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Shaking table tests on a SDOF structure with cylindrical and rectangular TLDs having rotatable baffles

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Abstract. Control of vibrations against extraordinary excitations such as wind and earthquake is very important to the protection of life and financial concerns. One of the methods of structural control is to use Tuned Liquid Damper (TLD), however due to the nature of TLD only one sloshing frequency can be created when the water is sloshing. Among various ideas proposed to compensate this problem, by changing the angle of some rotatable baffles embedded inside a TLD, a frequency range is created such that these baffles are tuned manually at different frequencies. In this study, the effect of cross sectional shape of container with rotating baffles on seismic behavior of TLD is experimentally studied. For this purpose, rectangular and cylindrical containers are designed and used to suppress the vibrations of a Single Degree-Of-Freedom (SDOF) structure under harmonic and earthquake excitations considering three baffle angles. The results show that the rectangular-shaped damper reduces the structural response in all load cases more than the damper with a cylindrical shape, such that maximum differences of two dampers to reduce the structural displacement and structural acceleration are 5.5% and 3% respectively, when compared to the cases where no baffles are employed.

Keywords: rectangular TLD; cylindrical TLD; SDOF structure; rotatable baffles; shaking table test

1. Introduction

The main purpose of building construction is to create a safe environment for its residents. Due to lack of space for structures and thus need for increasing height and more flexibility of structures, it is necessary to obtain different ways to control structures. Structural destruction caused by environmental loads like wind and earthquake not only cause financial losses, but also more importantly induce life casualty.

In recent decades, many researchers have investigated to control unwanted vibrations of structures and have developed and tested new methods in this regard. Vibration control is categorized in passive, active, semi-active and hybrid control (Housner *et al.* 1997). A wide variety of active/passive control systems have been proposed and used in practice. Passive control systems do not require external power and the mechanical properties of these systems cannot be modified in real time. The device moves along with the main structure and the control force is generated through this motion. Compared to active control systems, passive devices are simple in design and implementation and more reliable in performance. The simplicity, stability and reliability of passive control systems have made them an attractive method for structural motion control.

A special case of passive control devices is Tuned Liquid Damper (TLD) in which a liquid (water) is sloshing as the energy dissipater. Utilizing TLDs for structural control has been the subject of a wide variety of studies (e.g., Marsh *et al*. 2010). Sun *et al*. (1991) and Fujino *et al*. (1992) performed numerical studies on the flow inside of the TLD. They proposed the nonlinear two dimensions model of the flow in a rectangular TLD. Banerjee et al. in 2000 performed numerical and experimental modeling to investigate the TLD–structure (SDOF) interaction with different types of TLD, to find the optimal TLD. They examined the parameters affecting the TLD and proposed a general method for optimal design of TLD.

Biswal *et al.* (2003, 2004) embedded some annular baffles inside a cylindrical TLD and investigated the effects of baffles on cylindrical TLD behavior. Their result showed that the frequencies of liquid sloshing in the flexible-tank–baffle system are lower than those of the rigid system.

Tait *et al*. in 2005 proposed numerical flow models to simulate TLDs with slatted screens. Their results showed that the linear model is capable of providing an initial estimate of the energy dissipating characteristics of a TLD. The nonlinear model can accurately describe the response characteristics within the range of excitation amplitudes experimentally tested. Love & Tait (2011) developed a non-linear multimodal model which describes the sloshing behavior of a fluid in a flat-bottom tank of arbitrary geometry. Crowley & Porter in 2012 proposed a TLD composed of a rectangular tank fitted with an arbitrary

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configuration of vertical slatted screens to provide damping when the fluid is in motion. They studied different screen configurations and then considered to indicate general criteria for optimizing the TLD performance by reducing overall displacement across all forcing frequencies, by altering the number, placement and porosity of the slatted screens in the tank.

Zahrai *et al*. in 2012 proposed a new kind of rectangular TMD with some installed rotatable baffles and experimentally studied its harmonic and seismic performance. According to the their study, the best performance was achieved when $\theta = 70°$. Their results showed that the displacement and acceleration responses of the structure under the free vibration test utilizing the baffles reduced up to 2.5% and 3.9%, respectively, and the displacement and acceleration responses of the building under scaled down earthquakes also decreased up to 24.1% and 27.2%, respectively, when compared to the case where no baffles were employed. Also the dynamic magnification factor under harmonic excitation reduced up to 2.7% proportional to baffles angles. Damping of the structure equipped with this type of TLD increased in a range of 3.93–6.38% when compared to the case of using no damper. Lee and Juang in 2012 experimentally studied a typical tension-leg type of floating platform incorporated with underwater tuned liquid column damper system (UWTLCD) to improve the structural safety by means of mitigating the wave induced vibrations and stresses on the offshore floating Tension Leg Platform. They found that the properly designed UWTLCD system could effectively reduce the vibration amplitude and dynamic response of the offshore platform system.

Cheng *et al.* in 2015 considered Magneto-Rheological (MR)-fluid viscosity by transforming the non-linear damping term into an equivalent linear damping. To find a countable set of parameters for the design of the MR-TLCD system and also to realize its applicability to structures, they conducted some tests subjecting the system to strong ground excitations. They found that the accurately tuned MR-TLCD system could effectively reduce the dynamic response of structural systems. Bhosale and Murudi in 2017 conducted a set of experiments on flat bottom and sloped bottom TLD, 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. They experimentally showed that a properly designed TLD reduces structural response and observed that effectiveness of TLD increases with increase in mass ratio. They found that efficiency of sloped bottom TLD in reducing the response of structure is more as compared to that of flat bottom TLD. Enayati and Zahrai in 2017 proposed a variably baffled TLD to reduce seismic response of structures and evaluated its behavior under near and far field earthquakes. They changed damping of structural models using an efficient semi-active control algorithm by changing the angles of baffles. Considering maximum roof displacement and its root mean squared value showed that TLD with variable baffles exhibits excellent performance under both near and far-field earthquakes while creates further response reduction under near field earthquakes. However, decreases of responses in angles of 0° and 20° were more than those in angles of 50° and70°.

The main objective of this paper is to experimentally investigate the impact of cross sectional shape of TLD with four installed baffles on seismic behavior of a SDOF structure. The rectangular and cylindrical shapes are used in this research for the TLD containers to compare structural response reductions in an attempt to figure out about the geometry shape leading to the best performance. All the experimental conditions such as quantity of cross section, position of installed baffles and the mass of water inside the containers are identical.

2. Test specimen & experimental program

2.1 SDOF structure (mass-spring system)

Single Degree-Of-Freedom, SDOF structure employed in this study includes a mass of 260 kg and 14 springs each with 1000 N/m stiffness (Fig. 1). The mass is located on four wheels and seven springs on one side of mass and the others on the opposite side. Each of these springs was attached at one end to the mass and at the other end to the plates that were connected by bolts to the shaking table.

2.2 Design and manufacture of Tuned Liquid Dampers with rotating baffles

According to Fig. 1, which belongs to the structure employed for conducting the tests and due to the restrictions of the shaking table splint spacing on the SDOF, the diameter of cylindrical TLD was selected 46 cm (Fig. 2) and the length and width for rectangular TLD were selected 52 and 32 cm (Fig. 3) respectively. Both containers have a cross sectional area equal to 0.166 square meters.

Fig. 1 Single Degree-Of-Freedom (SDOF) structure (mass-spring system) used for the test specimen

Fig. 2 Cylindrical TLD used for the SDOF structure connected to the shaking table

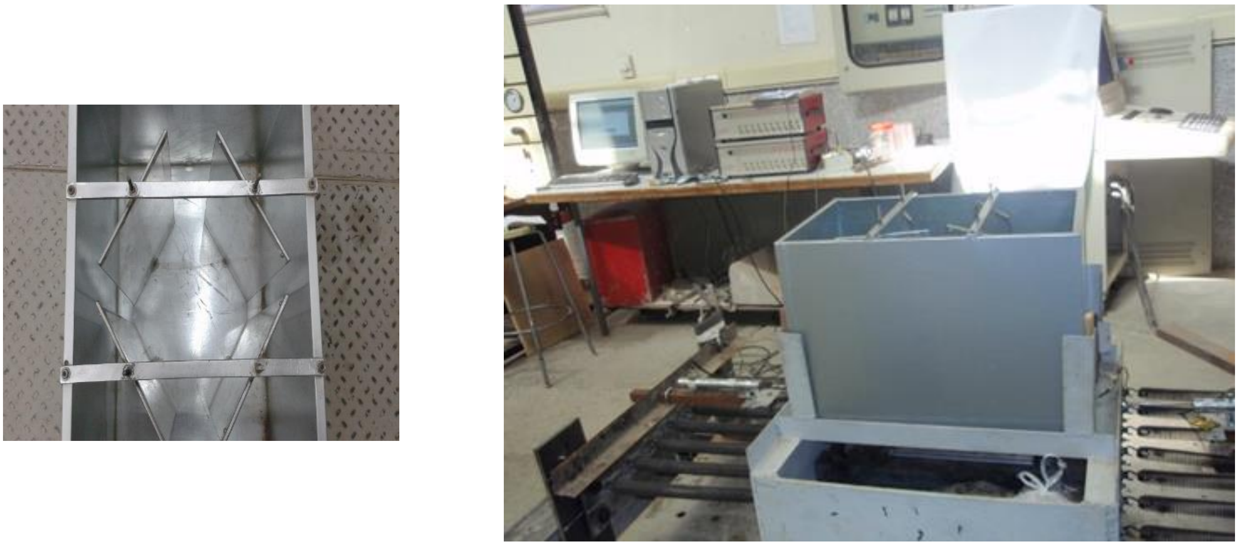

Fig. 3 Rectangular TLD used for the SDOF structure connected to the shaking table

The fixed criterion to compare two TLDs was the amount of their inside water. In this investigation the problem was that with a certain amount of water, how different shapes of TLD containers with the same cross sectional area could influence to ensure maximum reduction in the structural response. It should be noted that the baffles position was at 28% of the cylinder diameter due to the geometry of the cylindrical TLD (Fig. 2). Therefore, to maintain further integrity for the dampers, position of the baffles of rectangular TLD was considered at 28% of its length (Fig. 3).

Four baffles were used for both dampers and in these experiments they were rotated manually and then fixed at specific angles. The material of these baffles was made of Plexiglas. The length of baffles was 16 cm and 20.2 cm in rectangular and cylindrical TLDs respectively and the thickness and height of baffles was 5 mm and 45 cm respectively. The water height inside the dampers was 6.4 cm.

2.3 Instruments of experimental work

Some instruments were considered to measure the response of SDOF structure, such as two accelerometers and two displacement transducers (LVDT). In this study, one accelerometer was placed on the shaking table to record its actual acceleration and another one was placed on SDOF structure for determining its related acceleration. One of the LVDTs was used at the right of structure and another one was placed at the left side for recording the displacement of SDOF structure (Fig. 4).

Fig. 4 shows the graphical layout of physical model in experimental work. At first, the SDOF structure was fixed on the shaking table (standing on one-directional wheels and connecting to the table through 14 springs) and then the damper was placed on the SDOF structure. In order to record the acceleration and displacement of SDOF structure, accelerometers and LVDTs were installed on the structure and shaking table respectively. Then all

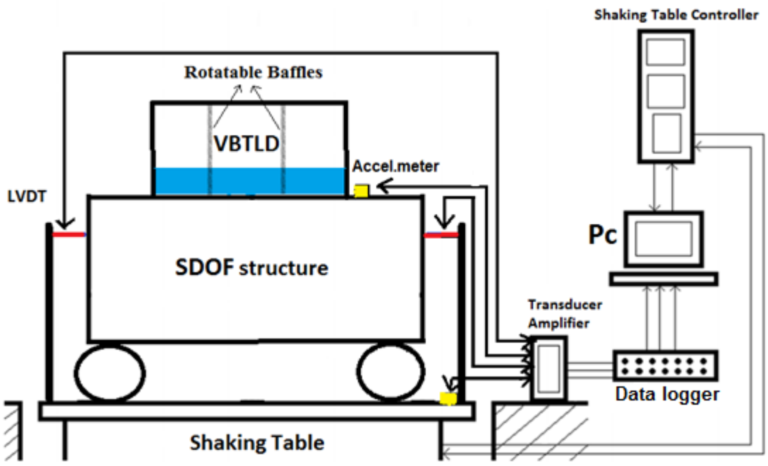

Fig. 4 Schematic view of experimental set-up and instrumentation

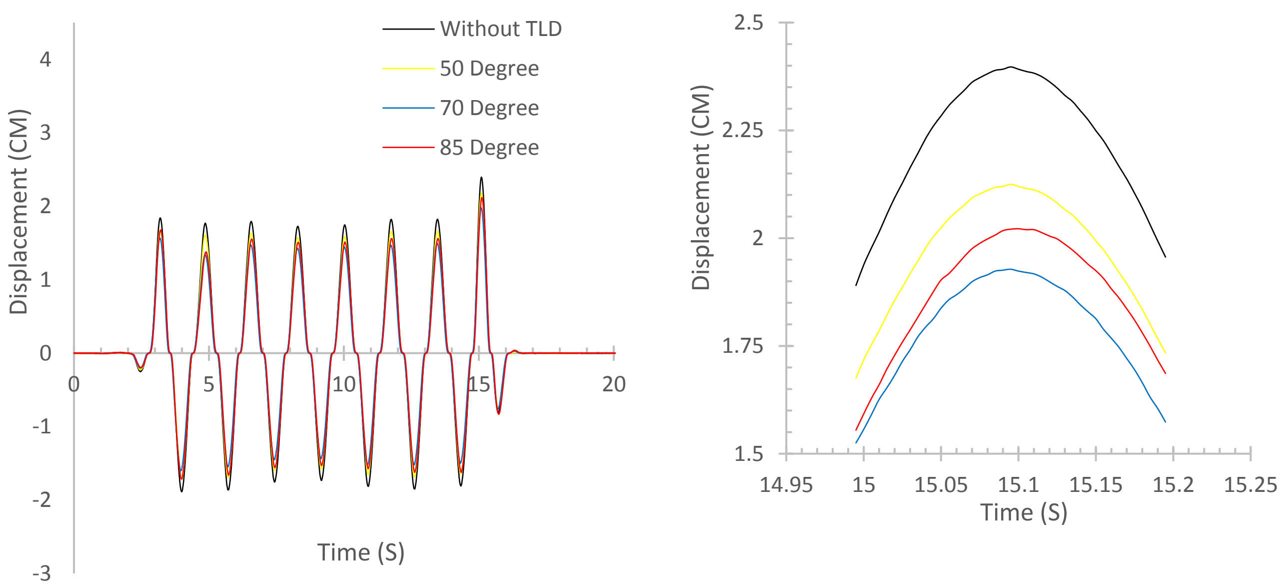

Fig. 5 Response of the SDOF structure under the harmonic excitation with 0.58 Hz frequency and 0.1g acceleration with utilizing the rectangular TLD

accelerations and displacements were recorded by data logger transferring the related data to a computer. This information was in the form of voltages that by calibrating the sensors, they were converted to specific data with their own sensors.

3. Experimental results

These experiments were undertaken for a range of baffle angles, i.e., 50, 70 and 85. Also one depth of water (6.4 cm) was used for both of dampers in this study. In total, 21 experiments were conducted including 14 harmonic excitation tests and 7 earthquake excitation tests.

3.1 Harmonic excitation tests

Fabricated TLDs have been placed under harmonic excitations with frequency ratios of 0.5 and 1.5. Since the natural frequency of the structure without damper was 1.17 Hz, so the frequency of excitation (shake table) was to be equal to 0.58 and 1.75 Hz.

Response of the SDOF structure under the harmonic excitation with 0.58 Hz frequency and 0.1 g acceleration with utilizing the rectangular and cylindrical TLDs with baffles are shown in Figs. 5 and 6 respectively. In each of the figures the maximum points of the curves are zoomed and shown on the right hand side of the chart for better illustration.

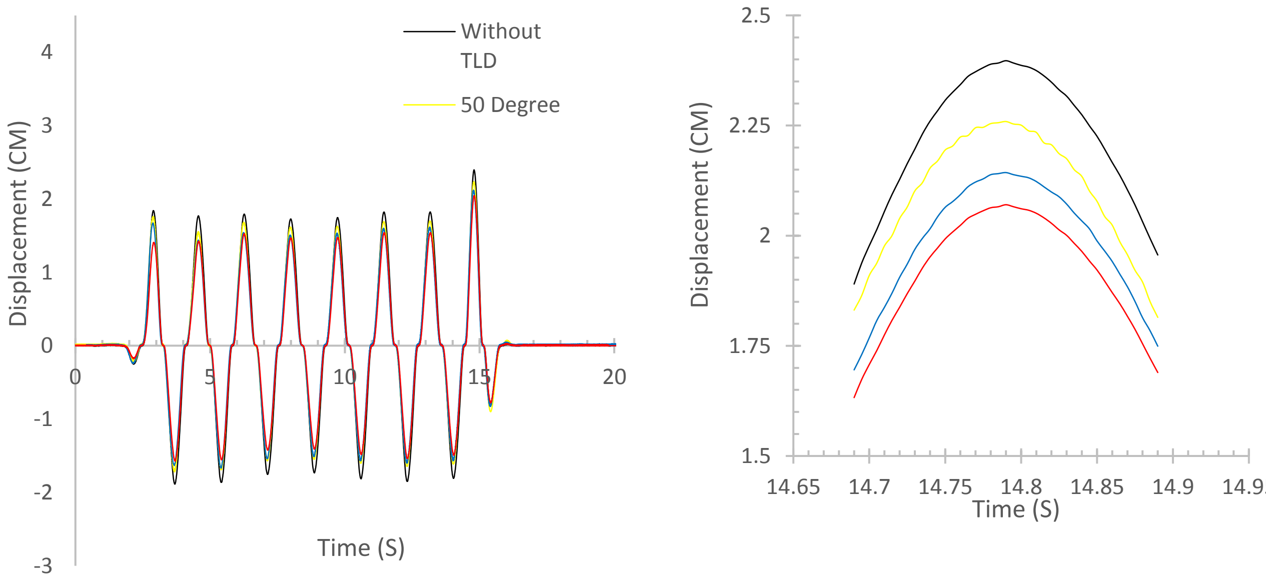

Fig. 6 Response of the SDOF structure under the harmonic excitation with 0.58 Hz frequency and 0.1 g acceleration with utilizing the cylindrical TLD

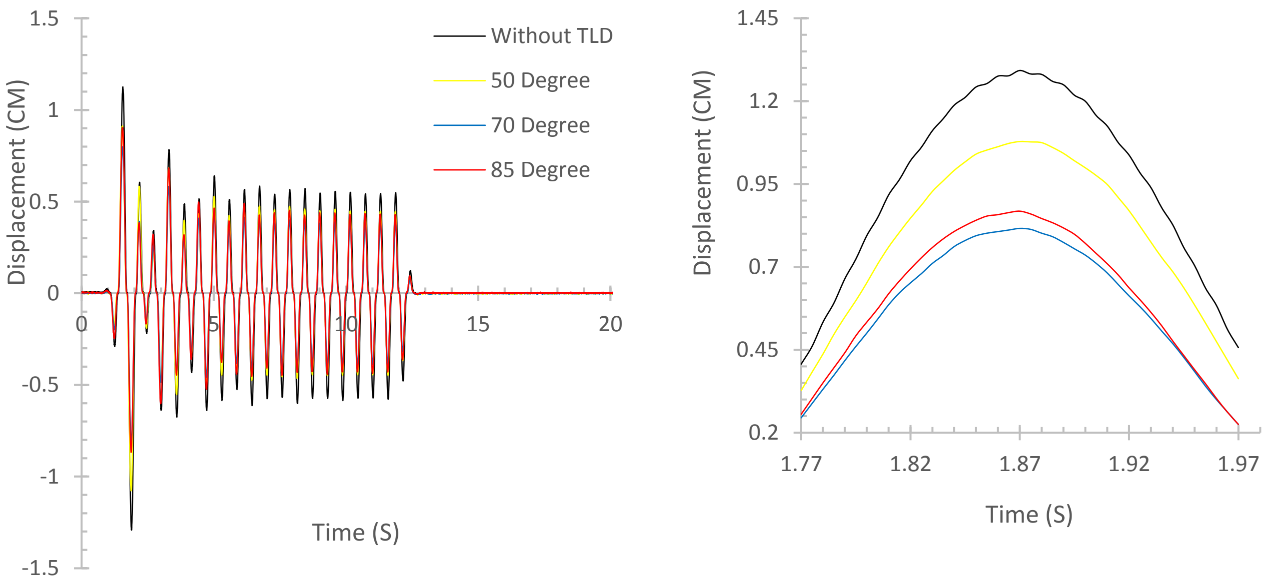

Fig. 7 Response of the SDOF structure under the harmonic excitation with 1.75 Hz frequency and 0.1 g acceleration utilizing the rectangular TLD

Fig. 5 shows that the maximum displacement of SDOF structure without TLD is 2.4 cm but with rectangular TLD at 70° baffles angle the maximum displacement is reduced to 1.93 cm. Fig. 6 shows that the maximum displacement of SDOF structure without TLD is 2.4 cm while with cylindrical TLD at baffles angle 85 ° the maximum displacement reduced to 2.07 cm.

According to Figs. 5 and 6, it is observed that adding baffles in both TLDs induces to reduce the structural response at various angles. This is because by changing the angle of baffles, the frequency of water sloshing within the TLD containers changes and at a specific angle when the frequency of water sloshing is closer to the main frequency of the SDOF structure it causes to create the maximum response reduction percentage for the SDOF structure. Accordingly, the variably baffled TLDs should be designed such that the main frequency of structure is between two frequencies of water sloshing when the baffles are fully opened and when fully closed. Also responses of the SDOF structure under the harmonic excitation with 1.75 Hz frequency and 0.1g acceleration showed that the maximum displacement of SDOF structure without TLD is 1.29 cm but with rectangular TLD at 70° baffles angle, it reduced to 0.82 cm as shown in Fig. 7 and with cylindrical TLD at 85° baffles angle, the maximum displacement reduced to 1.04 cm as shown in Fig. 8.

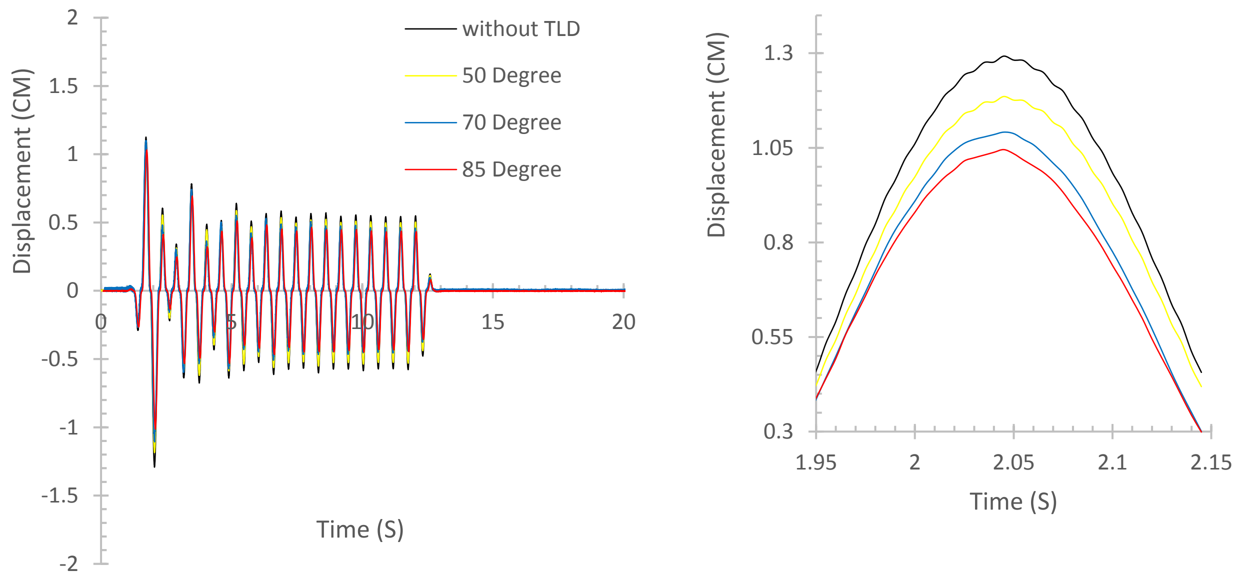

Fig. 8 Response of the SDOF structure under the harmonic excitation with 1.75 Hz frequency and 0.1 g acceleration utilizing the cylindrical TLD

Table 1 RMS values of displacement and acceleration of structure under harmonic excitation with 0.58 Hz frequency and 01 g acceleration

Baffle angle θ	Cylindrical TLD				Rectangular TLD			
	Displaceme (cm) nt	Displacement Reduction (%)	Acceleration (g)	Acceleration Reduction (%)	Displacement (cm)	Displacement Reduction (%)	Acceleration (g)	Acceleration Reduction (%)
50°	1.6419	6.758	0.100594	24.479	1.5863	9.915	0.098387	26.136
70°	1.6006	9.103	0.098732	25.877	1.5471	12.141	0.097769	26.600
85°	1.5754	10.534	0.098037	26.399	1.5589	11.472	0.097880	26.516
No damper	Displacement (cm)= 1.7609 Acceleration (g)= 0.1332							

Table 2 Maximum Displacement and acceleration of structure under harmonic excitation with 0.58 Hz frequency and 0.1 g acceleration

Baffle angle θ	Cylindrical TLD		Rectangular TLD	
	MAX Displacement (cm)	Reduction (%)	MAX Displacement (cm)	Reduction (%)
50°	2.2590	5.7611	2.1247	11.3637
70°	2.1432	10.5920	1.9278	19.5778
85°	2.0702	13.6373	2.0208	15.6981
No damper	Displacement (cm)= 2.3971			

In Figs. 5-8, the peak response clearly occurs when the excitation force starts or stops, and these cycles are displayed in the enlarged views. According to the mechanism designed for the tests as a mass-spring system and also due to using rubber wheels and springs with a little non-linear behavior, the system inertia increased. The SDOF structure was supposed to move only in the longitudinal direction and there was no movement in the transverse direction, therefore one-directional wheels were used and the force excitation was applied at the wheels direction. Also, the orientations of the LVDTs were recorded at the end of each test, to check whether the structure was slightly twisted or not, and there was no twisting in the structure.

The results of structural response under harmonic excitations are obtained and shown in Tables 1-4. The results of harmonic loading at 0.58 Hz frequency are presented in Tables 1 and 2 respectively.

As presented in Tables 1 and 2, for the harmonic excitation with frequency of 0.58 Hz and acceleration of 0.1g as RMS and maximum values, one can see that the rectangular TLD at all angles has better function than the

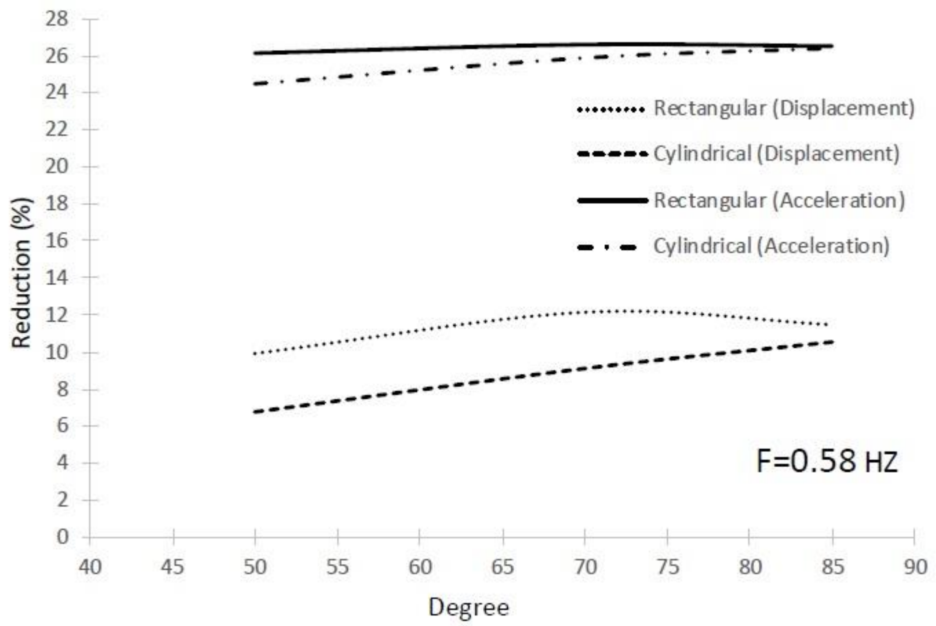

Fig. 9 Effect of changing baffle angles on reducing structural displacement under harmonic excitation

Table 3 RMS values of displacement and acceleration of structure under harmonic excitation with 1.75 Hz frequency and 0.1 g acceleration

Baffle angle θ	Cylindrical TLD				Rectangular TLD			
	Displacement (cm)	Displacement Reduction (%)	Acceleration (g)	Acceleration Reduction (%)	Displacement (cm)	Displacement Reduction (%)	Acceleration (g)	Acceleration Reduction (%)
50°	0.5466	5.186	0.096471	21.741	0.5201	9.783	0.093884	23.840
70°	0.5037	12.628	0.093312	24.304	0.4795	16.826	0.0907	26.423
85°	0.4912	14.796	0.092146	25.250	0.4857	15.750	0.091797	25.533
No damper	Displacement (cm)= 0.5765 Acceleration (g)= 0.123272							

cylindrical TLD. In addition, the rectangular TLD is more effective at an angle of 70 degrees to reduce the structural response compared to the cases at two other angles, but in the cylindrical TLD angle of 85 degrees is the best angle (however, with very little difference in the angle of 70°) to reduce the structural response in this type of loading.

The RMS values of displacement and acceleration were calculated from start and end of excitation when the SDOF had vibration.

According to Tables 3 and 4, it can be observed that the RMS and Maximum displacement and acceleration of structure reduced in the presence of dampers and the structural response reduction of the rectangular TLD is more than that of the cylindrical TLD at all angles. Also when the structure with dampers is under harmonic excitation with frequency of 1.75 Hz and an acceleration of 0.1g, rectangular and cylindrical TLDs at 70° and 85° angles create the maximum reduction in the structural response respectively.

Also from Tables 1-4, it can be concluded that the container shape has significant effect on the performance of TLDs and the length of TLD along wave direction plays more essential role than its width in suppressing structural vibration.

Note that due to the fact that the amount of selected excitation frequencies differ greatly from the natural frequency of the SDOF structure, the difference in displacement and acceleration in the dampers is low compared to each other, but at the resonance condition (at which the frequency of excitation equal to the frequency of the SDOF structure) these differences reach their maximum.

From Fig. 9, it can be observed that two TLDs at angles of 50 and 85 degrees show the maximum and minimum differences in displacement and acceleration reduction percentage respectively and with increasing the baffle angle from θ=50° to θ=85°, both TLDs have the same seismic performance as at completely closed baffles there is almost a set of TLDs with three containers and the effectiveness of flow streamlines induced due to shape of container would be less.

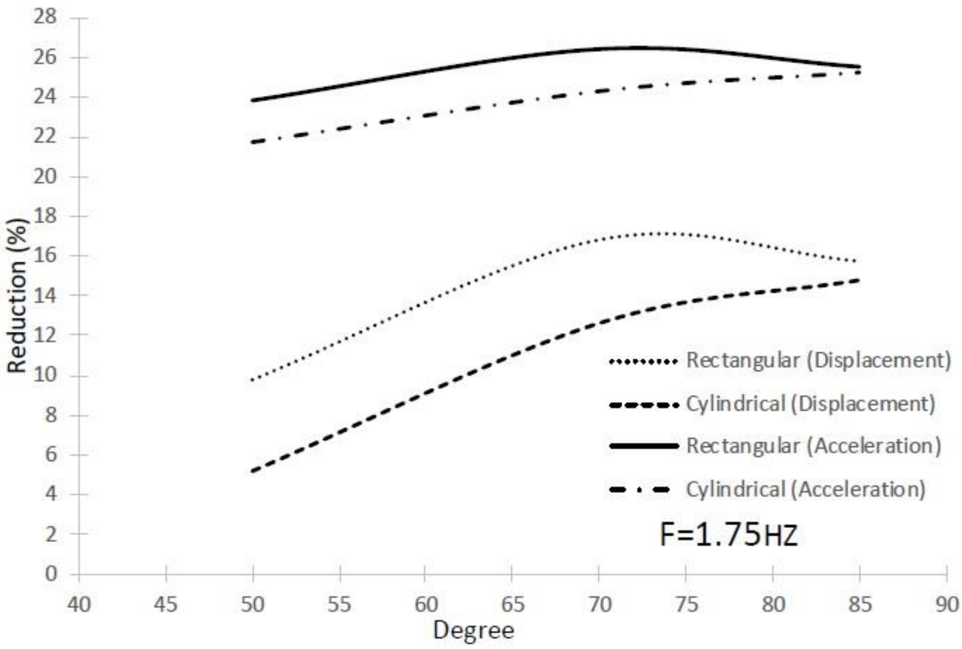

Fig. 10 Effect of changing baffle angles on reducing structural displacement under harmonic excitation

Table 4 Maximum displacement and acceleration of structure under harmonic excitation with 1.75 Hz frequency and 0.1 g acceleration

Baffle angle θ	Cylindrical TLD		Rectangular TLD	
	MAX Displacement (cm)	Reduction (%)	MAX Displacement (cm)	Reduction (%)
50°	1.1856	8.2566	1.0781	16.5751
70°	1.0914	15.5459	0.8160	36.8568
85°	1.0452	19.1209	0.8680	32.8329
No damper	Displacement (cm)= 1.2923			

Table 5 The RMS values of displacement and acceleration of structure under the Kobe 1995 earthquake excitation with scaled PGA of 0.1 g

Baffle angle θ	Cylindrical TLD				Rectangular TLD			
	Displaceme (cm) nt	Displacement Reduction (%)	Acceleration (g)	Acceleration Reduction (%)	Displacement (cm)	Displacement Reduction (%)	Acceleration (g)	Acceleration Reduction (%)
50°	4.8753	19.726	0.115880	22.875	4.8133	20.747	0.114032	24.105
70°	4.7774	21.338	0.110245	26.625	4.6092	24.107	0.109975	26.805
85°	4.7832	21.242	0.110788	26.264	4.5682	24.782	0.106812	28.91
No damper	Displacement (cm)= 6.0733 Acceleration (g)= 0.150249							

According to Fig. 10, it is observed that the highest reduction percentages in displacement and acceleration response of the structure belong to the rectangular TLD. It can also be observed that the differences of structural displacement percentage reduction are more than those for the structural acceleration while at an angle of 85 ° differences in the acceleration and displacement are minimal. The maximum structural response reduction for rectangular TLD occurs at an angle between 70° and 75° while it happens at an angle of 85° for the cylindrical TLD.

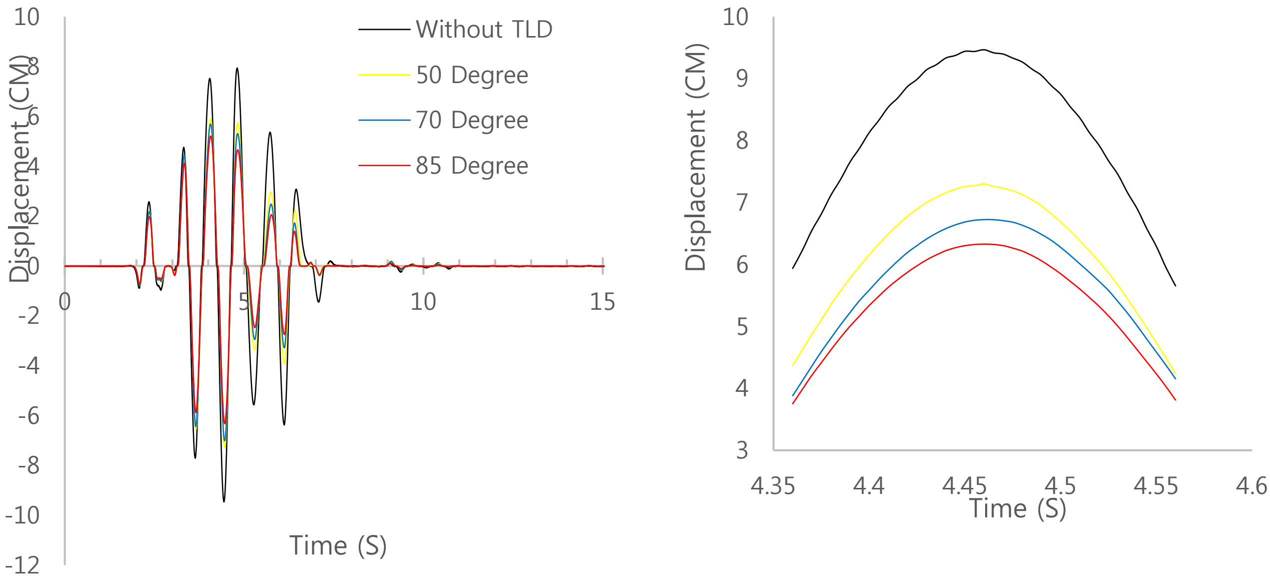

Fig. 11 Response of the SDOF structure under the Kobe 1995 earthquake excitation with scaled PGA of 0.1 g utilizing the rectangular TLD

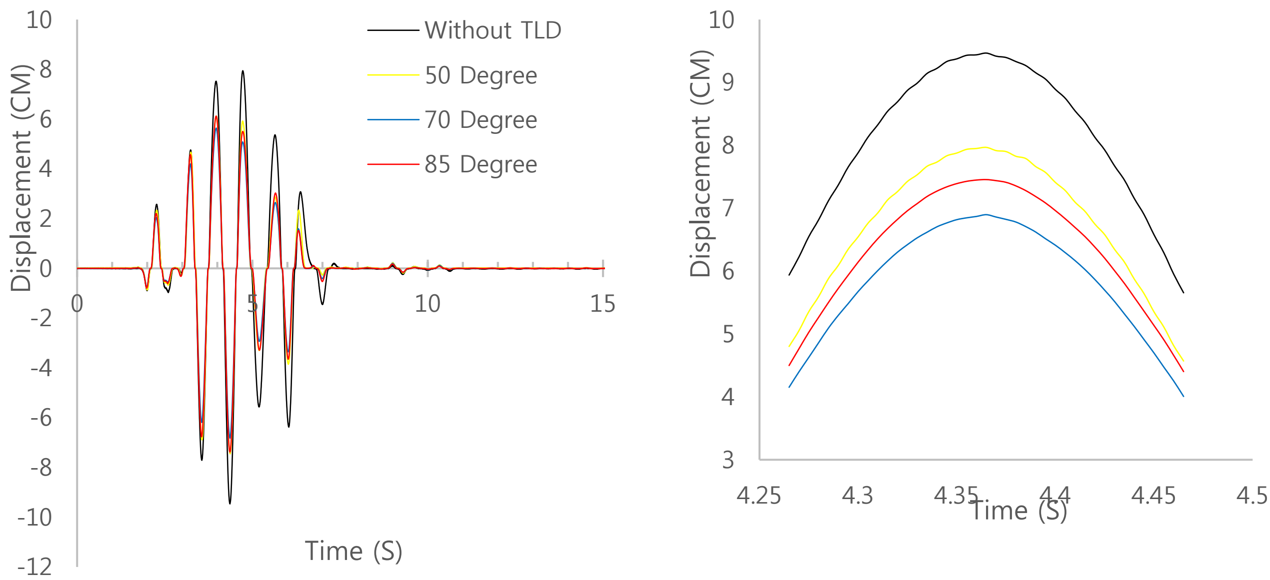

Fig. 12 Response of the SDOF structure under the Kobe 1995 earthquake excitation with scaled PGA of 0.1 g utilizing the cylindrical TLD

Most structural response (acceleration and displacement) reduction percentages of the rectangular and cylindrical TLDs are observed due to changing the angle of baffles from 50° to 70° while there has been minor impact on the structural response reduction when changing the angle from 70 to 85 degree. This is mainly because the frequency of water sloshing in the TLDs at an angle of about 70 degree is close to main frequency of SDOF structure and therefore TLDs impose better control over structure at an angle of around 70°.

3.2 Earthquake excitation tests

A detailed comparison between RMS and Maximum displacements and accelerations of the SDOF structure equipped with TLDs with rotating baffles subjected to the Kobe earthquake excitations is shown in Tables 5 and 6 respectively.

As presented in Tables 5 and 6, the maximum structural response reduction is allocated to rectangular TLD having more effectiveness in reduction response of structural than cylindrical TLD. The rectangular TLD had better function at angle of 85 degrees than the cases for 50 and 70 degrees but cylindrical TLD at an angle of 70 degrees had the best performance.

Table 6 The Maximum Displacement and acceleration of structure under the Kobe 1995 earthquake excitation with scaled PGA of 0.1 g

Baffle angle θ	Cylindrical TLD		Rectangular TLD	
	MAX Displacement (cm)	Reduction (%)	MAX Displacement (cm)	Reduction (%)
50°	7.9670	15.8392	7.3018	22.8661
70°	6.8968	27.1444	6.7240	28.9698
85°	7.4550	21.2478	6.3288	33.1446
No damper	Displacement (cm)= 9.4664			

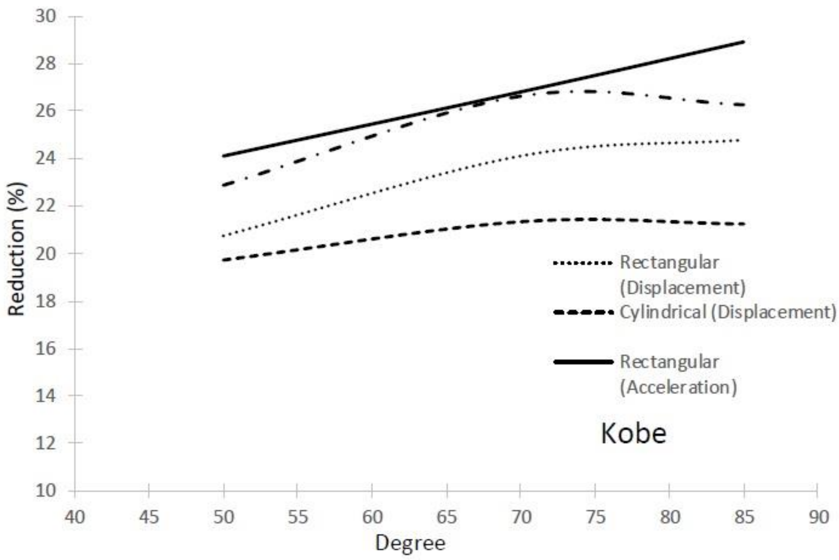

Fig. 13 Effect of changing baffle angle on acceleration reduction under the Kobe earthquake

Response of the SDOF structure under the Kobe 1995 earthquake excitation with scaled PGA of 0.1 g utilizing the rectangular and cylindrical TLDs with baffles are shown in Figs. 11 and 12 respectively. In each of the figures the maximum points of the curves are zoomed and shown on the right hand side of the chart for clarified illustration.

Based on Fig. 11, the maximum displacement of SDOF structure without TLD is 9.47 cm but with rectangular TLD at 85° baffle angle the maximum displacement reduced to 6.33 cm.

Fig. 12 shows that the maximum displacement of SDOF structure without TLD is 9.47 cm but with cylindrical TLD at 70° baffle angle the maximum displacement reduces to 6.9 cm. The performance of rectangular TLD is better than the cylindrical damper at various angles, because the length of rectangular TLD along water sloshing direction (direction of excitation) is greater than the diameter of cylindrical TLD in this study.

The main aim of this study is not to merely reduce the structural response, but to compare the effect of cross sectional shape of container with rotating baffles on seismic behavior of TLD and reduction in the structural response the structural response.

The TLD mass value should be chosen to be effective in reducing the structure response. If less than 1% of the mass of the structure is used for the TLD mass, the effect can be minor and if more than 4% of the mass of the structure is used it increases the inertial force of the structure which itself has a damaging effect. Therefore, the ratio of the TLD mass to the structure mass should be between 1% and 4% (Banerjee *et al.* 2000). In this study, the mass ratio (TLD to SDOF) is selected about 4% for which about 10.5 kilograms of water is used in both containers.

When the baffles are open (baffles are parallel to excitation direction) the container acts as a simple TLD with some obstacles, while when the baffles are closed the container is divided into three equal parts; each part with a new length.

From Fig. 13, it can be observed that the difference in structural displacement reduction percentage is increasing at angles from 50° to 85° in TLDs and two dampers reduced structural acceleration at angles from 65° to 70° equally.

4. Conclusions

The shape effect of the container with rotating baffles was innovatively studied in this paper using shaking table tests. Their effective performances had a range of frequency meaning that the frequency of sloshing water was able to change from low to high values. One of the explicit characteristics of the rectangular TLD at a constant area was to have several values for length and width, but cylindrical TLD in a constant area, only includes a certain diameter, therefore the rectangular TLD having a greater length than the diameter in cylindrical TLD showed more effectiveness in reducing structural response. The baffle position was considered at 28% of the cylinder diameter and at 28% of rectangle length.

The angle of baffles inside TLD container played two roles: increase of damping and change of frequency of sloshing phenomenon. Due to harmonic excitations with frequency of 0.58 and 1.75 Hz, the best baffle angles in the rectangular and cylindrical TLDs were 70° and 85° respectively, also in each of the above loading the reduction structural response in the rectangular TLD was higher than that of the cylindrical TLD.

Experimental results using shaking table tests showed that when utilizing dampers with four installed rotatable baffles, the displacement and acceleration reductions of SDOF structure under the Kobe earthquake excitation were 24.78% and 28.91% for the rectangular TLD and 21.34% and 26.63% for cylindrical TLD respectively. Also the results of Earthquake excitation tests showed that the best angles of baffles for the rectangular and cylindrical TLDs were 85° and 70° respectively. The experimental results in this study have shown that when the frequency of water sloshing is near the main frequency of structure, the resonance state occurs and the maximum reduction of structural response can be achieved.

In this study, only a SDOF structure has been evaluated, while if these dampers are used in MDOF structures they can show more efficiency. Since the rotation of the baffles also changes the frequency, the efficiency of these dampers increases reducing the structural response further by taking part of the energy depreciation mechanism on higher modes. Further work can be done to supplement the results like studying the effect of number, dimensions and spacing of baffles on TLD'S performance. In this way, the critical state of the vibration of the SDOF structure can be examined to disclose the effect of both dampers. For this purpose, it is necessary to select a frequency of excitation close or equal to the natural frequency of the SDOF structure.

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