Experiments of tuned liquid damper (TLD) on the reduced shear frame model under harmonic loads

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Abstract: In this study shaking table tests which are applied on 3-Storey reduced shear frame models with TLD's subjected to harmonic loadings are presented. Firstly, free vibration experiments are conducted on the structure and 1st free vibration frequency of the structure is determined. The structure is shaken under harmonic loading at a frequency equal to 1st frequency of the structure which provides the resonance condition. Displacements and accelerations are measured at storey levels of the structure. A container in a rectangular prism shape is manufactured as a TLD model. Liquid is poured in the container and the same experiments are repeated at different liquid heights. The effect of TLD application on the structural models considering displacement and acceleration of the structure are investigated. In addition the effect of TLD application and its allocation at different storey levels are calculated experimentally. As a result of the conducted experiments, most convenient TLD models considering both displacement and acceleration behavior are determined. It is observed that all the damping models cause significant levels of reduction in seismic behavior of the structure under harmonic loading.

1 Introduction

In recent days, a number of methods have been developed in order to reduce dynamic excitation such as wind and earthquake excitations. In civil engineering the use of tuned mass dampers (TMD's) and tuned liquid dampers (TLD's) are comprehensively approved by many researchers, so use of such control devices have been more and more preferred instead of conventional design [1,3,5,7]. As shown for a single degree of freedom system with TLD model in Figure 1, Tuned Liquid Dampers (TLD's) are passive energy dissipation systems which consist of water tank and sloshing viscous fluid. These devices absorb dynamic inputs; therefore, structures are protected against damage or collapse. For the condition of lateral accelerations of water tank, while part of water level rises, another part decreases simultaneously. This sway movement supplies energy absorption arising from dynamic forces. In these devices, wave movements and natural vibration periods depend on water tank geometry, length of dimensions, water depth and acceleration of gravity. When periods of TLD's are tuned to a particular value, they resonate out of phase with structural movement. Two types of Tuned liquid dampers are commonly used which are called (i) tuned liquid dampers which consist of rectangular section tank and (ii) tuned liquid column dampers which have two limbs of tubes filled with same kind of liquids as seen schematically in Figures 2 (a) and 2 (b).

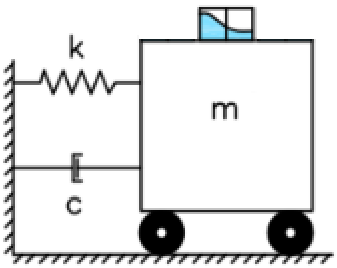
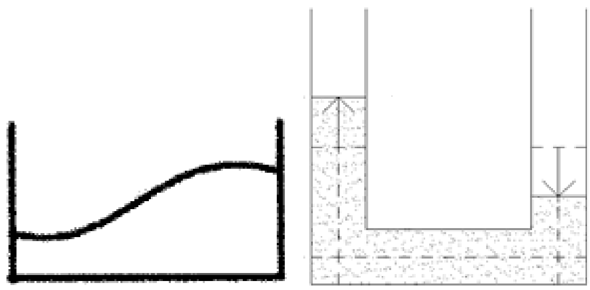


Fig. 1. Single degree of freedom system with TLD model



(a) (b)

Fig. 2 (a) Schematic demonstration of TLD and (b) Schematic demonstration of TLCD

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While TLD's use wave breaking in order to absorb input energy effect the system, TLCD's absorb this energy by adjusting atmosphere pressure at limbs of TLCD. In resonance condition, because of undesirable fluid behaviors of TLD's, TLCD's are superior to TLD devices.
Bauer [2] used very different two kinds of liquids by fully filled rectangular tanks in order to supply damping response through the movement of interfaces**.** Welt and Modi [8,9] proposed to use tuned liquid dampers (TLD's) enhancing ability of structure against wind and earthquake induced excitations. Owing to resemblance of these dampers, tuned liquid column dampers (TLCD's) system having partially filled tube including some internal orifices is suggested by Xu et al. [8]. Characteristics of multiple tuned liquid column dampers (MTLCD) were searched by Gao et al. [12] for suppressing structural vibration. They have discussed advantages and disadvantages of multiple tuned liquid column dampers in their research. They indicate that a multiple tuned liquid column damper (MTLCD) is less sensitive than a single tuned liquid column damper (TLCD). They also found out that increasing number of TLCD enhances efficiency of MTLCD. However, more than five TLCD's do not give contribution to augment performance behavior of structure against vibratory excitation forces. When MTLD's are taken into account, Fujino and Sun [4] found out that weakly excited small amount of liquid movement has similar feature covering efficiency and robustness to frequency ratio of device. For the condition of strongly forced much more liquid motion appearance, MTLD can't be more effective than TLD. On the other hand an MTLD has almost equal influence, if breaking waves has already existed.

2 General Formulation of TLD

As seen in Figure 3, rectangular section of liquid filled tank with width b has 2a length along x direction, liquid level h which is at rest condition. Sun et al. [6] proposed some formulation to define and design TLD's. These formulations are determined as:

$$\frac{\partial \eta}{\partial t} + h\sigma \frac{\partial(\phi u)}{\partial x} = 0 \qquad (1)$$

$$\frac{\partial u}{\partial t} + (1-T_H^2)u\frac{\partial u}{\partial x} + C_{fr}^2\, g\frac{\partial \eta}{\partial x} + gh\sigma\emptyset\frac{\partial^2 \eta}{\partial x^2}\frac{\partial \eta}{\partial x} = -C_{da}\lambda u - \ddot{x}_s \qquad (2)$$

Where $\eta(x,t)$ and $u(x,\eta,t)$ are independent variables which are elevation of undistributed water free surface and particle velocity of free water surface, respectively.
TLD's base acceleration is equal to base shear force acceleration, $\ddot{x}_s$ and g is acceleration of gravity.
By using Equations (1) and (2), σ, ϕ and T_H can be calculated as:

$$\sigma = \frac{tanh(kh)}{kh}, \qquad (3a)$$

$$\phi = \frac{tanh[k(h+\eta)]}{tanh(kh)}, \qquad (3b)$$

$$T_H = tanh(k+\eta) \qquad (3c)$$

Where k is number of wave, λ is damping parameter depending on boundary layer through bottom of tank, side walls and water free surface contamination. λ can be given as:

$$\lambda = \frac{1}{\eta+}\frac{1}{\sqrt{2}}\sqrt{\omega_1 \nu}\left[1 + \left(\frac{2□}{b}\right) + s\right] \quad (4)$$

Where $\omega_1$is linear fundamental frequency of sloshing water in tank which defined equation, ϑ is kinematic viscosity of water and s is unity surface contamination factor, respectively. Fundamental frequency of TLD can be written as:

$$\omega_1 = \sqrt{\frac{\pi g}{2a}}\tanh(\pi\Delta) \qquad (5)$$

in which, Δ = h/2a is called water depth ratio.

In Equation (2), when considering breaking wave coefficients C_{fr} and $C_{da,}$, η is taken bigger than h. If breaking wave doesn't exist, C_{fr} is empirically calculated as 1,05 and C_{da} is calculated from Equation (6) which is calculated according to top of the building maximum displacement $(x_s)_{max}$ which is considered without TLD. This equation is given as:

$$C_{da} = 0{,}57\sqrt{\frac{h^2\omega_1}{a\,v}\,(x_s)max} \qquad (6)$$

To calculate approximate F, shear force at base, Equations (1) and (2) are used to obtain $\eta(x,t)$ which is called free surface elevation. Neglecting some higher order terms, F can written as:

$$F = \frac{\rho g b}{2}\left[(\eta_n + □)^2 - (\eta_0 + □)^2\right] \qquad (7)$$

in which b is width of tank, ρ is mass density of water, η and η_0 are free surface elevations of right and left walls of water tank, respectively.

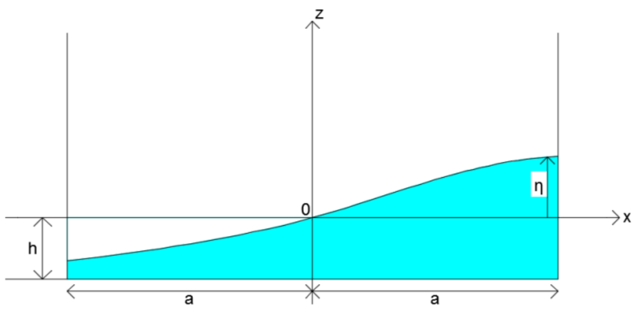


Fig. 3. Rectangular section of liquid filled tank

3 Experimental study

As seen in Figure 4, 3 storey Building frame shear model with TLD, which is used for experiment setup, is made of S235JR steel. Physical features of this model is summarized in Table 1 as shown below.

Table 1 Physical features of structural model

Shear frame weight	6500 gr
Weight located at 1st storey of model	10812 gr
Weight located at 2nd storey of model	8346 gr
Weight located at 3rd storey of model	6718 gr
Each storey height	35 cm
Shear frame column dimensions	1.0 cm x 0.3cm, thickness=0.1 cm
Shear frame beam dimensions	1.5 cm x 1.5 cm , thickness=0.1 cm
Shear frame floor dimensions	24 cm x 24 cm
1^{st} floor mass of Building frame shear model with connection element and added masses to floors	13 kg
2^{st} floor mass of Building frame shear model with connection element and added masses to floors	10.5 kg
3^{st} floor mass of Building frame shear model with connection element and added masses to floors	8.9 kg
Total mass of Building frame shear model with connection element and added masses to floors	35 kg
Dimensions of TLD cup	22.5 cm x 22.5 cm x 27.5 cm

Shaking table used in this experiment has 0-400 Hz frequency range. This liner-shaking table has a compact shape and its dimensions are 50 cm x 50 cm. It also has sensitive position taking capacity. Shaking table can produce one dimensional horizontal vibration that can produce desired number and range (1-10 Hz) of frequency and its amplitude changes in between -200 mm to + 200 mm. Gathering given data, general dynamic device is used. Displacement and acceleration measurements are connected to this device and a software data recorded from this device can be saved and used.

Fig. 4. 3-storey Building shear frame model with TLD

This experiment is designed for 3 mm amplitude and 1.5 Hz frequency which is also fundamental natural frequency of building model and 10 cycle harmonic load is applied to 3-storey model with and without TLD by means of shaking table. After this application, 3 storey building model displacements are measured without TLD and with TLD which are separable for three different TLD liquid height levels in cups. At each story of TLD location for 3 story model, experiments are repeatedly conducted. The reason for choosing 1.5 Hz shaking table frequency is to create an unfavorable condition which resonates 3 storey models. After measuring displacements of each cup, these displacements are plotted with respect to time in order to find most appropriate model. Rectangular sections of liquid filled tanks are shown in Figure 5 while TLD's models of experiment are provided in Table 2.

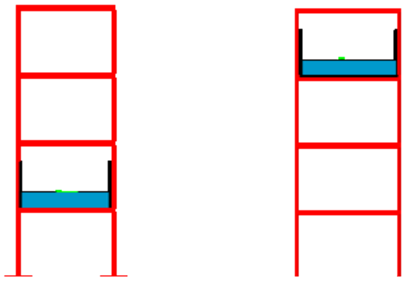
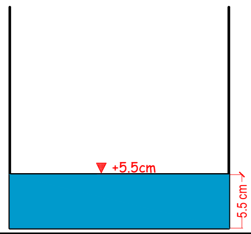
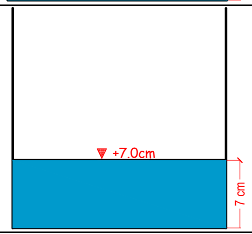
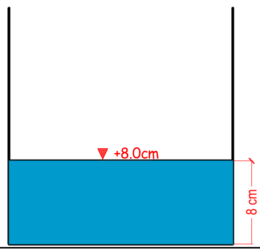


Fig. 5. Rectangular sections of liquid filled tanks

Table 2. TLD's models of experiment

Type of TLD model	Figure of model	Total mass of cup and water (kg)
MODEL 1		5.692 kg
MODEL 2		6.223 kg
MODEL 3		6.717kg

As seen in Figure 6 and Table 3, when TLD cup is located at first floor of the model, model 2-1 gives better performance than other cups in terms of percent decrease in performance which are 75.6838 % at third floor, 74.5454 % at second floor, and 72.9729 % at first floor, respectively.

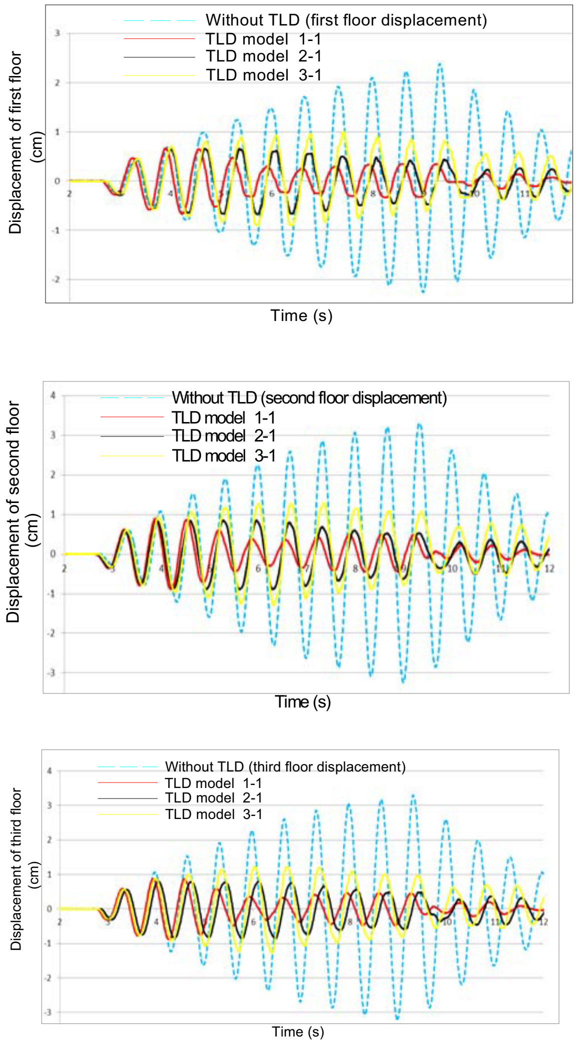


Fig. 6. Displacement of first, second and third storey of structural model without TLD and with TLD models which are located at first storey

Table 3. Comparison of first storey displacement of structural model considering different TLD models

Type of TLD model	Third floor Peak displacement of structural model	Second floor Peak displacement of structural model	First floor Peak displacement of structural model	Decrease in floor displacement due to TLD (%)		
Without TLD	3,29 cm	3,3 cm	2,368 cm	3rd Storey	2nd Storey	1st Storey
TLD model 3-1	1.21	1.28	1.004	63.22188	61.2121	57.6013
TLD model 2-1	0.8	0.84	0.64	75.68389	74.5454	72.9729
TLD model 1-1	0.87	0.89	0.66	73.55623	73.0303	72.1283

As can be understood from Figure 7 and Table 4, when TLD cup is located at third floor of the model, model 2-3 gives better performance than other cups in terms of percent decrease in performance which are 82,0668 % at third floor, 81,5151 % at second floor, and 82,68581 % at first floor, respectively.
For this experiment, model 2-3 gives best performance among all TLD's cups with respect to decrease in displacements of all storeys of structural models. These displacements are about 82% less.

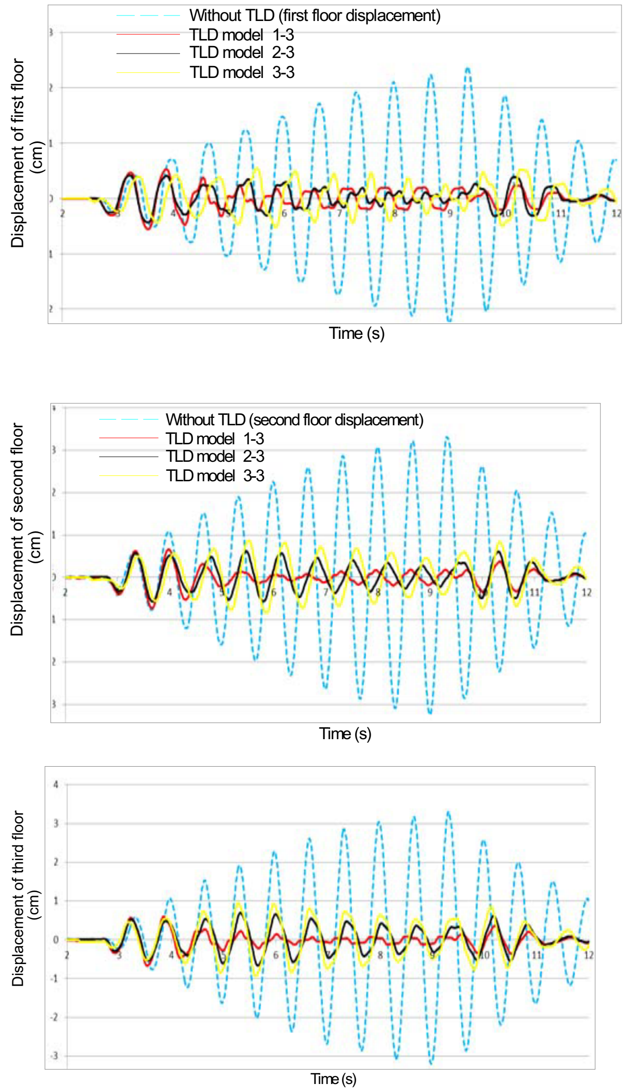


Fig. 7. Displacement of first, second and third storey of structural model without TLD and with TLD models which are located at third storey

4 Conclusions

Structural control systems are modern systems that develop ability to strengthen the structure against dynamic effects. TLD systems are also kinds of structural control systems for which deriving formulation and solution is not easy due to complex behavior of liquid sloshing in cup. However, these systems are very useful for lessening vibration effects on structures, even for their complex applications. TLD formulation can be simplified in order to explain their behavior associated to tuned mass damper (TMD) system. In this study, experiments for such complex devices are conducted in which harmonic effectiveness at resonance condition for fundamental frequency of structural system is evaluated. Considering the results of the presented study, the following conclusions can be expressed.

1) For this study, when considering achievement of the best displacement decrease, TLD model 2-3 which is model 2 located at 3rd storey has the best performance compared to other TLD models. As shown in results for this model, decrease in quantities as percentages are 79,02 % at 3rd floor, 81,51% at 2nd floor and 82,68 % at 1st floor, respectively.

2) If TLD models are evaluated relatively,

a) Location of TLD model-1 at 3rd floor has the best performance considering displacement reduction for 3th floor,

b) Location of TLD model-2 at 3rd floor has the best performance considering displacement reduction for 2nd floor,

c) Location of TLD model-3 at 2nd floor has the best performance considering displacement reduction for 2nd and 3rd floors.

3) As can be understood from the conducted experiments, TLD is very effective in reducing harmonic force effects at resonance conditions. The ranges of these reductions are approximately 79% -80 %. The shear forces lessen such that elements of structure are exposed to less strain. Accordingly, element sections can be chosen smaller than conventional design such that TLD's derogate the cost function of structure.

Table 4. Comparison of first storey displacement of structural model considering different TLD models

Type of TLD model	Third floor Peak displacement of structural model	Second floor Peak displacement of structural model	First floor Peak displacement of structural model	Decrease at floor displacement due to TLD (%)		
Without TLD	3,29 cm	3,3 cm	2,368 cm	3.storey	2. storey	1. storey
TLD model 3-3	0.94 cm	0.86 cm	0.54 cm	71.42857	73.93939	77.19594
TLD model 2-3	0.69 cm	0.61 cm	0.41 cm	79.02735	81.51515	82.68581
TLD model 1-3	0.59 cm	0.66 cm	0.52 cm	82.06686	80	78.04054

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