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Experimental study on TLDs equipped with an upper mounted baffle

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Abstract. Tuned Liquid Dampers (TLDs) have gained wide acceptance as a system for structural control and energy dissipation. However, they face limitation caused by low damping in deep water, which affects their efficiency. Another problem with deep water TLDs is that not all water depth participates in energy dissipation. This paper investigated the effect of upper mounted baffles on the effectiveness of TLDs. The Vertical Blockage Ratio (VBR) of baffles ranged from 10% - 90%. The TLD (with and without baffle), structure, and combined structure with TLD (with and without baffles) were subjected to free and harmonic forced vibrations. Results indicated that baffles could significantly enhance the energy dissipation of TLDs, thus reducing structural responses more than structures equipped with ordinary TLDs. It was found that, there was an optimum value of VBR in which the TLD's efficiency was maximized. When TLD had an appropriate VBR, the structural acceleration and displacement responses were suppressed significantly up to 51% and 56%, respectively.

Keywords: tuned liquid damper; baffle; vibration response; dynamic response; free vibration

1. Introduction

High-rise buildings and tall structures are often subjected to substantial vibration conditions due to earthquake and wind. The structure's height and nature of construction materials (light and high-strength) make these structures flexible. This flexibility causes a sway effect due to lateral load (wind) which has to be kept safe and within the serviceable limits. This can as well lead to fatigue of structural members and discomfort to top level occupants. Earthquake waves subject structures to displacement and acceleration that make them unstable, thus leading to partial or total collapse of the structure. One of the control devices designed to mitigate these effects is the Tuned Liquid Damper (TLD).

TLDs are passive energy-absorbing devices, which are installed at the top of buildings to solve the problem of excessive sway of buildings due to dynamic loads (e.g., wind and earthquake) (Kareem *et al*. 1999). The attention gained by TLD can be attributed to several advantages it offers over the Tuned Mass Damper (TMD). TLDs are simple to construct, cost effective, easy to install with low maintenance requirements (Chen *et al.* 1995, Soong and Dargush 1997). The Yokohama Marine tower in Japan (Hamelin 2007), Rincon Hill Tower in San Francisco (Kareem *et al*. 1999) and King West Building in Toronto (Hamelin 2007) are examples of application of TLDs in high-rise buildings to mitigate structural oscillations.

TLDs are tanks (cubic or cylindrical) containing liquid(s) which utilizes the liquid sloshing motions to dampen the structure's vibration and dissipating the energy through liquid boundary layer friction, wave breaking and free surface contamination (Ashasi-Sorkhabi 2014).

Another is the ability to control two structural sway modes if the tank has the proper dimension (Tait *et al.* 2007). They are classified as shallow or deep water, depending on the depth of water in the tank. A TLD is termed "shallow tank" when the depth ratio (water height/tank length) is less than 0.15 (Banerji *et al.* 2007) and "deep tank" when it is 0.2 (Noji et al. 1988). When the water is shallow, large damping which is good for small excitation amplitude is achieved (Fediw 1992). However, when the amplitude of excitation is high, the liquid behaves nonlinearly and becomes very difficult to analyse. In deep water, the sloshing exhibits linear behaviour for large amplitude excitation (Kim *et al*. 2006). It has been shown experimentally that when the frequency of tank motion and natural frequency of tank fluid are close, large sloshing amplitude occurs (Sun *et al*. 1992), if both frequencies are close enough, resonance takes place. Therefore, when the fundamental frequency of the TLD is same as the building's a large amount of sloshing and wave breaking occurs at the resonant frequencies of the combined Structure-TLD

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system. This result in a significant amount of energy dissipation (Kareem and Sun 1987) and affects the shear force developed at the tank base to resist the structures' motion.

The 1970s witnessed the introduction of TLDs in Civil Engineering to reduce structural motion. Since then, several studies have been carried out to study the complexity of TLDs to understand its behaviour in mitigating dynamic response. Vandiver and Mitome (1979) installed a TLD on a platform to reduce wind vibration effects. Bauer (1984) introduced two immiscible liquids in a rectangular tank to control a structural system. Tamura *et al*. (1995) studied the dynamic response control ability of cylindrical TLDs in both orthogonal directions of the structure. Recently, Novo *et al.* (2014) presented a study of a TLD installed in an existing reinforced concrete building to reduce earthquake impact. Sorkhabi *et al*. (2014) investigated the effectiveness of multiple TLDs to increase the control of vibration. Min *et al*. (2014) designed a two-way liquid TLD to reduce vibration of tall buildings.

In order to increase the efficiency of TLDs, several models with different levels of alterations and modifications have been proposed. These come in form of liquid viscosity, tank geometry (Deng and Tait 2009, Xin *et al.* 2009), screens (Tait *et al.* 2008) and baffles (Tait *et al.* 2007). The resonant frequency of a tank was altered using surface-piercing and bottom mounted vertical blocks (Evans and McIver 1987). The authors observed that the resonant frequency decreased with the increase in liquid depth. Jeyakumaran and Mciver (1995) presented an equation to estimate the natural frequency of a cylindrical tank with surface-piercing vertical baffle. This study indicated that the method applied by Watson and Evan (1991) is only acceptable for a restricted number of geometries. Cho *et al.* (2005) studied the resonance sloshing response of a baffled-TLD with numerical models. They concluded that by increasing the number of baffles and reducing baffle opening ratio, the natural frequency of the TLD decreases. Shang and Zhao (2008) numerically analysed a rectangular TLD with two adjustable-angle baffles. The periods of the TLD can be altered in a wide range by adjusting the baffles' angle, thus gaining more efficient vibration control of structure in a wide frequency range. Younes *et al.* (2007) subjected a tank with various vertical baffles (lower and upper with holes) with different opening ratios and different water level to free vibration. The result showed that vertical-lower mounted baffles had higher damping when compared to others. Recently, Zahrai *et al*. (2012) studied the effect of rotatable baffles on a TLD using two different water level to control the structural response of a 5-storey experimental building model. The free vibration and earthquake tests showed that tuning ratio was more significant than the mass ratio, and that baffles at 75^{o} had the best performance. Recently Chen *et al*. (2016) examined the application of a spherical tuned liquid damper for vibration control of wind turbine due to earthquake excitations. A 1/20-scale test model was constructed and was subjected to the free and forced vibration excitations. They reported that the proposed spherical damper improved the damping capacity of the test model. Results also indicated that the effectiveness of the proposed TLD was significantly influenced by the frequency content of earthquake excitations. In another study, Ashasi-Sorkhabi *et al*. (2017) investigated TLD-structure interactions at resonance frequency by examining multiple parameters. They employed the real-time hybrid simulation (RTHS) method in which the TLD response was obtained experimentally while the structure was modeled in a computer. TLD/structure mass ratio, TLD/structure frequency ratio, and structural damping ratio were the main parameters that their effects were investigated. They reported that increase in the mass ratio from 0.5% to 3% can enhance reduction in the dynamic responses. Moreover, the highest TLD contribution was achieved when the frequency ratio was set to 1.2. Jin *et al.* (2014) studied the application of an inner horizontal perforated plate in TLDs.

They examined the free-surface elevations on the side-walls and resonance frequencies. They showed that the excitation amplitude had a minimal influence on the frequency of the sloshing phenomenon and free surface elevation. Moreover, they found that the horizontal perforated plate could significantly restrain violent resonant sloshing in the tank under horizontal excitation. The effect of vertical baffles with the different configuration on suppressing sloshing pressure was studied by Xue *et al.* (2017). The immersed bottom-mounted vertical baffles, vertical baffles flushing with a free surface, surface-piercing bottom mounted vertical baffles and perforated vertical baffles were examined in their study. They reported that the vertical baffles altered the sloshing frequency of the water tank. They also suggested that change in the flow fields and natural frequency might effectively suppress the impact pressure on the tank walls. A new type of TLD was proposed by Ruiz and Lopez-Garcia (2016). The proposed TLD consisted of a conventional TLD with the addition of a floating roof. They claimed that the new TLD maintained the advantages of conventional TLDs while resulted in a simpler numerical characterization. Shad *et al.* (2016) investigated the effect of bottom mounted baffles on the dynamic characteristics of conventional TLDs. They found that the addition of bottom mounted baffles increased the damping capacity of conventional TLDs. Moreover, results of experimental tests showed that the optimal blockage ratio for baffles was 30% in which the peak acceleration response of the TLD-structure system was decreased up to 75%.

Despite these applications and studies, TLD still faces damping limitations, which restrict its efficiency. Such problem is low damping in deep water TLDs as compared to the control force generated by a TMD. Another problem associated with deep water TLDs is that not all water depth cooperates in dissipation of energy. In this view, this study investigates the effect of upper mounted baffles to enhance the efficiency of TLDs. This study investigates the effect of various vertical blocking ratios on the dynamic response of TLDs and structure-TLD system. This research is carried out by investigating the structural response mitigation ability of TLDs installed on a 1-storey steel frame structure. The analysis includes experimental tests on TLD, steel frame, steel frame with TLD (S-TLD), TLD with upper baffles (TU), and steel frame with TLD equipped with upper baffles (S-TU) under free vibration and harmonic load.

2. Performance parameters of TLD

Followings are the main parameters that control dynamic response of a TLD:

Mass ratio: TLD's mass to structure's mass

$$\mu = m_w/m_s \tag{1}$$

Tuning ratio: TLD's fundamental frequency to structure's natural frequency

$$\beta = f_w/f_s \tag{2}$$

This value is usually selected around 1, because when the natural frequency of TLD is tuned to the structures', at this point, the sloshing would be at maximum. For rectangular tanks, sloshing natural frequency can be estimated by applying any of two formulas as devised by Lamb (1932) and Housner (1963)

$$f_w = \frac{1}{2\pi}\sqrt{\frac{\pi g}{L}\tanh\left(\frac{\pi h_0}{L}\right)} \qquad \text{Lamb} \tag{3}$$

$$f_w = \frac{1}{2\pi}\sqrt{\frac{3.16g}{L}\tanh\left(\frac{3.16h_0}{L}\right)} \qquad \text{Housner} \tag{4}$$

Damping coefficient of TLD: based on linear wave theory (Limin 1991), where b, h, f_w and v_w are width of tank ,water depth, natural frequency of TLD and kinematic viscosity of water respectively.

$$\zeta_{TLD} = \frac{1}{2\pi}\sqrt{\frac{V_w}{\pi f_w}}\left(1+\frac{h}{b}\right) \tag{5}$$

Wave height: The dimensionless wave height

$$\eta' = \frac{\eta}{h} \tag{6}$$

Sloshing force: The dimensionless sloshing force (Shad 2015)

$$F_w' = \frac{F_w}{m_w\omega^2 A}\ , \quad F_w = 0.5\rho g b\left({h_0}^2 - {h_n}^2\right) \tag{7}$$

where F_w, A, ω and m_w are the sloshing force, amplitude of excitation, circular frequency of water sloshing and mass of water respectively. $m_w\omega^2 A$ is the maximum inertia force of water mass. Also, ρ, h_n, h_0 and g are density of water, water level of two sides of the tank and acceleration due to gravity, respectively.

Dissipation energy: The dissipation energy (dimension and dimensionless) are (Shad 2015)

$$E_w' = \frac{E_w}{0.5m_w(\omega A)^2}\ , \quad E_w = \int_{T_s} F_w\, dx_c \tag{8}$$

where, F_w, T_s, and x_c are base sloshing force, excitation period and displacement values, respectively.

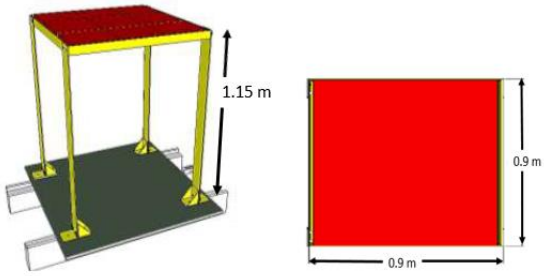
3. Description and properties of models

3.1Modelling of the steel structure

Fig. 1 shows a diagram of the structure used for this research, which is a one-storey steel frame. The structure is 0.9 m length, 0.9 m width and 1.15 m height and total mass of the structure which includes floor and members is 228 kg.

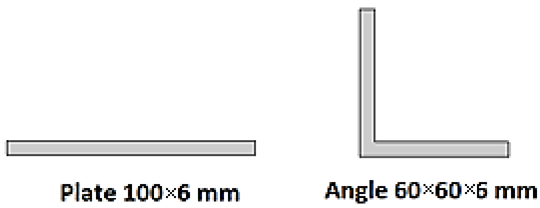
The beams and columns are made of steel plate and angle sections, while a steel plate makes the floor. Details of cross sections and properties are in Fig. 2. The employed steel is a mild steel and it mechanical properties are: density is 7800 Kg/m^3, Modulus of Elasticity (E) is 200GPa, Poisson ratio is 0.26 and shear modulus is 79.3GPa.

The structure was subjected to a free vibration test in order to obtain its natural frequency and damping ratio. Fig. 3 displays the measured time history of displacement at the roof level. Using the logarithmic decrement method, the damping ratio of the bar structure was found 1%. In addition, Fast Fourier Transform algorithm was employed to estimate the fundamental natural frequency of the structure. Results showed that the structure has a fundamental natural frequency of 1.12 Hz.



(a) (b)

Fig. 1 Shape and dimension of single degree of freedom system (a) 3-D view and (b) plan view from top



(a) (b)

Fig. 2 Cross section of (a) Columns and (b) Beams

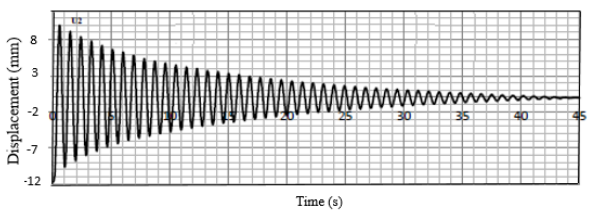
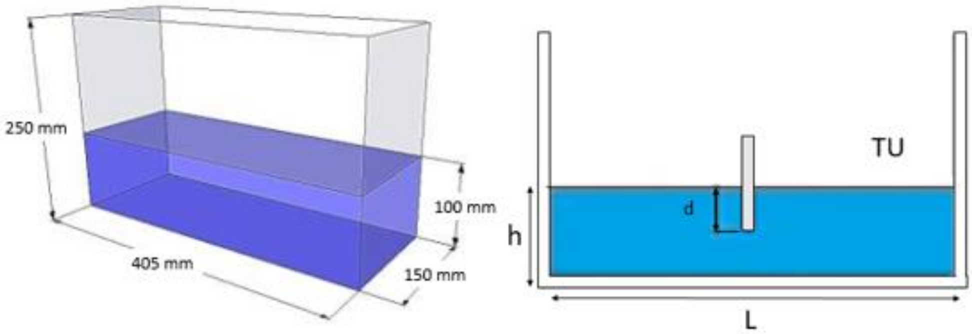


Fig. 3 Free vibration (displacement vs. time)



(a) (b)

Fig. 4 (a) The dimensions of TLD tank and (b) A 2-D schematic view of studied TLDs with upper vertical baffles (TU)

3.2 Description of the studied ordinary TLD

The TLD tank is rectangular and has the deep-water characteristics. The behaviour of TLD is assumed to be linear. The dimensions are 405 mm length by 250 mm height by150 mm width, while water height is 100 mm (Fig. 4(a)). This tank is made of clear Perspex plates with 6 mm thickness.

The natural frequency of the TLD is 1.12 Hz, depth ratio is 0.25, mass ratio is 2.63% and TLD mass is 6 kg. The tank's material properties are: E is 30 GPa, density is 1190 kg/m^3 and Poisson ratio is 0.5, and for the water: bulk modulus is 2.15 GPa, density is 1000 Kg/m^3 and dynamic viscosity is 10^{-6} Nm/s^2.

3.2.1 Description of the TLD with upper mounted baffle (TU)

The baffles locate at the middle of the tank and orthogonal to the direction of loading. The baffles are variable top-surface-piercing baffle with the vertical blocking ratio (VBR) ranging from 10% to 90%. Fig. 4(b) shows a typical TLD with baffle and Table 1 shows abbreviations used to describe studied TLD with baffles.

Assumptions made in TLD and baffles include: liquid is homogeneous and incompressible, tank walls and baffles are rigid, model is deep-water so linear behaviour is expected, free surface pressure is constant, base wall and baffles are without roughness.

Table 1 Abbreviations used to describe TLD with baffle models

Abbreviation of TLD with baffle models	Long form
TU	Combined TLD and Upper mounted baffle
TU10	Combined TLD and Upper mounted baffle with 10% vertical blockage ratio (VBR)
TU20	Combined TLD and Upper baffle with 20% vertical blockage ratio (VBR)

4. Experimental analysis

The experimental analysis involves free vibration and harmonic-base forced vibration tests on the TU models and combined structure and TU models.

4.1 Free vibration test of TU models

Fig. 5 shows the test setup that is used for free vibration test of TLD models. As can be seen from this figure, for free vibration test of TLD models a steel structure is constructed. The steel structure consists of 4 columns and 8 beams each of them with 1 m length that are welded together to form a cube. The steel structure sits on four rollers that are connected to its base. The rollers allow the steel structure to move freely along two steel rails that are located under the rollers and are fixed to the ground. Three steel beams are welded to the bottom side of the steel structure so that TLD models can be installed inside the cube and in the middle of the beams. In order to reduce the friction between TLDs and the steel frame, four rolling balls were embedded between the bottom of TLD models and beams. The steel structure is connected to a cable at the middle of the beam which is located at the left bottom side of the cube. The cable, at its other side, is connected to a 2 kg mass. During free vibration tests, the steel structure is pulled 5 cm toward the right side and then it is released to move toward the hanging mass. As can be seen from Fig. 5(b), a load cell is installed at the bottom left side of the steel structure to measure the time histories of sloshing forces. The moment that the steel structure reaches the end of steel rails it stops and the load cell records the imposed sloshing forces. A wave gauge is also installed inside the water tank of TLD models in order to record the free surface motion of water near to the wall of the tank.

4.2 Free vibration test of structure, and structure-TU system

As shown in Fig. 6, in order to perform the free vibration test on the bare structure and structure-TLD systems, the steel structure was fixed at its base to the steel platform of a shaking table. Then, the top of the steel structure was pulled 5 cm to the left side and then it was

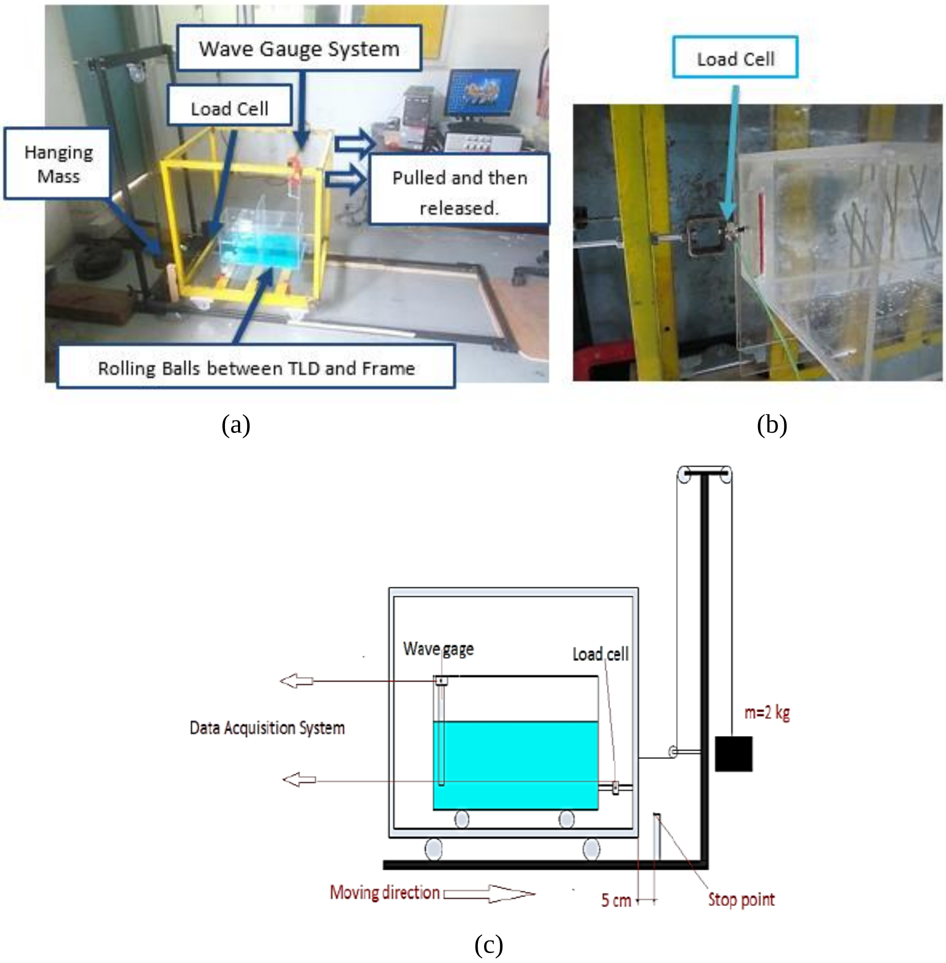


Fig. 5(a) Free vibration test setup of TLD models in order to record water sloshing forces and water height, (b) Zoom-in view from the location of the load cell and (c) side view of test setup

Fig. 6 The bare steel structure which is installed on the platform of a shake table

released to vibrate freely. An LVDT which was installed in the middle of the top beam of the steel structure measured the displacement time histories at the roof level. Later, the measured signals from this test were analysed and employed to extract the natural frequencies and damping ratios of the bare structure and structure-TLD system.

4.3 Forced vibration test of TU models

The TLD and TU models are subjected to harmonic load using a shaking table which can apply harmonic loads to the base of structures. These models are subjected to sinus displacement as given by Eq. (9). The amplitude (A) and

Table 2 Applied varying frequency ratio in the harmonic tests

TLD and types of TLD with baffle blocking ratio (10-90%)	Base displacement amplitude (mm)	Excitation frequency ratio (β)
TLD and TU Models	2.5	0.75,0.80,0.85,0.90,0.92,0.93, 0.94,0.96,0.98,0.99 ,1,1.01,1.02,1.04,1.06,1.07, 1.08,1.1,1.15,1.2

frequency (*f*) are 0.25 cm and 1.11 Hz respectively, while the tuning frequency ratio β ranges from 0.75 to 1.20. Table 2 shows the variation of frequency ratios applied in these harmonic tests. The blocking ratio of baffle in vertical direction varies from 10% to 90% .A mounted high-speed camera records the sloshing motion of each frequency ratio. This method captures the sloshing motion and maximum water height. Furthermore, the influence of blocking ratio of baffle on free surface response is studied.

$$D = Asin(2\pi\beta ft) \tag{9}$$

4.4 Forced vibration test of structure, and structure-TU system

As shown in Fig. 7 the forced vibration tests on structure-TLD systems were conducted by means of a shake table. At first, the bare steel structure was fixed at its base to the steel platform of the shake table. Then TLDs were installed at the centre of the roof of the bare structure. In order to measure the time history of displacement responses, an LVDT was installed in the middle of a roof beam parallel to the direction of excitation. In addition, an accelerometer was also installed at the roof level in order to measure the time history of acceleration responses. Another accelerometer was installed on top of the steel platform of the shake table in order to measure the imposed accelerations to the base of the steel structure.

Fig. 7 The test setup for forced vibration tests on TLD-structure systems

The structure-TLD systems were subjected to base-harmonic excitation that followed Eq. (10). In this equation, the amplitude (A') and frequency (f) are 5 mm and 1.11 Hz respectively, while the tuning frequency ratio (β') ranges from 0.75 to 1.20.

The free surface motion of water was recorded by a digital high-speed camera which was placed 1 m away from the steel structure and perpendicular to the direction of excitation. Structure without TLD, structure equipped with conventional TLD and structure equipped with modified TLDs (i.e., TU models) were three different cases that were studied.

$$D' = A'sin(2\pi\beta' ft) \tag{10}$$

5. Experimental results

This section is divided into two main parts: first part presents the water sloshing characteristics of TLD and TU models, and the second explains the effectiveness of TU models on dynamic properties of structure, and structural responses due to harmonic excitation.

5.1 Water sloshing characteristics of TLD and TU models

The free vibration was done with two displacements (5 cm and 10 cm); this is to study the effect of amplitude of excitation on the dynamic response of TLD and structure-TLD, followed by the harmonic vibration test.

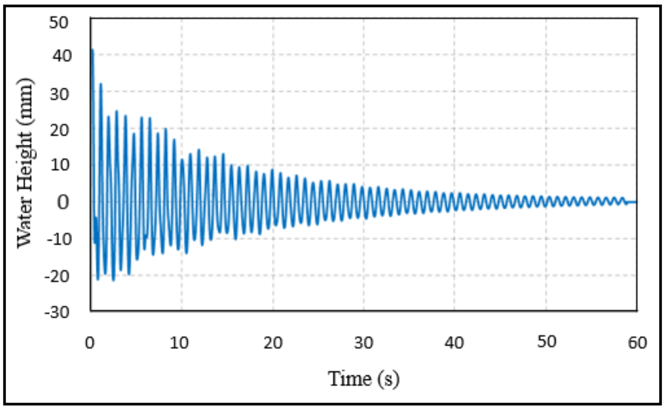
5.1.1 Free vibration tests of TLD and TLDs with baffle

The results are frequency, free surface motion, maximum water height and sloshing force of models

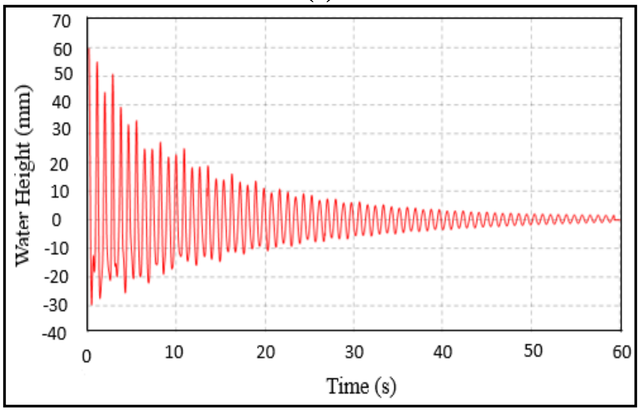
5.1.1.1 Frequency of TLD and TU

The natural frequency of TLD is measured using free vibration test. Fig. 8 shows the free surface responses of the water with the two initial displacements (5 cm and 10 cm).

The natural frequencies of models obtained from Fast Fourier Transform (FFT) algorithm. Fig. 9 shows an example of FFT curve extracted from FFT analysis. The resonance frequency of TLD in both amplitude of excitations was obtained 1.12 Hz. Fig. 10 shows the sloshing force response of TLD on the tank’s wall using the free vibration test with 50 mm initial excitation amplitude. It was seen that the amplitude of excitation did not have effect on natural frequency of TLD.



(a)



(b)

Fig. 8 Water height time histories of excited TLD (a) When frame pulled 5 cm and (b) When frame pulled 10 cm

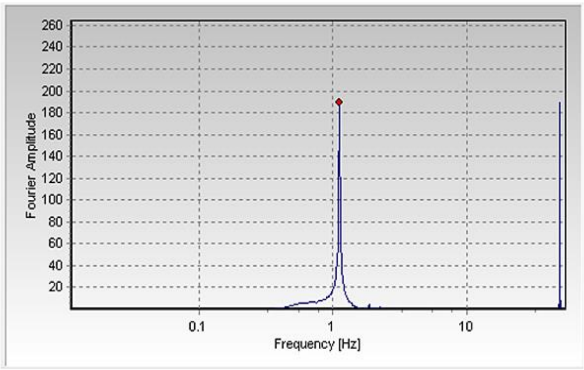


Fig. 9 FFT diagram extracted from water sloshing time histories to obtain the frequency of TLD

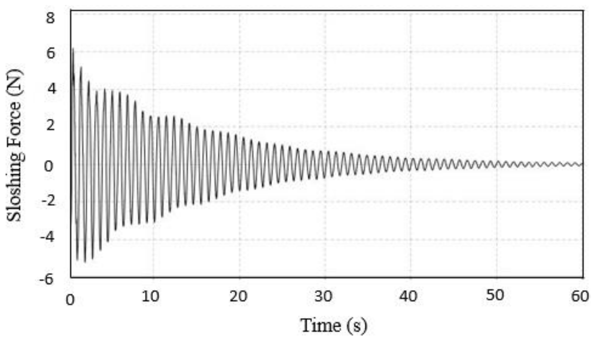


Fig. 10 Sloshing force response (When frame pushed 5 cm)

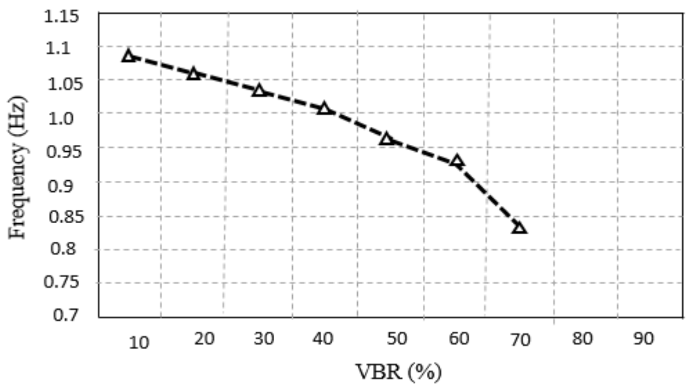


Fig. 11 Natural frequency of first mode in TU models versus various VBR

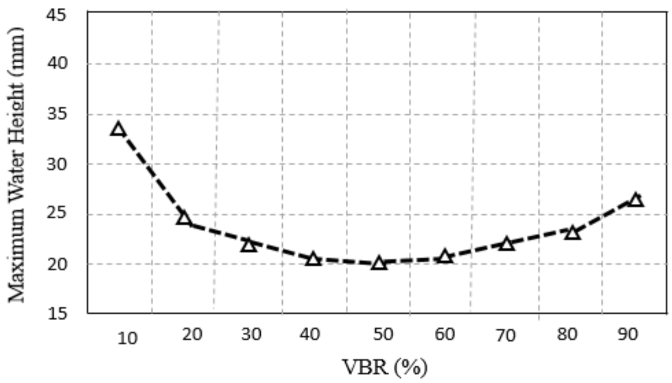


Fig. 12 Maximum water height of TU models versus various VBR

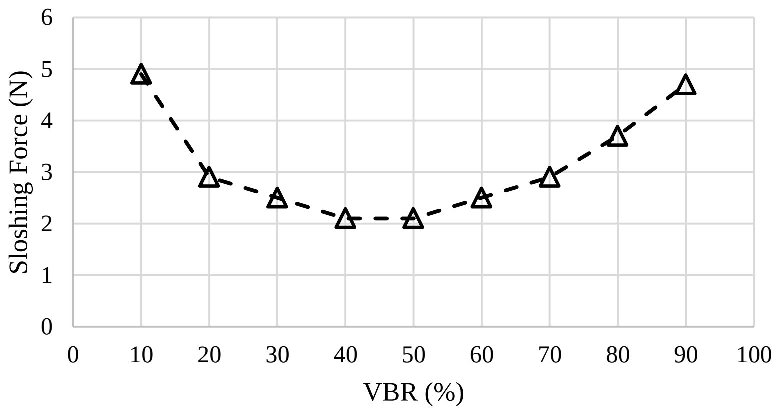


Fig. 13 Maximum sloshing force of TLD with upper baffle versus various VBR

Fig. 11 indicates the effect of various blocking ratios of baffle on the first mode of natural frequency in the TLD with baffle with varying Vertical Blocking Ratios (VBR).

The result illustrates that the first mode natural frequency decreases with increase in the blocking ratio of baffle. The natural frequency of first mode was not measurable for the blocking ratios of 80% and 90% in free vibration test.

5.1.1.2 Maximum water height of TLD and TU models

Fig. 12 shows a plot of maximum water height value of TLD with baffle against varying VBRs. It can be seen that the minimum water height is relative to the baffle with 50% vertical blocking ratio by an amount of 20 mm. The graph indicates that water height value decreases from 10% to 50% blocking ratio and increases slightly from 50% onwards. Such

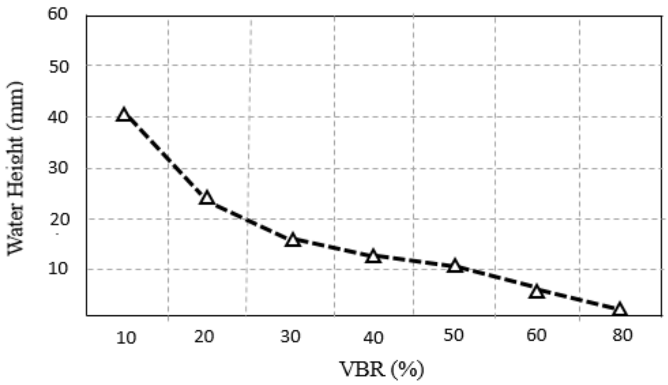


Fig. 14 Maximum water height of the first mode of water sloshing in TLD with upper baffle versus various VBR

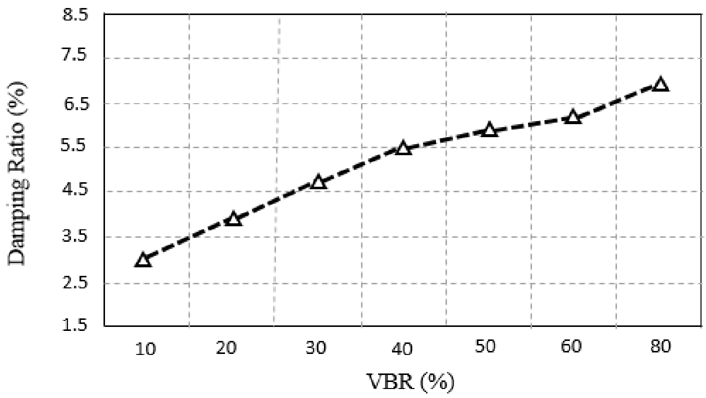


Fig. 15 Damping ratio of the first mode of water sloshing in TLD with baffle versus various VBR

a trend is attributed to the presence of baffles that splits the tank of TLD into two identical tanks.

5.1.1.3 Maximum sloshing force of TLD and TLD with baffle

This section shows the maximum sloshing force of TLD and TLD with baffles under free vibration tests with the displacement amplitudes of 50 mm and 100 mm. Fig. 13 shows the maximum sloshing force of the TLD with upper baffle versus VBR. From the graph, the amount of sloshing force of TLD with upper baffle is less than the referenced TLD (5.5N). The sloshing force decreases as the VBR increases up to 50%, this increases with a further rise in VBR. The minimum sloshing force (2.14 N) of TLD with upper baffle occurs in VBR of 50%.

5.1.2 Forced vibration test of TLD and TU models

The studied parameters of this section are the maximum water height, free surface motion and the first mode of natural frequency in models.

5.1.2.1 Maximum water height of TLD and TU models

Fig. 14 shows the change in the water height for the first sloshing mode of TLDs with upper baffles against VBR. The water height falls sharply from VBR of 10% to 30%, which is followed by gradual decrease of water height up to VBR of 80%. The maximum water height of TLD with baffle was 40 mm while the maximum for TLD without baffle was 60 mm.

5.1.2.2 Damping ratio of TLD and TLD with baffle

The damping ratios of the models were estimated by half-power bandwidth method using the water sloshing response curves. Fig. 15 describes the damping ratio of the first sloshing mode in TLDs with baffles against VBRs. The graph shows an increase in damping ratio (almost linear) as the VBR of the TLD with baffle increases. The damping ratios of all TLD with baffles are more than the damping ratio of referenced TLD.

5.1.2.3 Free surface motion of TLD and TU models

The curve of water free surface motion showed that the behaviour of water sloshing could be linear or nonlinear. Fig. 16(a) shows the curve of the water free surface motion of TLD without baffle in resonance condition of excitation. The graph shows that the behaviour of water sloshing is uniform and linear based on small excitation amplitude. Figs. 16(b) and 16(c) illustrates the examples of water free surface motion curve of TLD with two different VBR of 10% and 90%. It can be deduced from the graphs that the water free surface motion decreases with the introduction of baffles, and this decrement continues as the VBR increases.

The water height obtained for TLDs equipped with baffles are presented against excitation frequency ratios in Fig. 17.

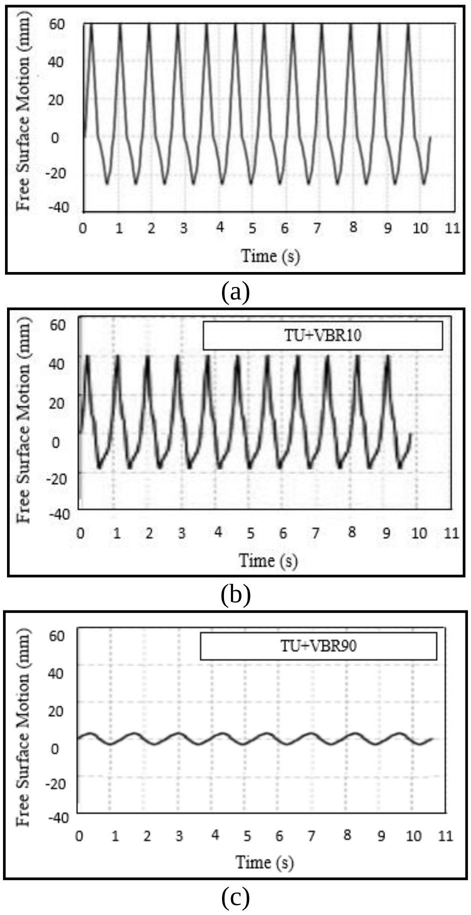


Fig. 16 Water surface motion in resonance condition versus time for (a) TLD without baffle, (b) TU+VBR10 and (c) TU+VBR90

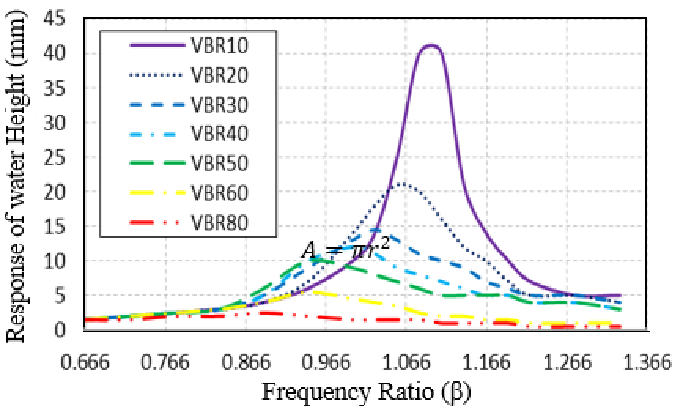


Fig. 17 Response of water height of TLD with upper baffle versus excitation frequency ratio

It can be seen that increase in the VBRs of TLDs results in the decrease in the peak of measured water heights. For instance, the maximum measured water height for the TLD with the VBR of 20% is 49% less than that of the TLD with the VBR of 10%. Results also show that increase in the VBR of TLDs shifts the peak of measured water heights toward a smaller excitation frequency ratio. For example, the peak in the water height of the TLD with the VBR of 20% occurs at the excitation frequency ratio of 1.066 while for the TLD with the VBR of 50% occurs at 0.96. Fig. 17 also shows that increase in the VBRs decreases the fluctuation in the measured water heights for the entire range of excitation frequency ratios. For instance, the difference between the maximum and minimum water

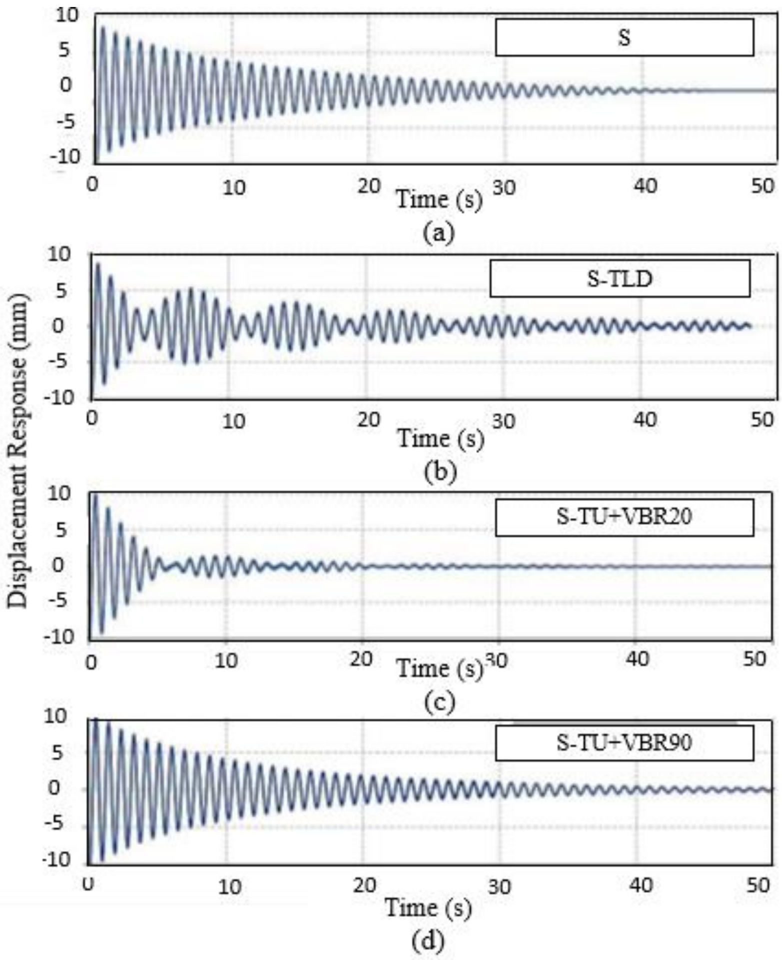


Fig. 18 Time histories of displacement response of (a) Structure, (b) Structure-TLD, (c) Structure-TU+VBR20 and (d) Structure-TU+VBR90

heights for the TLD with the VBR of 80% is less 1.6 mm while for the TLD with the VBR of 10% is more than 38.8 mm. It should be mentioned that, by an increase in VBRs, the water flow between the two parts of the tank which is separated by a baffle is reduced, therefore, the main TLD behaves like two separated but smaller size TLDs.

5.2 Performance of TLD and TLD with baffle in structural response

Free and force vibration tests are performed to estimate the influence of TLD and TU models in the reduction of structural response.

5.2.1 Free vibration test

The excitation displacement of the structure for all tests was 10 mm at the top of the structure. Fig. 18 shows time histories of the response displacements with and without damper. Fig. 18(b) shows the observed beating phenomenon in free vibration response of the structure with TLD. This occurs when two frequencies are close to each other. The presence of the TLD generates a system with two degrees of freedom having two frequency modes which are close to the frequency of the structure alone. In this system it is very difficult to estimate the damping from free vibration response of time histories. Figs. 18(c) and 18(d) shows the time histories of

structural displacement for structure-TU with VBR of 20% and 90%. It can be seen that, TLD with VBR of 20% decreases beat phenomenon and increases damping of system.

The graph in Fig. 19 shows the obtained FFT curves from free vibration test. The excitation frequency domain of the model with VBR of 20% is wider than the other models, thus, can perform better in controlling structural response than other VBRs. In the structure-TLD system with VBR of 20%, the frequency response of system is transferred from two peaks to one peak. Also this model with Fourier amplitude of 15 has the minimum value of Fourier amplitude compared to other models having different blocking ratio of baffle.

The frequency value of the structure-TLD system with upper baffle is indicated in Fig. 20. The effect of various VBR of upper baffles was observed on different types of sloshing waves. The result indicates that VBR of 10% and 20% have 2 distinct natural frequencies. But for models with VBR of 30% or more, the system behaves like a single degree of freedom. Also, there is a decreasing trend in the measured natural frequencies, a sharp drop to VBR of 20%, followed by a gradual decrement to VBR 90%

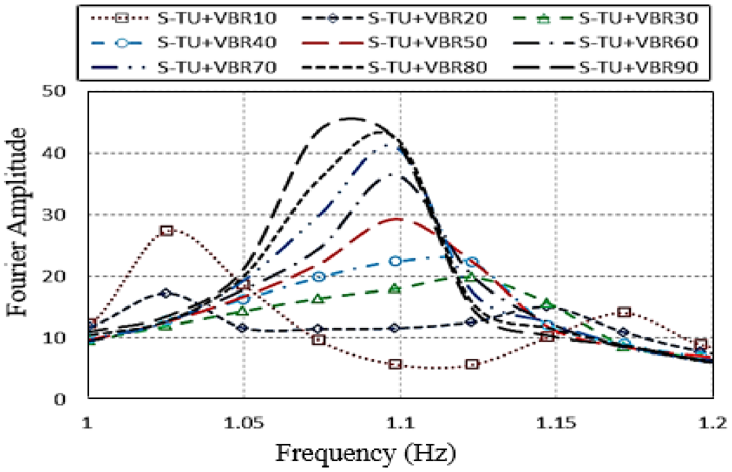


Fig. 19 Peak of Fourier amplitude versus frequency ratios of excitations

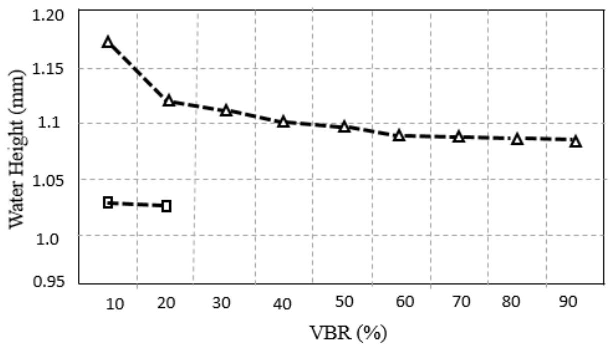


Fig. 20 Frequency of Structure-TLD with upper baffle versus VBR

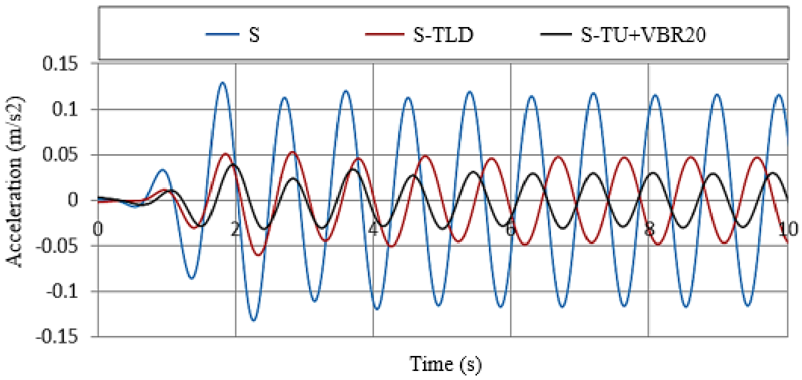


Fig. 21 Comparison of time histories of structural acceleration between structure and structure-TLD and structure-TU+VBR20

5.2.2 Force vibration test

The frequency of applied harmonic excitation varies from 0.88 to 1.32 Hz. The time histories of various measured parameters include structural displacement and acceleration which are recorded by different tests. The structural response is seen to depend on the frequency ratio and inherent damping of the vibration. Fig. 21 shows the response acceleration time histories for the structure with and without dampers considering the effect of baffles. This Figure indicates the effectiveness of baffle (S-TU+VBR20) in reducing harmonic acceleration response. Fig. 22 compares the acceleration response of TLD and TLD with baffle systems. When the VBR increases from 10 to 20%, the peak response decreases and then increases. The results indicate that the baffle with VBR of 20% possesses the best

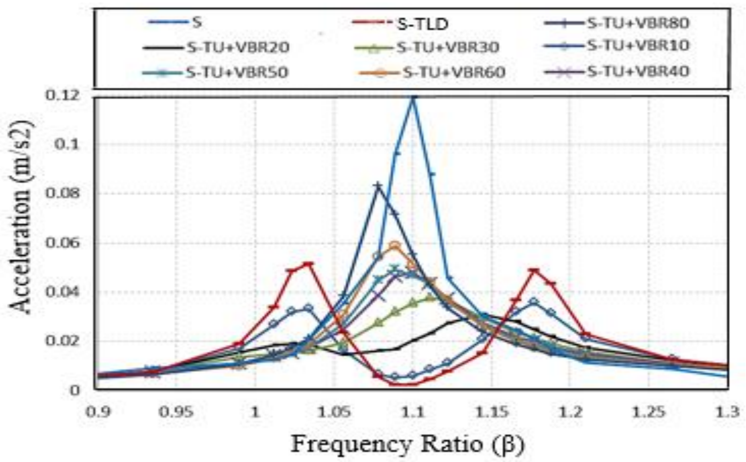


Fig. 22 Acceleration response of system against various range of frequency (Upper baffle)

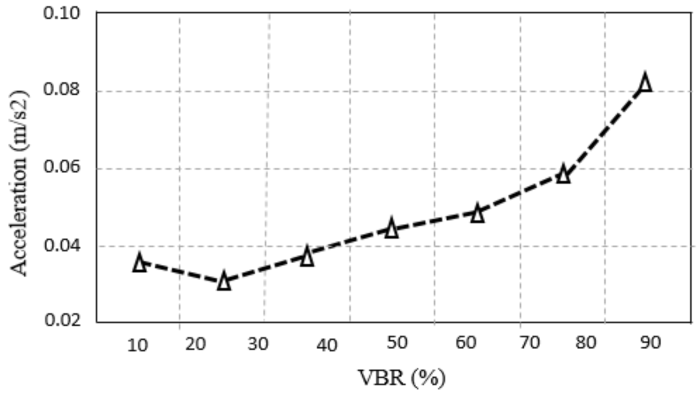


Fig. 23 Trend of response acceleration when the system is equipped with TLD (S-TU)

Table 3 Percentage reduction of response

Structure	Acceleration Reduction (%)	Displacement Reduction (%)
S-TLD	51	56
S-TU+VBR20	76	75

effect on reducing system's response to 0.031 m/s^2 (as can be seen in Fig. 23). This indicates a 76% reduction of the acceleration (structure-TLD with baffle), while it is 51% with structure-TLD. The percentage reduction of displacement structure-TLD and structure-TLD with baffle are 56% and 74%. Table 3 shows these reductions (acceleration and displacement).

6. Comparative study

This section compares the effect of upper mounted baffles on the dynamic responses of conventional TLDs with those obtained from authors' previous research on the bottom mounted baffles (Shad *et al*. 2016). Considering this fact that the test structure, mass and water depth ratios of TLDs and loading conditions in both studies have been similar a direct and unbiased comparison can be carried out. Table 4 compares the change in the sloshing frequency of TLDs when the upper and bottom mounted baffles are employed. It is seen that for both cases increase in the VBR decreases the sloshing frequency. However, the bottom mounted baffles show slightly faster reduction when compared with the upper mounted baffles. The maximum sloshing forces of upper and bottom mounted baffles obtained from the free vibration tests are presented in Table 5. It can be seen that while an increase in the VBR has decreased the measured sloshing forces of bottom mounted baffles, the upper mounted baffles experience a sharp increase in the sloshing forces from VBR of 50% onward. Results also show that the sloshing forces obtained for the upper mounted baffles are larger than those obtained for the bottom mounted baffles. The usage of bottom mounted

Table 4 Comparison of change in the sloshing frequencies for different blockage ratio (VBR)

VBR (%)	10	20	30	40	50	60	70	80	90
Upper Mounted (Hz)	1.09	1.08	1.07	1.05	1.03	0.97	0.92	0.82	0.72
Bottom Mounted (Hz)	1.08	1.06	1.03	1.01	0.96	0.93	0.83	-	-

Table 5 Comparison of maximum sloshing forces obtained from free vibration tests

VBR (%)	10	20	30	40	50	60	70	80	90
Upper Mounted (N)	4.9	2.9	2.5	2.1	2.1	2.5	2.9	3.7	4.7
Bottom Mounted (N)	4.2	3.5	2.5	1.9	1.8	1.4	1.3	1.2	1.2

Table 6 Comparison of maximum water heights obtained from free vibration tests

VBR (%)	10	20	30	40	50	60	70	80	90
Upper Mounted (mm)	34	24	23	21	20	21	24	25	27
Bottom Mounted (mm)	52	24	19	15	14	10	-	5	-

Table 7 Comparison of damping ratios obtained from free vibration tests

VBR (%)	10	20	30	40	50	60	70	80	90
Upper Mounted (%)	3	3.9	4.7	5.5	5.9	6.1	-	6.9	-
Bottom Mounted (%)	2.1	4.7	6	6.3	6.6	6.6	-	7.6	-

baffles is led to a continuous reduction in the measured water height as the VBR is increased. However, as can be seen from Table 6, the usage of the upper mounted baffles has resulted in a decrease in the water height until the VBR of 50% and an increase in the water height after that. Table 6 also shows that for larger VBRs the water heights in TLDs equipped with the bottom mounted baffles are smaller than that of the upper mounted baffles. The obtained results for damping ratios indicate that increase in the VBR enhances the damping capacity of both cases. However, in general, the bottom mounted baffles provide larger damping ratios when compared with the upper mounted baffles. This correlates well with the results obtained for sloshing forces. In other words, since the bottom mounted baffles provide a higher damping ratio, when compared with the upper mounted baffles, they dissipate more energy through wave breakage and therefore impose smaller sloshing forces to the wall of the water tank. It should be also mentioned that a comparison between the results obtained from forced vibration tests shows that the optimal blockage ratio for the bottom mounted baffles is 30% while for the upper mounted baffles is 20%. The upper and bottom mounted baffles at their optimal blockage ratios reduce the uncontrolled response accelerations 75% and 76%, respectively. This can be concluded that the bottom mounded baffles provide larger damping ratios, smaller sloshing forces and water heights when compared with the upper mounted baffles. However, at their optimal blockage ratios, both systems result in a significant reduction in the dynamic responses of the uncontrolled structure.

7. Conclusions

This paper investigates the effect of upper mounted baffles on the dynamic characteristics of conventional TLDs. At first, a conventional TLD with the mass ratio of 2.63% and the depth ratio of 0.25 was constructed. Baffles with the vertical blockage ratios (VBR) ranging from 10% to 90% were installed at the middle length of the TLD. The conventional TLD together with the TLDs equipped with the upper mounted baffles were subjected to the free vibration tests. Results indicated that addition of baffles reduced the sloshing frequency of the conventional TLD. Presence of upper mounted baffles inside the water tank altered the measured sloshing forces and water heights. Up to VBR of 50% increase in the blockage ratio decreased the measured water heights and the sloshing forces. From the VBR of 50% onward increase in the VBRs raised the water heights and the sloshing forces. In the second phase of the study, a single-bay single-story steel structure was constructed. The conventional TLD together with the TLDs equipped with baffles were installed at the roof level of the steel structure and were subjected to the free and forced vibrations. Results of free vibration tests indicated that the damping capacities of TLDs equipped with the baffles are larger than that of the conventional TLD. It was also found that increase in the blockage ratio enhances the damping ratio of structure-TLD systems. Forced vibration tests showed that when the studied structure was equipped with the TLD with blocking ratio of 20% the peak acceleration and displacement responses were reduced by 76% and 75%, respectively. However, the conventional TLD could reduce the responses up to 56%. In short, it was concluded that compared to the conventional TLD, the presence of upper mounted baffles could significantly reduce the displacement and acceleration responses especially when a proper blocking ratio was selected.

References

Ashasi-Sorkhabi, A., Kristie, J. and Mercan, O. (2014), "Investigations of the use of multiple tuned liquid dampers in vibration control", In Structures Congress 2014 (pp. 1185-1196). Boston, Massachusetts, April 3-5, ASCE.

Ashasi-Sorkhabi, A., Malekghasemi, H., Ghaemmaghami, A. and Mercan, O. (2017), "Experimental investigations of tuned liquid damper-structure interactions in resonance considering multiple parameters", *J. Sound Vib*., **388**, 141-153.

Banerji, P., Murudi, M., Shah, A.H., and Popplewell, N. (2000), "Tuned liquid dampers for controlling earthquake response of structures", *Earthq. Eng. Struct. D*., **29**(5), 587-602

Bauer, H.F. (1984), "Oscillations of immiscible liquids in a rectangular container: a new damper for excited structures", *J. Sound Vib*., **93**(1), 117-133.

Chen, J., Zhan, G. and Zhao, Y. (2016), "Application of spherical tuned liquid damper in vibration control of wind turbine due to earthquake excitations", *Struct. Des. Tall Spec. Build*., **25**(10), 431-443.

Chen, Y.H., Hwang, W.S., Chiu, L.T. and Sheu, S.M. (1995), "Flexibility of TLD to high-rise building by simple experiment and comparison", *Comput. Struct*., **57**(5), 855-861.

Cho, J.R., Lee, H.W. and Ha, S.Y. (2005), "Finite element analysis of resonant sloshing response in 2-D baffled tank", *J. Sound Vib*., **288**(4), 829-845.

Deng, X. and Tait, M.J. (2009), "Theoretical modeling of TLD with different tank geometries using linear long wave theory", *J. Vib. Acoust*., **131**(4), 041014.

Evans, D.V. and McIver, P. (1987), "Resonant frequencies in a container with a vertical baffle", *J. Fluid Mech*., **175**, 295-307.

Fediw, A.A. (1992), Performance of a one dimensional tuned sloshing water damper, ME Sc (Doctoral dissertation, Thesis, University of Western Ontario, London, Canada).

Hamelin, J. (2007), The Effect of Screen Geometry on the Performance of a Tuned Liquid Damper. MASc. thesis, McMaster University, Canada.

Housner, G.W. (1963), "The dynamic behavior of water tanks", *B Seismol. Soc. Am*., **53**(2), 381-387.

Jeyakumaran, R. and McIver, P. (1995), "Approximations to sloshing frequencies for rectangular tanks with internal structures", *J. Eng. Math*., **29**(6), 537-556.

Jin, H., Liu, Y. and Li, H.J. (2014), "Experimental study on sloshing in a tank with an inner horizontal perforated plate", *Ocean Eng*., **82**, 75-84.

Kareem, A. and Sun, W.J. (1987), "Stochastic response of structures with fluid-containing appendages", *J. Sound Vib*., **119**(3), 389-408.

Kareem, A., Kijewski, T. and Tamura, Y. (1999), "Mitigation of motions of tall buildings with specific examples of recent applications", *Wind Struct*., **2**(3), 201-251.

Kim, Y.M., You, K.P., Cho, J.E. and Hong, D.P. (2006), "The vibration performance experiment of Tuned Liquid damper and Tuned Liquid Column damper", *J. Mech. Sci. Technol*., **20**(6), 795-805.

Lamb, H. (1932), Hydrodynamics. Cambridge University Press. Cambridge, UK.

Limin, S.U.N. (1991), Semi-analytical modelling of tuned liquid damper (TLD) with emphasis on damping of liquid sloshing (Doctoral dissertation, University of Tokyo).

Min, K.W., Kim, J. and Lee, H.R. (2014), "A design procedure of two-way liquid dampers for attenuation of wind-induced responses of tall buildings", *J. Wind Eng. Ind.Aerod*., **129**, 22-30.

Noji, T., Yoshida, H., Tatsumi, E., Kosaka, H. and Hagiuda, H. (1988), "Study on vibration control damper utilizing sloshing of water", *J. Wind Eng*., **37**, 557-566.

Novo, T., Varum, H., Teixeira-Dias, F., Rodrigues, H., Silva, M.F., Costa, A.C. and Guerreiro, L. (2014), "Tuned liquid dampers simulation for earthquake response control of buildings", *Bull. Earthq. Eng*., **12**(2), 1007-1024.

Ruiz, R.O., Lopez-Garcia, D. and Taflanidis, A.A. (2016), "Modeling and experimental validation of a new type of tuned liquid damper", *Acta Mechanica*, **227**(11), 3275-3294.

Shad, H., Adnan, A., Behbahani, H.P. and Vafaei, M. (2016), "Efficiency of TLDs with bottom-mounted baffles in suppression of structural responses when subjected to harmonic excitations", *Struct. Eng. Mech*., **60**(1), 131-148.

Shad, H. (2015), Performance of Tuned Liquid Damper with Baffle in Reduction of Structural Dynamic Response, PhD Thesis, Faculty of Civil Engineering, Universiti Teknologi Malaysia;

Shang, C.Y. and Zhao, J.C. (2008), "Periods and energy dissipations of a novel TLD rectangular tank with angle-adjustable baffles", *J. Shanghai Jiaotong University (Science)*, **13**, 139-144.

Soong, T.T. and Dargush, G.F. (1997), Passive energy dissipation systems in structural engineering, Wiley.

Sun, L.M., Fujino, Y., Pacheco, B.M. and Chaiseri, P. (1992), "Modelling of tuned liquid damper (TLD)", *J. Wind Eng. Ind. Aerod*., **43**(1-3), 1883-1894.

Tait, M.J. (2008), "Modelling and preliminary design of a structure-TLD system", *Eng. Struct*., **30**(10), 2644-2655.

Tait, M.J., Isyumov, N. and El Damatty, A.A. (2007), "Effectiveness of a 2D TLD and its numerical modeling", *J. Struct. Eng. -ASCE*, **133**(2), 251-263.

Tait, M.J., Isyumov, N. and El Damatty, A.A. (2007), "Effectiveness of a 2D TLD and its numerical modeling", *J. Struct. Eng. -ASCE*, 133(2), 251-263.

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