Seismic Control of Liquid Storage Tank Isolated by Variable Radius Friction Pendulum System

[1]Smeet Faldu [2]V. R. Panchal [3]Mehul Katakiya

[1]Post graduate student (Structural Engineering), M. S. Patel Department of Civil Engineering, Chandubhai S. Patel Institute of Technology, Charotar University of Science and Technology, Changa, Gujarat, India
[2] Professor and Head, M. S. Patel Department of Civil Engineering, Chandubhai S. Patel Institute of Technology, Charotar University of Science and Technology, Changa, Gujarat, India
[3]Assistant Professor M. S. Patel Department of Civil Engineering, Chandubhai S. Patel Institute of Technology, Charotar University of Science and Technology, Changa, Gujarat, India
smitfaldu4521@gmail.com[1]
vijaypanchal.cv@charusat.ac.in[2]
mehulkatakiya.cv@charusat.ac.in[3]

Abstract: Investigation for the earthquake response has been carried out of isolated liquid storage steel tank with variable radius friction pendulum system (VRFPS) under normal component of earthquake excitation. The consistent fluid mass of the tank is demonstrated as lumped masses known as impulsive, convective and rigid masses. Motion equation which are governing on liquid storage tank is solved using Newmark's linear acceleration method. The efficiency comparison has been made between response of isolated liquid storage tank using VRFPS and response of the same tank isolated with Friction pendulum system (FPS). It is observed that base shear, impulsive displacement and convective displacement are reduced in VRFPS as compared to that of FPS. Displacement which is Isolator and residual are more in VRFPS as compared to that of FPS.

Keyword - Base isolation; sliding systems; near-field ground motions; liquid storage tank; VRFPS

I. 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. The several failures of liquid storage tanks seen in recent time earthquakes such as (a) California's Northridge earthquake (1994), (b) Japan's Kobe earthquake (1995) and (c) Taiwan's Chi-Chi earthquake (1999). Such failure of liquid storage tanks has a number of causes for the destruction. This destruction follows the economic loss of the structure, but that is not enough to cope up with them only, it can cause spreading of diseases which may lead the loss of life due to the harmful spillage of liquid in surroundings and also makes the environment polluted. Therefore, the safety of liquid storage tanks has become a prime concern against the severe earthquake excitation. Throughout the years, base-isolation has been perceived as one of the best options for ensuring safety of tanks against serious earthquake excitation.

Base-isolation is passive earthquake protective system in which tank is uncoupled from the surface of earth by providing specially designed isolators between the superstructure and foundation. Base isolation is a method in which the super-structure is separated from the foundation by introducing a suspension system between the foundation and the super-structure that allows structure to lessen 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. [1], Panchal and Jangid [2-3], Krishnamoorthy [4], 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 [5] 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 [6] 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 [7] 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.

Present investigation is conducted on response of isolated liquid storage slender steel tank with VRFPS under six earthquake excitations as listed in Table 1. 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.

II. 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 centre 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 (x_b), 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 centre of VRFPS (at $x_b = 0$).

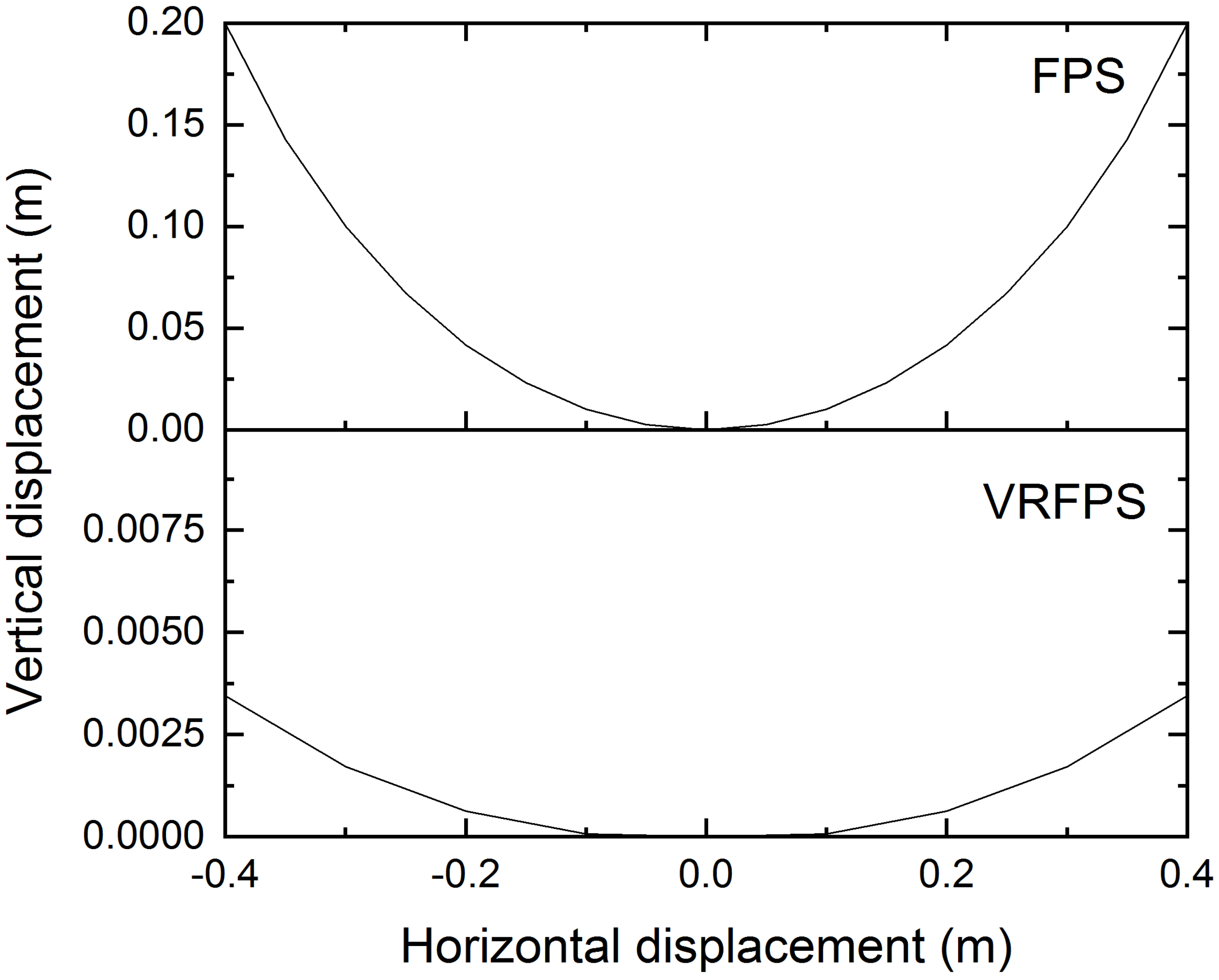

Figure 1 Geometry of FPS and VRFPS isolators [8]

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

Normal component of Near-field Ground excitation	PGD (cm)	PGV (cm/s)	PGA (g)
Imperial Valley, 1979 (ElCentro Array #5)	76.5	98	0.37
Imperial Valley, 1979 (ElCentro Array #7)	49.1	113	0.46
Northridge, 1994 (Newhall)	38.1	119	0.72

Landers, 1992 (Lucerne Valley)	230	136	0.71
Northridge, 1994 (Rinaldi)	39.1	175	0.89
Northridge, 1994 (Sylmar)	31.1	122	0.73

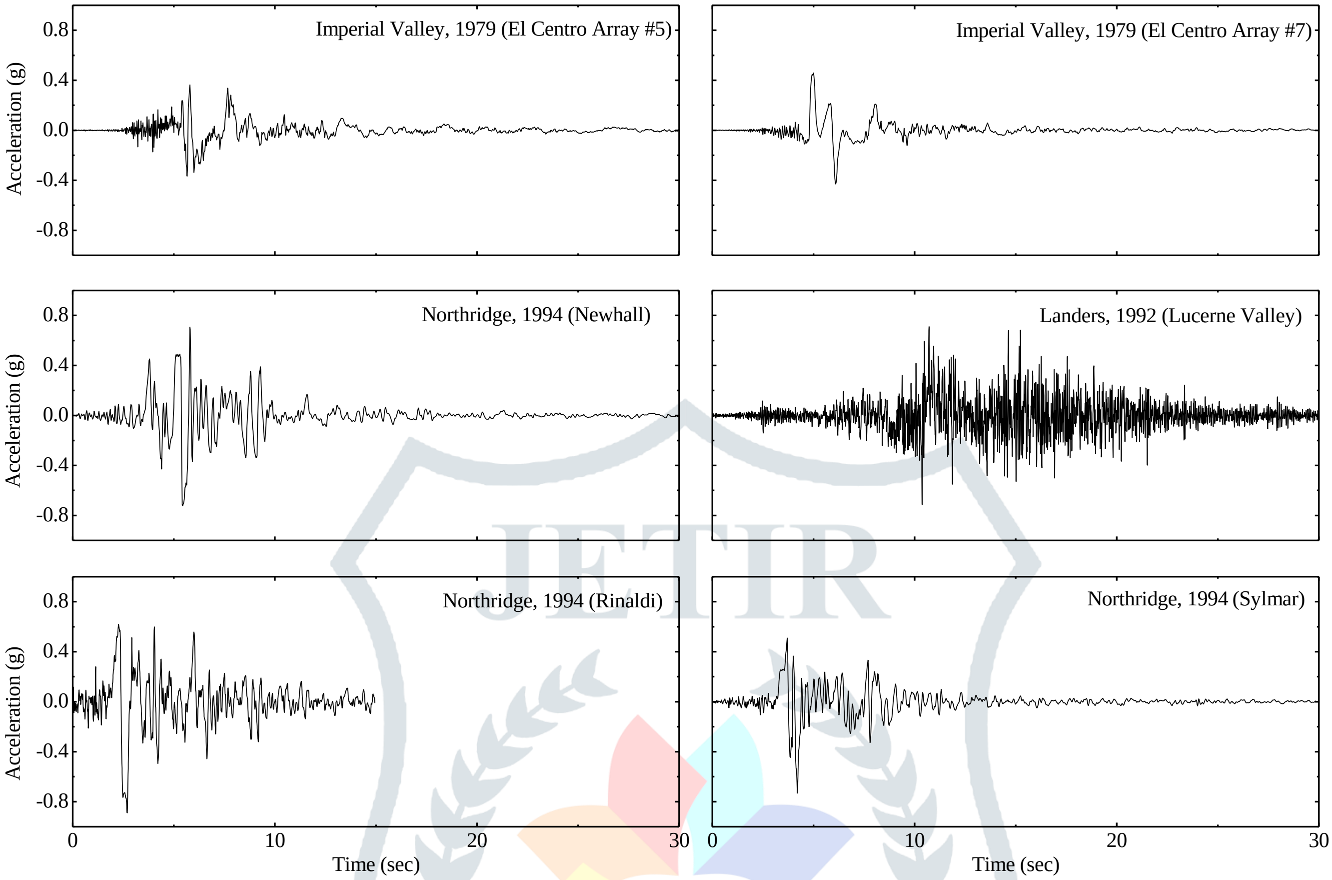

Figure 2 Time histories of near-fault ground motions considered in the study

III. 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 (m_c), impulsive mass (m_i) and rigid mass (m_r) 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 [5] and experimentally by Kim and Lee [10]. 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 x_c, x_i and x_b 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 [11]; (d) The force needed for re-centring 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 near-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 near-field ground excitations [12].

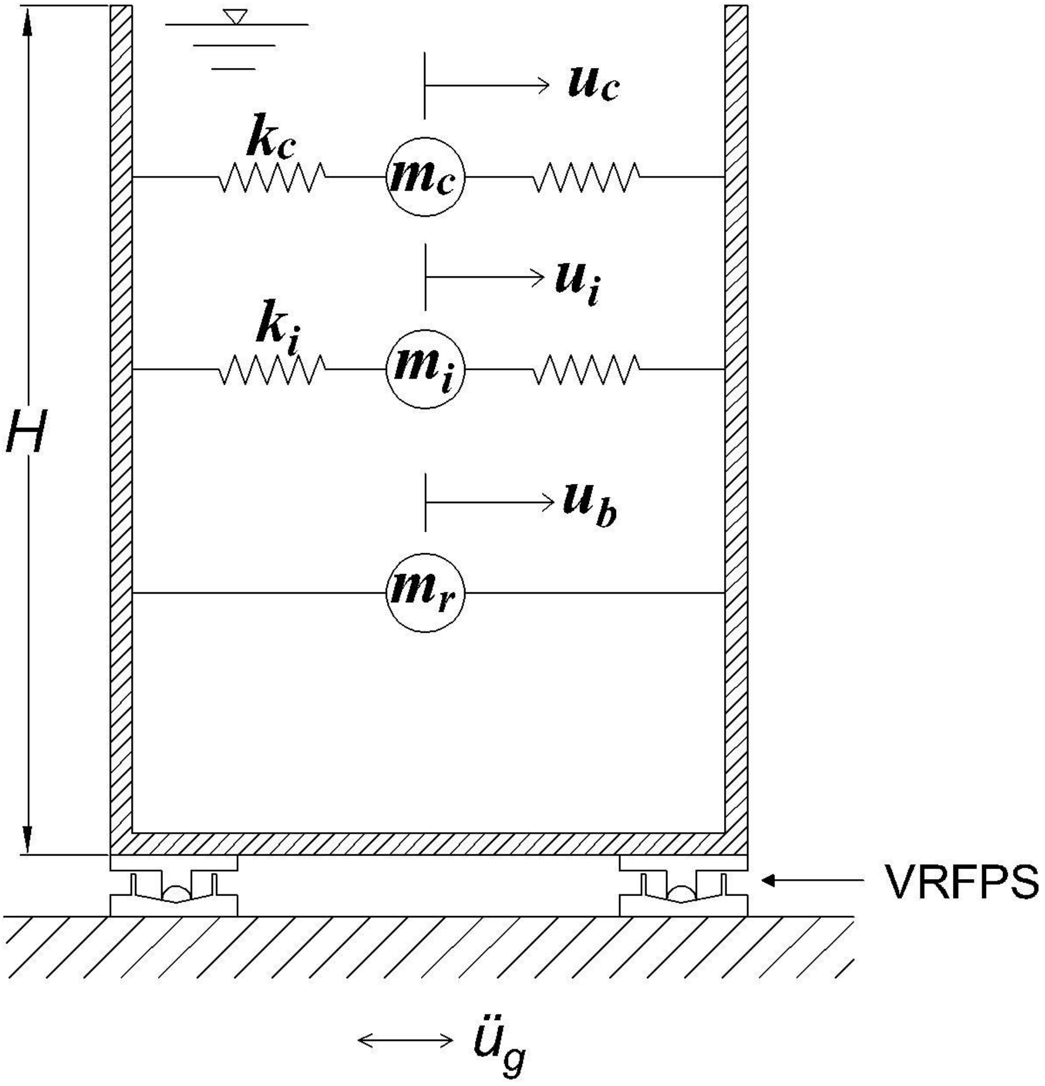

Figure 3 Mathematical modelling of liquid storage tank isolated with VRFPS

Convective, impulsive and rigid masses in relation to liquid mass, *m* and various mass ratios for t_h/R = 0.004 [9] are introduced as:

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

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

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

$$m = \pi R^2 H \rho_w \tag{6}$$

$$Y_c = 1.01327 - 0.87578S + 0.35708S^2 - 0.06692S^3 + 0.00439S^4 \tag{7}$$

$$Y_i = -0.15467 + 1.21716S - 0.62839S^2 + 0.14434S^3 - 0.0125S^4 \tag{8}$$

$$Y_r = -0.01599 + 0.86356S - 0.30941S^2 + 0.04083S^3 \tag{9}$$

where, Y_c, Y_i, and Y_r are denoted as mass ratios, which depends on the aspect ratio of tank, $S = H/R$; 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:

$$\omega_i = \frac{P}{H}\sqrt{\frac{E}{\rho_s}} \tag{10}$$

$$\omega_c = \sqrt{1.84\left(\frac{g}{R}\right)\tanh\left(1.84S\right)} \tag{11}$$

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

$$P = 0.037085 + 0.084302S - 0.05088S^2 + 0.012523S^3 - 0.0012S^4 \tag{12}$$

Equations used (Equations 3-12) for modeling of the tank and for value of t_h/R = 0.004 are selected from Panchal and Jangid [2]. For different ratios of t_h/R, similar equations can be resolved. The damping and stiffness, equivalent with the convective and impulsive masses are introduced as:

$$k_c = m_c \omega_c^2 \tag{13}$$

$$k_i = m_i \omega_i^2 \tag{14}$$

$$c_c = 2\xi_c m_c \omega_c \tag{15}$$

$$c_i = 2\xi_i m_i \omega_i \tag{16}$$

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:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} + \{F\} = -[M]\{r\}\ddot{u}_g \tag{17}$$

where $[K]$, $[M]$ and $[C]$ are stiffness matrix, mass matrix and damping matrix; $\{x\} = \{x_c, x_i, x_b\}^T$ is the relative displacement; $\{F\} = \{0, 0, F_x\}$ 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; F_x is the frictional force in the VRFPS;. T denotes transpose; $\ddot{u}_g$ is the earthquake ground acceleration and over dots indicate derivative with respect to time.

Force-deformation behavior 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 near-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 [2].

1. Aspect ratio, S is 1.85;
2. Height, H is 11.3 m;
3. The natural frequency of ω_i and ω_c is 5.963 and 0.273 Hz, respectively;
4. Ratio of damping of ξ_c and ξ_i is 0.5% and 2%, respectively;
5. Elastic modulus, E is 200 GPa;
6. Density of mass, ρ_s is 7900 kg/m^3 and
7. Thickness of wall of tank to radius ratio, t_h/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 (T_b = 1.418 sec and μ = 0.036) and (ii) FPS (T_b = 1.418 sec and μ = 0.036).

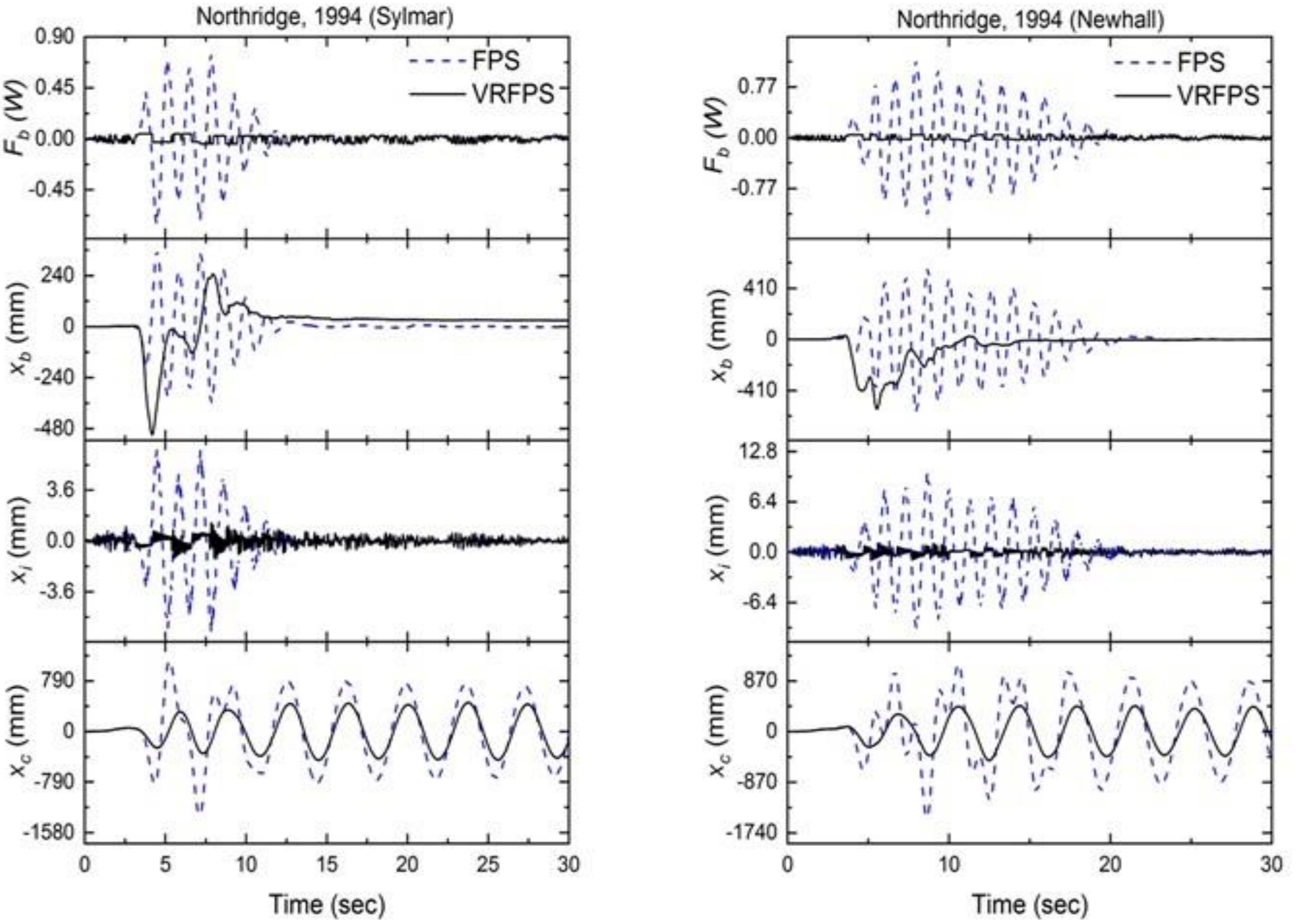

Figure 4 Time versus base shear, sloshing displacement, impulsive displacement and isolator displacement of slender tank isolated with FPS (T_b = 1.418 sec and μ = 0.036).and VRFPS (T_b = 1.418 sec and μ = 0.036)

Table 2 Comparison of Peak response quantities of FPS and VRFPS

Near-field ground motion	Base Isolator	Peak response quantities			
		F_b (W)	x_c (mm)	x_i (mm)	x_b (mm)
Imperial Valley, 1979 (El Centro Array #5)	FPS	0.31	1698.90	2.72	135.40
	VRFPS	0.05	598.83	1.19	1313.60
Imperial Valley, 1979 (El Centro Array #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

Figure 4 exhibits deviation of base-shear (F_b), displacement of isolator (x_b), impulsive displacement (x_i) and convective displacement (x_c) versus time. Figure 5 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 2.

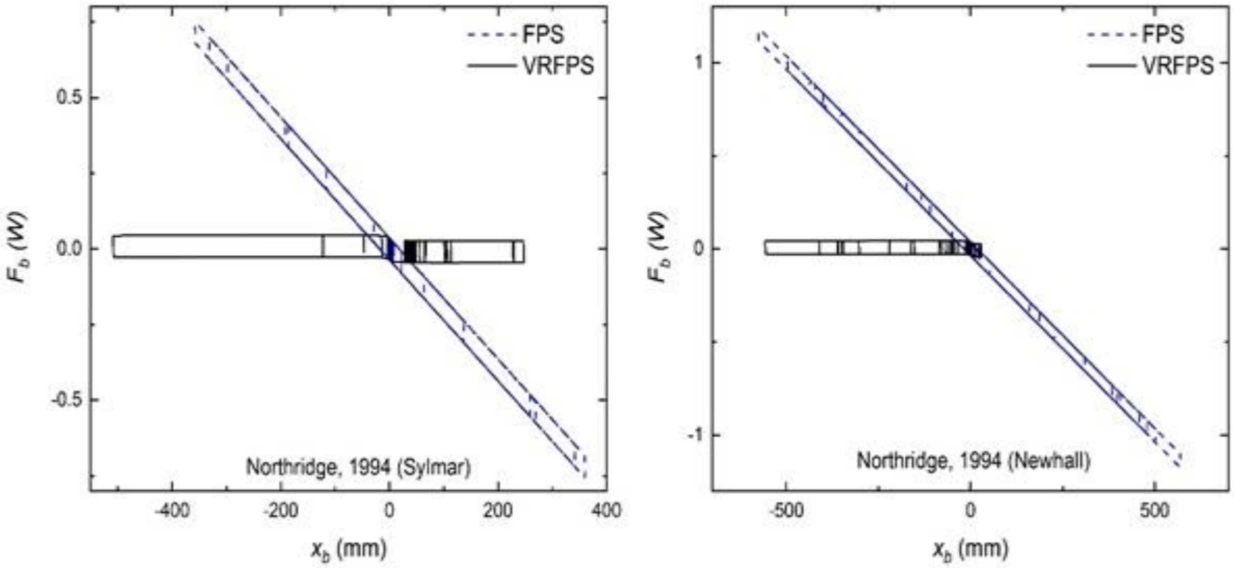

Figure 5 Comparison of Hysteresis Loop of Tank Isolated with VRFPS and FPS

IV. 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) Setting up VRFPS at the base of liquid storage slender tank is effective than use of same tank isolated by FPS.
2) The impulsive displacement, convective displacement and base shear are reduced in VRFPS as compared to that of FPS.
3) Isolator displacement is more in tank isolated with VRFPS as compared to that of FPS.
4) Residual displacement is more in tank equipped with VRFPS as compared to FPS.

REFERENCES

[1] Panchal, V. R., Soni, D. P. and Amin, J. A. (2010), 'Harmonic Response of VFPS-Isolated Liquid Storage Tanks', Proceedings of National Conference CRDCE10, SVIT, Vasad.

[2] Panchal, V. R. and Jangid, R. S. (2008), 'Variable friction pendulum system for seismic isolation of liquid storage tanks', *Nuclear Engineering and Design*, Vol. 238, pp. 1304-1315.

[3] Panchal, V. R. and Jangid, R. S. (2012), 'Behavior of liquid storage tanks with VCFPS under near-fault ground motions', Structure and Infrastructure Engineering, Vol. 8, pp. 71-88.

[4] Krishnamoorthy (2010), 'Seismic isolation of bridges using variable frequency and variable friction pendulum isolator system', *Structural Engineering International*, Vol. 20, pp. 178-184.

[5] Malhotra, P. K. (1997), 'New methods for seismic isolation of liquid storage tanks', *Earthquake Engineering and Structural Dynamics*, vol. 26, pp. 839-847.

[6] Tejani Keyurkumar R. and Panchal V. R. (2017), 'Modified Variable Friction Pendulum System for Seismic Isolation of Liquid Storage Steel Tanks', *International Journal of Emerging Technology and Advanced Engineering*, Vol. 7, pp. 192-197.

[7] Dhundhiyawala Hojefa H. and Panchal V. R. (2017), 'Seismic Response of Liquid Storage Steel Tank Isolated with Variable Frequency and Variable Friction Pendulum Isolator', *International Journal of Emerging Technology and Advanced Engineering*, Vol. 7, pp. 166-172.

[8] Krishnamoorthy (2015), 'Seismic control of continuous bridge using variable radius friction pendulum systems and viscous fluid dampers', *International Journal of Acoustics and Vibration*, Vol. 20, pp. 24-35.

[9] Haroun, M. A. (1983), 'Vibration studies and test of liquid storage tanks', *Earthquake Engineering and Structural Dynamics*, Vol. 11, pp. 179-206.

[10] Kim, N. S. and Lee, D. G. (1995), 'Pseudodynamic test for evaluation of seismic performance of base-isolated liquid storage tanks', *Engineering Structure*, Vol. 17, pp. 198-208.

[11] Fan, F. G., Ahmadi, G. and Tadjbakhsh, I. G. (1990), 'Multi-storey base-isolated building under a harmonic ground motion-Part II: sensitivity analysis', *Nuclear Engineering and Design*, Vol. 123, pp. 17-26.

[12] Jangid, R. S. and Kelly, J. M. (2001), 'Base isolation for near-fault motions', *Earthquake Engineering and Structural Dynamics*, Vol. 30, pp. 691-707.