Structural Engineering and Mechanics, *Vol. 64, No. 2 (2017) 233-241*
DOI: https://doi.org/10.12989/sem.2017.64.2.233

Seismic control of structures using sloped bottom tuned liquid dampers

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(Received April 4, 2017, Revised August 24, 2017, Accepted Sptember 2, 2017)

Abstract. Earlier numerous studies have been done on implementation of Tuned Liquid Damper (TLD) for structural vibration control by many researchers. As per current review there is no significant study on a sloped bottom TLD. TLD's are passive devices. A TLD is a tank rigidly attached to the structure and filled partially by liquid. When fundamental linear sloshing frequency is tuned to structure's natural frequency large sloshing amplitude is expected. In this study set of experiments are conducted on flat bottom and sloped bottom TLD at beach slope 20°, 30° and 45°, for different types of structures, mass ratio, and depth ratio to investigate the overall effectiveness of TLD and specific effect of TLD parameters on structural response. This experimental study shows that a properly designed TLD reduces structural response. It is also observed that effectiveness of TLD increases with increase in mass ratio. In this experimental study an effectiveness of sloped bottom TLD with beach slope 30° is investigated and compared with that of flat bottom TLD in reducing the structural response. It is observed from this study that efficiency of sloped bottom TLD in reducing the response of structure is more as compared to that of flat bottom TLD. It is shown that there is good agreement between numerical simulation of flat bottom and sloped bottom TLD and its experimental results. Also an attempt has been made to investigate the effectiveness of sloped bottom TLD with beach slope 20° and 45°.

Keywords: tuned liquid dampers; vibration control; sloshing; energy dissipation; TLD design and base excitation

1. Introduction

Large civil engineering structures are frequently exposed to severe dynamic loading from several sources including earthquakes and high winds. During high winds the sway motion at the top of a tall building and the vertical deflection on long suspension bridges may be substantial. Therefore, one of the most important problems facing civil engineers today is to find the ways to reduce the motions of a large civil structure to ensure structural integrity and human comfort.

Migration of people, shortage of land and high cost of land in the cities are reasons for tall buildings. Tall buildings are often made light and flexible, possessing low damping, which makes it vibration prone. To ensure functional performance of structure, it is required to keep the dynamic response of structure below certain value to reduce the damage of structure.

Until recently large civil engineering structures have been built in a conventional manner by designing for dynamic loads. The external dynamic loads are resisted solely by the mass and stiffness of the structure. However, as the structures have become taller and more flexible, the demand for safety has increased and the need for building structures with some degree of adaptability to external forces has been recognized.

In the last two decades structural control concepts have received considerable attention for the design of large civil structures. Several tall buildings have been constructed with various types of movement control devices installed. Most of these movement control devices are passive devices. The most commonly used passive systems are base isolation, visco-elastic dampers, and tuned mass dampers. TLD, which can effectively control vibrations induced by winds (Fujii *et al.* 1990, Kareem *et al.* 1999, Karna 2009, Tamura *et al.* 1995) and has the potential to mitigate earthquake-induced vibrations as well (Banerji *et al.* 2000, Banerji and Samanta 2011, KoH *et al.* 1994, Love and Tait 2013, Love and Tait 2015, and Zahrai *et al.* 2012).

Now a day due to innovative and effective techniques, unique multi-model TLD systems are designed to mitigate the torsional response of high rise buildings (Ross *et al.* 2015). The performance of flat bottom TLD with deep water condition when subjected to harmonic excitation is found to be improved by installing baffles (Shad *et al.* 2016). A turned liquid column damper (TLCD) is a device that is becoming increasingly popular for the control and dissipation of oscillatory motion in skyscrapers. The standard design involves two identical liquid columns connected together to form a *U*- tube oscillator (Matteo *et al.* 2016).

Tuned liquid dampers are passive dampers. TLD is a tank rigidly attached to the structure and filled partially by liquid. When frequency of tank motion is close to one of the natural frequencies of tank liquid, large sloshing amplitude is expected. If these frequencies are reasonably close to each, a resonance will occur. By tuning the fundamental sloshing frequency of TLD to the structural natural frequency, a large amount of sloshing and wave breaking will take place and will dissipate a significant amount of energy (Banerji *et al.* 2010).

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http://www.techno-press.com/journals/sem&subpage=7
ISSN: 1225-4568 (Print), 1598-6217 (Online)


Fig. 1 Schematic of recirculation zone at a flat bottom TLD corner (Morsy 2010)

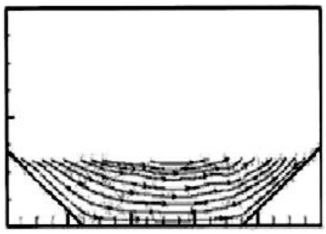
Fig. 2 Streamlines inside a sloped bottom TLD showing no recirculation zone (Morsy 2010)

1.1 Flat and sloped bottom TLD

Tuned liquid dampers with flat bottom have been used as a passive structural control device for quite some time. The sloped bottom TLD has been investigated recently by Gardarsson (1997), Gardarsson *et al.* (2001). Its behavior is markedly different from the more familiar flat bottom TLD. The flat bottom TLD is a stiffness-hardening system and displays a beating property (Lepelletier and Raichlen 1988), when the force of excitation has ceased. The motivation for the use of the sloped bottom tank came from the desire to reduce or if possible prevent the phenomenon of beating.

The effective liquid mass, for a sloped bottom TLD is much larger than that of a flat bottom TLD. From a fluid dynamic perspective, this was expected, as a relatively large portion of liquid mass does not contribute to the sloshing force due to recirculation in flat bottom tank corner as shown in Fig. 1. The Fig. 2 shows streamlines inside a sloped bottom TLD. It is immediately evident how the sloped bottom geometry almost eliminates the recirculation zones and results in a higher contributing sloshing mass.

Greater amount of water mass participates in sloshing, in sloped bottom TLD, resulting in greater magnitude of moment and base shear exerted at the TLD base. Fig. 3 and Fig. 4 show comparative schematic of flat bottom and sloped bottom TLD tanks, where, H is height of tanks, h is depth of water in tanks, b is width of tanks, L is overall length of flat bottom tank, θ is beach slope and Lo is horizontal length of sloped bottom tank.

The linear natural frequency of water sloshing motion of a flat bottom TLD can be evaluated using the dispersion relation is given by Lamb (1932) as

$$f_w = \frac{1}{2}\sqrt{\left(\frac{g}{\pi L}\right) tanh\left(\frac{\pi h}{L}\right)} \tag{1}$$

Where f_w is the frequency, g is the acceleration due to gravity, h is the water depth and L is the overall length of tank. In contrast, it is not simple to evaluate the dispersion

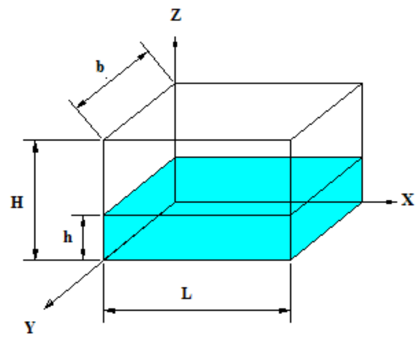

Fig. 3 Schematic of flat bottom TLD

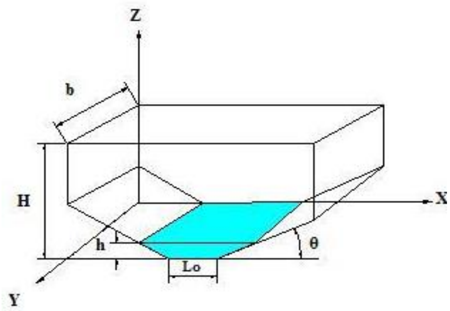

Fig. 4 Schematic of sloped bottom TLD

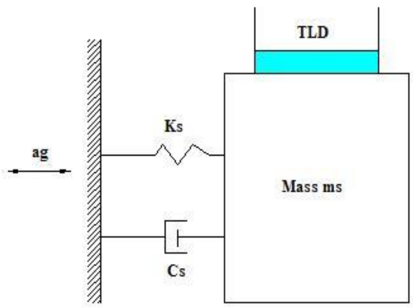

Fig. 5 Schematic of a single-degree-of-freedom structure with a rectangular tuned liquid damper

relation for sloped bottom TLD because two different slopes *viz*. horizontal and inclined are involved (Gardarsson 1997). Olson and Reed **(**2001**)** determined the experimental frequency of flat bottom TLD and compared it with numerical equation as given in Eq. (1) by replacing L by wetted perimeter L_1, defined as

$$L_1 = L_0 + \frac{2h}{sin\,\theta} \tag{2}$$

Where, L_0 is the length of the flat part of sloped bottom tank and θ is the beach slope. Using the length L_1 in Lamb's Eq. (1) instead of L resulted in a fairly close estimate of natural frequency of sloped bottom TLD. The only limitation of the above equation is that it is not defined for sinθ=0.

2. Formulation of flat bottom TLD equations

The rigid rectangular tank, which is shown in Fig. 6 has

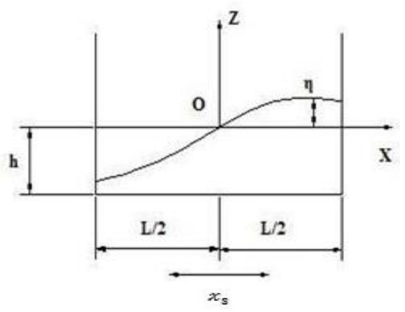

Fig. 6 Dimensions of the rectangular tuned liquid damper

a length L and width b (not shown in Fig. 6), and an undisturbed water depth of h. It is subjected to a lateral base excitation x_s that is identical to the excitation of the structure's top. The equations of motion of the water inside the tank can be defined in terms of the free surface motion, as the water depth is assumed to be shallow (Sun *et al.* 1989). Since strong earthquake ground motion generally results in large amplitude TLD excitation, the equations of motion should include the effects of wave breaking. The formulation used here has been suggested by Sun *et al.* (1992), and the governing equations of motion of the water are

$$\frac{\partial \eta}{\partial t} + h\sigma \frac{\partial (\emptyset u)}{\partial x} = 0 \tag{3}$$

$$\frac{\partial u}{\partial t} + (1 - T_H^2)\, u \frac{\partial u}{\partial x} + C_{fr}^2\, g \frac{\partial \eta}{\partial x} + gh\sigma\Phi \frac{\partial_\eta^2}{\partial x^2} \frac{\partial \eta}{\partial x} = -C_{da}\, \lambda_u\, \ddot{x}_s \tag{4}$$

Where $\eta(x, t)$ and $u(x, \eta, t)$ are the independent variables. They denote the free surface elevation above the undisturbed water level and the horizontal free surface water particle velocity, respectively. Both these variables are a function of the horizontal distance, x from o, (see Fig. 6) and time t. The horizontal acceleration of the TLD base, which is identical to the total acceleration of the structure's top is $\ddot{x}_s$, and the acceleration due to gravity is g. Eq. (3) represents the integrated form of the continuity equation for the water, and Eq. (4) is derived from the two-dimensional Navier-Stokes equation. The parameters σ, Φ and T_H in Eqs. (3) and (4) are given by following expressions (Sun *et al.* 1989, Fujino *et al.* 1992).

$$\sigma = \tanh kh/kh,$$
$$\Phi = \tanh k\,(h+\eta)/tanhkh, \tag{5}$$
$$T_{H=\tanh k(h+\eta)}$$

Where, k is the wave number. The λ in Eq. (4) is a damping parameter that accounts for the effects of the boundary layer along the tank bottom, side walls and the waters free surface contamination that can be given semi-analytically (Sun et al 1992, Fujino *et al.* 1992) as

$$\lambda = \frac{1}{(\eta + h)} \frac{1}{\sqrt{2}} \sqrt{\omega_l v} \left[1 + \left(\frac{2h}{b}\right) + s\right] \tag{6}$$

In which ω_l is the fundamental linear sloshing frequency of the water in the tank, v denotes the kinematic viscosity of water, and s denotes a surface contamination factor which can be taken as unity (Fujino *et al.* 1992). The fundamental linear sloshing frequency of the TLD is given by Fujino *et al.* (1992), which is same as given by Lamb (1932) in Eq. (1).

$$\omega_l = \sqrt{\frac{\pi g}{L} tanh(\pi\Delta)} \tag{7}$$

Where Δ is the ratio of undisturbed water depth h to the tank length L, called the water depth ratio in this paper.

The coefficient C_{fr} and C_{da} in Eq. (4) are incorporated to modify the water wave phase velocity and damping, respectively, when waves are unstable (η>h) and break (Sun *et al.* 1992). These coefficients take a unit value when waves do not break. Conversely, when waves break, C_{fr} is found empirically (Sun *et al.* 1992) to essentially have a constant value of 1.05, whereas C_{da} has a value that is dependent on the amplitude, (x_s) max, of motion of the structure's top when it does not have a TLD attached to it. This C_{da} value is given as (Sun *et al.* 1992).

$$C_{da} = 0.57 \sqrt{\frac{2h^2\, \omega_l}{Lv} (x_s)\, max} \tag{8}$$

Where, h and L are the water depth and tank length, respectively, and ω_l is sloshing frequency given by Eq. (7).

By solving Eqs. (3) and (4) simultaneously for the free surface elevation η, and neglecting higher-order terms and shear stresses along the bottom of the tank, a reasonable estimate of the shear force, F, at the base of TLD is given by the following expression (Fujino *et al.* 1992)

$$F = \frac{\rho g b}{2} \left[(\eta_n + h)^2 - (\eta_o + h)^2\right] \tag{9}$$

Where ρ is the mass density of water, b is the tank width, and η_n and η_o are the free surface elevations at the right and left walls, respectively, of the tank.

2.1 Formulation for sloped bottom TLD

Sloshing frequency of sloped bottom TLD is found to be almost the same as that of the flat bottom TLD. Using Eq. (1) as given by Lamb (1932) and by replacing L with wetted perimeter L_1 as given in Eq. (2), the sloshing frequency of sloped bottom TLD is found to be almost same as that of flat bottom TLD. The frequencies of sloped bottom TLD using Eq. (1) are experimentally compared by Olson and Reed **(**2001**)** and found that numerically computed values match with experimental results. Therefore the surface elevation η and the frequency for sloped bottom TLD are taken same as that of a flat bottom equivalent TLD, by replacing L by L_1. The objective of this study paper is to investigate the effectiveness of flat bottom and sloped bottom TLD experimentally and compare their effectiveness. The numerical study for sloped bottom TLD is limited to validate the experimental results.

2.2 TLD-structure interaction

The response of SDOF structure coupled with a TLD can be found out, using the following equation.

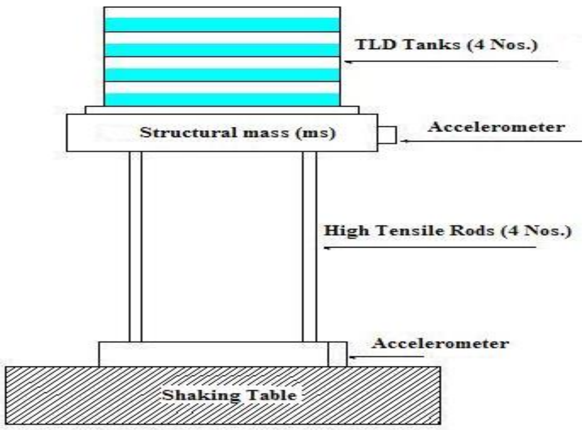

Fig. 7 Schematic diagram of TLD structure model


Fig. 8 Test setup, specimen and shaking Table


Fig. 9 Behavior of liquid inside TLD during the test

$$m_s \ddot{u_x} + c_s \dot{u_x} + k_s u_x = -\ddot{u}_g m_s + F \quad (10)$$

Where, m_s=mass of the structure, $\ddot{u}_x$ =the acceleration at the top of structure, $\dot{u}_x$=velocity at the top of structure, u_x=displacement at the top of structure, k_s=the stiffness of structure, $\ddot{u}_g$ =ground acceleration and F=total sloshing force imparted by liquid in TLD, which is obtained by solving the equation of motions of water in TLD, i.e., Eqs. (3) and (4).

3. Experimental set-up and test procedure

Fig. 7 shows a schematic representation of the TLD-structure model used for this study. 'Unidirectional spectral dynamic medium force shaker series' shaking table model (SD-10-240/GT1075M) is used for the experiments. The model SD-10-240 vibration test system is a wide frequency band electro-dynamic vibration test system capable of producing a total since vector force rating of 1000 kgf, driven by model DA-10 power amplifier and a 4 KW cooling blower. It is fully automatic shaking table controlled by central computer. Besides controlling the shaking table, it is also used for data acquisition and processing which is done by "Puma software". The size of table in plan is 1.0 m×0.75 m. The range of maximum displacement is ±51 mm. The maximum operating velocity is 0.18 m/sec and the operating frequency is in between 0 Hz to 3000 Hz. In this shaking table many in-built sensors are attached which monitor its activity. The data acquisition is done with Oras system. It is an instrument in which data can be acquired, stored and analyzed. NVGATE is the software used by Oras to process the data. It has 24 channels and is more user friendly.

The picture of the test setup, specimen, shaking table and the behavior of liquid inside TLD during experiments is shown in Figs. 8 to 10. The TLD tanks were made up of acrylic sheets, having 5 mm thick side walls and 5 mm thick base plate. For sloped bottom TLD at beach slope 20° and 45° acrylic sheets, having 3 mm thick side walls and base plate are used. For flat bottom and sloped bottom TLD at beach slope 30°, four TLD tanks were stacked one above the other and for case number 3 at beach slope 20° and 45°, eight TLD tanks are stacked one above the other and rigidly connected to each other to act as a single unit. The free board, i.e., the gap between the free surface and the roof of the TLD tank was provided on the basis of numerical simulations of the expected water profiles, carried out in advance, and with the objective that wave profiles should not be disturbed due to splashing on the roof of the tank during the experiments. A small notch was kept on side wall parallel to the direction of excitation to facilitate pouring water in TLD. This TLD tank unit was rigidly connected to the top of structure, which was mounted on the shaking table. The structural model was made up of mild steel plates of varying thickness to ensure that the mass given in Table 1 was achieved in each case, but thick enough to represent a rigid floor, supported on four high tensile steel rods of 6.3 mm diameter, which represent the columns. As welding a high tensile rod makes it brittle, which eventually cause it to break even at small displacement, a barrel-and-wedge system was used to connect both roof and base steel plates rigidly to high tensile rods. This innovative technique offered not only the desired flexible structure but also the flexibility in changing the frequency of this single-degree-of-freedom model by changing the position of mild steel plates along the high tensile steel rods. The base plate of structural model was directly bolted to the shake table to avoid any relative displacement between the structural base and the shake table. Care was taken to ensure that structure is symmetrical. Accelerometers were placed at the top and at the base of the structural model (as shown in Fig. 7) to

Fig. 10 Eight TLD tanks stacked one over the another (case 3 at beach slope 20°) showing behavior of liquid inside TLD during the test

Table 1 Structural properties and TLD parameters for flat bottom TLD

Case No.	Mass kg	Structural period (Ts) sec.	Structural damping %	Tank size m		Depth ratio Δ	Mass ratio μ %
				L	b		
1	83.379	0.800	1.600	0.228	0.051 0.102	0.157	0.50, 1.00, 2.00, 4.00
2	83.379	0.675	1.434	0.162	0.1015 0.203	0.157	0.50, 1.00, 2.00, 4.00
3	83.379	0.854	1.600	0.154	0.228	0.077	0.50, 1.00, 2.00

measure structural and base acceleration respectively. There were two control accelerometers placed at the two extreme corners at the floor level in the direction perpendicular to the direction of motion. These were provided to monitor the transverse and torsion motion of the floor. It was consistently noted that these accelerometers gave almost a zero signal, which implied that the transverse and torsion motions of the floor were negligible and the motion of the floor was along the direction of shaking only, as is evident from Fig. 9.

The mass ratio, μ, which is the ratio of the water mass in the TLD to the structure mass, was controlled by selectively filling water in the individual tanks to the desired depth defined by the depth ratio (Δ), which is the ratio of the depth of water to the length of tank in the direction of shaking. Therefore, in any experiment it was possible to consider four different sets of mass ratios, depending on whether one, two, three, four or all eight of the tanks were filled with water to the desired depth ratio. However, in the actual experiments one, two, four or eight tanks were used for specific mass ratios considered.

3.1 Structural properties and TLD parameters

Tables 1 to 4 show structural properties and TLD parameters considered in this study. A set of experiment was planned by considering all aspects of TLD design parameters viz. mass ratio and depth ratio. Mass of TLD tank which was rigidly attached to the structure was included in the structural mass. Depending upon the structural frequency, size of TLD's was designed by using Eq. (1) for given depth ratio. Width of the tank was adjusted to get desired mass ratio for different set of experiments. Structural damping was determined before each set of the experiment. Set of TLD-structure was subjected to harmonic sinusoidal motions with different excitation frequencies and amplitude of motion was kept constant as 0.039 m/s².

Where,

L_1 = Wetted perimeter of sloped bottom TLD,

Table 2 Structural properties and TLD parameters for sloped bottom TLD (beach slope 20°)

Case No.	Mass kg	Structural period (Ts) sec.	Structural damping %	Tank size m		Depth ratio Δ	Mass ratio μ %
				L_1	b		
1	83.379	0.800	1.600	0.228	0.0995 0.199	0.157	0.50, 1.00,2.00
2	83.379	0.675	1.434	0.162	0.195	0.157	0.50, 1.00, 2.00
3	83.379	0.854	1.600	0.145	0.168	0.077	0.50, 1.00, 2.00

Table 3 Structural properties and TLD parameters for sloped bottom TLD (beach slope 30°)

Case No.	Mass kg	Structural period (Ts) sec.	Structural damping %	Tank size m		Depth ratio Δ	Mass ratio μ %
				L_1	b		
1	83.379	0.800	1.600	0.232	0.0765 0.153	0.157	0.50, 1.00, 2.00, 4.00
2	83.379	0.675	1.434	0.162	0.157 0.314	0.157	0.50, 1.00, 2.00, 4.00
3	83.379	0.854	1.600	0.145	0.310	0.077	0.50, 1.00, 2.00

Table 4 Structural properties and TLD parameters for sloped bottom TLD (beach slope 45°)

Case No.	Mass kg	Structural period (Ts) sec.	Structural damping %	Tank size m		Depth ratio Δ	Mass ratio μ %
				L_1	b		
1	83.379	0.800	1.600	0.228	0.0715 0.143	0.157	0.50, 1.00, 2.00
2	83.379	0.675	1.434	0.162	0.140	0.157	0.50, 1.00, 2.00
3	83.379	0.854	1.600	0.145	0.149	0.077	0.50, 1.00, 2.00

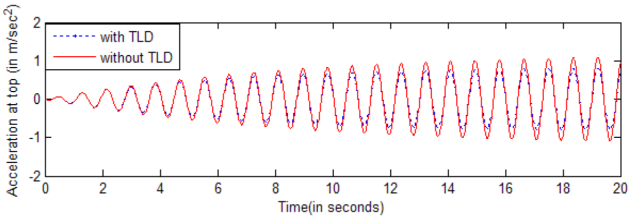

Fig. 11 Structural response history of peak acceleration with and without flat bottom TLD subjected to harmonic base excitation (Structure type Case 3, T_s=0.854s, Δ=0.077, A_o=0.039 m/s² and μ=1%)

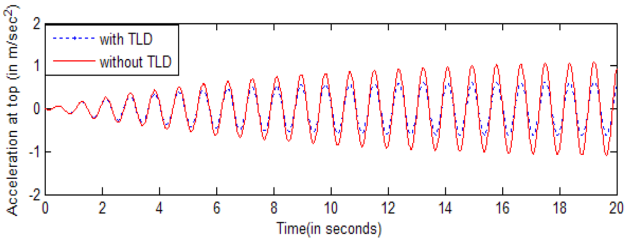

Fig. 12 Structural response history of peak acceleration with and without flat bottom TLD subjected to harmonic base excitation (Structure type Case 3, T_s=0.854s, Δ=0.077, A_o=0.039 m/s² and μ=2%)

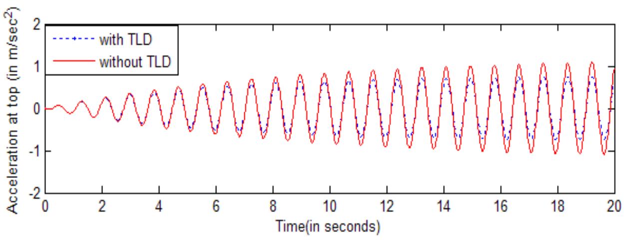

Fig. 13 Structural response history of peak acceleration with and without sloped bottom TLD at beach slope 30°, subjected to harmonic base excitation (Structure type Case 3, T_s=0.854s, Δ=0.077, A_o=0.039 m/s² and μ=1%)

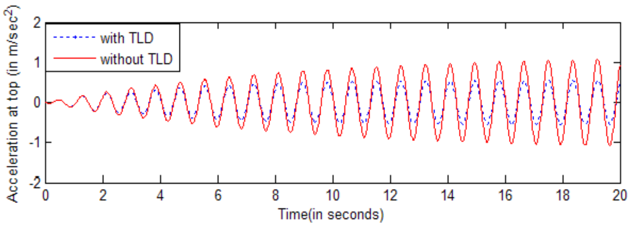

Fig. 14 Structural response history of peak acceleration with and without sloped bottom TLD at beach slope 30°, subjected to harmonic base excitation (Structure type Case 3, T_s=0.854s, Δ=0.077, A_o=0.039 m/s² and μ=2%)

Table 5 Comparison of experimental and numerical results of percentage reduction in peak structural acceleration for structures with different mass ratio (%) - Flat bottom TLD

Structure Type	Percentage reduction in peak structural acceleration - Flat bottom TLD					
	μ=0.5%		μ=1%		μ=2%	
	Experimental	Numerical	Experimental	Numerical	Experimental	Numerical
Case 3 T_s= 0.854 Sec. Δ= 0.077	16.686	15.369	20.770	26.779	50.641	42.232

Table 6 Comparison of experimental and numerical results of percentage reduction in peak structural acceleration for structures with different mass ratio (%) - Sloped bottom TLD (beach slope 30°)

Structure Type	Percentage reduction in peak structural acceleration - Sloped bottom TLD (beach slope 30°)					
	μ=0.5%		μ=1%		μ=2%	
	Experimental	Numerical	Experimental	Numerical	Experimental	Numerical
Case 3 T_s= 0.854 Sec. Δ= 0.077	19.486	18.417	40.140	31.853	53.208	48.936

L = Actual Length of Flat bottom TLD,
b = Breadth of Flat bottom and Sloped bottom TLD.

4. Results and discussion

4.1 Behavior of structure with TLD

Comparison of time history of peak acceleration at the top of structure for case 3 without TLD and structure with flat bottom TLD and structure with sloped bottom TLD is shown in Figs. 11 to 14, the tuning ratio is considered as one.

Figs. 11 to 14 show the manner in which TLD reduces peak response of structure. It can also be seen that TLD is not effective in initial phase of structure vibration because water motion is then weak. Ones strong motion of water starts TLD becomes increasingly effective in reducing response as water sloshing dissipates more energy. Comparing response of flat bottom and sloped bottom TLD, it is observed that effectiveness of sloped bottom TLD is more. This may be due to reason that relatively large portion of liquid mass does not contribute to sloshing force due to recirculation in flat bottom tank corner. While sloped bottom geometry almost eliminates recirculation zone, resulting in higher contributing sloshing mass as explained in section 1.1.

4.2 Comparison of experimental results with numerical results

A MATLAB program is used to solve governing differential equations of TLD when subjected to horizontal motion using Runge-Kutta-Gill's method. This exercise is done to compare the experimental results with numerical simulation. Table 5 and Table 6 show, experimental and numerical results of the percentage reduction of peak structural acceleration, for case 3 for flat bottom and sloped bottom TLD at beach slope 30° respectively. Table 5 and Table 6 compare the experimental results with numerical

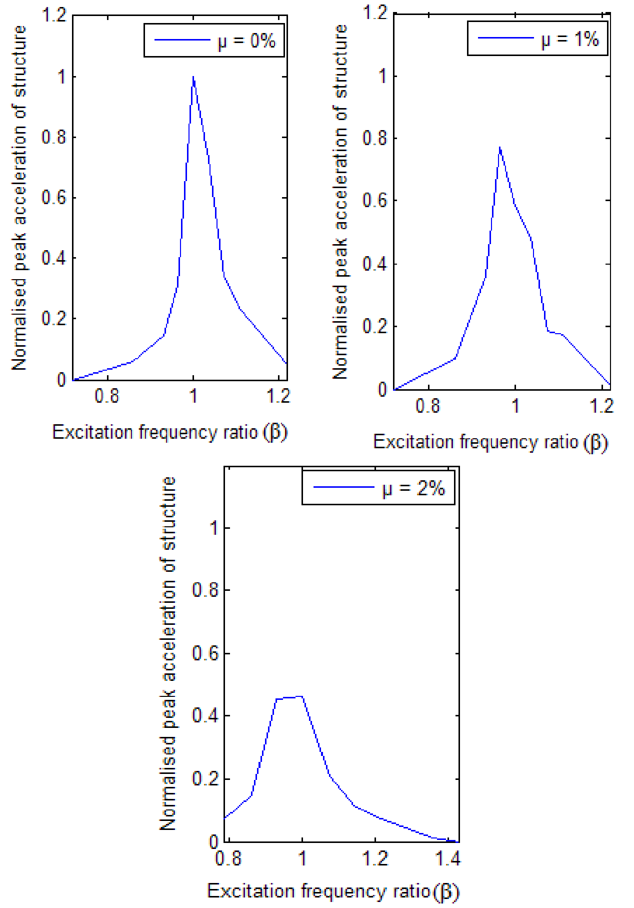

Fig. 15 Normalized peak acceleration for different mass ratio and varied β ratio, for flat bottom TLD, (Structure type Case 3, T_s=0.854 sec., Δ=0.077, A_o=0.039 m/s²)

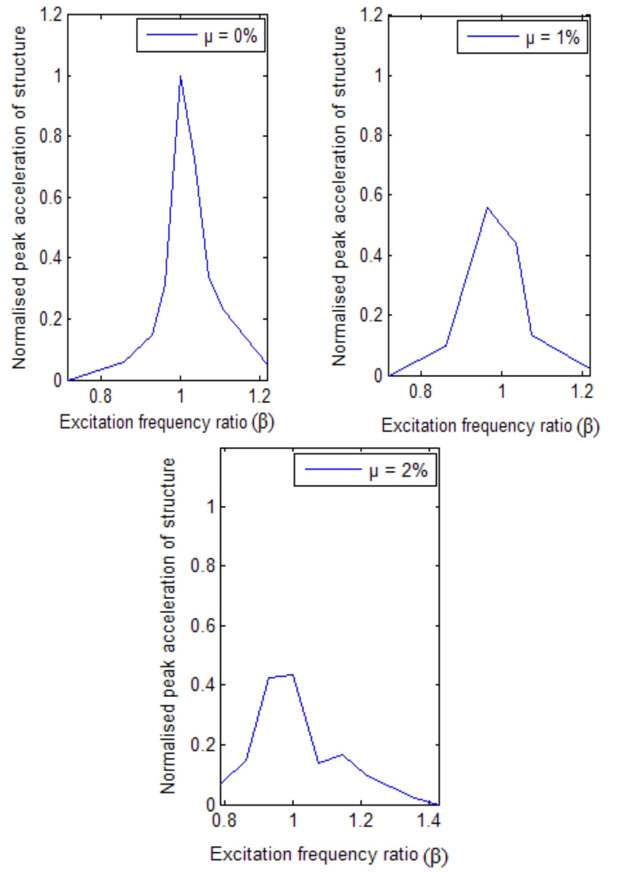

Fig. 16 Normalized peak acceleration for different mass ratio and varied β ratio, for sloped bottom TLD, at beach slope 30° (Structure type Case 3, T_s=0.854, Δ=0.077, A_o=0.039 m/s²)

simulation. The results are presented for three mass ratios i.e., 0.5%, 1% and 2%. From the comparison it is seen that the experimental results are in good agreement with the numerical results. The effectiveness of TLD obtained from experiments is higher than that of numerical simulation for both flat bottom and sloped bottom TLD. Thus the TLD in real situation is more effective than predicted by numerical simulation. As explained earlier in section 2.1, the numerical simulation for sloped bottom TLD is done using the equation of motion in flat bottom TLD by replacing L by L_1. Hence results from numerical simulation are almost close to the experimental results. Therefore henceforth only experimental results are presented.

4.3 Experimental results and discussion

The comparison of frequency response graphs for structure without TLD, with flat bottom TLD and sloped bottom TLD are presented in Figs. 15 and 16 for case 3. From these frequency response graphs it can be observed that, sloped bottom TLD with 30° slope is more effective in reducing the structure response as compared to flat bottom TLD.

Figs. 15 and 16 show a comparison of experimental results of normalized peak acceleration at the top of structure with both flat bottom and sloped bottom TLD for harmonic base excitation. The graphs are for varying excitation frequency ratio, β, (which is the ratio of the frequency of the harmonic excitation say $\bar{\omega}$ and the fundamental natural frequency ω of the structure) and for different mass ratios, μ.

4.4 Effect of mass ratio and depth ratio

The percentage reduction in peak structural acceleration obtained from experiments both, for flat bottom and sloped bottom TLD (beach slope, θ=30°) for four different mass ratios are presented in Table 7 for cases 1 to 3.

In all experiments and in all three cases, the amplitude of base excitation is kept constant as 0.039 m/s². Amplitude is low due to the limitations of experimental setup. The diameter of column in experimental setup is 6.3 mm. At high level excitation the structure will behave nonlinearly and will get damaged, therefore the amplitude of excitation is restricted.

4.4.1 Effect of mass ratio

From Table 7 it is seen that as the mass ratio increases, the effectiveness of both flat bottom and sloped bottom TLD increases. This is because larger volume of water for a higher mass ratio absorbs and dissipates more energy. From a practical point of view, however higher water mass

Table 7 Percentage reduction in peak structural acceleration for structures with Flat bottom and Slopped bottom TLD (beach slope 30°) with different mass ratio (%)-Experimental

Mass ratio μ %	Percentage reduction in peak structural acceleration -Experimental					
	Flat bottom TLD			Sloped bottom TLD (beach slope 30°)		
	Case 1 Δ=0.157 T_s=0.80	Case 2 Δ=0.157 T_s=0.675	Case 3 Δ=0.077 T_s=0.854	Case 1 Δ=0.157 T_s=0.80	Case 2 Δ=0.157 T_s=0.675	Case 3 Δ=0.077 T_s=0.854
0.5%	1.952	14.726	16.686	8.026	17.123	19.486
1%	5.856	20.119	20.770	9.544	23.373	40.140
2%	21.691	45.119	50.641	41.648	51.626	53.208
4%	26.898	57.791	***	63.340	63.356	***

***: Reading could not be taken due to practical reason.

implies a greater space requirement to install TLD tank in structure which may not always be feasible. In this study four values of mass ratio i.e., 0.5%, 1%, 2% and 4% are considered which are small enough to be generally practical and large enough for TLD to be effective as a control device.

The percentage reduction response for sloped bottom TLD is more than that of flat bottom TLD for the same mass ratio. This is due to the fact that relatively large portion of liquid mass does not contribute to sloshing force due to recirculation in flat bottom tank corner. While sloped bottom geometry almost eliminates recirculation zone, which results in higher contributing sloshing mass.

4.4.2 Effect of depth ratio

In Table 7, results are presented for different depth ratios i.e., Δ=0.157 for case 1and 2 and Δ=0.077 for case 3. From these results it can be observed that the effectiveness of both flat bottom and sloped bottom TLD is more for depth ratio Δ=0.077 as compared to depth ratio Δ=0.157. This is because the amplitude of base motion is low i.e. 0.039 m/s². The earlier studies have used data originally developed from low excitation level and using shallow water theory (Sun *et al.* 1989, Fujino *et al.* 1992, Chaiseri 1989). Further Banerji *et al.* (2000) have shown that for low level of excitation, small depth ratio is more effective.

4.4.3 Effect of beach slope

The percentage reduction in peak structural acceleration obtained from experiments for sloped bottom TLD with two different slopes i.e., 20° and 45° beach slopes are presented in Table 8.

From Tables 7 and 8 it is observed that for depth ratio Δ=0.157 for case 1 and 2 the effectiveness of sloped bottom TLD with beach slope 20° and 45° is highest as compared to that of sloped bottom TLD with beach slope of 30°. For sloped bottom TLD with beach slope equal to 30° and for depth ratio Δ=0.077 i.e., case 3 the effectiveness of sloped bottom TLD is highest as compared to those of sloped bottom TLDs with beach slope 20° and 45° (Refer Table 7). For some cases for sloped bottom TLD with beach slope 20° and 45° the response of structure with sloped bottom

Table 8 Percentage reduction in peak structural acceleration for structures with Sloped bottom TLD (beach slope 20° and 45°) with different mass ratio (%)-Experimental

Mass ratio μ %	Percentage reduction in peak structural acceleration -Experimental					
	Sloped bottom TLD (beach slope 20°)			Sloped bottom TLD (beach slope 45°)		
	Case 1 Δ=0.157 T_s=0.80	Case 2 Δ=0.157 T_s=0.675	Case 3 Δ=0.077 T_s=0.854	Case 1 Δ=0.157 T_s=0.80	Case 2 Δ=0.157 T_s=0.675	Case 3 Δ=0.077 T_s=0.854
0.5%	18.416	27.952	-37.016	31.770	48.212	-26.887
1%	50.520	31.202	3.683	50.208	63.705	-50.828
2%	52.041	45.395	47.513	25.625	52.329	24.861

TLD is more than the structure without TLD and results are not consistent. Hence effect of beach slope for sloped bottom TLD is needs further investigation.

5. Conclusions

An experimental study on the effectiveness of flat bottom and sloped bottom TLD in controlling the response of a structure subjected to harmonic ground motion is carried out. The experimental results show that a properly designed TLD can significantly reduce response of structure. This is because of additional damping provided to the structure due to increased sloshing. For the given mass ratio, the effectiveness of sloped bottom TLD with 30° beach slope is significantly higher, compared with flat bottom TLD. The effectiveness of both flat bottom TLD and sloped bottom TLD increases with increase in the mass ratio.

On the basis of experimental and numerical results optimum value of depth ratio for flat bottom and sloped bottom TLD with beach slope 30° is found to be 0.077. In the present investigation the sloped bottom TLD with beach slope 30° is found to be more effective. The effectiveness of sloped bottom TLD with beach slope other than 30° needs further investigation.

Acknowledgments

The research described in this paper was financially supported by the TEQIP-II. This financial support is heartily acknowledged.

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