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Parametric Analysis of Liquid Storage Tanks Base Isolated by Double Concave Friction Pendulum System

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***Abstract*—In recent years using of base isolation systems due to improve in seismic performance of liquid storage tank was expanded. In this paper, the seismic behavior of the Liquid storage tank supported on DCFP isolation system under seven ground motions was investigated. The effects of essential parameters including slender of tank, period and coefficient of friction of the isolation system were investigated. In the parametric study, mass of liquid was idealized as convective mass, impulsive mass and rigid mass. In this analysis simplified three-degree freedom model to represent flexural and rocking vibrations of the tank was used. The results represent increasing of the slender ratio increases base shear and isolators forces and affects slightly on drift and isolation displacement. It is also shown that the period of isolators affects significantly on relative displacement of convective mass and isolators are remarkable.**

***Keywords*—Double Concave Friction Pendulum, Dynamic analysis, slender ratio**

I. Introduction

The liquid storage tanks are most commonly used in water distribution systems, industries and nuclear power plants for the storage of drinking water, toxic and flammable liquid and nuclear fuel, respectively. Earthquakes can cause damage to industrial liquid storage tanks resulting in loss of functionality, fires or environmental contamination due to the leakage of hazardous chemicals. Past earthquakes, 1989 Loma Prieta, 1994 Northridge, Ji-Ji Taiwan and 1999 Kocaeli, caused significant damages is storage tanks in the form of cracking at the corner of the bottom plate and compression buckling of tank wall (elephant foot buckling) due to uplift, sliding of the base, anchorage failure, sloshing damage around the roof, failure of piping systems and plastic deformation of base plate [1], [2]. Consequently, protection of liquid storage tanks against severe seismic has become important issue. For over three decades, one of the effective ways to reduce seismic effects on liquid storage tanks has been isolation systems. The main concept in isolation is to increase the fundamental period of structural and the other purpose is to provide an additional means of energy dissipation, thereby, reducing the transmitted acceleration into the superstructure. Location of isolation system is most commonly between structure and ground, used generally in the horizontal direction, in order to reduce the transmission of the earthquake motion to the structure.

A number of authors have discussed the effectiveness of base isolation for aseismic design of liquid storage tanks. Malhotra investigated the seismic response of base-isolated tanks and found that isolation was effective in reducing the response of the tanks compare to traditional fixed base tank [3]. Wang et al. studied the seismic isolation of rigid cylindrical ground tanks using friction pendulum bearings (FPS) and mentioned several benefits of FPS in this structure [4]. Shrimali and Jangid surveyed the seismic response of liquid storage tanks isolated by lead–rubber bearings under two horizontal components of earthquake and concluded that the seismic response of isolated tanks is insensitive to interaction effect of the bearing forces [5]. Shrimali and Jangid also studied the response of liquid storage ground tanks isolated by sliding systems considering the influence of parametric variation and found that the sliding systems were effective in reducing the response [6]. Seleemah studied the performance of various degrees of frictional coefficients of sliding isolation systems due to short and long-term contamination of the sliding interfaces [7]. Cho et al. investigated the seismic response of base-isolated liquid storage tanks considering fluid–structure–soil interaction using a coupling method that combines the finite elements and boundary elements [8]. Shekari et al. studied seismically isolated cylindrical liquid storage tanks using a coupled boundary element-finite element to represent the fluid–structure interaction [9]. Abalı and Uckan studied both broad and slender tanks isolated by FPS bearings. They utilized Haroun and Housner’s (1981) model [10] to represent the fluid. Moreover, they took the effects of overturning moments and vertical accelerations on the variation of the axial load of the bearings into consideration [11].

This paper investigated the earthquake performance of liquid storage tanks base isolated by double concave friction pendulum (DCFP) bearings and further focus on the effects of variety of essential parameters such as slender of tank, effective period and friction coefficient of bearing. In order to model fluid of liquid storage tank, Haroun and Housner’s (1981) model [10] have been used. Housner 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’’ [12]. Haroun modified the Housner's model and took in to account the flexibility of the tank wall in the seismic analysis [10], [13]. In this study, MATLAB Code was developed to analysis liquid storage tanks and it has been verified by SAP2000 computer software.

II. Structural Model of Isolated Liquid Storage Tank

With regarding to obtained results from Christovasilis and Whittaker study; it concluded that the Housner's [13] mechanical analog could be used with confidence for the preliminary analysis and design of conventional and isolated tanks [14]. The mathematical model used in the present study is based on the Haroun and Housner's spring mass model in which the horizontal flexibility of the tank is considered [10].

As shown in Fig. 1 the fluid–structure interaction response of liquid containment of the liquid storage tank is represented by the convective mass, mc, the mass of the liquid portion that accelerates with the tank is represented by the ‘‘impulsive mass’’ mi, and the mass of the liquid which moves with the rigid base is referred as m_r. The convective and impulsive masses are connected to the tank wall by springs having stiffness of $k_c = m_c \omega_c^2$ and $k_i = m_i \omega_i^2$, respectively. The damping constant of the convective and impulsive masses are denoted as $c_c = 2m_c \zeta_c \omega_c$ and $c_i = 2m_i \zeta_i \omega_i$, respectively. The parameters ω_c, ω_i, ζ_c, and ζ_i denote the convective and impulsive frequencies and damping of the liquid mass respectively. The self-weight of the tank is neglected since it is very small mass compared to the effective weight of the liquid. The liquid is considered as incompressible and has non-rotational flow. It is also considered that there is sufficient free board so that sloshing waves do not impact the roof of the tank during the earthquake. The geometrical parameters of the tanks considered are liquid height, H; radius, R and average thickness of tank wall, t_h: The various masses, convective and impulsive frequencies of the liquid mass are expressed as:

$$m_c = m\gamma_c \,. \tag{1}$$

$$m_i = m\gamma_i \,. \tag{2}$$

$$m_r = m\gamma_r \,. \tag{3}$$

$$m = \pi R^2 H \rho_w \,. \tag{4}$$

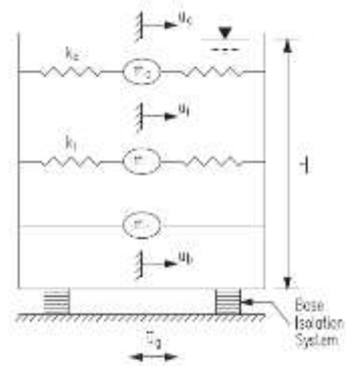

Figure 1. Three-degree of freedom of liquid storage tank

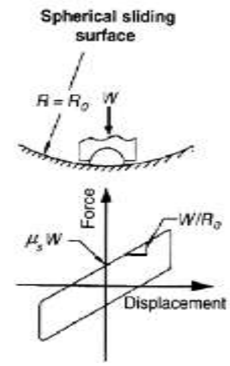

Figure 2. Model of Isolation System (FPS)

$$\omega_i = \frac{P}{H}\sqrt{\frac{E}{\rho_s}} \,. \tag{5}$$

$$\omega_c = \sqrt{1.84\frac{g}{R}\tanh(1.84S)} \,. \tag{6}$$

Where, γ_c, γ_i and γ_r are the mass ratios related to convective, impulsive and rigid mass of the liquid mass, respectively; ρ_w is the mass density of the liquid mass; E and ρ_s are the modulus of elasticity and density of the tank wall, respectively; $S = H/R$ is the aspect ratio of the tank; g is the acceleration due to gravity and P is a non-dimension parameter. The parameters, γ_c, γ_i, γ_r and P are functions of the aspect ratio of the tank, S and t_h/R. For t_h/R = 0:004; the above parameters are expressed by:

$$\begin{Bmatrix} \gamma_c \\ \gamma_i \\ \gamma_r \\ P \end{Bmatrix} = \begin{bmatrix} 1.01327 & -0.8757 & 0.35708 & -0.06692 & 0.00439 \\ -0.15467 & 1.21716 & -0.62839 & 0.14434 & -0.0125 \\ 0.01599 & 0.86356 & -0.30941 & 0.04083 & 0 \\ 0.037085 & 0.084302 & -0.05088 & 0.012523 & -0.0012 \end{bmatrix} \begin{Bmatrix} 1 \\ S \\ S^2 \\ S^3 \\ S^4 \end{Bmatrix} . \tag{7}$$

III. The double concave friction pendulum system

The double concave Friction Pendulum (DCFP) bearing is an adaptation of the well-known single concave Friction Pendulum bearing. The displacement capacity of a DCFP bearing is approximately twice that of a traditional FPS bearing with the same plan dimensions. When surface with equal friction are used, there is simultaneous sliding on both surfaces over the entire range of motion, regardless of the radii of curvature. The hysteretic behavior is rigid-linear like that of traditional FPS bearing [15]. Fig. 2 shows an idealized force–displacement loop of a traditional FPS bearing. The model is characterized by six parameters, namely, the radius of bearing concave surface curvature Rb, maximum coefficient of sliding friction at almost zero pressure $f_{\max}$, minimum coefficient of sliding friction $f_{\min}$, constant which controls the transition of coefficient of sliding friction from maximum to minimum, a; yield displacement, Dy; and initial normal force at the sliding interface, N. The coefficient of sliding friction is modeled by the equation suggested by Tsopelas et al. as following:

$$\mu = f_{\max} - (f_{\max} - f_{\min})\exp(a|\dot{u}|). \qquad (8)$$

Where, $\dot{u}$ is the velocity of sliding. Values of parameters $f_{\max}$, $f_{\min}$ and a have been reported [16].

IV. Governing equations of motion

The basic equations of three-degrees of freedom of motion of isolated liquid storage tank subjected to unidirectional ground motion are expressed in the matrix form as:

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

where, $\{x\} = \{x_c \quad x_i \quad x_b\}^T$ is the displacement vector; xc=uc-ub is the relative displacement of the convective mass; xi=ui-ub is the relative displacement of the impulsive mass; xb=ub-ug is the displacement of bearings relative to the ground; $\{F\} = \{0 \quad 0 \quad F_b\}^T$ is the resisting force vector; $[m]$, $[c]$, and $[k]$ are the mass, damping and stiffness matrices respectively; $\{r\} = \{0 \quad 0 \quad 1\}^T$ is the influence coefficient vector; Fb is the resisting force of the isolation system; $\ddot{u}_g$ is the ground motion acceleration and M is the total effective mass of the isolated liquid storage tank.

V. Parametric study

In the present study, seismic response of isolated liquid storage tank supported on DCFP bearing is investigated under unidirectional excitation of seven near-field earthquake ground motions. The specifications of earthquakes such as station, M_W and PGA are represented in Table I.

The response of liquid storage tank isolated by DCFP is investigated respect to following parameters: period of isolation system (Tb), slender ratio of tank (S) and friction coefficient of bearing (μ). The ranges of these parameters were selected carefully in order to depict the effects of them. Some parameters also were considered to be constant. The modulus of elasticity and mass density of tank wall are taken as E=200 MPa and ρ_s=7900 kg/m3, respectively. The radius of liquid storage tank and the thickness of wall are kept R=1 m and th=0.004 m, respectively.

TABLE I. LIST OF THE GROUND MOTIONS USED

Earthquake name	Station Name	M_W	Year	PGA (g)
Duzce, Turkey	Lamont	7.3	1999	0.134
Northridge	LA-Baldwin Hills	6.7	1994	0.239
Trinidad, California	Rio Dell Overpass, FF	7.2	1980	0.147
Victoria, Mexico	Cerro Prieto	6.4	1980	0.621
Hollister	SAGO South-Surface	5.5	1986	0.09
Imperial Valley	Parachute Test Site	6.9	1979	0.204
Morgan Hill	Carralitos	6.1	1984	0.109

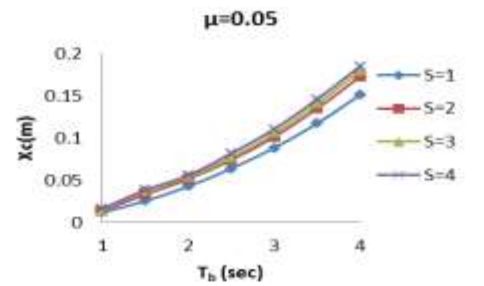

Figure 3. The variation of relative displacement of convective mass w.r.t period of isolation system

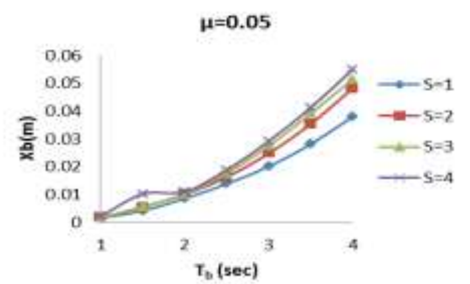

Figure 4. The variation of displacement of bearings relative to the ground w.r.t period of isolation system

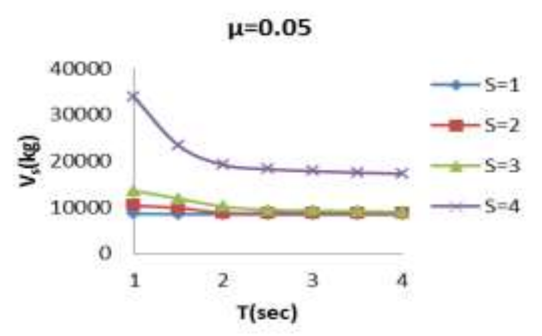

Figure 5. The variation of base shear w.r.t period of isolation system

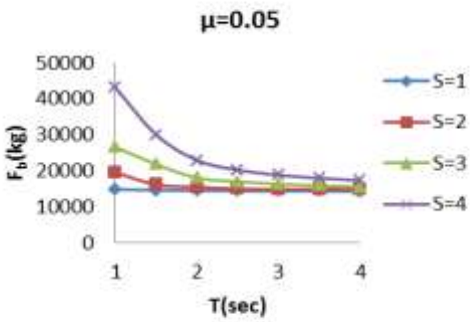

Figure 6. The variation of resisting force of the isolation system w.r.t period of isolation system

A. *Effect of period of isolation system*

Period of isolation system (Tb) is one of the most important parameters which have remarkable effects on isolated structures. Fig. 3 to Fig. 6 are plotted to show the effects of Tb on the Vs, Fb, xc and xb of isolated liquid storage tank under seven unidirectional excitation ground motions. The isolator period is varied from Tb=1 to Tb=4. The study has been done for different amount of μ and S. μ is varied from 0.5 to 2. And S supposed to be from 1 to 4. From figures 3 and 4, it can be seen that, as expected, increase of Tb causes xc and xb to increase remarkable because period is directly proportional to stiffness. Whereas the mass remained unchanged, increase of period makes the stiffness to decrease, consequently; displacement will increase. For example in isolated liquid storage tank with μ=0.05, with increasing in Tb from 1 to 4, the amount of xc and xb increase 91% and 96% at most, respectively. It is noticed that the effect of slender ratio of tank can be negligible.

Fig. 5 and Fig. 6 show the effects of Tb on the force parameters. When Tb increases, Fb and Vs are decrease due to the stiffness reduction. With increase in S, reduction rate of Fb and Vs increase. In isolated liquid storage tank with μ=0.05 and S=1, increasing in Tb from 1 to 4 leads Fb to reduction approximately 10 percent, but for one with S=4, percent of reduction is about 57, Fig. 5.

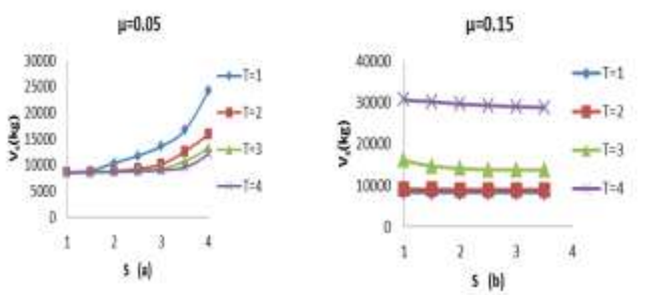

Figure 7. The variation of base shear w.r.t slender ratio of tank: a. μ=0.05, b. μ=0.15

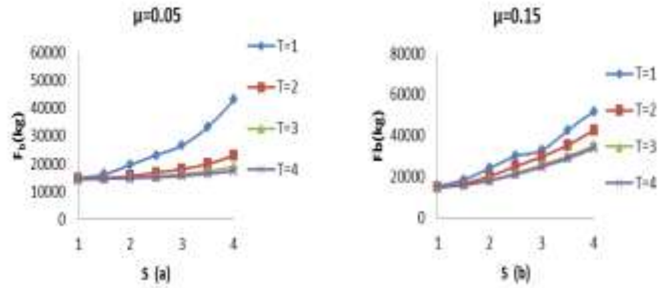

Figure 8. The variation of resisting force of the isolation system w.r.t slender ratio of tank: a. μ=0.05, b. μ=0.15

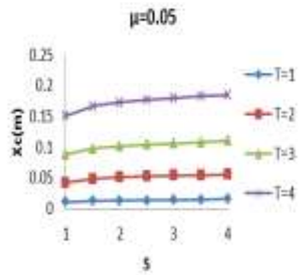

Figure 9. The variation of relative displacement of convective mass w.r.t slender ratio of tank

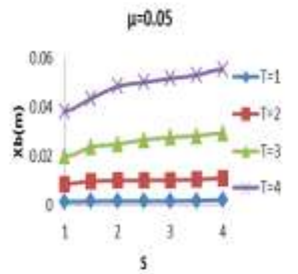

Figure 10. The variation of displacement of bearings relative to the ground w.r.t slender ratio of tank

B. *Effect of slender ratio of tank*

Slender ratio of tank is the important parameter in liquid storage tank. In order to evaluate the effects of slender ratio of tank on the seismic response of structure, Fig. 7 to Fig. 10 are presented for μ =0.05 and μ =0.15. As it is observed in Fig. 7 and Fig. 8, increase of slender ratio cause Fb and VS to increase and its effectiveness is more in liquid storage tank with short period. Fig. 8 depicts that with increase in μ, the effect of S on the Fb of the tank with longer period, is increases. Whereas effect of S decreases on VS with increase in the amount of μ from 0.05 to 0.15. With regard to Fig. 9 and Fig. 10, effect of S can be negligible on relative displacement of the impulsive mass and the displacement of bearings relative to the ground. As a result, broad tank have an appropriate seismic behavior in short period isolated liquid storage tank in comparison to slender tank. But in long period one the seismic performance of slender and broad tank is equivalent.

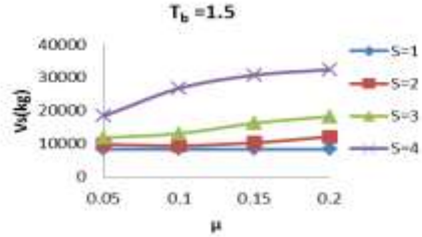

Figure 11. The variation of base shear w.r.t friction coefficient

C. *Effect of Friction coefficient of isolator*

In friction pendulum isolation system, friction coefficient is so more significant parameter. The effects of friction coefficient of isolation system in isolated liquid storage tank are exhibited in Fig. 11 to Fig. 14. Fig. 11 and Fig. 12 reveals that μ have a significant effect on the V_b and F_b of the slender tank. Decrease of slender reduces the effect of μ. In isolated liquid storage tank with S=2, increase of μ makes 48% growth in F_b, whereas; for the tank with S=4 this growth is about 61%. As it is demonstrated in Fig. 13 and Fig. 14, Increase of μ cause x_c and x_b to decrease. It is noticed that the rate of reduction in x_b with respect to x_c is faster. For instance with increasing μ from 0.5 to 2, x_c decrease about 37% mostly, while x_b decrease about 73% at most.

VI. Conclusion

This study has investigated the effects of parameters such as slender ratio of tank, isolation period and friction coefficient of bearing on seismic behavior of isolated liquid storage tank supported on DCFP system. In order to considered fluid–structure interaction response of liquid, three-degree freedom of isolated liquid storage tank have been used including the convective mass, impulsive mass and the mass of the liquid which moves with the rigid base. Analysis was performed under seven unidirectional excitation ground motions.

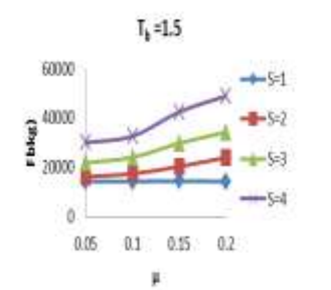

Figure 12. The variation of resisting force of the isolation system w.r.t friction coefficient

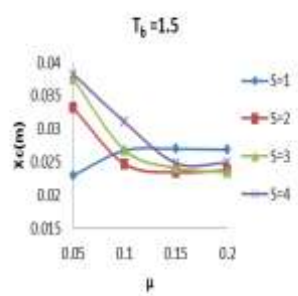

Figure 13. The variation of relative displacement of convective mass w.r.t friction coefficient

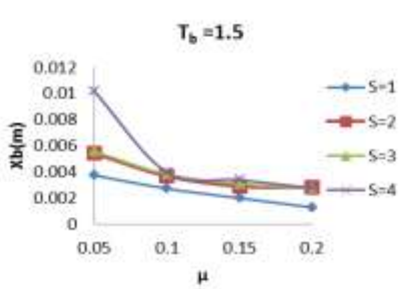

Figure 14. The variation of displacement of bearings relative to the ground w.r.t friction coefficient

From the results of the present study, the following conclusions can be stated:

Increase of isolation period causes F_b and V_s to decrease; it also causes x_c and x_b to increase in isolated liquid storage tank.

Increase in the friction coefficient of DCFP system, dissipates more seismic energy, therefore; displacement reduces and base shear and isolator force increase.

To improve effectiveness of DCFP system in slender tank, isolation period have to increases. It's make seismic behavior of slender tank as well as broad tank.

Slender ratio of tank has an insignificant effect of displacement of isolated liquid storage tank. Thought, its effect on F_b and V_s are significant in short period tank.

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