Seismic Response of Connected Liquid Tanks with MR Dampers

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SUMMARY:

The liquid storage tanks are life line structures, since they have wide applications for industries such as chemical storage nuclear power plants and water supply etc. Therefore, safety of such structure is vital against natural hazard. This has attracted considerable attention of researchers to safe guard against possible earthquake for increasing vulnerability of the life line structures The liquid storage tanks are very important since there failure due to earthquake leads to catastrophic effect (San Juan earthquake, 1977 and Alska earthquake, 1964). From the past studies it has been observed that damages to tanks are mainly due to stretching of ties, buckling of struts, tearing, warping and rupture of gussets plates (steel tanks) at end connections, failure of accessories, liquefaction of foundation, piping system, cat-walk and total collapse. It was also observed that during Livermore, California, 1982 (Niwa and Clough) that failure of tanks took place due to collision of adjacent tanks. The collision of the tanks leads to damages to piping system as well as cat-walk. The seismic behavior of elevated liquid storage tanks is highly complex due to liquid structure-interaction leading to a tedious design procedure from seismic resistant design point of view. In general, there are three methods to protect the structure against the natural hazard, namely conventional resistance method, passive control and semi-active control. The conventional method involves strengthening of the structure by means of increasing the size of different component members whereby increase stiffness of the structure attracted more seismic forces. The passive control method is also referred as isolation which involves the implanting the isolation devices at base of the structure to decouple the structure from ground and increases the fundamental period of structure whereby the seismic forces transmitted to the structure are reduced significantly. The semi-active control method needs very less power to get activated the system during the earthquake.

Keywords: *MR dampers, seismic response of connected tanks, earthquake.*

1. INTRODUCTION

The behavior of liquid storage tank is very complex under seismic excitation due to interaction between fluid and structure. The various investigators have carried out the performance of ground supported tanks (Housner, 1957, 1963, Nemarks et al. 1972, Epistein et al. 1976). In addition to this there are extensive studies on performance of ground supported isolated liquid storage tanks (Kelly and Chalhoub, 1990; Kim and Lee, 1995; Malhotra, 1997; Shrimali and Jangid, 2002). The performance of elevated liquid tanks also carried out by various researchers to understand the seismic behavior (Bleiman and Kim 1993; Shenton III and Hampton 1999; Shrimali and Jangid, 2003).

The considerable attention is given to safe guard the structure against earthquakes forces. The earthquake damages have been due to stretching of ties, buckling of struts, tearing, warping and rupture of gussets plates (steel tanks) at end connections, failure of accessories, liquefaction of foundation and total collapse. There are aseismic techniques by which protection against possible earthquakes is ensured referred as Control methods. The control methods can be broadly categorized as: (i) passive control, (ii) active control, and (iv) semi-active control. The passive control method is also referred as isolation. The conventional technique involves the strengthening of the structure by means of increasing the size of different component members whereby the enhanced stiffness of the structure attracted more earthquake forces. The isolation approach involves the implanting the isolation devices at the base of the structure to decouple the structure from ground and increases the fundamental period of structure. The semi-active technique is the recent one in which the safety of structure is ensured by implanting the semi-active devices at identified locations in the structure to control the response of the structure. Some of the most common types of semi-active devices are: stiffness control devices, electrorheological (ER) dampers, magnetorheological (MR) dampers, friction control devices, fluid viscous dampers, tuned mass dampers and tuned liquid dampers.

In recent years, considerable attention has been paid for the development of structural control and it has become an important part of designing new structures and retrofitting existing structures to resists the earthquake and wind. There have been significant efforts by researchers to investigate the possibilities of using various control methods to mitigate earthquake hazard for different structures (Datta and Jangid 1997, Soong 1996, Spencer et al. 1997, Housner et al. 1997, Soong and Spencer 2002; Shrimali and Jangid 2002, Spencer and Nagarajaiah et al 2003).

1.1 Magnetorheological (MR) dampers

MR dampers are essentially magnetic analogs of ER dampers. Qualitatively, the behaviour of the two types of types of dampers is very similar except that the control effect is governed by the application of electric field in one case and by magnetic field in other. MR damper typically consists of a hydraulic cylinder containing micron-sized, magnetically polarizable particles suspended within a fluid (usually oil). MR fluid behaviour is controlled by subjecting the fluid to a magnetic field in the absence of a magnetic field, the MR fluid flows freely while in the presence of a magnetic field the fluid behaves as a semi-solid.

1.2 Semi-active control

In recent years, semi-active control of structures has attracted the attention of many researchers, an excellent state of the art review of this has been provided by Symans and Constantinou (1999). The close attention received in this area in recent years can be contributed to the fact that semi-active control devices offer the adaptability of active control devices without requiring the associated large power sources. In fact many can operate on battery power, which is critical during seismic events when the main power source to the structure may fail.

The application of semi-active devices have been explored by various investigators such as Dyke et al. (1996) proposed a clipped-optimal control strategy based on acceleration feedback for controlling MR dampers to reduce the structural responses due to seismic loads. The effectiveness of proposed control algorithm and the usefulness of MR dampers for structural response reduction were demonstrated through a numerical example of three story model structure. The authors used Modified Bouc-Wen model (Spencer, 1997) of MR damper to accurately predict the dynamic behaviour of the damper.

Spencer et al. (1997) proposed a model to predict the dynamic behaviour of MR damper, and demonstrated that the MR damper has applications over a wide range of operating conditions and is adequate for control design and analysis. Sadek et al. (1998) investigated the effectiveness of variable dampers for seismic response control. It was confirmed that the semi-active damper system applied in the actual building was effective in controlling the response of the building during a severe earthquake.

Djajakesukma et al. (2002) studied a semi-active stiffness damper (SASD) in two building models of five-storey (with different first natural frequencies) under four benchmark earthquake records. Zhang and Iwan (2002b) assessed the performance of active interaction control (AIC) algorithms within the context of two realistic building models. Kurata et al. (2002) studied the effectiveness of the semi-active structural control technique in high rise buildings. Nagarajaiah and Narasimhan (2007) developed a new semiactive device, namely, semiactive independently variable damper (SAIVD), the device along with H_∞ controller shown to be effective in response reduction of smart base isolated buildings subjected to near-field earthquake. The results showed that the devices are most effective when they have low damping ratio and the excitation frequency can be tracked. In all, the performance of the semi-active was investigated for building and other structures. But so far the application has not been explored for liquid storage tanks.

Therefore, in this paper, seismic response of dissimilar ground anchored liquid storage tanks connected with MR Dampers has been investigated under real ground motion. In addition to this performance of unconnected tanks is also compared with connected tanks for wide range of the liquid storage tanks. This will cover both slender as well as broad tanks. The result indicates that the due to coupling the displacement of sloshing mass in marginally increased, however influence on impulsive mass in very minimal.

2. STRUCTURAL MODEL OF COUPLED LIQUID STORAGE TANKS

The structural model of connected liquid storage tanks anchored to the ground is shown in the Figure 1. The tank liquid has been modeled as two lumped mass model (Housner 1963). The top liquid mass is referred as convective/sloshing mass, m_c and the bottom mass is referred as impulsive mass which also known as rigid mass, m_i moves along with tank wall (Kim and Lee, 1995; Malhotra, 1997). The convective and impulsive masses are connected to the tank wall by corresponding equivalent springs having stiffness k_c and k_i, respectively. The damping constant of the convective and impulsive masses are c_c and c_i, respectively. The degrees-of-freedoms are associated with convective mass and impulsive mass under a uni-directional excitation. They are u_c and u_i, which denote the absolute displacements of convective mass, impulsive mass, respectively.

2.1. Governing equations of motion

The governing equations of motion of the coupled system in matrix form is expressed as:

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}= [D]\{f_m\}-[M][r]\{\ddot{u}_g\} \tag{2.1.1}$$

where, M, C, and K are mass, damping, stiffness matrices of the combined system respectively; f_m is the vector consisting of forces in the MR dampers; D is the damper location matrix; u is the relative displacement vector with respect to the ground a r is a influence coefficient vector which contains elements equal to unity; and $\ddot{u}_g$ is the earthquake ground acceleration. The matrices M, K and C are for the combined system are explicitly defined as

$$\underset{(2n+m,2n+m)}{M}=\begin{bmatrix} \underset{(n+m,n+m)}{[M_1]} & \underset{(n+m,n)}{[O_1]} \\ \underset{(n,n+m)}{[O_2]} & \underset{(n,n)}{[M_2]} \end{bmatrix};\ \underset{(2n+m,2n+m)}{K}=\begin{bmatrix} \underset{(n+m,n+m)}{[K_1]} & \underset{(n+m,n)}{[O_1]} \\ \underset{(n,n+m)}{[O_2]} & \underset{(n,n)}{[K_2]} \end{bmatrix};\ \underset{(2n+m,2n+m)}{C}=\begin{bmatrix} \underset{(n+m,n+m)}{[C_1]} & \underset{(n+m,n)}{[O_1]} \\ \underset{(n,n+m)}{[O_2]} & \underset{(n,n)}{[C_2]} \end{bmatrix} \tag{2.1.2}$$

where, $[M_1]$, $[M_2]$; $[K_1]$, $[K_2]$; $[C_1]$, $[C_2]$ and $[O_1]$ & $[O_2]$ are mass, stiffness, damping and null matrices for the tanks 1and 2 respectively. The suffix n and m referred as degree-of-freedom system 1 and 2 respectively.

2.2. Computation of MR damper force

The above governing Eq. (2.1.2) is solved by state-space form which is expressed as

$$\{\dot{Z}\} = [A]\{Z\}+[B]\{f_{m/f}\}+[E]\{\ddot{u}_g\} \tag{2.2.1}$$

where, Z is the state vector, A is the system matrix; B and E are the distribution matrix of the control force and the excitation, respectively. The matrices Z, A, B and E are defined as below:

$$Z=\begin{bmatrix} u \\ \dot{u} \end{bmatrix};\ A=\begin{bmatrix} O & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix};\ B=\begin{bmatrix} O \\ M^{-1}D \end{bmatrix};\ E=-\begin{bmatrix} O \\ r \end{bmatrix} \tag{2.2.2}$$

where, I and O are the identity and null matrices, respectively.

In this study, Lyapunov's direct approach is employed for the control algorithm. In developing the control law, it is to be noted that the control voltage is restricted to the range $V \in [0, V_{max}]$ for a fixed set of states. The approach requires the use of Lyapunov function, denoted by $L(\{Z\})$, which must be a positive definite function of the states of the system, $\{Z\}$. According to Lyapunov stability theory, if the rate of change of the Lyapunov function $\dot{L}(\{Z\})$ is negative semi-definite function, the origin is stable in the sense of Lyapunov. Thus in determining the control law, the goal is to choose a control input, which will result in making $\dot{L}$ as negative as possible. An infinite number of Lyapunov functions may be chosen which may result in a variety of control laws. Leitmann (1994) applied Lyapunov's direct approach for the design of semi-active controller. In this approach, a Lyapunov function is chosen of the form

$$L(\{Z\})=\frac{1}{2}\left\|\{Z\}\right\|_p^{2} \tag{2.2.3}$$

where $\left\|\{Z\}\right\|_p$ is the P-norm of sate defined by

$$\left\|\{Z\}\right\|_p=\left[\{Z^T\}[P_L]\{Z\}\right]^{1/2} \tag{2.2.4}$$

where, $[P_L]$ is real, symmetric, positive definite matrix. In the case of a linear system, to ensure $\dot{L}$ as negative definite, $[P_L]$ is found using Lyapunov equation

$$\left[A^T\right][P_L]+[P_L][A]=-[Q_P] \tag{2.2.5}$$

for a positive definite matrix $[Q_p]$ and is chosen as a unit matrix. The derivative of the Lyapunov function for a solution of state-space equation is

$$\dot{L}=-\frac{1}{2}\{Z^T\}[Q_P]\{Z\}+\{Z^T\}[P_L][B]\{f_m\}+\{Z^T\}[P_L][E]\{\ddot{u}_g\} \tag{2.2.6}$$

Thus the control law, which will minimize $\dot{L}$ is

$$V=V_{max}\,H\left(\{-Z^T\}[P_L][B]\{f_m\}\right) \tag{2.2.7}$$

where, H (.) is Heaviside step function. When H (.) is greater than zero, voltage applied to the damper should be V_{max},, otherwise, the command voltage is set to zero.

For predicting the MR damper force accurately there are several models which have been used. (Wen, 1976; Stanway et al. 1987; Spencer et al.1997). In this study, modified Bouc-Wen model (Spencer et al. 1997) is used (Figure 2). The equation governing the force predicted by this model is

$$f_m = c_1\dot{x} + k_1(u_d - x_0) \tag{2.2.8}$$

where, the evolutionary variable z is given by

$$\dot{z} = -\gamma\left|v_d - \dot{x}\right|(z)\left|z\right|^{(n-1)} - \beta(v_d - \dot{x})\left|z\right|^n + A_m(v_d - \dot{x}) \tag{2.2.9}$$

and

$$\dot{x} = \left\{\frac{1}{(c_0 + c_1)}\right\}\{\alpha_0 z + c_0 v_d + k_0(u_d - x)\} \tag{2.2.10}$$

where, u_d is the displacement of the damper; x is the internal pseudo-displacement of the damper; z is the evolutionary variable that describes the hysteretic behavior of the damper; k_1 is the accumulator stiffness ; c_0 is the viscous damping at large velocities; c_1 is viscous damping for force roll-off at low velocities**;** k_0 is the stiffness at large velocities; and x_0 is the initial stiffness of spring k_1; α_0 is the evolutionary coefficient; and γ, β, n and A_m are shape parameters of the hysteresis loop. The model parameters dependent on command voltage, c_0, c_1, α_0, are expressed as follows:

$$c_0 = c_{0a} + c_{0b}U \tag{2.2.11}$$

$$c_1 = c_{1a} + c_{1b}U \tag{2.2.12}$$

$$\alpha_0 = \alpha_{oa} + \alpha_{ob}U \tag{2.2.13}$$

where, U is given as output of first order filter (Eq. 2.2.1)

$$\dot{U} = -\eta(U - V) \tag{2.2.14}$$

3. NUMERICAL STUDY

The earthquake responses of coupled dissimilar liquid storage tanks with MR dampers has been investigated under the Loma Prieta 1989 earthquake is investigated. The dissimilar between the connected tanks has been created by selecting different aspect ratio. The dampers are placed at the level of centre of gravity of the sloshing and impulsive masses, respectively. The peak acceleration of the ground motion is 0.57g (N00E). In order to cover wide range of practical liquid storage tanks the aspect ratio, S [defined as height of liquid to radius of the tank] is varied to cover slender as well as broad tanks. The height of tank in all cases was kept fixed (as 10m). The modulus elasticity and mass density of tank wall considered are: E=200MPa and ρ_s=7,900kg/m^3, respectively. The damping ratio for convective and the impulsive masses are taken as 0.005 and 0.02, respectively while density of tank liquid is taken as 1000kg/m^3. The MR damper parameters have been suitably scaled to suit the damper deformation behaviour and the values of which are: η= 195s$^{-1,}$ c_{1a}= 8106.20 kN-s/m, c_{1b}=7807.90 kN-s/m/V, c_{0a}= 50.30 kN-s/m, c_{0b}=48.70 kN-s/m/V, α_{0a}= 8.70 kN/m, α_{0b}= 6.40 kN/m/V, γ= 496m^{-2}, β= 496 m^{-2}, A_d= 810.50, n= 2, k_0= 0.0054 kN/m, χ_0=0.18 m, k_1=0.0087 kN/m (Yang et al. 2002).

In order to cover wide range of liquid storage tanks the aspect ratio of the tanks is varied and displacement for convective and impulsive masses is computed. The aspect ratio for both the tanks was kept different in order to create dissimilarity. Table 1 shows the peak response of the tank one and Table 2 shows the response for Tank 2. By varying the aspect ratio the period of the tank is varied which created dissimilarity. The aspect ratio for Tank 1 and Tank 2 is referred as S_1 and S_2, respectively.

The response quantities of interest are displacement of convective and impulsive masses and acceleration of both the masses for both the coupled tanks. The damper force is also estimated at both the locations.

It has been observed from Tables 1 and 2 that there is increase of displacement of convective mass of Tank 1 as S_1 is increased from 0.5 to 2 keeping S_2 as constant. This effect is more when S_1 is lower than unity while it close to one or more the comparative increase of displacement is not very significant. This indicates the effect is more in slender tank in comparison to broad tanks. Similar type of trend is observed for Tank 2 as well. However, the increase of displacement is less in comparison to Tank 1. Further, it has been also observed that increase of displacement of impulsive mass is comparatively less; however the acceleration of the mass in Tank 2 is marginally increased.

The damper force in the damper connecting convective masses of both the tanks increases as aspect ratio of S_1 is increased. The increase in the damper force is more when S_1 reaches in vicinity of one. This indicates that effect is more in broad tank in comparison to slender tank. However, the damper in connecting impulsive is vey less and remains mainly unchanged. This is due to fact that impulsive masses moves rigidly with the tank wall.

4. CONCLUSIONS

From above study it has been observed that the force in the damper is more in connecting convective masses while the damper force is very less in damper connecting impulsive masses. Therefore, damper must be placed at the level of convective masses only to optimize the location of dampers. In addition to this, damper placement has increased displacement of convective masses marginally.

Table 5.1. Peak response quantities of Tank 1

S_1	S_2	Displacement (cm)		Acceleration (g)		Damper force m_c (kN)	Damper force m_i (kN)
		mass m_c	mass m_i	mass m_c	mass m_i		
0.5	1	55.5645	0.8912	0.587	0.872	158.4	0.0016
0.6	1	57.9321	0.8507	0.605	0.908	195.4	0.0016
0.7	1	64.2739	0.8399	0.625	0.932	224	0.0016
1.8	1	135.8763	0.6353	0.841	0.826	607.6	0.0016
1.9	1	139.021	0.6543	0.819	0.847	647.6	0.0016
2	1	139.6445	0.6788	0.856	0.87	679.5	0.0016

Table 5.2. Peak response quantities of Tank 2

S_1	S_2	Displacement (cm)		Acceleration (g)		Damper force m_c (kN)	Damper force m_i (kN)
		mass m_c	mass m_i	mass m_c	mass m_i		
0.5	1	69.8408	0.8912	0.644	0.872	158.4	0.0016
0.6	1	75.9673	0.8507	0.654	0.908	195.4	0.0016
0.7	1	83.8139	0.8399	0.66	0.932	224	0.0016
1.8	1	98.4754	0.6353	0.667	0.826	607.6	0.0016
1.9	1	98.5366	0.6543	0.667	0.847	647.6	0.0016
2	1	98.578	0.6788	0.667	0.87	679.5	0.0016

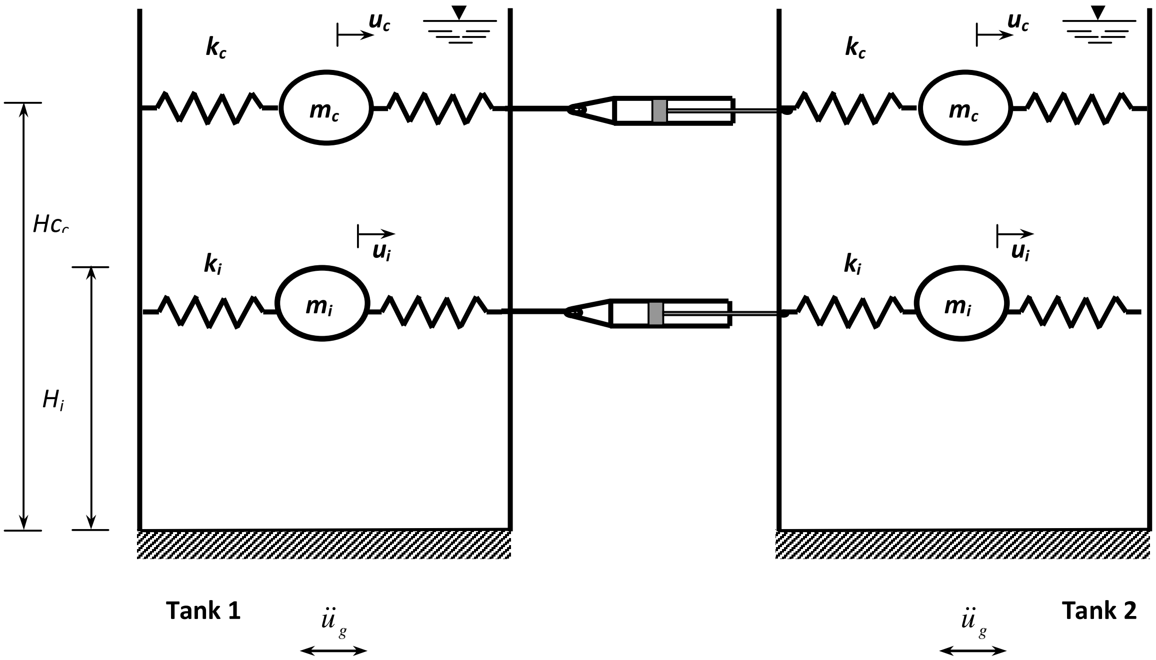

Figure 1 Structural Model of Connected liquid storage tanks

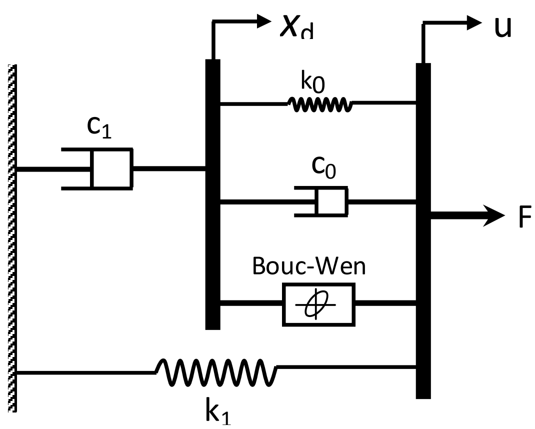

Figure 2 Modified Bouc-Wen Model of MR Damper (Spencer et al 1997)

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