Seismic Vibration Control of Elevated Water Tank by TLD and Validation of Full-Scale TLD Model through Real-Time-Hybrid-Testing

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Abstract. Elevated water tanks (EWTs), being top-heavy structures, are highly vulnerable to earthquake forces, and several have experienced damage/failure in past seismic events. However, as these are critical facilities whose continued performance in the post-earthquake scenario is of vital concern, it is significant to investigate their seismic vibration control using reliable and cost-effective passive dampers such as the Tuned Liquid Damper (TLD). Here, this aspect is studied for flexible EWT structures, such as those with annular shaft supports. The criterion of tuning the sloshing frequency of the TLD to the structural frequency necessitates dimensions of the TLD larger than those hitherto examined in literature. Hence the nonlinear model of the TLD based on established shallow water wave theory is verified for large container size by employing Real-Time-Hybrid-Testing (RTHT). Simulation studies are further carried out on a realistic example of a flexible EWT structure with TLDs. Results indicate that the TLD can be applied very effectively for the seismic vibration mitigation of EWTs.

Keywords: Real-Time-Hybrid-Testing (RTHT), Tuned Liquid Damper (TLD), Elevated Water Tank (EWT), Sloshing, Full-scale test, Experimental validation

1. Introduction

Elevated water tanks (EWTs) must remain operational in the post-earthquake scenario for carrying out the vital functions of drinking water distribution and fire-fighting. Moreover, the damage of such tanks may cause considerable economic loss. EWTs are generally slender and the large water and tank mass concentrated on the supporting tower attract significant seismic forces.
Ghosh et al. (2013) earlier conducted a detailed review on the seismic performance of existing EWTs and found that in past earthquakes several tanks have sustained moderate to heavy damage while some have failed. It was further reported that the tanks on shaft supports have been more affected as compared to those on framed supports as the former often do not have adequate redundancy and ductility.

Normal strengthening practices for EWTs cause an increase in the structural frequencies resulting in greater seismic base shear. To avoid this, the use of vibration control technologies is being examined for the seismic protection of these structures. Investigations on seismic isolation of EWTs by several researchers (Shenton III and Hampton 1999, Shrimali and Jangid 2006, Shrimali 2007) reported its effectiveness. However, base isolation techniques involve considerable cost and difficult implementation. Retrofitting of elevated steel water tanks by viscous and friction dampers proved beneficial (Potty and Nambissan, 2008). A simple tuned mass damper (TMD) was also proposed to mitigate the vibration of reinforced concrete (RC) elevated tanks under earthquake loads (Jaiswal, 2004). Another popular passive control device, the tuned liquid damper (TLD), considered as an effective, reliable and comparatively economic solution, is widely studied and is in application for structural protection under dynamic environmental actions, especially for wind-excited tall buildings (Fujii et al., 1990, Kareem, 1990, Wakahara et al., 1992, Soong and Dargush, 1997). The key advantages attributable to the TLD are affordable installation, operational and maintenance costs, ease of installation in case of existing structures, easy adjustment of natural frequency, effectiveness even against small-amplitude vibrations, function not restricted to unidirectional vibration, no need for low friction bearing surface etc.

This paper investigates the TLD for seismic vibration control of EWTs. As the TLD is a long period system, the study considers flexible EWT structures, such as those with annular shaft supports. The criterion of tuning the sloshing frequency of the TLD to the structural frequency necessitates dimensions of the TLD larger than those hitherto examined through experimentation and available in literature. A nonlinear model of the TLD based on the established shallow water wave theory is used and it is felt necessary to experimentally validate this model for large container size, as would be required in case of EWTs. This is undertaken by employing Real-Time-Hybrid-Testing (RTHT), in which a physical full-scale model of the TLD is tested while a numerical model of the EWT developed in Matlab/Simulink environment is used to calculate the response of the coupled system numerically in real-time. Simulation studies are further carried out on a realistic example of a flexible EWT structure with TLDs.
2. Modelling of structure-TLD system

A reinforced concrete (RC) EWT with an annular shaft support is considered. It is modelled as a single-degree-of-freedom (SDOF) system (see Fig. 1(a)). The lateral flexural stiffness of the staging is evaluated from the deflection of the shaft support acting as a cantilever and is denoted by \( k_s \). The mass denoted by \( m_s \) consists of the mass of the empty tank container, \( 2/3 \) rd of the mass of the supporting shaft and the total water mass within the tank container. This mass is

\[
m_s = m_c + 0.66m_{ss} + m_l
\]

\( m_c \) is the mass of the empty tank container, \( m_{ss} \) is \( 2/3 \) rd of the mass of the supporting shaft and \( m_l \) is the total water mass within the tank container.

The damping coefficient of the SDOF structural system is denoted by \( c_s \). The damping ratio and the natural frequency of the EWT’s SDOF system model respectively, where \( T_s \) is the structural time period.

\( \xi_s \) and \( \omega_n = 2\pi/T_s \) represent the damping ratio and the natural frequency of the SDOF structural system. The lateral displacement of the mass \( m_s \), relative to the base, is subject to the ground acceleration denoted by \( \ddot{z}(t) \).

The model of the SDOF structural system with attached TLD is shown in Figure 1 (b). The TLD is assumed to be placed on the top of the EWT tower. The TLD container is a rigid rectangular tank, as shown in Figure 1 (c), having a length \( 2a \), width \( b \) and height \( H \). It is partly filled with liquid that has a free upper surface. The quiescent or undisturbed liquid depth is \( h \). The established nonlinear shallow water wave theory (Sun et al., 1992) is employed to model the
TLD in the present paper. This model is reproduced here in brief. The liquid is presumed as incompressible and irrotational. The liquid pressure is constant at the free surface. The liquid particle motion is assumed to build up in the two-dimensional vertical $x$-$z$ plane only, where $o$-$x$-$z$ denotes the local Cartesian coordinate system attached to the tank with its origin at the centre of the mean liquid surface. The internal friction between the fluid particles is dominant only in the boundary layer near the solid surfaces. The effect of wave breaking is taken into consideration.

3. Equations of Motion

The equation of motion for the EWT equipped with TLD, normalized with respect to the structural mass, is expressed as

$$\ddot{x}(t) + \ddot{z}(t) + 2\xi_1 \omega_i \dot{x}(t) + \omega_i^2 x(t) = \frac{F(t)}{m_s}$$

(1)

where, $F(t)$, is the horizontal shear force due to liquid sloshing developed at the base of the TLD, exerted on the structure. This sloshing force of the TLD is estimated by the difference between the hydrostatic pressure across the left and right inner walls of the TLD container and given by

$$F(t) = \frac{\rho_gb}{2} \left[ (\eta_l(t)+h)^2 - (\eta_r(t)+h)^2 \right]$$

(2)

where $\eta_l$ and $\eta_r$ represent the liquid surface elevations at the right and left walls of the TLD container respectively.

The equations governing the liquid motion in the TLD, obtained by integrating the continuity equation and by eliminating the pressure term from the two-dimensional Navier-Stokes equations (Sun et al., 1992), are as follows.

$$\frac{\partial u(\eta)}{\partial t} + (1 - T_H^2)u(\eta)\frac{\partial u(\eta)}{\partial x} + C_{fr}g \frac{\partial \eta}{\partial x} + gh \sigma \phi \frac{\partial^2 \eta}{\partial x^2} \frac{\partial \eta}{\partial x} = -C_d \lambda u(\eta) - \dot{x}_s$$

(3)

$$\frac{\partial \eta}{\partial t} + h a \frac{\partial [\phi u(\eta)]}{\partial x} = 0$$

(4)

where, $u(\eta) [= u(x,\eta,t)]$ is the horizontal velocity of the liquid particle at the free surface, $\eta[=\eta(x,t)]$ is the liquid surface elevation, $k$ is the wave number, $g$ is the acceleration due to gravity, $S$ is the surface contamination factor, $\omega_i$ is the characteristic frequency of liquid motion, $\dot{x}_s$ is the horizontal excitation at the TLD base, $\lambda$ is the damping parameter. The value of $S$ is taken as 1 for fully contaminated surface.

$$T_H = \tanh[k(h+\eta)]$$

(5)

$$\sigma = \frac{\tanh(kh)}{kh}$$

(6)

$$\phi = \frac{\tanh[k(\eta+\eta)]}{\tanh(kh)}$$

(7)
\[
\lambda = \frac{1}{(q + h)^{1/2}} \sqrt{\omega_{l} \left[ 1 + \left( \frac{2h}{b} \right) + S \right]}
\]

The fundamental linearized sloshing frequency of the liquid in the TLD is expressed by (Fujino et al., 1992)

\[
\omega_{l} = \sqrt{\frac{\pi g}{2a} \tanh \left( \frac{\pi c}{2} \right)}
\]

where, \( c = h/a \) is the ratio of mean liquid depth to half the length of the container. The wave breaking coefficient \( C_{fr} \) is taken equal to 1.05 and \( C_{da} \) is given by the following expression.

\[
C_{da} = 0.57 \sqrt{\frac{h \omega_{l}}{au} (x)_{max}}
\]

Here, \( (x)_{max} \) is the maximum displacement of structure without damper, when subjected to the same base acceleration.

Equations (3) and (4) are discretized with respect to \( x \) into difference equations involving staggered mesh (i.e. different mesh points for liquid velocity and free surface elevation). Thereafter, the Runge-Kutta-Gill method is used for solving the difference equations to obtain \( u \) and \( \eta \). The horizontal base shear force from the TLD is then computed. Again, the same numerical procedure i.e. Runge-Kutta-Gill method, is applied for calculating the structural response in time domain.

4. Verification of TLD model by RTHT

To validate the TLD model and to study the performance of the TLD in the vibration control of the base-excited EWT, a typical RC EWT structure with annular shaft staging of 30 m height is considered. The fundamental natural frequency of the structure is evaluated as 3.256 rad/s, \( (T_s = 1.93 \text{ s}) \). The value of the structural damping of the EWT is assumed to be 1%.

For shallow depth, the ratio of the still liquid depth to length of TLD container is recommended to lie between 0.04 and 0.5 (Sun et al., 1992) for greater energy dissipation through sloshing action. Considering a value of 0.25 and from the tuning criterion, the length of the TLD container is calculated to be about 1.9 m. A manufactured damper container of 1.93 m length is used for the RTHT. With the fixed size of the TLD container, the resulting water mass is only dependent on the liquid (water here) depth. Two different liquid levels of TLD are examined, namely 235 mm and 298 mm. The fundamental frequencies of the TLD, mass ratios and tuning ratios for these depths are tabulated in Table 1. Here the value of the ratio of the still liquid depth to the length of TLD container remains in the range 0.12 to 0.15.
Table 1. Parameters of TLD for different cases

| Sl. No. | Water depth in TLD (mm) | Fundamental frequency (rad/s) | Mass ratio (%) | Tuning ratio |
|---------|-------------------------|------------------------------|----------------|-------------|
| 1       | 235                     | 2.333                        | 0.14           | 0.74        |
| 2       | 298                     | 2.594                        | 0.17           | 0.82        |

4.1 General description and Implementation of the hybrid model test set-up

The RTHT reported in this work was conducted using the MTS real-time hybrid testing system in the Vibration Control Laboratory at Trinity College Dublin, Ireland. The test comprises of two components: testing of an experimental substructure of a TLD and simulation of a numerical model of EWT in the MATLAB/Simulink environment. A photograph of the test setup and the experimental substructure (i.e. the TLD) is presented in Figure 2. The setup is composed of a hydraulic actuator in the horizontal direction, a reaction frame and the data acquisition system. The MTS 244 actuator has a load capacity of 150 kN and maximum stroke of ±125 mm. It is attached to the left side of the TLD. For the measurement of the actuator displacement and the interactive force, a linear variable displacement transducer (LVDT) and a load cell are connected to the actuator. The full-scale model of the TLD is a rectangular container having inner dimensions of 1.93 m (length) × 0.59 m (breadth) × 1.2 m (height). As the breadth of the TLD container is much less compared to its length, the sloshing of the liquid (water here) is expected to be predominantly two-dimensional. With the purpose of minimizing the friction when the TLD container is compelled to relocate by the actuator, four steel cables are used to suspend the container from the top of the reaction frame. Moreover, two capacitance wave gauges are mounted (with the sampling rate of 10 Hz/s) at the two end walls (left and right) of the container to measure the water surface elevations at the left and right walls.

Figure 2. Photograph of experimental set-up
4.2 Numerical Results

The input, given to the numerical substructure, is harmonic. The amplitude of the harmonic input is 0.005 m/s². The input frequency in both the tests is equal to the structural frequency i.e. 3.256 rad/s.

Figure 3 shows the comparison of the structural displacements obtained by RTHT and the nonlinear model based on the shallow water wave theory for the two cases of different TLD water levels. The outcome from the nonlinear shallow water wave theory shows very good agreement with the test result as shown in Figure 3(a), (b). It may be noted that in the present cases, the values of tuning ratio are away from unity. The condition with tuning ratio equal to unity (resonance condition) resulted in a water depth of 445 mm and due to excessive sloshing the test could not be performed.

Figure 3. Comparison of the EWT displacements obtained by RTHT and by simulation for different water depths in the TLD (a) 235 mm, (b) 298 mm.

Figure 4 shows a comparison of the values of the control force generated by the TLD from RTHT and from simulation for the two cases of water height in the TLD. Acceptable agreement between the experimental and simulated results is obtained.
5. Simulation Study on Seismic Vibration Control of EWT by TLD

Reasonably significant response reductions are possible with tuned absorbers provided the mass ratio is not very small. The mass ratio of a single TLD unit as in Table 1 is very low and it is necessary to provide multiple units to have higher mass ratios. So having established that the nonlinear model of TLD based on the shallow water wave theory may be used for studying the performance of TLDs for flexible EWTs, a simulation study is now carried out to examine the response reduction that may be achieved with mass ratios higher than that which could be achieved by a single tank (as in Table 1). Here, values of mass ratio equal to 1%, 2% and 3% mass ratio are considered. The mass of the TLD container is neglected. The values of tuning ratios are same as those in Table 1. Harmonic as well as the recorded 1940 El Centro earthquake accelerogram are used to characterize the input excitation. The amplitude of the harmonic input is 0.05 m/s² and frequency equal to the structural frequency. The reductions in the peak and root mean square (RMS) structural displacement response for the different mass ratios and for the different input are presented in Table 2. A sample set of time histories of the displacement of the EWT with and without TLD for the El Centro earthquake excitation is presented in Figure 5.

As can be seen from the tabulated values, even with tuning ratios away from unity, substantial reduction is achieved for all the cases both in the peak and the RMS displacement responses of the considered EWT structure. The response reduction increases with increase in the mass ratio. As expected, for the same input, the tuning ratio that is comparatively closer to unity is providing better reductions. Overall, the TLD represents a promising control device to protect EWTs from earthquake excitation.
Table 2. Structural displacement reduction for different mass ratios and different inputs

| Input                    | Mass ratio (%) | Tuning ratio | Reduction in EWT displacement (%) |
|-------------------------|----------------|--------------|-----------------------------------|
|                         |                |              | Peak                             | RMS                          |
| Harmonic                | 1              | 0.74         | 34.01                            | 30.25                        |
|                         | 2              | 0.74         | 44.72                            | 41.10                        |
|                         | 3              | 0.74         | 52.38                            | 48.86                        |
|                         | 1              | 0.82         | 36.89                            | 33.46                        |
|                         | 2              | 0.82         | 51.22                            | 48.09                        |
|                         | 3              | 0.82         | 60.05                            | 57.20                        |
| Elcentro earthquake     | 1              | 0.74         | 10.61                            | 8.74                         |
|                         | 2              | 0.74         | 16.80                            | 14.28                        |
|                         | 3              | 0.74         | 23.19                            | 19.91                        |
|                         | 1              | 0.82         | 11.21                            | 10.92                        |
|                         | 2              | 0.82         | 19.08                            | 19.20                        |
|                         | 3              | 0.82         | 25.74                            | 25.30                        |

Figure 5. Displacement time histories of EWT to El Centro input, uncontrolled and controlled (TLD tuning ratio of 0.82 and mass ratio 3%)

6. Conclusions

This paper presents a study on the use of a well-established passive control device, namely the TLD, for the seismic vibration mitigation of elevated water tank (EWT) structures. This is an important issue considering the susceptibility of these structures to ground excitation coupled with their necessity to function unhindered in the post-earthquake scenario. Here the analysis of the EWT-TLD system employs a nonlinear model of the TLD based on established shallow water wave theory. Experimentation on the latter has so far been restricted to TLD container sizes
which are considerably smaller than those that would be required for the fairly common flexible annular shaft-supported EWTs. This is investigated in the present paper through RTHT, with container length close to 2 m. It is seen that the structural displacement and TLD base shear force obtained by RTHT are in good agreement with the simulation results, thereby validating the nonlinear model of the TLD for the present application. Simulation results with realistic damper mass ratio indicate significant response reductions, even under non-optimal conditions. Hence, the TLD is identified as an efficient passive control device for EWTs under seismic excitation.

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