

## Research Article

### Performance Evaluation of Tuned Liquid Dampers on Response of a SDOF System Under Earthquake Excitation and Harmonic Load

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**Abstract:** A Single-Degree-of-Freedom system with the addition of Tuned Liquid Damper (TLD) was analyzed experimentally and numerically. In this study, a shaking table and finite element software were used in order to obtain the acceleration responses of seven structure-TLD systems. The TLD frequencies were calculated by formula and models frequencies were calculated via finite element software and experimental work. The models were excited by a sine and an earthquake load. The results obtained from the software and experimental works were compared to each other and the results have been found to be in good agreement. Finally, it was concluded that the tuned liquid damper decreases the response of a structure under earthquake excitation and sine load. In addition, it was determined that the frequency tuning ratio and mass ratio of the damper are very effective parameters in reducing of structural response.

**Keywords:** Earthquake excitation, response of structure, tuning ratio

#### INTRODUCTION

In recent decades, researchers have investigated the effectiveness of a variety of dampers in tall buildings, bridges and marine structures such as Tamura *et al.* (1995) and Ding *et al.* (2009). Active and passive dampers are two damper categories. Comparatively, the passive systems are more popular than other systems because there is no necessity for extra structural power during a destructive event. Tuned Mass Damper (TMD), Tuned Liquid Dampers (TLD) and Tuned Liquid Column Dampers (TLCD) are examples of passive systems. A TMD consists of a mass connected to a structure by a spring; a TLD uses liquid primarily water instead of mass; and a TLCD is a special type of an auxiliary damping device, which relies on the inertia of a liquid column in a U-tube to counteract the forces acting on the structure (Fig. 1).

One of the most common passive dampers is the TLD, which can be rectangular or cylindrical with a variety of materials and properties. Tuning ratio and mass ratio are the most important parameters which determine the effectiveness of TLD-structure systems. As a passive energy-damping device, the TLD has several advantages such as low maintenance cost, fewer mechanical problems and easy installation in new and existing buildings (Jin *et al.*, 2007). The earlier known research into this subject was carried out in the mid 1980s by Bauer. In addition, Wakahara *et al.* (1992) was among the first to suggest the use of dampers utilizing liquid motion for civil engineering structures. Tait *et al.*

(2007) investigated the effectiveness of a bidirectional (2D) tuned liquid damper. Furthermore, Ostermann (2009) studied the behavior of TLDs with experimental and analytical solutions and Samanta and Banerji (2010) analyzed structural vibration control using a modified TLD. Previously, several TLDs were attached to various buildings to decrease the level of structural vibration. For example, a TLD system was installed in the Rincon Hill South Tower in 2008.

Few of previous studies consider the effects of adding TLD to a structure when excited with earthquake load. In this study, an experimental work was carried out to investigate the effectiveness of TLD on a scaled-down steel structure when subjected to earthquake load and harmonic force. The effectiveness of TLD was assessed in reduction of acceleration and displacement response of the structure. The effects of tuning ratio and mass ratio were considered. The finite element software of ANSYS was used to simulate fluid, structure and the interactions between them. The results of finite element models show good agreement with the experimental results.

#### EXPERIMENTAL WORK

In this part, a structure and TLDs were tested in a laboratory using a shaking table. A shaking table is able to vibrate a structure in two directions simultaneously. The structure considered was based on the limitations of the shaking table.

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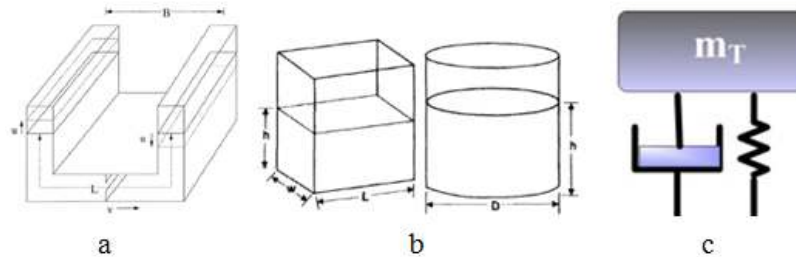


Fig. 1: a) TLCD b) TLD c) TMD

Table 1: Properties of steel bars

Diameter (m)	Cross section (m <sup>2</sup> )	Modulus Of elasticity (Pa)	Poisson's ratio	Density (kg/m <sup>3</sup> )	Inertia moment (m <sup>4</sup> )
0.012	0.000113	2.1e11	0.3	7800	0.0178e-8

Table 2: The details of the TLDs used in this experimental work

Model	Height of water (m)	Frequency of TLD	Tuning ratio	Mass ratio
TLD3.5	0.035	1.406	0.95	0.89
TLD4	0.040	1.482	1.0	1.01
TLD4.5	0.045	1.55	1.04	1.14
TLD8.5	0.085	1.85	Tuned with 2ed mode	2.16
2TLD4	0.040	1.482	1.0	2.03
3TLD4	0.040	1.482	1.0	3.05



Fig. 2: An excited structure with TLD8.5

**Description of structure and TLDs:** In this study a one-storey Single-Degree-of-Freedom (SDOF) structure with height of 1.0 m, dimensions of 0.8 m×0.8 m and the natural period of 0.67 was used. Beams and columns were composed of uniform steel bars with its properties as described in Table 1. Fig. 2 shows the structure with the damper secured to the top.

TLDs used in this test were rectangular in shape. The rectangular tank made for this study was made of Perspex in three equal parts with a thickness of 0.005 m. The TLDs' details are shown in Fig. 3 and 4. Length of each tank in excitation direction = 0.2 m; width of the tank = 0.15 m; height = 0.2 m. The liquid used for all of TLDs was water with a density of 1000 kg/m<sup>3</sup> and bulk modulus of 2.15e9 Pa.

**Experiment set-up:** The TLDs were designed according to the dominant structural frequency. In order to check the effects of tuning ratios, the depth of the liquid inside the dampers was adjusted to tuning ratio of 0.95, 1.0 and 1.04. In addition, a second test was done by a damper tuned to the second most dominant structural mode. The

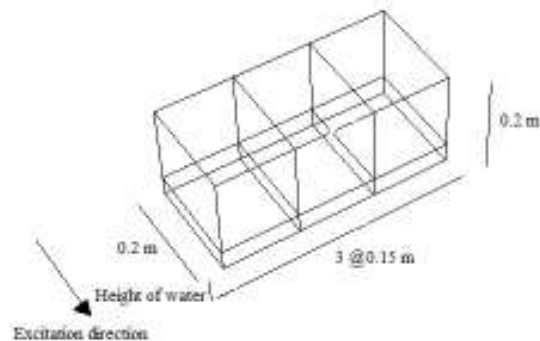


Fig. 3: Shape and dimensions of TLD

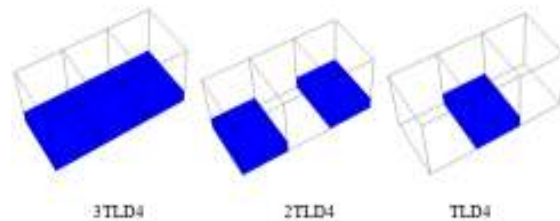


Fig. 4: Three types of TLD4s with different mass and same frequency

frequency of each model was calculated with Eq. (1) (Housner, 1963). In this formula h and g are the height of water and gravity acceleration, respectively. Table 2 shows the output of the frequencies calculations and the mass of TLDs:

$$f_{TLD} = \frac{1}{2\pi} \sqrt{\frac{3.16 \times g \times \tanh(3.16 \times \frac{h}{l})}{l}} \quad \text{(Housner, 1963)} \quad (1)$$

Two accelerometers were used to record data, with one attached to the shake table and the other attached to the top of the structure. The sine load which was applied to the structure is based on Eq. (2):

$$F = \sin(1.406 \times 2\pi \times t) + \sin(1.482 \times 2\pi \times t) + \sin(1.55 \times 2\pi \times t) + \sin(1.85 \times 2\pi \times t) \quad (2)$$

Table 3: Comparison of frequencies calculated by formula to results obtained from software

	Mass ratio	Height of water (m)	TLD Fundamental frequency based on formula (Hz)	TLD Fundamental frequency based on ANSYS (Hz)	Ratio of calculated frequency in ANSYS to formula
TLD3.5	0.89	0.035	1.406	1.375	0.978
TLD4.0	1.01	0.040	1.482	1.468	0.99
TLD4.5	1.14	0.045	1.55	1.508	0.972
TLD8.5	2.16	0.085	1.85	1.817	0.982
2TLD4.0	2.03	0.040	1.482	1.468	0.99
3TLD4.0	3.05	0.040	1.482	1.468	0.99

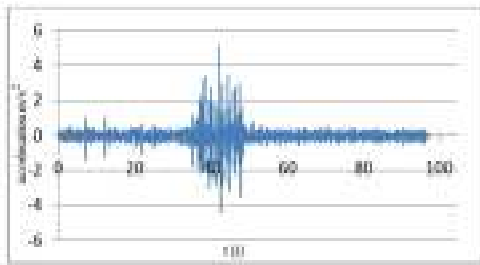


Fig. 5: Malaysia earthquake input

A Recorded Malaysian Earthquake Time History in Kuala Lumpur was then applied to the structure with the damper tuned to the frequency of the structure. The acceleration responses of the structure with tuned dampers were subsequently measured (Fig. 5).

### FINITE ELEMENT WORK

ANSYS is the finite element software used in this study. Two elements (Beam4, Link3) and (Shell63, Fluid80) were used to model the structure and TLDs respectively. First, the TLD models were analyzed as the modal to obtain their fundamental natural frequencies. It was verified that the frequency of the damper in practice is the same as what is calculated in theory. Then, TLD-Structure models were simulated in software and all models were analyzed as modal, harmonic (sine load) and transient (recorded earthquake of Malaysia).

### FINDINGS AND DISCUSSIONS

**TLDs frequency based on software and theory:** TLD frequencies as calculated and shown in Table 3 display reasonably good agreement between ANSYS and formula results.

**Acceleration response of experimental test:** Fig. 6 and 7 show the acceleration response spectrum comparison between laboratory and software results. As can be seen, the graphs of the excited structure response in laboratory and software are very close in excited structure, unlike the TLD-Structure system.

The models were tested by a shaking table under sine load (1). Table 4 and Fig. 8 present results obtained from the shaking table for all TLD-structure Systems.

As can be seen, the acceleration structural response was reduced by adding TLD. The effect of TLD 8.5

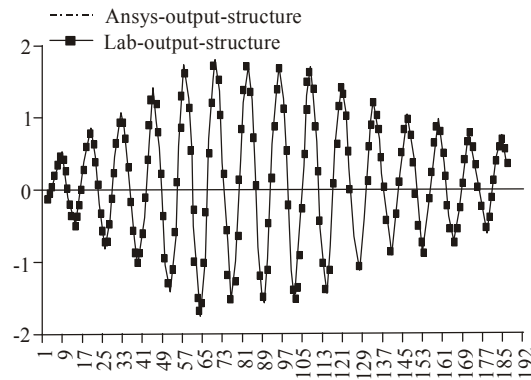


Fig. 6: Comparison of acceleration responses between experiment and software results (structure alone) under sine load

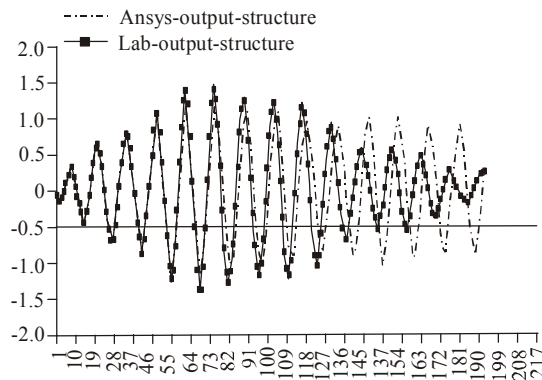


Fig. 7: Comparison of acceleration responses between experiment and software results (structure that TLD4 is attached to) under sine load

Table 4: Maximum acceleration of models of TLD-structure system

Model	Maximum acceleration response (m/s <sup>2</sup> )	Reduction of structure response (%)
Structure	1.68	---
S+TLD3.5	1.152	31.4
S+TLD4	1.117	33.5
S+TLD4.5	1.146	31.8
S+TLD8.5	1.575	6.3
S+2TLD4	.919	45.3
S+3TLD4	.648	61.4

structural response is not considerable with only a 6.3% response reduction. The maximum reduction of 31.4% is attributed to structure with TLD4. The TLD4 frequency had been tuned to the natural structural

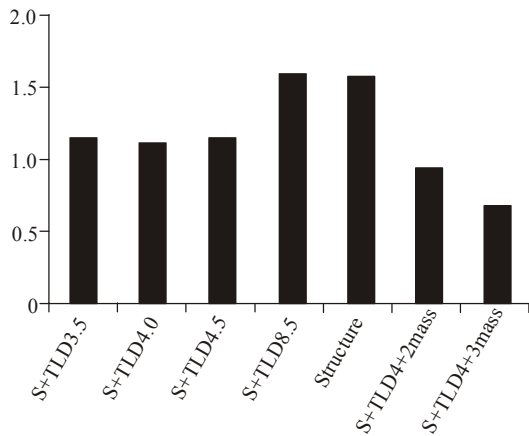


Fig. 8: Acceleration response of models based on experimental test



Fig. 9: Some mode shapes of TLD

Table 5: The acceleration response under earthquake excitation recorded in Malaysia

	Applied Acc. (m/s <sup>2</sup> )	Response Acc. (m/s <sup>2</sup> )	Reduction (%)
Str.	0.81	0.92	-
S+TLD	0.82	0.83	10

on frequency. Other TLDs showed less response reduction than TLD4.

In addition, by increasing the number of TLD4s, the acceleration response decreased up to 45.3% in a structure with 2 TLD4s and 61.4% in structure with 3 TLD4s, which shows the importance of mass ratio on structural response. Figure 9 shows three shape modes of structure with TLD 8.5 during testing.

**Response of system under earthquake load:** A recorded earthquake in Malaysia was applied to the structure (Fig. 8). The maximum acceleration of an earthquake, which was simulated by the shake table, as well as maximum response acceleration of a structure with and without a damper, is shown in Table 5.

As can be seen, in a similarly applied acceleration by the shaking table, the acceleration response of a structure with TLD decreased 10% in comparison to structure alone.

### CONCLUSION

In order to investigate the effectiveness of Tuned Liquid Damper on a SDOF system under earthquake excitation and harmonic load, an experimental work and a finite element work were carried out. The results were

compared to each other and showed reasonably good agreement.

Generally, it was seen that adding TLD at structure caused a reduced acceleration response of the system during simulated seismic tremors. In addition, a tuned Structure-TLD system is more effective than structure alone when excited by sine load rather than earthquake load. Furthermore, it was found that both tuning ratio and mass ratio have significantly affected the response of the Structure-TLD system. Finally, increasing the mass ratio has a significant effect on response reduction of a structure.

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