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EARTHQUAKE VIBRATION CONTROL OF STRUCTURES USING TUNED LIQUID DAMPERS: EXPERIMENTAL STUDIES

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Earlier studies have shown conclusively that a Tuned Liquid Damper (TLD) is effective for controlling vibrations in structures subjected to narrow-banded wind excitations. A recent numerical study has shown that if the design parameters of a TLD are properly set, this device could also be very effective for controlling structural vibration to broad-banded earthquake excitations. Here the results of a reasonably comprehensive set of experiments are presented to investigate the overall effectiveness of TLDs and the specific effect of TLD parameters (depth and mass ratios) for earthquake vibration control of structures. Effects of various earthquake ground motions parameters such as amplitude, frequency content, duration of excitation etc. are also evaluated. It is shown that there is good agreement between the numerical simulation and experimental results. This experimental study conclusively shows that a properly designed TLD reduces structural response to broad-band earthquake excitations. It is also observed that effectiveness of TLD increases with increase in mass ratio, depth ratio and amplitude of ground motion.

Keywords: base excitations, earthquake motions, vibration control, tuned liquid dampers, control device design

1. Introduction

Earthquakes are highly unpredictable, destructive and cause tremendous loss of life and property. Recent destructive earthquakes – such as those in China (2008), Iran (2003), India (2001),

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Taiwan (1999), India (1999), India (1997), Japan (1995), and USA (1994) – have demonstrated the importance of mitigating effects of earthquakes through appropriate measures in the design of both old and new structures. In fact, one of the challenges that a structural engineer faces is to both retrofit old structures and design new structures while finding effective and economical means of protecting structures and their contents from the damaging effects of earthquake ground motions.

Recent research studies have concentrated on innovative methods for controlling the earthquake response of structures by installing additional devices at proper locations in the structure. A tuned liquid damper (TLD) system represents an efficient and simple technique to increase the damping of a structure and thereby control its earthquake response. It involves the attachment of one or multiple appropriately designed liquid-filled tanks to the structures. The TLD system relies on the sloshing of the liquid to dissipate a portion of the dynamic energy of the structure subjected to earthquake ground motions and thus controlling the structural response. The growing interest in liquid dampers is due to their low capital and maintenance cost and their ease of installation into existing and new structures.

Banerji et al. (2000) have shown through numerical studies that if the design parameters of a TLD are set appropriately, that TLD can be very effective in controlling earthquake response of structures. The numerical model for the TLD used in the above study was based on a shallow water theory suggested by Sun and his co-researchers (1989, 1991 and 1992). Most of the experimental studies carried out in the past (Koh et al. (1994), Simizu and Hayama (1987) and Fujino et al. (1992)) are for TLDs subjected to small amplitude base motions. It is well understood that the response of a TLD to large amplitude base motions would potentially be significantly different from that for small amplitude base motions due to the larger probabilities of surface wave breaking occurrence.

This study here is an attempt to investigate the effect of large amplitude base motion of the TLD on the response of a structure subjected to earthquake type broad-banded base excitations. The model structures were designed such that the natural frequencies of these structures were in the region of highest vulnerability to typical earthquake ground motions. The study is in continuation of the earlier numerical study done by Banerji et al. (2000). The performance of a TLD in controlling the structural response for varying TLD and structure base motion parameters is evaluated experimentally. The design values of the TLD parameters, the frequency ratio, depth ratio and mass ratio, which affect the performance of TLD in controlling the earthquake response of a structure, are verified experimentally. Various values of the base motion central frequency, frequency band, and amplitude are considered in the experiments to study the TLD effectiveness for structures subjected to a wide variety of earthquake ground motions.

2. Experimental Set-up and Test Procedure

Figure 1 shows a schematic representation of the TLD-structure model used for this study. Uni-directional shaking table (transnational degree of freedom) is available in Heavy structures laboratory (HSL) of IIT Bombay, which operates on servo-controlled actuator. The size of table in plan is 1.2 m x 1.2 m; weighs approximately 500 kg and is anchored securely down to a concrete slab. The range of maximum displacement is ±125 mm. The maximum operating velocity is 0.88 m/sec and the operating frequency is in between 0 to 50 Hz. The pictures of the test setup, specimen, shaking table and the behavior of liquid inside TLD during experiment are shown in Figure 2. The TLD tanks were made up of acrylic sheet, having 6 mm thick sidewall and 8 mm thick base plate. Four TLD tanks were 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. Later video profiling during the experiments showed that there was no splashing of water on the roof of any of the tanks. A small notch was kept on sidewall parallel to the direction of excitation to facilitate pouring water in TLD. This TLD tank unit was rigidly connected to the top of a 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 7-mm diameter, which represent the columns. As welding a high tensile rod makes it brittle, which eventually causes it to break even at small displacements, a barrel-and-wedge system was used to connect the both the roof and base steel plates rigidly to the 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 the structural model was directly welded to the shaking table to avoid any relative displacement between the structural base and the table. Care was taken to ensure that the structure is symmetrical. Accelerometers were placed at the top and at the base of the structural model (as shown in Figure 1) to measure structural and base acceleration respectively. There were 2 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 torsional motion of the floor. It was consistently noted that these accelerometers gave almost a zero signal, which implies that the transverse and torsional motions of the floor are negligible and the motion of the floor is along the direction of shaking only, as is evident from Figure 2(b) also.

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 the 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 or all four of the tanks were filled with water to the desired depth ratio. However, in the actual experiments, one, two or four tanks were filled, as specific mass ratios were considered as given in Table 1.

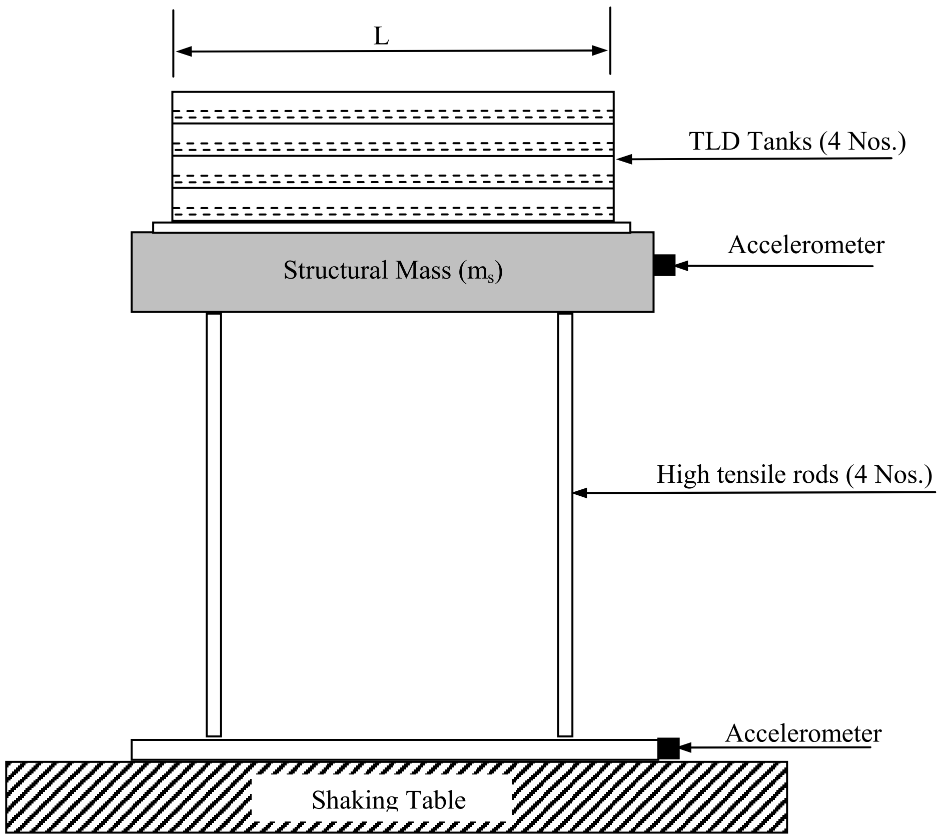


Figure 1. Schematic diagram of TLD-structure model

Table 1. Structural properties and TLD parameters

Case No.	Mass (Kg)	Structural period (T_s) (s)	Structural damping (%)	Tank size		Depth ratio (Δ)	Mass ratio (μ) (%)
				Length (m)	Width (m)		
Case 1	91	0.9	1.6	0.153	0.228	0.077	0.49, 0.97, 1.95
Case 2	93	0.9	1.6	0.228	0.141	0.118	1.01, 2.02, 4.04
Case 3	130	0.7	1.3	0.175	0.28	0.155	0.94, 1.88, 3.76
Case 4	101	0.9	2.0	0.28	0.175	0.151	2.05, 4.10
Case 5	55	0.9	2.0	0.16	0.52	0.078	1.81, 3.62

(a) (b)

Figure 2. a) test setup, specimen and shaking table; and b) behavior of liquid inside TLD during the test

Table 1 shows the structural and TLD properties considered in this study. Five sets of experiments were planned in such a way that all aspects of TLD design parameters such as mass ratios and depth ratios are covered. In each set of experiments three different types of mass ratios were considered (except case no: 4 and 5, where only two mass ratios were considered). Structural frequencies were chosen to reflect the structures, which were commonly vulnerable during majority of the earthquake motions. The mass of TLD tanks, which were rigidly attached to the structures, was included in the structural mass. Depending upon the structural frequencies, sizes the TLDs were designed as given in Banerji et al. (2000). The width of the tank was adjusted to get desired mass ratios for a particular set of experiments. Structural damping was determined before each set of experiments by using half power bandwidth method, with a harmonic base excitation sweep over a range of frequencies. Once the TLD-structure was installed on shaking table, B&K make low mass Deltraton 4507B ICP accelerometers were attached to the base and top of the structure. A B&K Pulse 3560D computerized data acquisition and analysis system was used to acquire and analyze the experimental data. In the first phase of experiments, each set of TLD-structure system was subjected to harmonic sinusoidal base motions with different excitation frequencies and amplitude of motions. In the second phase each set of TLD-structure system was subjected to various different sets of earthquake base motions, each reflecting different ground motion characteristics as defined below.

3. Characteristics of Ground Motions

The structural response subjected to earthquake ground motions is mostly governed by ground motions characteristics such as intensity, frequency content and duration of ground excitation. This is particularly true when studying the effectiveness of a TLD in controlling the earthquake response of a structure. The amplitude variations observed in records of strong-motions earthquakes usually follows some general pattern. Typically, the recorded earthquake ground motions begin with small amplitudes, increasing with time until a period of strong motion occurs, after which the amplitude dies out over a period of time. In this study, ten artificial acceleration time histories were generated for each set of earthquake base motions using the software *PSEQGN* (Ruiz and Penzien, 1969), from the time-modulated Kanai-Tajimi spectrum by defining particular values for its frequency parameter ω_g and damping parameter ξ_g. The time modulation function chosen is as given by (Ruiz and Penzien, 1969), with a linear rising function from 0 to 4 seconds, constant value of unity from 4 to 15 seconds, and an exponentially decaying function from 15 seconds to the final duration of 30 seconds. Adjusting these parameters a variety of ground motions were generated, which reflects all possible combination of characteristics of the actual ground motions. Figure 3 shows a pseudo-acceleration response spectrum for a typical base motion for case 2. The mean pseudo-acceleration response spectra of the ground motion sets considered for all the TLD-structure systems are given in Figure 4.

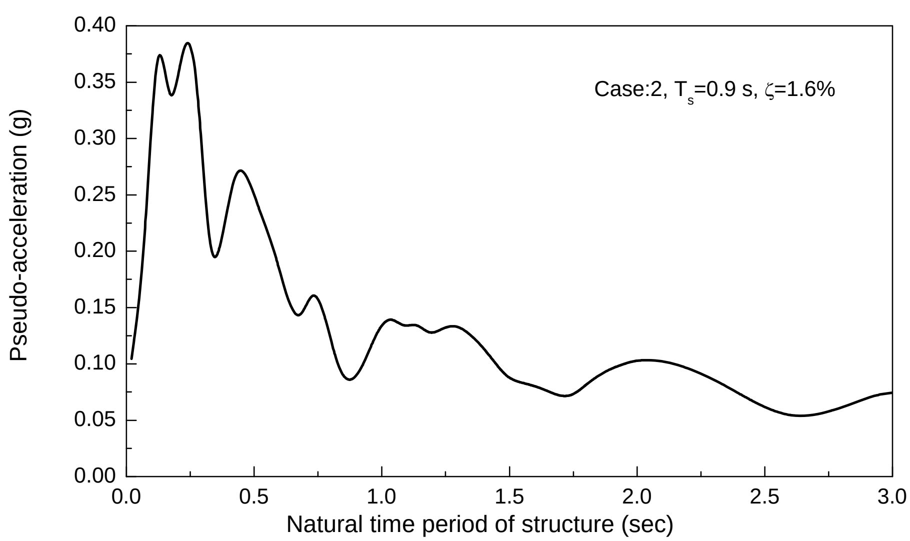


Figure 3. Typical plot of individual response spectra of artificially generated ground time-histories used for shaking table experiments (Case2)

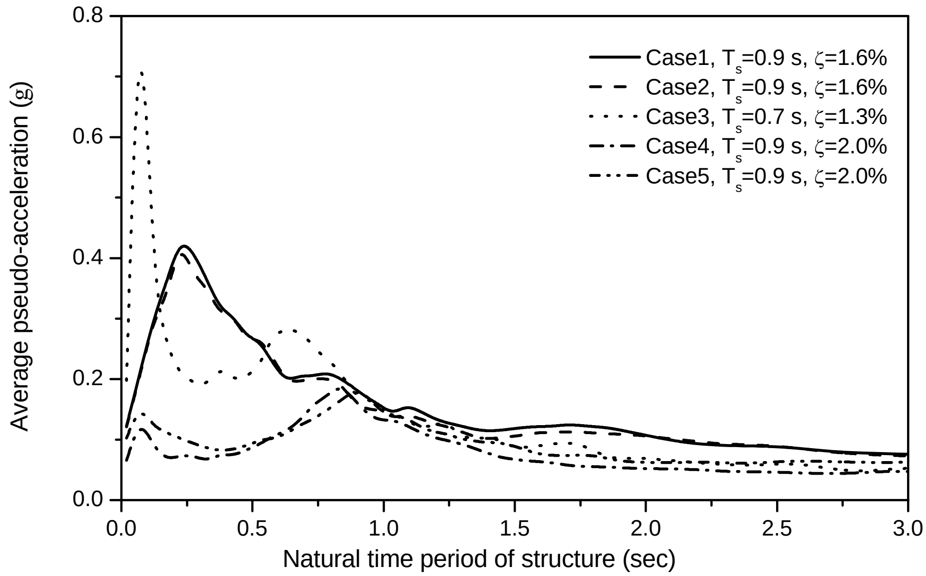


Figure 4. Average response spectra of artificially generated ground time-histories used for shaking table experiments for all five cases

4. Theoretical Formulation

4.1. Formulation of TLD Equations

Classical shallow water theory is used in this study to simulate the sloshing of liquid in a rigid, rectangular TLD that moves in a coupled horizontal and rotational manner. Consider a rigid, rectangular container that is subjected to a coupled horizontal and rotational motion, as shown in Figure 5. Let L and B be the length and the width of the container, respectively, and suppose h_0 is the initially quiescent depth of the liquid within the container. The TLD's absolute horizontal motion is defined by x_b while the corresponding rotational motion is specified by θ. The equations that govern the liquid sloshing are derived as given in (Lu, 2001) using shallow water theory (Stoker, 1992). Here, h is the (sloshing) liquid depth at x, v is the horizontal velocity of the liquid at x, relative to the base of the container. It is assumed that the vertical (y) component of the acceleration of the liquid particles has a negligible effect on the liquid pressure or, that the liquid pressure is hydrostatic. The velocity profile is uniform at a vertical cross section. For this to be true, the rotational motion, θ, has to be small (say, below about 10 degrees). In deriving the governing equations, two principles namely, the principle of continuity (i.e. the conservation of mass) and the principle of momentum (i.e. Newton's law), are used. The governing equations are (Lu, 2001):

$$\frac{\partial h}{\partial t} + h\frac{\partial \mathrm{v}}{\partial x} + \mathrm{v}\frac{\partial h}{\partial x} = 0 \tag{1}$$

$$\frac{\partial \mathrm{v}}{\partial t}+\mathrm{g}\frac{\partial h}{\partial x}+\mathrm{v}\frac{\partial \mathrm{v}}{\partial x}+\frac{\partial^2 x_{\mathrm{b}}}{\partial t^2}-\mathrm{g}(\theta-S)=0 \tag{2}$$

Equation (2) reduces to the classical shallow water equation when the container is stationary (i.e. when x_{b} and θ are both set to zero). S is related to τ_b, by (Lu, 2001):

$$S=\frac{\tau_b}{\rho g h} \tag{3}$$

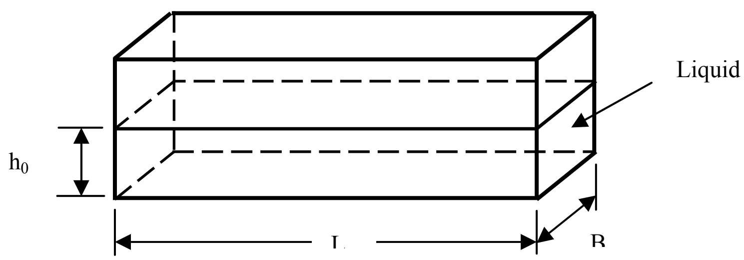
where, τ_b the shear stress at the container's floor. The simplified expression for τ_{b} is (Lu, 2001):

$$\tau_{\mathrm{b}}=\frac{\mu_l \mathrm{v}_{\max}}{h} \qquad \text{for} \qquad z \le 0.7 \tag{4}$$

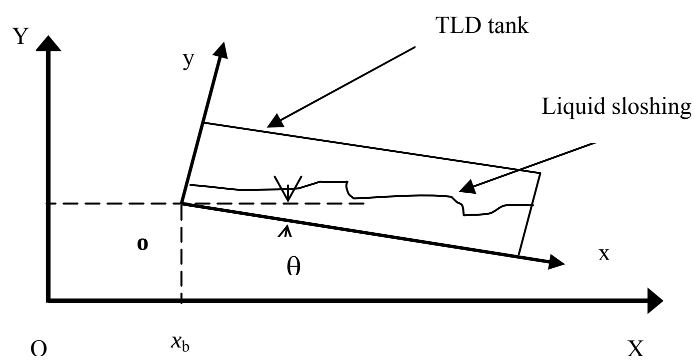
$$\tau_{\mathrm{b}}=\sqrt{\rho\mu_l\omega}\,\mathrm{v}_{\max} \quad \text{for} \qquad z > 0.7 \tag{5}$$

where ρ is the density of the liquid; μ_l is its dynamic viscosity (which is related to the kinetic viscosity, υ, by $\mu_l=\rho\upsilon$); ω is the circular frequency of the vibration, and z is the liquid's dimensionless sloshing depth defined by (Lu, 2001):

$$z=\sqrt{\frac{\omega g}{2\mu_l}}h \tag{6}$$



(a)



(b)

Figure 5. Schematic diagrams of TLD tank and liquid sloshing inside it under coupled horizontal and rotational motion

In order to account for the velocity variation (that varies from zero at the container's floor to its maximum value at the liquid's free surface), Equations (1) and (2) are to be modified by treating v as the average velocity, v_{avg}, over the cross-section. The relationship between v_{max} and v_{avg}, over a given cross-section, is found in to be (Lu, 2001):

$$v_{avg} = v_{max}(-0.0011z^6 + 0.0169z^5 - 0.0936z^4 + 0.2093z^3 - 0.1181z^2 + 0.0129z + 0.5012) \quad (7)$$

for $z \leq 5$, and:

$$v_{avg} = v_{max}[1 - \exp(-0.0853z - 2.2807)] \quad (8)$$

for $z > 5$. Equations (1) and (2) have to be solved in conjunction with the boundary conditions:

$$v|_{x=0} = v|_{x=L} = 0 \quad (9)$$

and the appropriate initial conditions. If the liquid is at rest at time $t = 0$:

$$h|_{t=0} = h_0 \text{ and } v|_{t=0} = 0 \qquad \forall x \in [0, L] \quad (10)$$

4.2. Computation of TLD Base Shear Force

The base shear force is developed at the base of TLD due to liquid sloshing and transferred to the top of shear beam structure as the TLD is rigidly attached to it. The total horizontal force that is exerted on the TLD's walls and floor due to the sloshing of the liquid, F is given by the following expression (Reed et al., 1998):

$$F = \frac{1}{2}\rho g B(h_R^2 - h_L^2) \quad (11)$$

where, h_L= wave height at the end wall on the left side,

and h_R= wave height at the end wall on the right side.

4.3. Equation of Motion of Shear-Beam Structure with TLD

A shear-beam structure with TLD attached at its top is shown in Figure 6. It has horizontal motion of mass (m_s) as degree of freedom. The equation of motion of such structure with TLD attached at its top and subjected to horizontal ground motion can be written as:

$$m_s \ddot{u}_x + c_s \dot{u}_x + k_s u_x = -m_s \ddot{u}_g + F \quad (12)$$

The base shear force, F is computed using Equation (11). The damping coefficient c_s is given by $c_s = 2\zeta m_s w_s$, where ζ is the damping ratio and w_s is the natural frequency of the structure.

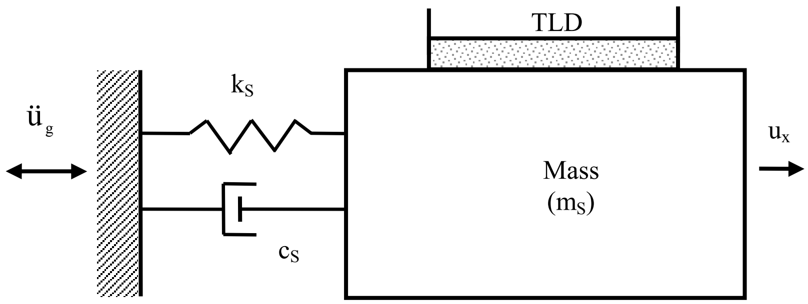


Figure 6. Schematic diagram of a single-degree-of-freedom shear beam structure with a rectangular tuned liquid damper

4.4. Solution Procedure for TLD-Structure System

The equation of motion of a structure is coupled with TLD equations and all these equations must be solved simultaneously to get the response of the structure with a TLD rigidly attached to it. The TLD equations (Equations (1) and (2)) are first solved using Lax finite difference scheme (Lu, 2001 & Samanta and Banerji, 2006) to obtain the base shear force (*F*). Then this obtained force is used in Equation (12) to obtain structural response. Equation (12) has been solved using Newmark-β average acceleration method in this paper. The analyses have been performed using very small time steps of 0.001 seconds. At each step convergence of the liquid and the appropriate structure equations are ensured through an iterative procedure where the liquid equations are solved first and then the structure equations, before proceeding to the next step. As the time steps are very small, the convergence happens typically within the first iteration step.

5. Results and Discussions

In a few of the cases considered in the study, the earthquake-type base motions given to the shaking table differ from the output time history obtained from the accelerometer placed on the base of the structure due to the limitations of the servo-hydraulic system used to drive the shake table. To avoid this discrepancy in numerical analysis, measured base acceleration time history was taken, instead of original time history given to the shaking table, as the base excitation in the numerical simulations.

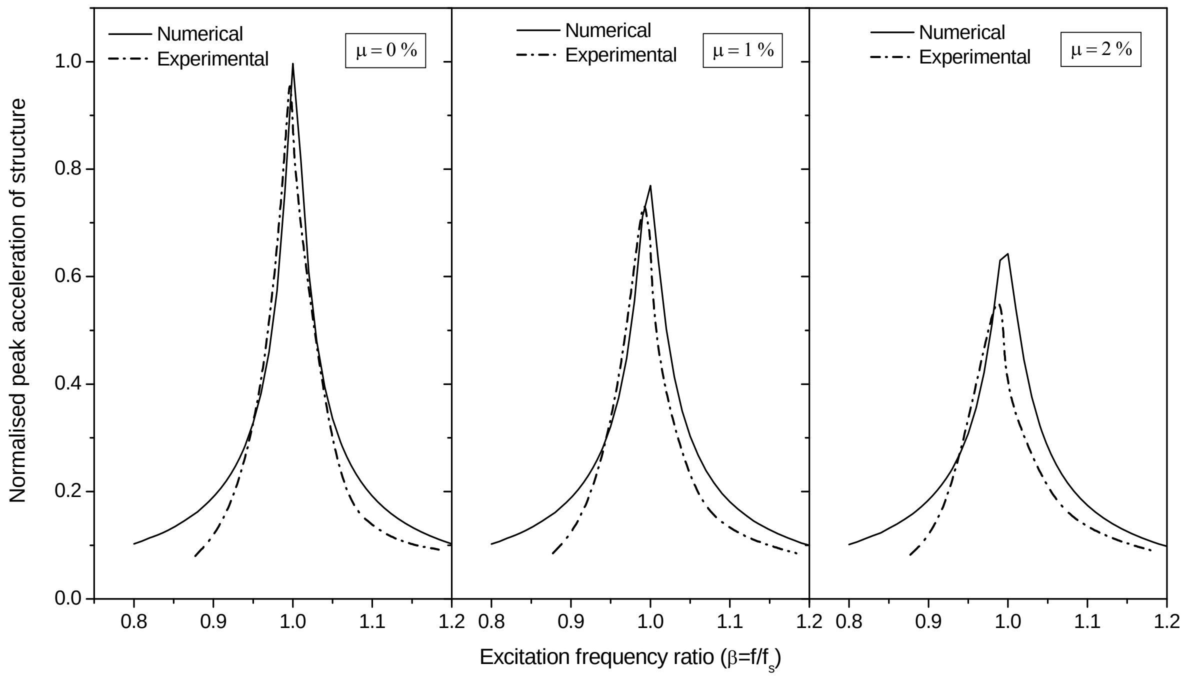


Figure 7. Normalized peak acceleration for different mass ratio and varied β ratio (Structural type: Case 1, T_s=0.9s, Δ= 0.077, A_0=0.053 m/sec^2)

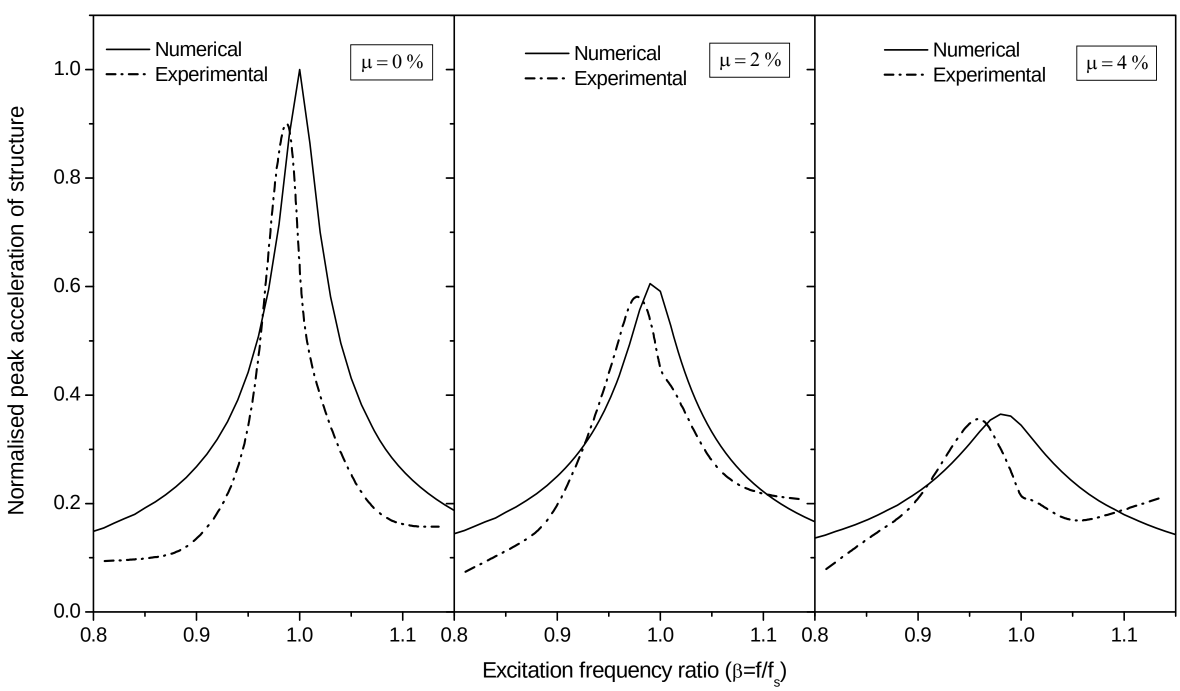


Figure 8. Normalized peak acceleration for different mass ratio and varied β ratio (Structural type: Case 4, T_s =0.9s, Δ= 0.151, A_0=0.0963 m/sec^2)

Figures 7 and 8 show a comparison of experimental and theoretical values of normalized peak acceleration at the top floor for case 1 and case 4 structures and for harmonic base excitations. The plots are for varying excitation frequency ratios, β, which is the ratio of the frequency of the harmonic excitation, f and the fundamental natural frequency of structure, f_s) and for different mass ratios, μ. Both small and large excitation amplitude levels are considered. In a general sense good agreement is observed between experimental and theoretical results for various mass ratios. It is noted that typically the experimental response shows that the TLD is more effective than the numerical simulations suggest. One other important point noted from these results has a direct relationship to the difference in design of the TLD for narrow-banded harmonic excitations and broad-banded earthquake excitations. In Figure 7, which is for a TLD with small depth ratio, the plot for 2% mass ratio shows that the peak acceleration amplitude of the structure is reduced by almost 50% but the frequency response plot shows a sharp peak, implying that the effectiveness is only for a very narrow-band of frequencies. However, in Figure 8, which is for a TLD with larger depth ratio, the plot for 2% mass ratio shows that the peak acceleration amplitude of the structure is reduced by about 40% but the frequency response plot shows a flatter peak, implying that the effectiveness, although slightly lower, is spread over a broader band of frequencies. Thus smaller depth ratios are very effective for harmonic excitations, whereas larger depth ratios are effective for broad-band excitations. This point would again be illustrated for earthquake-type motions.

Typical plots of comparison of experimental and numerical structure top acceleration time histories for the Case-1 structure subjected to earthquake-type base excitation and for varying mass ratios are shown in Figure 9. Figure 10 shows a comparison of experimental and numerical structure top acceleration time histories for various structural cases. Good agreement is observed between experimental and theoretical results for structure top acceleration time histories for all these cases. For relatively smaller amplitudes of base excitation, a TLD with higher mass and depth ratios has a relatively smoother wave profile. Thus in such a situation the experimental and numerical are closer to each other. However, as the amplitude of harmonic base motion increases, it was seen that there was significant wave breaking and the wave profile was very irregular. Although the theory does account for wave breaking to a certain extent, it will always underestimate the energy dissipation due to sloshing of water when there is significant turbulence in the water. This point is highlighted in the results presented in Table 2, where a comparison of experimental and numerical results for different structural cases when subjected to large amplitude earthquake-type base excitations is made. Thus it can be stated that numerical simulations using the theoretical formulation given here are a reasonable approximation of the actual situation for both harmonic and earthquake base excitations and do provide conservative estimates of the TLD effectiveness, i.e. the TLD in a real situation is more effective than that predicted by numerical simulations.

Table 2. Reduction in mean peak structural acceleration for structures with different mass ratio (%)

Structure type	Percentage reduction in mean peak structural acceleration (PSA)					
	μ=1%		μ=2%		μ=4%	
	Exp	Num	Exp	Num	Exp	Num
Case 1, T_s=0.9 s, Δ=0.077	5.8	8.5	12.1	14.2	-	-
Case 2, T_s=0.9 s, Δ=0.118	10.3	6.5	16.5	9.4	22.9	14.5
Case 3, T_s=0.7 s, Δ=0.155	18.4	12.6	30.7	23.3	43.3	36.4
Case 4, T_s=0.9 s, Δ=0.151	-	-	29.8	27.5	38.1	34.5
Case 5, T_s=0.9 s, Δ=0.078	-	-	24.5	31.1	40.0	39.9

The Case 4 structure-TLD system and Case 3 structure-TLD system, results for which are presented in Figure 11, have almost identical TLD characteristics (see Table 1) and are subjected to similar base motion acceleration time histories (although the Case 3 motion has very intense high frequency components, which the Case 4 motion does not), with the Case 3 system subjected to a slightly higher intensity of ground motion. Thus a properly designed TLD is effective for different structures subjected to similar broad-banded base motions, illustrating the robustness of the TLD as a structural control device. Figure 11 also illustrates the fact that a TLD behaves as a classical damping device. It is not effective in the first few cycles of vibration when the liquid motion has just been initiated. It becomes effective when the liquid motion is fully developed and sloshing dissipates energy after a few cycles. In typical broad-band far-field type earthquake motions this type of behavior is acceptable as the intense ground motions are initiated only after a few cycles of motion. However, for near-field motions, which are characterized by very short-duration pulse type motions, a TLD would not be effective.

Figures 7 and 8 for harmonic base excitations, Figure 12 and Table 2 for earthquake base excitations, all illustrate that a larger TLD mass ratio makes a TLD more effective in controlling structural response. This aspect is fairly obvious as a larger water mass leads to larger dissipation of energy and hence a smaller structural response for a given earthquake base motion.

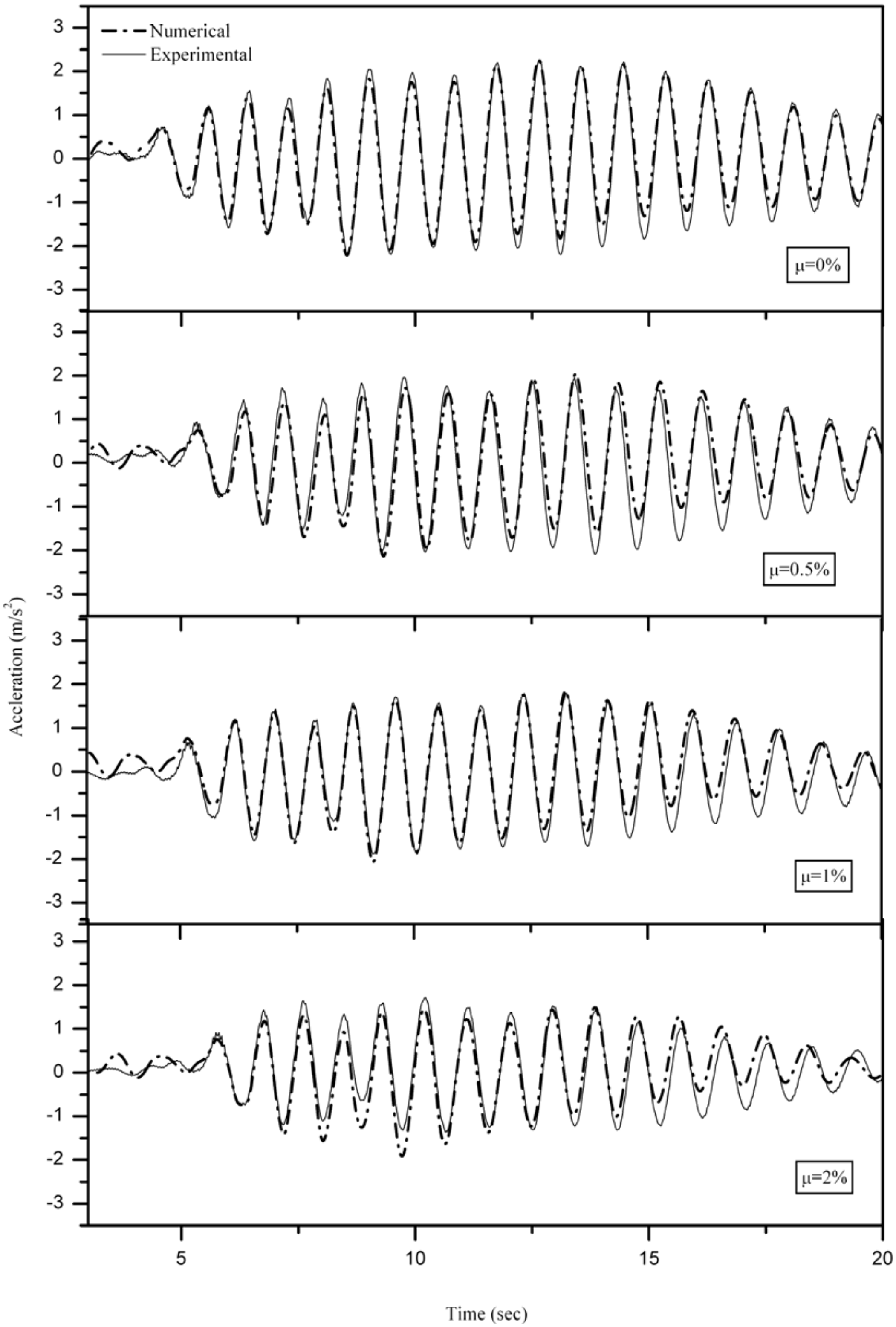


Figure 9. Comparison between numerical and experimental structural acceleration time histories for a structure (Case 1: T_s=0.9s) with TLD (Δ=0.077) subjected to a typical artificial ground time history

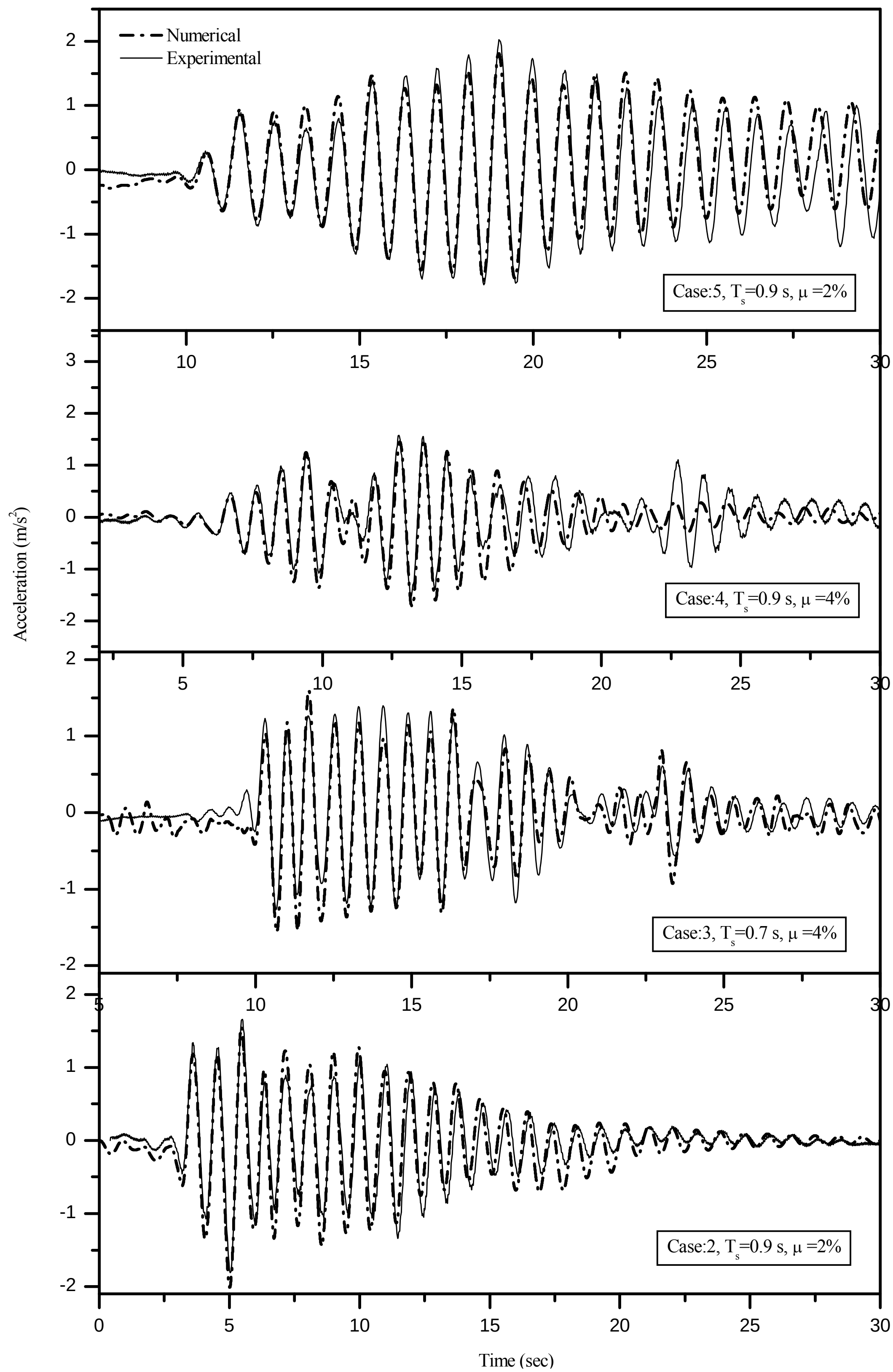


Figure 10. Comparison between numerical and experimental structural acceleration time histories of different structures attached with TLD subjected to typical base excitation

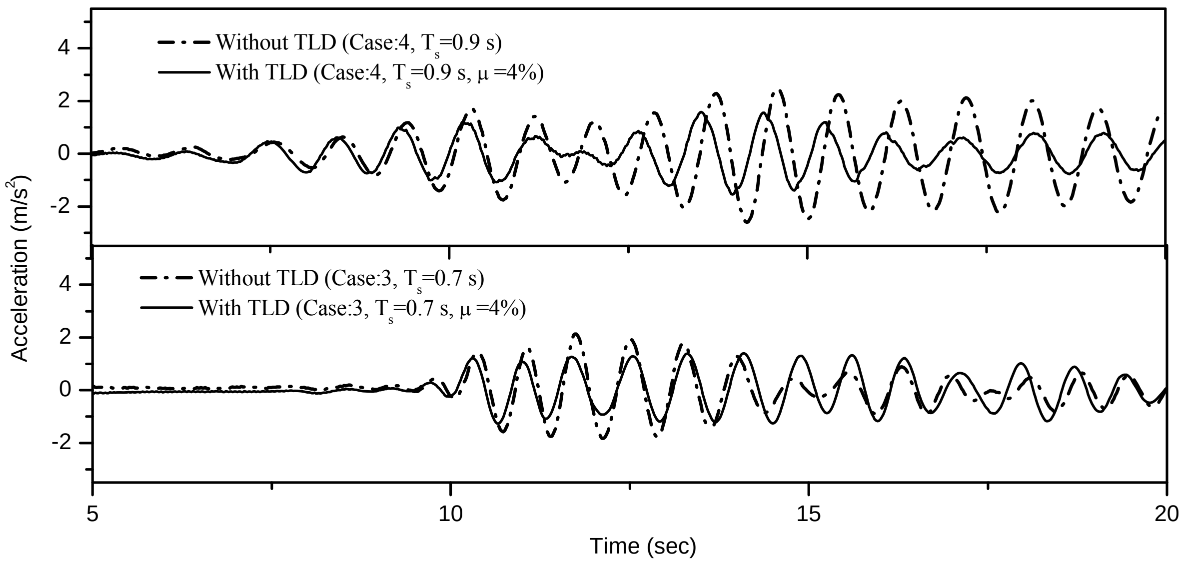


Figure 11. Effectiveness of TLD on structural performance having different frequencies subjected to typical base excitation

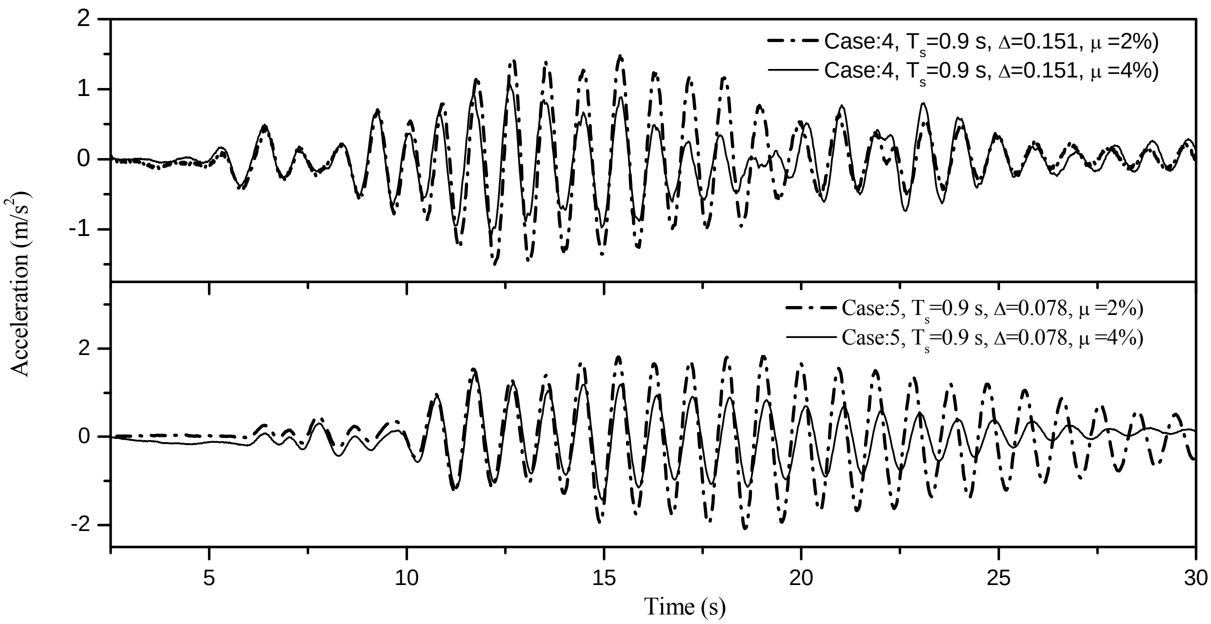


Figure 12. Effect of mass ratio on structural performance

The effect of depth ratio on the effectiveness of the structural response control of a TLD has been mentioned for harmonic motions. Consider the cases where the depth ratio is maintained at around 0.075, Cases 1 and 5, respectively. From Figure 4, it can be seen that for the Case 1 structure, the frequency band of the ground motion is not tuned to the structure and TLD frequencies, while for the Case 5 structure, the frequency band coincides with the structure and TLD frequencies. From the results in Table 3, it can be seen that for the same mass ratio of 2%, the TLD is twice as effective for the Case 5 structure as it is Case 1 structure. This illustrates the point that a small depth ratio TLD is effective only when the frequency band of the ground motion coincides with the structure and TLD frequencies. This implies that a small depth ratio TLD is not a robust control device. Note that Case 1 and Case 2 structure characteristics and ground motion characteristics are identical. The only difference is the TLD where the Case 1 depth ratio is approximately 0.075, while the Case 2 depth ratio is approximately 0.12. Note that the results in Table 3 and Figure 13 illustrate that the TLD is more effective for the Case 2 structure, for the same mass ratios. This illustrates the point that increasing the depth ratio makes the TLD more robust as an earthquake vibration control device. When the structure and TLD frequencies are in the frequency band of the earthquake ground motion, as is the case for Case 4 and 5 structures, it is interesting to note that the effectiveness of the TLD does not seem to depend on the depth ratio when the mean peak acceleration response is considered as given in Table 3. However if Figure 13 is seen, for a particular ground motion, the acceleration response time history comparison clearly shows that the larger depth ratio is beneficial in reducing the acceleration level.

Table 3. Effect of depth ratio on reductions in mean peak structural acceleration (%)

Mass ratio (μ)	Experimental results			
	Case 1 Δ=0.077 T_s=0.9 s	Case 2 Δ=0.118 T_s=0.9 s	Case 4 Δ=0.151 T_s=0.9 s	Case 5 Δ=0.078 T_s=0.9 s
1%	5.8	10.3	-	-
2%	12.1	16.5	29.8	24.5
4%	-	22.9	38.1	40.0

Thus in conclusion it can be stated that a TLD with a large depth ratio, of the order of 0.15, is an effective and robust device for controlling the earthquake response of structures, irrespective of the characteristics of the ground motion, as long as it is broad-banded and has the intense part of the motion occurring after the first few cycles of ground motion. Both experiments and numerical simulations show that a TLD is more effective in reducing structural response as the excitation amplitude increases and for structures whose response is large for a given base motion. For TLD with small depth ratio ($\Delta \approx 0.08$) wave breaking and wave mixing is observed as a result of vigorous sloshing, while fairly smooth wave profiles are observed for TLD with higher depth ratio ($\Delta \approx 0.15$) and higher mass ratio ($\mu \approx 4\%$). On an average, 25% to 40% reduction in the peak value of acceleration is observed for any structure with TLD having approximately 4 % mass ratio and 0.15 depth ratio subjected to any type of broad-banded ground motion.

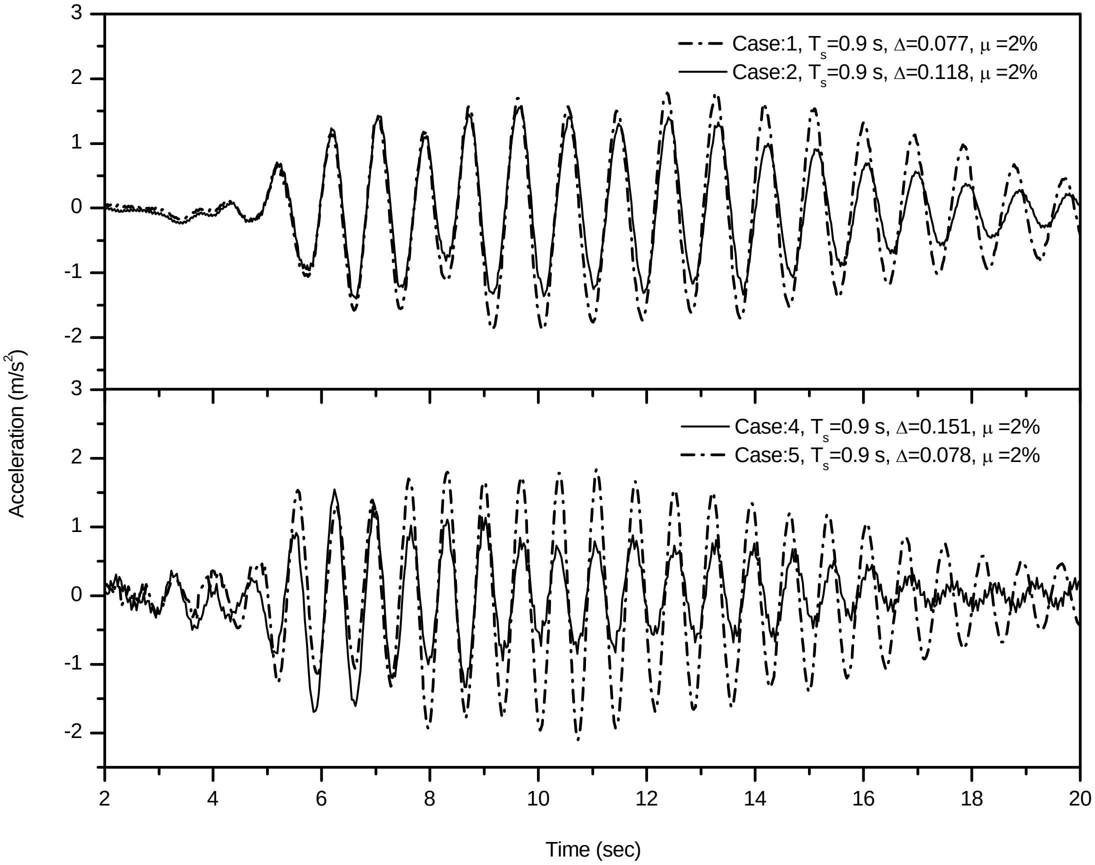


Figure 13. Effect of depth ratio on structural performance

6. Summary and Conclusions

A fairly comprehensive experimental study on the effectiveness of a TLD in controlling the earthquake response of a structure is carried out. The experimental results show that a properly designed TLD can significantly reduce response of structure for an earthquake-type ground motions. Both experiments and numerical simulations show that a TLD is more effective in reducing structural response as the ground excitation amplitude increases and for structures whose response is large for a given earthquake motion. This is because of additional damping provided to the structure due to increased sloshing. An interesting point to be noted is that experiments show that a TLD is generally *more* effective than what is predicted by numerical simulations. However, it must be stated that the shallow water wave theory presented in this paper for modeling the TLD sloshing provides fairly accurate structural response prediction (both peak value and time history) for earthquake-type base motions. The effectiveness of a TLD is less sensitive towards variation in the values of its parameters for larger mass and depth ratios. Thus it is preferable to design a TLD with as large a mass ratio as feasible without increasing the inertial force on the structure significantly and as large a depth ratio as possible without violating the shallow water assumption that allows sloshing of the water surface. On the basis of experimental results, it can be concluded that the optimum values of depth ratio is about 0.15 and of mass ratio is about 4 %.

A properly designed TLD is equally effective for all types of broadband ground motions, reducing the response of a structure up to 40%, although it is obviously more effective when the structure and TLD sloshing frequencies are in the frequency band of the ground motion. It can, therefore, be stated that if the design parameter of a TLD are as suggested by Banerji et al. (2000), a TLD would be a cost-effective strategy as an earthquake response control device.

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References

Banerji, P., Murudi, M.M., Shah, A.H. and Popplewell, P. (2000), "Tuned liquid damper for controlling earthquake response of structure", *Earthquake Engineering and Structural Dynamics*, Vol. 29, Pages 587-602.

Fujino, Y., Sun, L.M., Pacheco, B.M. and Chaiseri, P. (1992), "Tuned liquid dampers (TLD) for suppressing horizontal motion of structures", *Journal of Engineering Mechanics, ASCE*, Vol. 118, No. 10, Pages 2017-2030.

Koh, C.G., Mahatma, S. and Wang, C.M. (1994), "Theoretical and experimental studies on rectangular tuned liquid dampers under arbitrary excitations", *Earthquake Engineering and Structural Dynamics*, Vol. 23, Pages 17-31.

Lu, M.L. (2001), "Predicting ice accretion and alleviating galloping on overhead power lines", *Ph.D. thesis*, University of Manitoba, Winnipeg, MB., Canada.

Reed, D., Yu, J., Yeh, H. and Gardarsson, S. (1998), "Investigation of tuned liquid dampers under large amplitude excitation", *Journal of Engineering Mechanics, ASCE*, Vol. 124, No. 4, Pages 405-413.

Ruiz, P. and Penzien, J. (1969), "Probabilistic study of behavior of structures during earthquakes", *EERC Report No. 69-03*, Earthquake Engineering Research Center, University of California, Berkeley, CA., USA.

Samanta, A. and Banerji, P. (2006), "Efficient numerical schemes to analyse earthquake response of structures with tuned liquid dampers", *13th Symposium on Earthquake Engineering*, Roorkee, India, Pages 1372-1381.

Shimizu, T. and Hayama, S. (1987), "Nonlinear response of sloshing based on the shallow water wave theory", *JSME International Journal*, Vol. 30, No. 263, Pages 806-813.

Stoker, J.J. (1992). "Water Waves: The Mathematical Theory with Applications", John *Wiley & Son*, New York, NY., USA.

Sun, L.M., Fujino, Y., Pacheco, B.M., and Isobe, M. (1989), "Nonlinear waves and dynamic pressure in rectangular tuned liquid damper (TLD): Simulation and experimental verification", *Structural Engineering Earthquake Engineering, JSCE*, Vol. 6, No. 2, Pages 251-262.

Sun, L.M., Fujino, Y., Pacheco, B.M. and Chaiseri, P. (1991), "Modeling of tuned liquid damper (TLD)", *8th International Conference on Wind Engineering, IAWE*, London, ON., Canada, Pages 1883-1894.