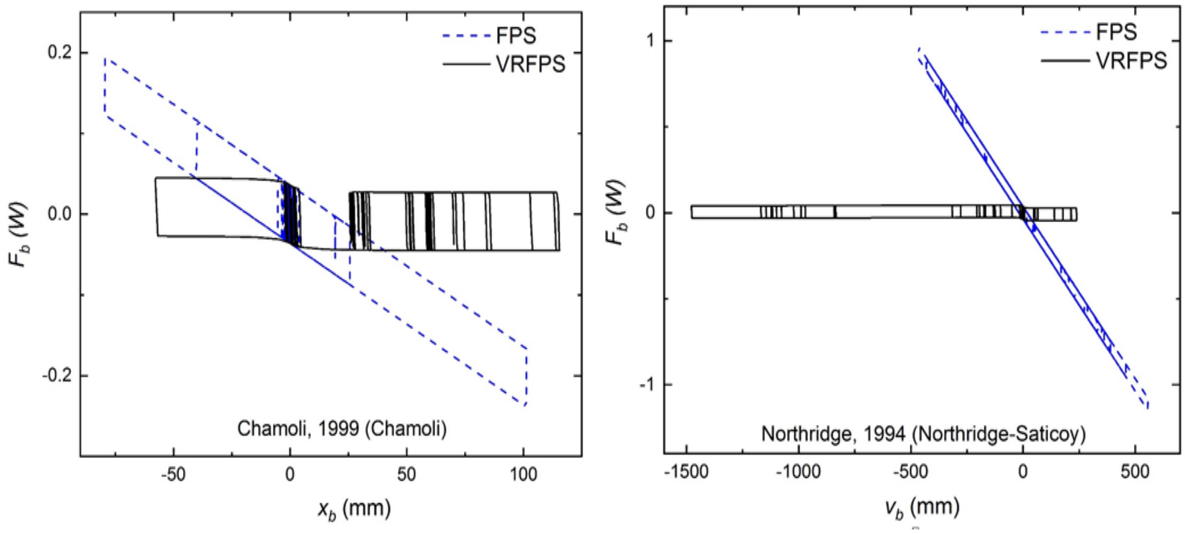

Fig. 6 – Hysteresis loop of slender tank isolated under Far-Fault ground motions

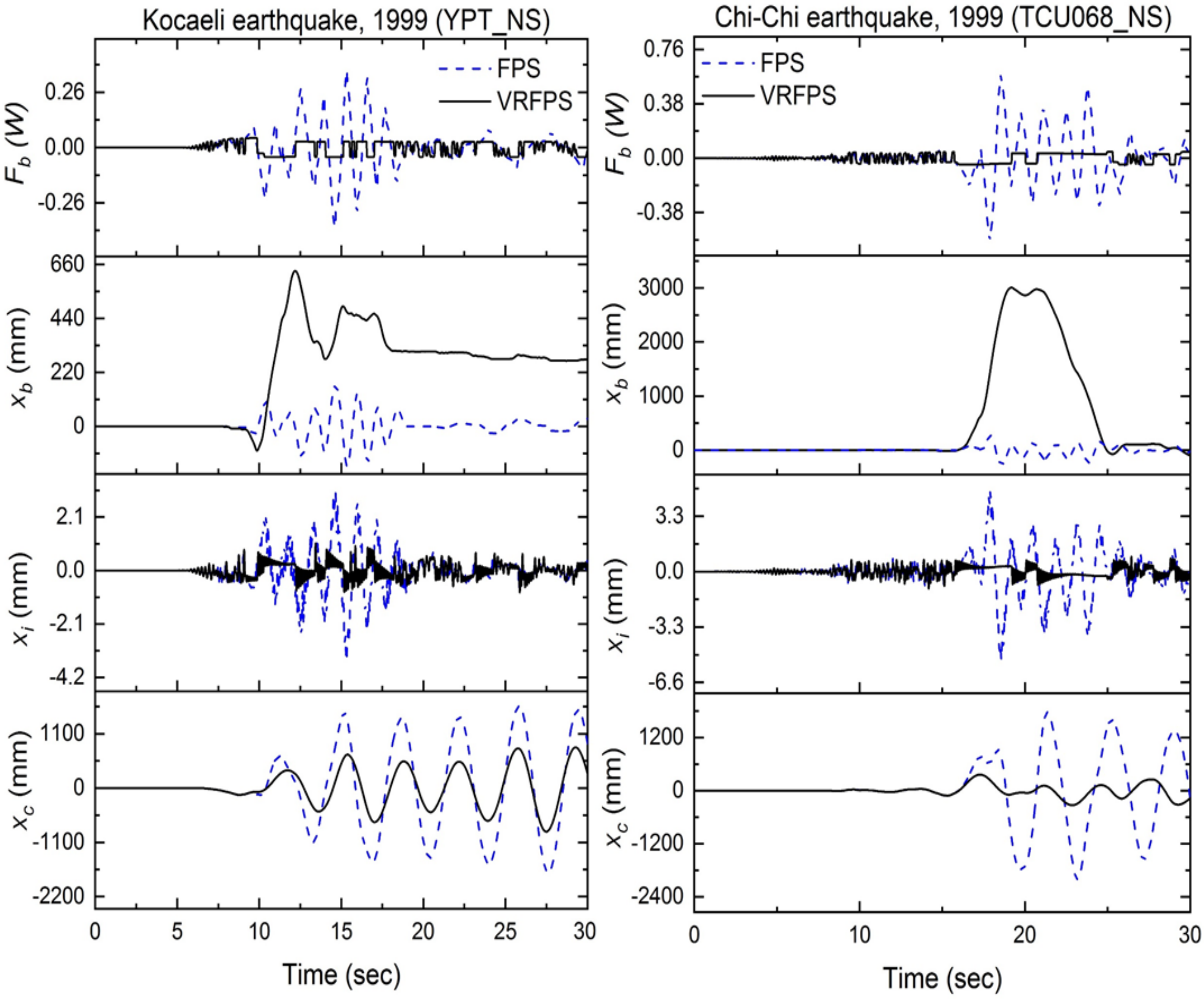

Fig. 7 – Response quantities of slender tank under Fling step ground motions

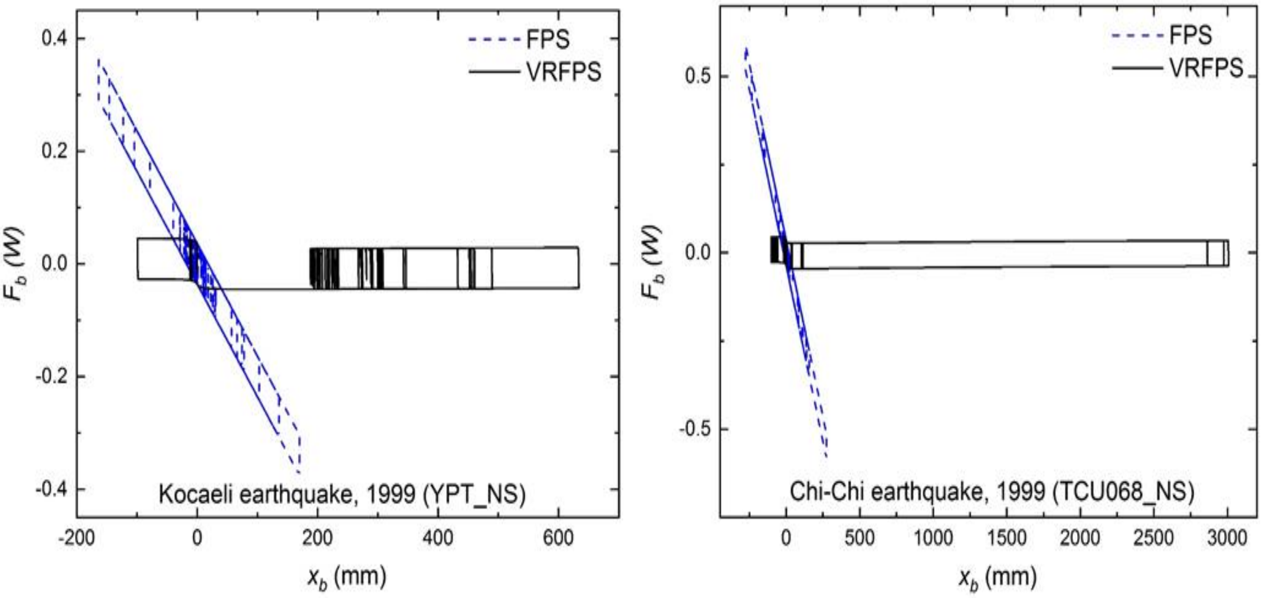

Fig. 8 – Hysteresis loop of slender tank isolated under Fling step ground motions

Table 4 – Peak response quantities under Near-Fault ground motions

Near-Fault Ground Motions	**Base Isolator**	**Peak Response Quantities**			
		F_b (W)	**x_c (mm)**	**x_i (mm)**	**x_b (mm)**
Imperial Valley, 1979 (El Centro #5)	FPS	0.31	1698.90	2.72	135.40
	VRFPS	0.05	598.83	1.19	1313.60
Imperial Valley, 1979 (El Centro #7)	FPS	0.42	1663.40	3.68	191.46
	VRFPS	0.05	753.80	1.03	941.00
Northridge, 1994 (Newhall)	FPS	1.19	1482.40	10.10	575.43
	VRFPS	0.05	496.19	1.20	557.10
Landers, 1992 (Lucerne Valley)	FPS	0.38	1740.10	3.01	170.15
	VRFPS	0.05	548.81	1.39	1402.60
Northridge, 1994 (Rinaldi)	FPS	1.61	1406.70	13.71	788.41
	VRFPS	0.05	271.19	1.30	536.66
Northridge, 1994 (Sylmar)	FPS	0.76	1308.50	6.52	360.61
	VRFPS	0.05	451.27	1.29	508.89

Table 5 – Peak response quantities under Far-Fault ground motions

Far-Fault Ground Motions	**Base Isolator**	**Peak Response Quantities**			
		F_b (W)	**x_c (mm)**	**x_i (mm)**	**x_b (mm)**

Loma Prieta, 1989 (Capitola)	FPS	2.190	3467.50	18.92	1075.70
	VRFPS	0.045	820.30	1.15	1828.80
Chamoli, 1999 (Chamoli)	FPS	0.240	220.19	2.28	101.38
	VRFPS	0.045	171.66	1.04	115.54
Superstition Hill, 1987 (El Centro Imp. Co.)	FPS	0.120	477.44	1.17	41.51
	VRFPS	0.045	360.67	0.88	55.88
Imperial Valley, 1940 (El Centro)	FPS	0.440	1221.20	3.68	200.51
	VRFPS	0.045	523.23	1.19	242.94
Northridge, 1994 (Canoga Park - Topanga Canyon)	FPS	1.130	1926.80	8.78	548.02
	VRFPS	0.045	582.09	1.30	971.08
Northridge, 1994 (Northridge-Saticoy)	FPS	1.150	2655.70	9.39	557.47
	VRFPS	0.045	495.76	1.18	1478.10

Table 6 – Peak response quantities under Fling step ground motions

Fling step Ground Motions	**Base Isolator**	**Peak Response Quantities**			
		F_b (W)	**x_c (mm)**	**x_i (mm)**	**x_b (mm)**
Chi-Chi, 1999 (TCU052_NS)	FPS	0.950	1108.30	8.16	458.62
	VRFPS	0.045	559.10	0.89	2447.70
Chi-Chi, 1999 (TCU074_EW)	FPS	0.860	1008.20	7.06	413.48
	VRFPS	0.045	311.07	1.25	264.15
Chi-Chi, 1999 (TCU084_NS)	FPS	0.330	743.27	2.69	146.90
	VRFPS	0.045	437.33	1.36	140.20
Chi-Chi, 1999 (TCU129_NS)	FPS	0.220	331.75	1.96	94.09
	VRFPS	0.045	323.45	1.60	117.05
Chi-Chi, 1999 (TCU068_EW)	FPS	0.590	2007.90	5.28	276.15
	VRFPS	0.045	360.35	1.02	3007.00
Kocaeli, 1999 (YPT_NS)	FPS	0.390	1705.00	3.57	169.84
	VRFPS	0.045	883.53	1.23	633.53

Figure 3, 5 & 7 exhibits deviation of base-shear (F_b), displacement of isolator (x_b), impulsive displacement (x_i) and convective displacement (x_c) versus time. Figure 4, 6 & 8 exhibits variation of base shear of the isolated tank with respect to isolator displacement. Comparison of peak value of different response quantities of FPS and VRFPS is shown in Table 4, 5 & 6.

4. Conclusions

The isolated liquid storage slender tank has been analyzed by providing VRFPS at base under earthquake excitation. In order to check efficiency of VRFPS isolated tank, the seismic response obtained from the VRFPS isolated tank is compared with FPS isolated tank. In the above study, following conclusions are made:

1) Results shows that under different ground motions effectiveness of VRFPS isolator is favorable as compared to the same tank isolated by FPS isolator at the base.
2) The impulsive displacement, base shear and convective displacement are increased in FPS as compared to that of VRFPS.
3) Isolator displacement is less in tank isolated with FPS as compared to that of VRFPS.
4) Residual displacement is less in tank equipped with FPS as compared to VRFPS.

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