Effect investigation of combination isolation system for liquid storage tank in different seismic levels

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SUMMARY:
The effect of combination isolation system for liquid storage tank, which insists of the friction pendulum bearings and viscous dampers, is investigated. For some liquid storage tanks, not only the isolation system should meet the performance of the very rare earthquake, but also tank should run regularly in the more frequent seismic events. However, sometimes the displacement of isolation layer still couldn't meet the requirement by using the friction pendulum only. A combination system of the friction pendulum bearing and viscous damper is most attractive to solve the problem as the base displacements may be substantially reduced by using viscous dampers. It is worth discussing to distribute the friction pendulum bearings and viscous dampers in different seismic levels and liquid levels to meet the different performance metrics. The theoretical analysis results show the low friction coefficient and some viscous damping may reduce the earthquake response in the different seismic levels.

Keyword: liquid storage tank; friction pendulum bearing; viscous damper; isolation; different seismic level

1. INTRODUCTION

The liquid storage tanks are commonly used in nuclear engineers, industries, liquid gas tank (LNG), water distribution systems, etc. Earthquake not only can cause direct damage to these structures, but also can cause secondary hazards like fires, environmental contamination due to the leak of hazardous chemicals or society problems. Lots of damages to liquid storage tanks have been reported such as the 1960 Chilean earthquake, the 1964 Alaska earthquake, the 1977 San Jan Argentina earthquake, the 1979 Imperial County earthquake, the 1980 Livermore earthquake, the 1983 Coalinga earthquake, the 1989 Loma Prieta earthquake, the 1994 Northridge earthquake, the 1999 Ji-Ji Taiwan earthquake and the 2001 Bhuj earthquake. The problem of liquid sloshing in moving or stationary containers remain great concern to aerospace, civil, nuclear engineers, physicists, designers of road tankers and ship tankers. This is a difficult mathematical problem to solve analytically, since the dynamic boundary condition at free surface is nonlinear and the position of the free surface varies with time in a manner not known a priori. So the equivalent mechanical models have been introduced to simplify the former problem. Housner [1] developed a mathematical model in which the mass of the liquid portion that accelerates with the tank is called as the ‘‘impulsive’’ and the mass of the liquid portion that causes sloshing motion of the free surface near the tank roof is called as the ‘‘convective’’. Haroun [2] modified the Housner's model and took into account the flexibility of the tank wall in the seismic analysis.

In recent years, the base isolation has been recognized as an effective method for the protection and retrofitting of an existing structure by the engineering profession. One of the alternate isolators is the friction pendulum system (FPS) of which sliding surface takes spherical shape [3]. Tsai [4] built an advanced analytical model and finite element formulations including local bending moment effects for the friction pendulum bearing. Shigeki and Fujita etc. [5] considered that the non rubber-type isolation systems can be applied to important industrial facilities, such as LNG tanks, boiler facilities and so on to refine their seismic reliabilities since the period of the isolation system is independent of the storage level. Montazar Rabiei and Malekzadeh [6] investigated the seismic response of isolated elevated liquid storage tanks with bilinear and tri-linear double concave friction bearings. It is demonstrated that the tri-linear double concave friction pendulum bearings, in comparison with bi-linear bearings, can significantly increase the response of isolated elevated liquid storage tanks. Emre Abali and Eren Uckan [7] found that FPS was effective in controlling the earthquake responses of the slender tank compared to the broad one when taking overturning moment and vertical acceleration on axial load variation at the bearings into consideration. As the isolation period or coefficient of friction increases, the bearing displacements increase and the base shears decrease. D.P. Soni and B. B. Mistry [8] found that the performance of the double variable frequency pendulum can be optimized by designing the top sliding surface with high initial stiffness relative to the bottom one and the coefficient of friction of both sliding surfaces to be equal for a slender tank whereas both surfaces should be designed with equal initial stiffness and coefficient of friction for a broad tank.

Over recent years, viscous type seismic energy absorption devices have been well developed and come into wide use all over the world, resulting in increase in use of such devices as oil dampers for high-rise buildings and seismically isolated buildings. The velocity-dependence devices have been employed by focusing on the fact that viscous type device is superior to displacement-dependence devices in that viscous type devices display damping effect even under small or medium earthquakes and the viscous type devices display stable performance for accumulated deformation. However, almost all the applications of viscous damper are usages to buildings and bridges. In traditional seismic design, isolation bearings with significant strength or damping capability are used to withstand the ground motions in very rare earthquake. But this design may reduce the isolation effect when the tank under more frequent earthquake. In fact, for some liquid storage tanks, not only the isolation system should meet the performance of the very rare earthquake, but also tank should run regularly in the more frequent seismic events. In this paper, we make use of viscous damper to storage tank combined with multiple friction pendulum system (MFPS) to build up a combination isolation system for different seismic levels.

2. THE MATHEMATICAL MODEL OF LIQUID STORAGE TANK

2.1. The Simplified Mechanical Model

The finite element model of a liquid storage tank with combination isolation system is extremely complicated and difficult to solve. Christovasilis and Whittaker [9] compared the analysis results of finite element model and the mechanical analogy of Haroun and Housner [1-2]. They concluded that the Housner's mechanical model could be used to the analysis and design of normal liquid storage tanks with or without isolation.

Figure **1** shows a schematic diagram of an equivalent mechanical model consisting of a rigid mass m_r moving in unison with the tank, and a convective mass, m_c, representing the fluid-structure interaction response of liquid containment of the cylindrical tank, the mass of the liquid distribute that accelerates with the tank is represented by the impulsive mass, m_i. Each modal mass is restrained to the tank wall by a spring, K_c and K_i. The damping property of convective and impulsive are represented by a dashpot, C_c and C_i. The liquid is considered as incompressible, inviscid and has irrotational flow. It is also assumed that there is sufficient freeboard so that sloshing waves do not impact the roof of the tank during the earthquake. The equivalent model should satisfy the following conditions: fluid total mass m_F ,

$$m_F = m_r + m_c + m_i \tag{1}$$

mass moment of inertia about the y-axis that passes through the center of mass of the solidified liquid I_f,

$$I_F = I_r + m_r h_r^2 + m_c h_c^2 + m_i h_i^2 \tag{2}$$

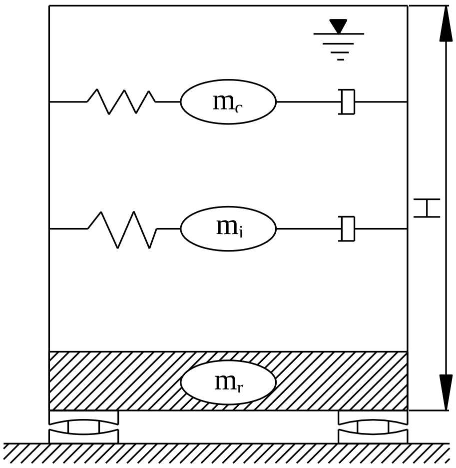


Figure 1. Mathematical model of a cylindrical liquid storage tank with MFPS

The natural frequencies of sloshing mass ω_c and impulsive mass ω_i are given by Haroun [2],

$$\omega_c = \sqrt{1.84(\frac{g}{R})\tanh(1.84S)} \tag{3}$$

$$\omega_i = \frac{P}{H}\sqrt{\frac{E}{\rho_s}} \tag{4}$$

In which, g is the acceleration due to gravity; E and ρ_s are the modulus of elasticity and density of tank wall, respectively. The non-dimensional parameters P are functions of the tank aspect ratio, $S = H / R$ and t_h / R, t_h is the thickness of the tank wall.

The equivalent stiffness and damping of the convective and impulsive mass are expressed as,

$$K_c = m_c \omega_c^2 \tag{5}$$

$$K_i = m_i \omega_i^2 \tag{6}$$

$$C_c = 2\zeta_c m_c \omega_c \tag{7}$$

$$C_i = 2\zeta_i m_i \omega_i \tag{8}$$

Where, ζ_c and ζ_i are the damping ratios of the sloshing and impulsive masses, respectively.

2.2. Governing Equations of Motion

The basic governing equations of the simplified liquid storage tank model subjected to earthquake excitation is expressed in the matrix form as,

$$[m]\{\ddot{x}\}+[c]\{\dot{x}\}+[k]\{x\}+\{F\}=-[m]\{r\}\ddot{u}_g \tag{9}$$

Where, $\{x\}=\{x_c,x_i,x_r\}^T$ is the displacement vector; $x_c=u_c-u_r$ the relative displacement of the convective mass; $x_c=u_c-u_r$ the relative displacement of the impulsive mass; $x_r=u_r-u_g$ the displacement of bearings relative to the ground; $\{F\}=\{0,0,F_r\}^T$ the resisting force vector; $[m]$, $[c]$ and $[k]$ the mass, damping and stiffness matrices respectively; $\{r\}=\{0,0,1\}^T$ the influence coefficient vector; $\ddot{u}_g$ the earthquake acceleration.

3. THE COMBINATION ISOLATION SYSTEM

The combination isolation system consists of the MFPS isolation system which to separate the earthquake energy input and viscous dampers which to dissipate the input energy. The two parts of this system have distinct function in different seismic levels. The Schematic diagram of the combination isolation system is shown in
Figure **2**.

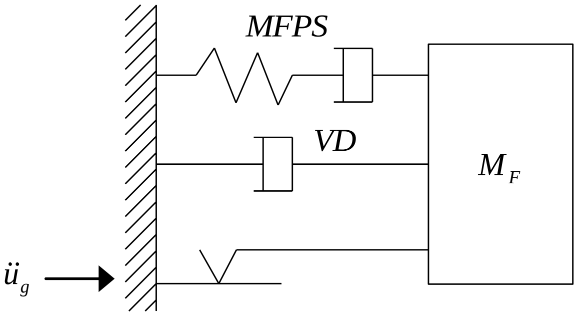


Figure 2. Schematic diagram of the combination isolation system

3.1. The MFPS Isolation System

Double concave friction pendulum (DCFP) which is one type of multiple friction pendulum systems, can be modelled by two single concave friction pendulum bearings connected in series [10]. The single concave friction pendulum bearings consist of an articulated slider and a concave surface which resisting forces are the sum of the restoring force due to the rise of the mass and the friction force between the slider and the concave surface.

In practice applications, it is usually treat the friction coefficient of the upper concave sliding surface μ_1 and the friction coefficient of the lower concave sliding surface μ_2 as the same value μ, neglecting the insignificant slider inertia force and the height of the bearings [11]. The equation of the force F is expressed by,

$$F=F_r+F_f=\frac{W}{R_1+R_2}u+\frac{R_1\mu W\,\mathrm{sgn}(\dot{u}_1)+R_2\mu W\,\mathrm{sgn}(\dot{u}_2)}{R_1+R_2}=K_b u+F_f \tag{10}$$

Where F is the resisting force, F_r and F_f are the resisting force of the upper and lower concave sliding surfaces, W is the load on the DCFP; R_1 and R_2 are the radius of curvature of the upper and lower concave sliding surfaces, u is the horizontal displacement, u_1 and u_2 are the horizontal displacements of the upper and lower concave sliding surfaces, and K_b is the horizontal stiffness due to the rise of the mass.

The isolation period is a function of the radius of curvature which of the sliding surface is independent of the mass. Such bearings are particularly important for the base isolation of industrial tanks since the isolation period is independent of the storage level. The isolation period T of DCFP is obtained by,

$$T = \sqrt{T_1^2 + T_2^2} = 2\pi\sqrt{\frac{R_1 + R_2}{g}} \tag{11}$$

T_1 and T_2 are the isolation periods of the upper and lower concave sliding surfaces.

3.2. Viscous Damper (VD)

The axial force developed by a viscous damper F_d is given by,

$$F_d = C_v \operatorname{sgn}(\dot{x})\left|\dot{x}\right|^{\alpha} \tag{12}$$

Where $\dot{x}$ the relative velocity between the two is ends of the damper, C_v the damper constant and α is a fractional power law exponent. If $\alpha = 1$ the damper is linear, the experienced force is proportional to the velocity between its ends. In order to reduce the force at high velocities α should be lower than 1. The value of the damping constant C_v and the exponent α are usually determined from regression analysis of damper force output from laboratory tests run at a constant frequency, but at variable displacement amplitude. The damping constant will be different if the test is run at a different frequency.

4. NUMERICAL STUDY FOR LIQUID STORAGE TANK

A parametric numerical study has been made to compute the seismic responses of liquid storage tanks with combination isolation system under different earthquake ground motions.

4.1. Dimensions of Liquid Storage Tank

The radius r of the steel inner tank is 40 m with a total height of 35 m which is fully anchored to a concrete slab. The liquid height of the tank H is 33 m and the density of the liquid ρ_1 in the inner tank is 480 kg/m^3. The tank wall is made of three courses, and 10 m, 10 m and 15 m high. The lower course is 25 mm thick, the middle course is 18 mm and the upper course is 12 mm thick. The modulus of elasticity and mass density of tank wall are taken as $E_s = 200MPa$ and $\rho_s = 7850 kg/m^3$, respectively.

The parameter of MFPS and viscous damper are listed in Table 1 and Table 2.

Table 1. Parameter of MFPS

Bearing capacity(ton)	$\mu_{\min}$	$\mu_{\max}$	R_1 (m)	R_2 (m)	T (s)	Amount
500	0.02	0.05-0.30	2	2	4	360

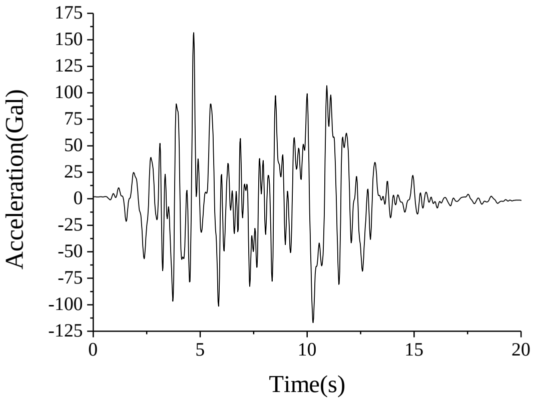
Table 2. Parameter of viscous damper

Capacity(ton)	α	C_v ($kN/(mm/s)^{\alpha}$)	F_d (kN)	Amount
150	0.3	310	1500	60

4.2. Seismic Response Input

Three artificial seismic waves have been chosen to computer the seismic response of the numerical investigation. Artificial seismic waves are generated by design response spectrum which is suitable for the local field conditions based on Eqn. (13). One of three used seismic waves is showed in Fig.3. Fig.4 shows the design response spectrum curves of the two time history, respectively. The acceleration summits of the analysis are 0.16 g for the operating basis earthquake (OBE) design, and 0.30 g for the safe shutdown earthquake (SSE).

$$\beta=\begin{cases}1 & 0s\le T\le 0.04s\\ 1+9.375(T-0.04) & 0.04s\le T\le 0.2\\ 2.5 & 0.20s\le T\le 0.9\\ 2.5(0.9/T)^{1.2} & 0.90s\le T\le 10s\end{cases} \tag{13}$$



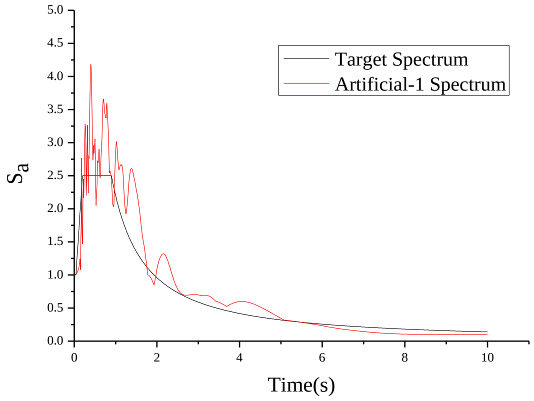


Figure 3. Artificial-1 artificial time history curve

Figure 4. Artificial-1 response spectrum curve

4.3. Analysis Results of the Model

In this numerical investigation, there are six different analysis conditions considered for the consideration of different friction coefficient. ST1 to ST5 is the liquid storage tank with maximum friction coefficient 0.05, 0.10, 0.15, 0.20 and 0.30. ST0 is the tank without MFPS.

4.3.1. Modal analysis results

The model detail information is shown in Table 3. The results fit will with the theory solution.

Table 3. Model information

Modes	Period(s)					
	ST0	ST1	ST2	ST3	ST4	ST5
Convective period	9.90	10.14	10.14	10.14	10.14	10.14
Impulsive period	0.47	3.24	3.24	3.24	3.24	3.24

4.3.2. Effects and optimum of friction coefficient

The mean maximum value of the analysis results are listed in Table 4 and Table 5. The effects of friction coefficient, on the response of different seismic time history, are plotted in Fig. 5 to Fig. 8. For the liquid storage tank, sloshing response is not quite sensitive to the friction coefficient in any case. But isolation displacement response is sensitive to the friction coefficient, are decreased gently from 0.10 to 0.30 in the SSE response. In the OBE case, compare with ST0, the base shear and impulsive acceleration are magnified with friction coefficient increasing. The reason for this phenomenon is that the external excitation of the OBE curve is smaller than the breakout friction when the friction coefficient is more than 0.10 approximately, so the advantage of the large friction coefficient cannot exert as the MFPS cannot slide in proper function. Yet for the SSE time history, the isolator play isolation role, and the base shear and impulsive acceleration are magnified are decreased. Because the base shear is greater than the breakout friction, so the MFPS can slide as expectation and the large friction coefficient can play a role in shocking absorption. From Fig. 7, the acceleration of impulsive mass and base shear increase as the friction coefficient increase not only in OBE curve, but also in SSE curve. So a friction coefficient balance and optimum between the displacement control and the acceleration decrease should be found. Shrimali and Jangid [12] pointed out that the optimum value of friction coefficient in the sliding systems depends on the properties of the tank, isolation system and the characteristics of the earthquake ground motion. From the analysis, the optimum of friction coefficient for this tank is about 0.10. If the value larger than 0.10, the displacement decrease is not obvious in OBE condition and will dramatically increase the acceleration response.

Table 4. Mean maximum value in OBE

Case	Technique indicator	Units	ST0	ST1	ST2	ST3	ST4	ST5
OBE	Isolation story displacement	mm	––––––	10	3	2	2	2
	Base shear	kN	147404	75648	134591	174118	234146	321810
	Impulsive mass acceleration	cm/s^2	184	115	169	195	208	216
	Convective mass acceleration	cm/s^2	8	8	8	8	8	8
	Impulsive mass displacement	mm	10	15	12	12	12	13
	Convective mass displacement	mm	202	200	202	202	202	202

Table 5. Mean maximum value in SSE

Case	Technique indicator	Units	ST0	ST1	ST2	ST3	ST4	ST5
SSE	Isolation story displacement	mm	––––––	117	54	29	17	6
	Base shear	kN	442178	116221	165850	229997	299173	436653
	Impulsive mass acceleration	cm/s^2	551	162	294	370	437	561
	Convective mass acceleration	cm/s^2	24	23	24	24	25	24
	Impulsive mass displacement	mm	30	123	64	43	37	34
	Convective mass displacement	mm	608	577	590	603	604	607

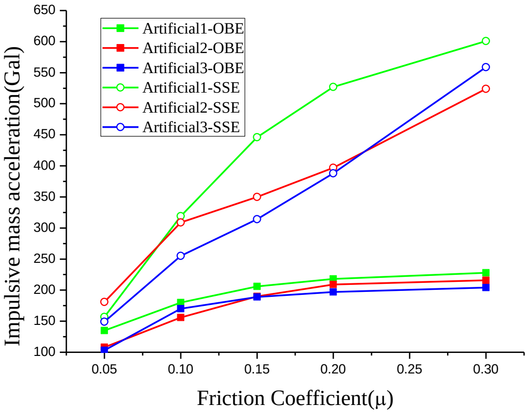


Figure 5. Impulsive acceleration

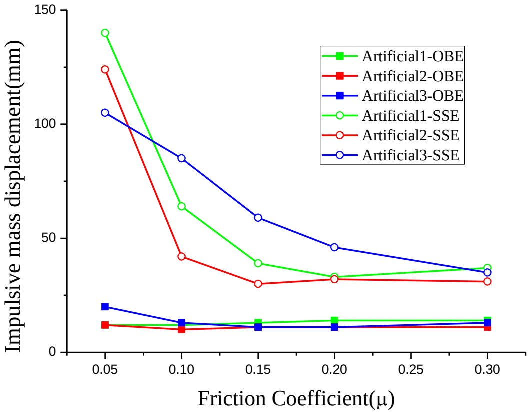
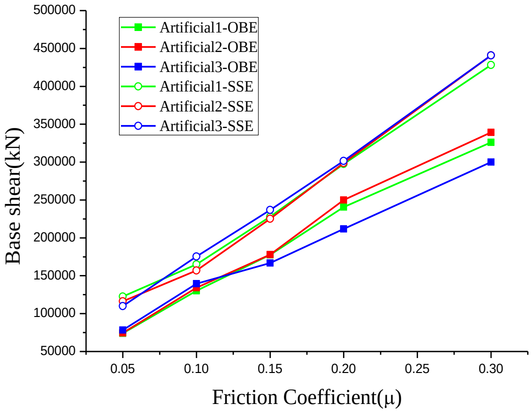


Figure 6. Impulsive displacement μ



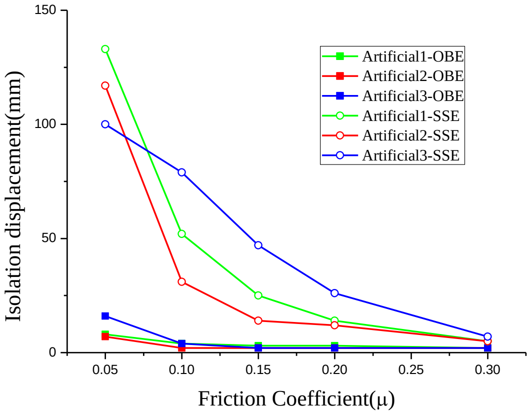
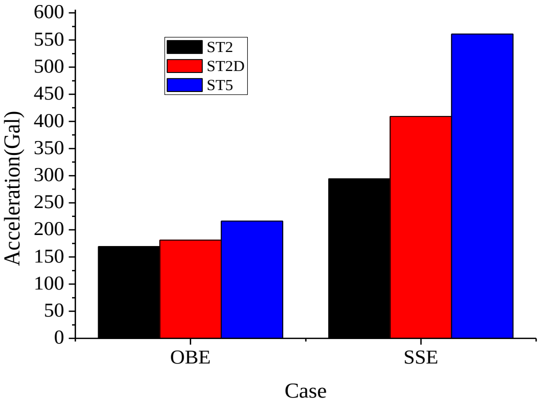


Figure 7. Base shear

Figure 8. Isolation displacement

4.3.3. Analysis results with viscous damper

From 4.3.2, the optimum friction coefficient 0.10 has been chosen. For low friction coefficient, the MFPS can effectively decrease the acceleration of impulsive mass in both OBE and SSE conditions, but the devices cannot control the displacement of isolation. In the combination isolation system, the viscous damper has been used to solve this problem and improve the seismic performance of the liquid storage tank. The maximum mean analysis values of the tank with viscous damper are shown in Fig. 9 to Fig. 12, including the maximum responses of the numerical models for the three earthquake ground motions, scaled for both OBE and SSE shaking. ST0 and ST2 are same to the former analysis; ST2D is the tank with viscous damper and friction coefficient 0.10 MFPS. The results indicate that the combination isolation system can effectively control the isolation displacement. The viscous damper and MFPS are complementally to each other.



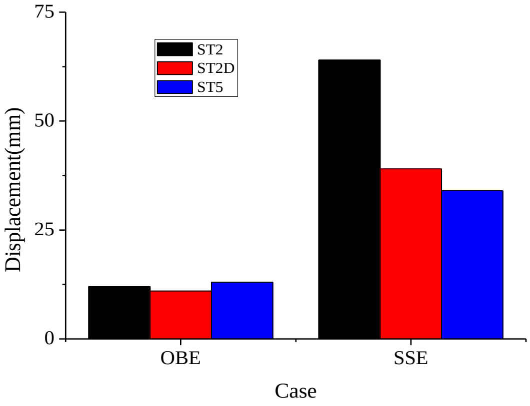


Figure 9. Impulsive mass acceleration

Figure 10. Impulsive mass displacement

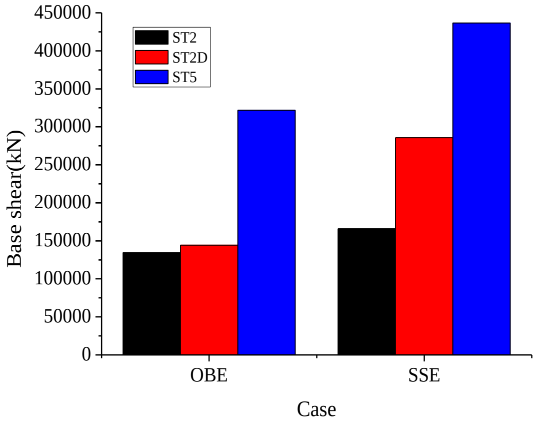


Figure 11. Base shear

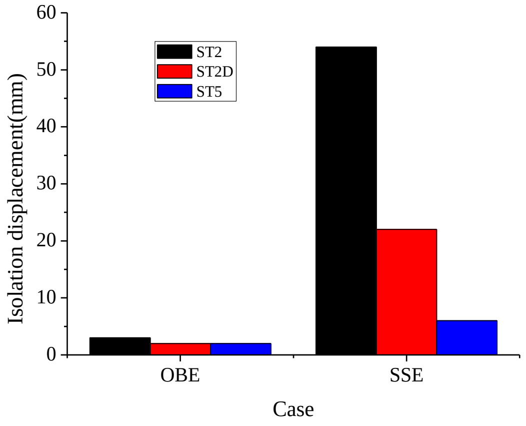


Figure 12. Isolation displacement

5. CONCLUSIONS

This paper brings forward a combination isolation system which constitute of MFPS and viscous dampers to decrease the seismic response of the liquid storage tanks. The tank is simplified by the model of Haroun and Housner for numerical investigation and seismic analysis. For the present study, the conclusions can be drawn below.

(1) The analysis results show that the combination isolation system is effective in controlling seismic response for liquid storage tanks.

(2) The modal period of the tanks with combination isolation system is much longer than that of the normal structure, which can change the periods of impulsive mass dramatically.

(3) The displacements of impulsive mass are not dramatically decreased as the friction coefficient increase in the OBE condition, though it can work in SSE condition. The optimum of the friction coefficient is about 0.10.

(4) The usage of viscous damper can effectively control the displacement of the tank with friction coefficient 0.10 MFPS. The MFPS and the viscous damper are complementally to each other.

ACKNOWLEDGEMENTS

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REFERENCES

Housner, G. W. (1990). Dynamic pressures on accelerated fluid containers, Boston, MA, USA.

Haroun, M. A. (1983). Vibration studies and tests of liquid storage tanks. *Earthquake Engineering & Structural Dynamics* **11: 3**,179-206.

Fenz, D. M. and Constantinou, M. C. (2008). Spherical sliding isolation bearings with adaptive behavior: Theory. *Earthquake Engineering and Structural Dynamics* **37:2**,163-183.

Tsai, C. S. (1997). Finite element formulations for friction pendulum seismic isolation bearings. *International Journal for Numerical Methods in Engineering* **40:1**,29-49.

Shigeki, O., Fujita, S. and Ikenaga, M. (2004). Motion analysis of pendulum-type isolation systems during earthquakes dynamic test. *Transactions of the ASME* **126:1**,34-45.

Rabiei, M. and Malekzadeh, M. (2009). Evaluation of seismic response of isolated elevated liquid storage tanks with bilinear and tri-linear double concave friction pendulum bearings. *11th World Conference on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures*. **vol 1:**140-155.

Abali, E. and Uckan, E. (2010). Parametric analysis of liquid storage tanks base isolated by curved surface sliding bearings. *Soil Dynamics and Earthquake Engineering* **30:1**,21-31.

Soni, D. P., Mistry B. B. and Panchal, V. R. (2011). Double variable frequency pendulum isolator for seismic isolation of liquid storage tanks. *Nuclear Engineering and design* **241:6**,700-713.

Christovasilis I. P. and Whittaker A. S. (2008). Seismic analysis of conventional and isolated LNG tanks using mechanical analogs. *Earthquake Spectra* **24:3**,599-616.

Fenz D. M. and Constantinou M. C. (2006). Behaviour of the double concave Friction Pendulum bearing. *Earthquake Engineering & Structural Dynamics* **35:2**,1403-1424.

Ruifu Z., Dagen W. and Xiaosong R. (2011). Seismic analysis of a LNG storage tank isolated by a multiple friction pendulum system *Earthquake Engineering and Engineering Vibration* **10:3**,253-262.

Shrimali M. K. and Jangid R. S. (2002). Seismic response of liquid storage tanks isolated by sliding bearings. *Engineering Structures* **24:1**,909-921.