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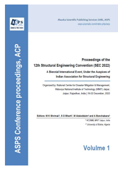

Mitigating Structural Vibrations due to Earthquake with Application of Slope Bottom Tuned Liquid Dampers

G. R. Patil[1,*], K. D. Singh[2] and B. Nanda[3]

[1]Department of Civil Engineering, Research Scholar, Indian Institute of Technology, Guwahati, Assam, India
[2] Department of Civil Engineering, Professor, Indian Institute of Technology, Guwahati, Assam, India
[3] Department of Civil Engineering, Assistant Professor, Veer Surendra Sai University of Technology, Burla, Orissa, India

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Abstract

Earthquakes are one of man's most feared natural phenomena, producing almost instantaneous destruction of buildings and other constructed facilities. In order to mitigate damage of structures and save the life, various measures are adopted and use of structural control devices is one of them . Structural control devices can enhance the integrity of structures without increasing the dimensions of structural members.In this study, an attempt has been made to systematically investigate the performance of structural control device namely, tuned liquid damper (TLD) for controlling the dynamic response of reinforced concrete (RC) framed structure. Dynamic analysis of a 10 story RC framed structure with both flat and slope (W or central slope) bottomrectangular TLDs, subjected to five earthquake time histories have been performed. Key results have been presented in the form of tuning ratio, liquid mass reduction and displacement response reduction due to slope at bottom TLD. For the case of TLDs with central slope, the analyses have been performed for slope angle ranging from 5-14º. Based on the study, it has been observed that,tuning ratio of TLD decreases with increase of central slope at the bottom of TLD, the variation of liquid mass reduction with slope angle has been observed to be linear and reduction in displacement of structure increases with increase in central slope angle.

Keywords: Structural control devices, Tuned liquid damper, Displacement response reduction, Tuning ratio, Liquid mass reduction

Introduction

Useof Tuned Liquid Damper (TLD), for mitigating the response of structures (e.g. buildings) started since by Bauer (1984). TLD is a device consisting of tank, partially filled with liquid/water and tank is rigidly attached (generally) to the roof level of structure. During vibration of structure, sloshing motion of liquid occurs at the free surface of liquid in a tank. Properly tuned TLD imparts force against the motion of structure, due to sloshing of liquid, thereby reducing the dynamic response of structure. TLDs have gained attention due to their simplicity, low installation and maintenance cost and bidirectional properties. TLDs are effectively used in reducing dynamic response of tall buildings subjected to strong winds (e.g. Tamura et. al., 1995 and Wakahara et. al. 1992). Sloshing motion of liquid in a tank exhibits highly nonlinear behaviour at large response amplitude (Tait et. al. 2004). Most of researchers (Chen et.al., 1995, Reed et.al. 1998, Sheng and Hua 2001etc.) have investigated performance of TLDs attached to structures subjected to harmonic excitation. These researches provide resemblance to the response of structure with TLD, subjected to wind excitations. Koh et. al. (1994) conducted numerical study to investigate use of TLDs for mitigating seismic response of suspension bridge. A reduction in dynamic response of bridge of order 20% to 30% was observed with 1% mass of TLD relative to generalized mass of bridge. Response of TLD subjected to large excitation amplitude was investigated by Reed et. al., (1998). It was observed that, nonlinearity of sloshing motion makes TLD, more effective and robust for control of structural response. A considerable reduction in ductility demand of reinforced concrete members was observed with use of multiple tuned liquid dampers. A large number of studies have been conducted on use of flat bottom TLDs to mitigate dynamic response of structures, subjected to wind (Chang C. C. and Gu M. 1999) and earthquake excitations (Murudi and Banerji 2012). However very few studies on sloped bottom TLDs have been reported in the literature (Gardarsson 2001, Olson and Reed 2001, Xin 2006, Idir and Ding 2009).

It is observed from literature that flat bottom TLD exhibits a phenomenon of beating, which has adverse effect of giving energy, back to the structure after end of external excitation. Researchers have studied W and V shape slopes of 5º to 30º (Xin 2006) with density variable liquids. Idir and Ding (2009) suggested formula for evaluating sloshing frequency for W and V shape bottom TLD.

Therefore, an attempt to evaluate the performance of slope bottom (central or W shape or single triangular hereafter will be referred as central slope has been made in this study, to investigate the effectiveness of TLD with range of maximum possible slopeangle at bottom of TLD using finite element analysis.

In the study, the influence of various parameters such as tuning ratio (sloshing frequency of liquid / structure's

*Corresponding author. Tel: +9324972109; E-mail address: grpatil@mes.ac.in

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natural frequency), mass ratio (mass of liquid / mass of structure) on the performance of TLD in reducing the dynamic response (such as displacement) of structure are investigated. Numerical investigations on flat bottom TLD are presented first, followed by responses of central slope TLDs. The results of the analysis are then presented in the form of variation of displacement with time.

2. Structural Model with TLD

A two bay ten storey representative reinforced concrete frame is shown in Figure 1. The details of the structural 2D frame are listed as under:

- Type of structure: Multi-storey rigid jointed plane frame
- Number of stories: G + 9
- Floor height: 3.5 m
- Bay width: 5.0 m
- Live load: 3.5 kN/m^2
- Concrete (M25) and Steel (Fe415)
- Density of RCC: 25 kN/m^3
- E=2.5x10^{10} N/m^2 of concrete
- M I of column: 1.9x10^{-3} m^4
- M I of beam: 1.33x10^{-3} m^4
- Self weight of column: 2.81 kN/m
- Load on beam (DL+LL): 3245 kN/m
- Mass column: 286.69 kg/m
- Equivalent mass of beam: 3312 kg/m (With considerarion of weight of infill, weight of floor and live on floor).

The fundamental natural frequency of the frame in it's own plane is observed to be 2.5038rad/sec. However, it is to be noted that stiffness of frame due to infills is not considered in the analysis.

The equation of motion of structure-TLD system is given as,

$$[M]\{\ddot{X}\} + [K]\{X\} = -[M]\{\ddot{X}_g\} + \{F_{TLD}\} \quad (1)$$

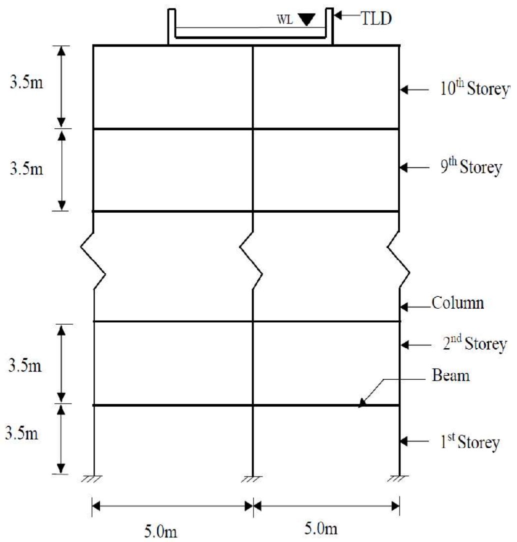

Figure 1. Structural model of a 2D representative frame

Where $[M]$ and $[K]$ are mass and stiffness matrices of structure respectively.$\{\ddot{X}_g\}$is ground acceleration

Discretization of 2D frame has been done with plane frame element (i.e., 2 noded element) with three degrees of freedom per node (2 displacements and 1 rotation).

2.1. Modeling of Sloped Bottom Tank

Figure 3 shows elevation of central slope TLD and Figure 4 represents an equivalent flat bottom TLD.

The equivalent length called as wet length, suggested by Xin (2006) is given as

$L' = 2y$(3)

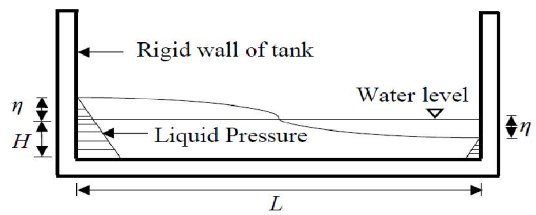

Figure2. Schematic view of flat bottom tank partiallyfilled with water$\{F_{TLD}\}$is resisting force to the structure at respective nodes due to TLD and is given as

$$F_{TLD} = \frac{1}{2}\rho g b[(\eta_n + H)^2 - (\eta_o + H)^2] \quad (2)$$

where ρ is density of liquid, η_n and $\eta_o$is wave height at right and left wall respectively, and H is the still height of the liquid in the tank (Figure 2). Discretization of liquid domain is done by using 2D four noded quadrilateral elements (with two displacement degrees of freedom per node).

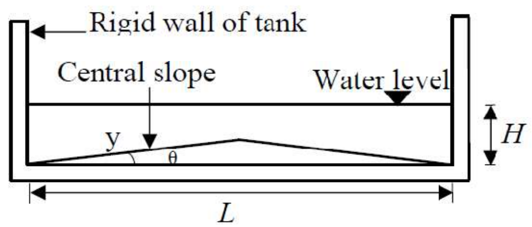

Figure 3. Sloped bottom tank for shallow water depth

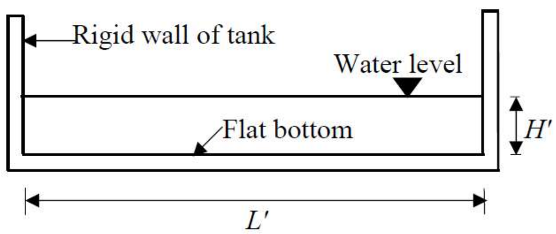

Figure4. Equivalent flat bottom tank for central slope TLD.

Table 1. Dimensions of equivalent flat bottom TLD (Depth of liquid H =0.2235m)

Sr. No.	θ°	Dimensions (m)		TR	MR(%)
		L	B		
1	0	1.72	1.00	1.05	-
2	5	1.72	0.99	1.04	16.82
3	7.5	1.73	0.99	1.04	25.33
4	10	1.74	0.98	1.03	33.92
5	12.5	1.76	0.97	1.02	40.87
6	14.0	1.77	0.97	1.02	47.96

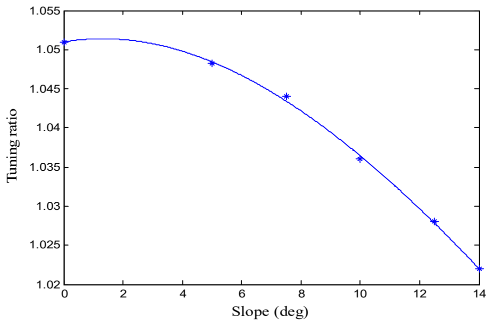

Figure 5. Variation of tuning ratio with central slope of TLD

Considering a constant mass of water in the tank, the width of the virtual flat bottom tank is determined by:

$B' = \frac{V_w}{H'L'}$ (4)

Where H = H' and V_w is volume of liquid in sloped bottom tank.

The sloping bottom would reduce the natural frequency of water sloshing because of more wetting length in the tank, therefore $L' > L$ and $B' < B$.

Figure 5 shows a plot of tuning ratio vs central slope angle and it is seen that the tuning ratio decreases with increase in central slope angle at bottom of TLD. The variation of tuning ratio is seen to be nonlinear. With the increase of central slope, the state of TLD changes from over-tuned to the state of fine-tuned. Maximum tuning ratio (=~1.05) has been observed at 0° (flat bottom) slope whereas minimum (=~1.022) tuning ratio is found to correspond to slope angel of 14°.

A plot of liquid mass reduction in TLD vs central slope is shown in Figure 6. The liquid mass reduction is seen to increase with increase in central slope value. The variation of liquid mass reduction is seen to be linear. The reduction in liquid mass due to application of slope at bottom of TLD is observed to be ~16.82 %, 25.33 %, 33.92 %, 40.87 % and 47.96 % for the central slopes of 5, 7.5°, 10°, 12.5° and 14° respectively.

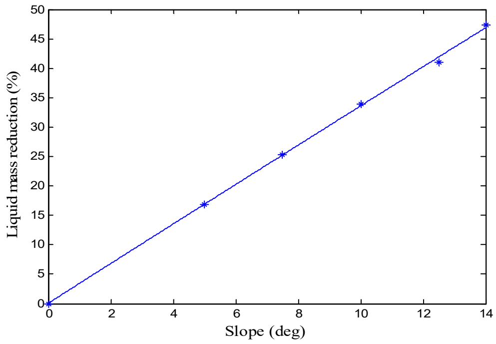

Figure 6.Variation liquid mass reduction with central slope of TLD

3. Dynamic Analysis

Finite element analysis of structure-TLD system is performed with the application of MATLAB. Linear dynamic analysis of the structure with TLD having central slope at the bottom (see Figure 3. for schematic diagram) has been performed for slope angles of 5°, 7.5°, 10°, 12.5° and 14° (maximum possible angle as the depth of the liquid is limited to 0.2235 m). The results of analysis for various earthquake input motions are presented in Table 2.

Five earthquake time histories viz., El Centro (1940), Loma Prieta (1989), Northridge (1994), San Fernando (1971) (http://strongmotioncenter.org), and Indian Standard (IS) 1893 (Kumar 2004) compatible time history have been used as base excitation inputs, for the analyses. It may be noted that structure's fundamental frequency (0.39 Hz or 2.5 rad/sec) necessarily lies within the range of frequency content of chosen earthquakes (0.1-12 Hz).

Typical plots of time histories of undamped and damped responses of structure subjected to El Centro earthquake ground motion for 5°, 7.5°, 10° and 14° central triangular slopes in Figures 7. The variation of displacement reduction with application of central slope TLD to various base motions is shown in Figure 8.

It can be observed that, there is an improvement in reduction of displacement of structure with application of central slope at the bottom of TLD. For all the input ground motion considered, for all the bottom slopes of TLD considered, displacement reduction (*DR*) values in the range 21-53% could be obtained, with minimum (21-26%) and maximum (40-53%) displacement reduction ranges associated with IS compatible time histories and El Centro, respectively. The displacement reduction (*DR)* is seen to increase with increase of central slope. The rate of improvement in the reduction of displacement is observed to be marginal for the central slope up to 7.5°. The rate improvement in *DR* values due to application of central slope of 7.5° over flat bottom TLD is observed to be maximum (*DR* = 6.67 %) and minimum (*DR* = 1.10 %) for El Centro and IS compatible time histories, respectively. The rate improvement in DR values for TLD with central slope ≥ 7.5° are observed to be relatively higher than that of central slope values ≤ 7.5°. The rate improvement in reduction of displacement due to central slope of TLD from 7.5° to 14° are observed to be ~8.20 %, 3.90 %, 5.20 %, 9.60 % and 3.90 % for the input motions of

El Centro, Loma Prieta, Northridge, San Fernando and IS time histories respectively. The reduction in displacement of structure with TLD is found to be relatively higher for earthquake motions having lesser Fourier amplitude values and less strong motion duration.

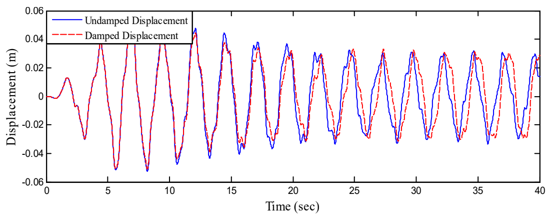

Figure 7a. Response of structure with 5° central slope TLD to El Centro earthquake

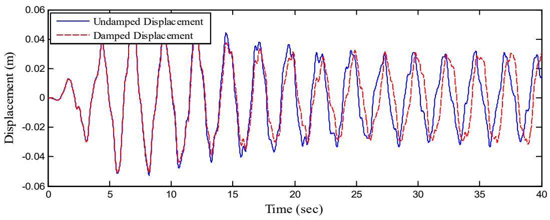

Figure 7b. Response of structure with 7.5° central slope TLD to El Centro earthquake

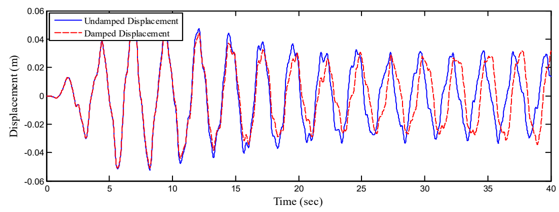

Figure 7c. Response of structure with 10° central slope TLD to El Centro earthquake

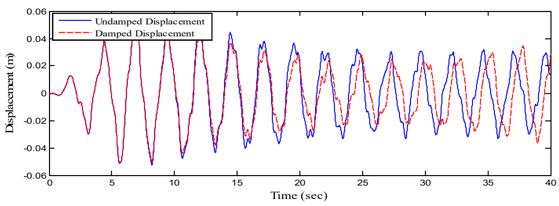

Figure 7d. Response of structure with **12.5°** central slope TLD to El Centro earthquake

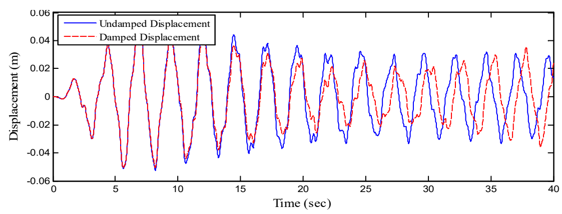

Figure 7e. Response of structure with 14° central slope TLD to El Centro earthquake

Table 2. Effect of slope angle on the response reduction

Sr. No.	θ°	Displacement reduction (%)				
		El Centro	Loma Prieta	Northridge	San Fernando	History (%)
#1	0	40.97	26.90	26.60	33.20	21.00
2	5	40.71	27.60	27.70	34.70	21.50
3	7.5	45.53	28.30	28.70	36.20	22.10
4	10	47.01	30.00	31.00	40.00	23.50
5	12.5	51.04	31.40	32.80	43.50	25.00
6	14.0	53.73	32.20	33.90	45.80	26.00

Displacement reduction with application of flat bottom TLD

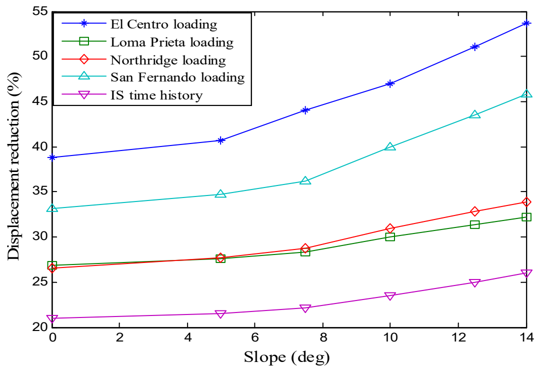

Figure 8. Variation of reduction in displacement of structure with central slope of TLD subjected to earthquakes and IS time history

4. Conclusions

- Original TLD (before applying slope at the bottom) is required to be tuned to the frequency, slightly greater than structure's natural frequency. In the present study the tuning ratio of original TLD is evaluated as 1.05.
- When central slope is introduced at TLD bottom it is seen that, reduction in displacement of structure increases with increase in central slope angle. Maximum reduction in displacementof structure, of ~ 53.73 % and 26.00 % has been observed at 14° central slope TLD for input motions of El Centro earthquake and IS time history base motion, respectively.
- Tuning ratio of TLD decreases with increase of central slope at the bottom of TLD and variation of tuning ratio is observed to be nonlinear. With the increase of central slope, tuning ratio changes from over-tuned to the value close to 1.

- Liquid mass reduction in TLD is increases with central slope and this may be considered as additional benefit of sloped bottom TLD. The variation of liquid mass is observed to be linear. In the present study liquid mass reduction for central slope of 14º is observed as 47.93 %.

Disclosures

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