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Effect of Tuned Liquid Damper on Highrise Building

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Abstract
Urbanization has led the current trend in construction industry to lighter and taller structure. Generally, these structures have low damping value and are flexible in nature which might increase the likelihood of the failure in serviceability point of view. So, for this we need to introduce control system in the structure. Nowadays, there are several techniques available to control the structural vibration and response of the structure, out of which the concept of Tuned liquid damper (TLD) is newer one. This study was made to study the effectiveness of TLD for high-rise building in controlling the vibration and response of the structure. In this study, analysis was carried out on a 10 and 15 Storied building, with and without TLD at the top of the building. The building was analyzed with the combination of the different mass ratio (2 %, 3 %, 4 % and 5%), with the depth ratio of 0.2. TLD was placed at the center top of the building maintaining symmetry. IS 1893:2016 (part I) response spectra were used for the analysis. Effectiveness of the TLD was expressed in terms of the percentage of reduction of amplitude of the displacement of the structures for different mass ratio. From this study, it is found that increasing the mass ratio will increase the effectiveness of the Tuned Liquid Damper and the effectivenss of TLD increases with increase in the storey of the structure and optimum mass ratio was found to be between 3% and 4%.

Keywords
Liquid Damper, Damper, Etabs2018, Dynamic Response, Sloshing, Mass ratio.

1. Introduction

1.1 General

With the growing population and urbanization, current trend demands the construction of the high rise building to maximize the limited space available. These structures are made light, flexible and possess quite low damping thus making the structure more prone to deflection and vibration. High rise buildings are generally made with high strength concrete which might satisfy limit of collapse but it is hard for tall and flexible building possessing low damping to satisfy limit of serviceability during the earthquake condition. Therefore, to ensure functional performance of high rise building during earthquake it is important to keep the deflection and vibration within the limit. One of the ways to keep the deflection within the limit is by introducing the control system. These are use to increase the damping property of the building.

Damping is one of the most important parameters that limit the response of the structures during the dynamic events. Damping increases the ability of the structure to dissipate the energy from the incoming dynamic loading event. Nowadays researches are being carried out on the devices that add external damping to the structures. Some of these devices are viscoelastic dampers, base isolation system, metallic yield dampers, tuned mass dampers, etc.

1.2 Tuned Liquid Damper

Tuned Liquid Dampers (TLDs) are generally of rectangular in shape. These are installed on the topmost floor of the building which is the most effective location for TLD with the objective for controlling the vibration [1]. A TLD can be classified as shallow water type or deep-water type depending on height of water in the tank. This classification of the TLDs is based on shallow water wave theory[2]. Shallow water type has a large damping effect for a small scale of externally excited vibration, but it is very difficult to analyze the system for a large scale of externally excited vibration as sloshing of water in a tank exhibits nonlinear behavior. In case of deep-water type, the sloshing exhibits linear behavior for a large scale of externally excited force. The depth of the liquid in a container vary, depending on the natural frequencies of the structure under control.

When the frequency of water in the tank is close to the natural frequencies of the structure under control, large sloshing amplitudes can be expected. If both the frequencies are close to each other, resonance will take place. Generally, tuning the fundamental sloshing frequency of the TLD to the natural frequency of the structure causes a large amount of sloshing in the tank, which dissipates a significant amount of incomming seismic force [3]. TLD is one of the easiest control system to install and has very low maintenance and operating cost.

1.2.1 Parameter of TLD

1. **Mass Ratio**

   Mass ratio is defined as the ratio of mass of the water in the TLD to that of structure itself. The effect of damping by TLD increases with the increase in the mass ratio [4]. This is because as the mass ratio increases the mass of sloshing water also increase resulting in increase of sloshing force which counteract with the lateral incomming forces .

2. **Tuning Ratio**

   It is the ratio of frequency of liquid in TLD to that of fundamental frequency of the structure. TLD is most effective when the tuning ratio is equal to one and it is found that detuning the TLD might increase the response of the structure [3].

3. **Depth Ratio**

   It is the ratio of depth of the liquid in the tank to that of length of the liquid in slohing direction. Smaller depth ratio is much effective than larger depth ratio [4].

4. **Position of tank**

   Position of tank also affects the behaviour of TLD. It is found that the TLD is most effective when it is placed at the top of storey of the structure.[1]

1.3 Objectives

The main objective of this work is to find out the response of the structure with and without the TLD for which the following sub objectives are set.

1. To determine the effect of mass ratio on the response of the structure.
2. To evaluate the response of the structure with TLD on the different storey.
3. To find the optimal mass ratio for the structures.

2. Methodology

Entire methodology can be broken down as following:

1. Modelling of Structure
2. Modelling of TLD
3. Analyzing and Comparing results

2.1 Modelling of Structure

A typical regular structure of 10 storey and 15 storey having four bays in each direction with 6m width is considered for modelling the building. Different models are created with different combination of mass ratio (2%, 3%, 4% and 5%) with the depth ratio of 0.2. A RC framed structure with TLD and without TLD was modelled in ETABS 18 [5]. For this study TLD was placed at the top of the structure[1] i.e., at the tenth storey and fifteenth storey. IS 1893:2016 (part I) response spectrum analysis has been used for the analysis. For this purpose, the building is considered as special moment resisting frame. Soil type is considered as type II and the seismic zone V. Sailent features of the buildings are as shown in the table 1.

Table 1: Sailent features of modeled structures

S. N	Item	10 and 15 storied building
1	Grade of concrete	M25
2	Grade of steel	Fe500
3	Density of concrete	25 KN/m3
4	Storey height	3m
5	No. of bay	4 on each side
6	Dimension of beam	300mm*500mm
7	Dimension of column	500mm*500mm
8	Slab thickness	125mm
9	Live load	2 KN/m2
10	Wall load exterior	9.936 KN/m
11	Wall load interior	4.968 KN/m

2.2 Modelling of TLD

2.2.1 Determination of dimension of tank

Dimension of tank determined by equating the fundamental frequency of structure with sloshing frequency of liquid in the tank. Sloshing frequency of water is calculated using the equation suggested by Fujino et al.(1990) [2].

$$\omega_f = \sqrt{\frac{\pi \cdot g}{L} \cdot \tanh(\frac{\pi \cdot h_f}{L})} \quad (1)$$

2.2.2 Modelling of water

TLD is modelled as simple spring mass system as suggested by Novo, Varum et al. (2014)[5]. The steps adopted for the simplified simulation of the passive energy dissipation system based on TLD are as follows:

1. A damper type link and linear link was defined in order to simulate the damping properties of TLD.
2. Each link is connected to the structure with stiffness K.
3. Concentrated mass were introduced at the end as impulsive mass (M_o) and at the middle of the spring mass system as convective mass (M_1) to simulate the static mass and dynamic mass respectively. Here, impulsive mass is rigidly connected to the structure and moves with structure while convective mass is the mass that represent the sloshing of the water [6].

The model was implemented in ETABS 18. The model used in this study to represent TLD group is as shown in the figure 1.

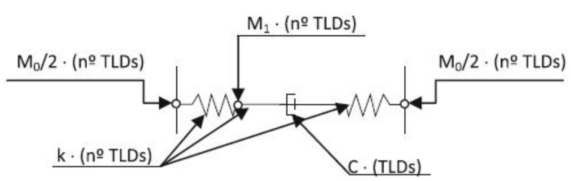

Figure 1: Schematic representation of the macro-model of TLDs

These parameter shown in the figure 1 for a rectangular tank is calculated using Newmark and Rosenbluth (1971) and Jin et al. (2007): [7, 8].

$$M_o = \frac{\tanh(1.7 * \frac{L}{2}/h_f)}{1.7 * \frac{L}{2}/h_f} \cdot m_f \quad (2)$$

$$M_1 = \frac{0.83 * \tanh(1.6 * h_f/\frac{L}{2})}{1.6 * h_f/\frac{L}{2}} \cdot m_f \quad (3)$$

$$K = \frac{3 * g * M_1^2 * h_f}{m_f * L^2} \quad (4)$$

$$\xi = \sqrt{\frac{\mu_f * \omega_f}{2}} \cdot [1 + \frac{2 * h_f}{b} + s] \cdot \frac{L}{h_f \sqrt{g * h_f}} \quad (5)$$

$$C = 2 * m_f * \omega_f * \xi_f \quad (6)$$

Where M_o is impulsive mass, M_1 is convective mass, L and B are the dimension of TLD, m_f is the mass of water in one TLD, h_f is the height of fluid in TLD, m_s is the mass of the structure, K is the stiffness of the spring mass stiffness, ξ_f is the damping ratio, C is the damping coefficient,v_f is the viscosity of the liquid used, ω_f is the sloshing frequency of the water, μ_f is the mass ratio. Here, β = 2 is the parameter due to hydrodynamic moment on the tank base. Here S is contamination factor which is taken as 1 [9]. The parameter shown in figure 1 can be seen in table 2.

Table 2: Properties of TLD

Number of storey		10 storey	15 storey
Dimension of tank	H (m)	0.3	0.6
	L (m)	1.2	3
mf (Kg)		345.6	3882
ξ		0.010146	0.005826
Mo		102.5856	943.6215
M1		319.5372	2939.225
K (N/m)		1062.52	4664.566
C (N-s/m)		315.8773	1152.613

For 10 storey structure From free vibration analysis of building it was found that the fundamental frequency of structure was 3.64 rad/s. By using the equation suggested by Fujino et al.(1990) the sloshing frequency of water was found to be 3.78 rad/s with the tuning ratio of 1.03 which is apprximately equal to 1.

A 10 storied structure with TLD of mass ratio of 3% is shown in figure 2 and the number of TLD for each mass ratio is shown in table 3.

Table 3: Number of TLDs for 10 storey

Mass ratio (μ)	2%	3%	4%	5%
Number of tanks	330	490	650	810

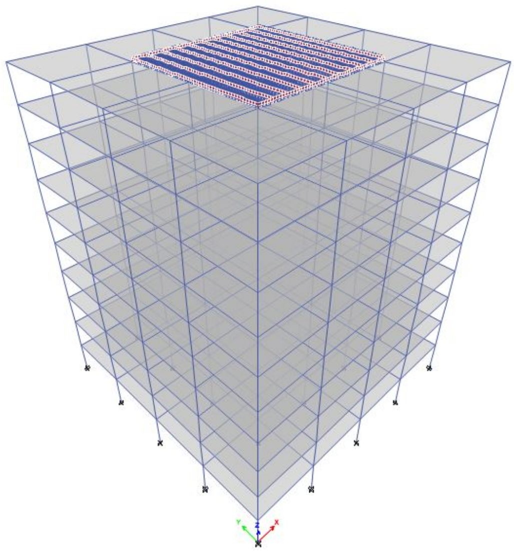

Figure 2: 10 storey structure with TLD (μ = 3%)

For 15 storey structure Similarly for 15 storey structure free vibration analysis of building was done and it was found that the fundamental frequency of structure was 2.513 rad/s. By using the equation suggested by Fujino et al.(1990) the sloshing frequency of water was found to be 2.39 rad/s with the tuning ratio of 0.95 which is apprximately equal to 1. A 15 storied structure with TLD of mass ratio of 3% is shown in figure 3 and the number of TLD for each mass ratio is shown in table 4.

Table 4: Number of TLDs for 15 storey

Mass ratio (μ)	2%	3%	4%	5%
Number of tanks	44	64	88	108

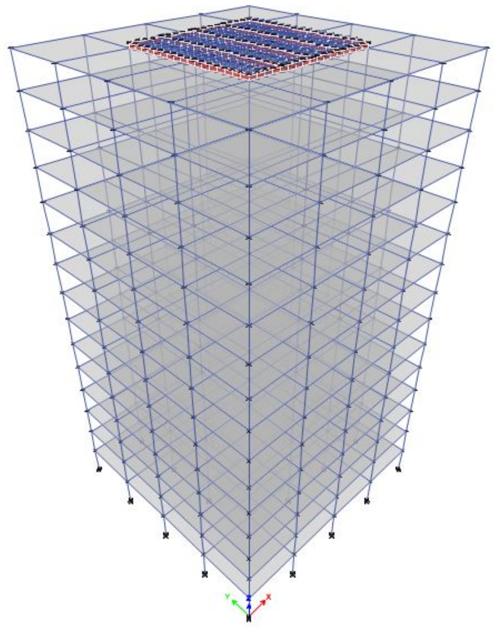

Figure 3: 15 storey structure with TLD (μ = 3%)

So, to satisfy the mass ratio (mass of water/mass of structure) increasing the mass ratio increases the number of tanks. Tanks are placed at the top centre part of the structure to avoid torsion and is most effective for controlling the response of the structure [1].

3. Result and Discussion

The modelled buildings was analyzed for the dynamic loading (Response spectrum) using IS 1893:2016 in Etabs 18 with and without TLD. The displacement of the top storey and drift of 10 storied and 15 storied structure is recorded and compared with each other under such loading.

3.1 Effect of mass ratio on the response of structure

Different structure with and without the TLD was modelled and displacement and drift was plotted which can be seen in figure 5 6 8 and 9 . Four different model was modelled for the structure with the TLD having different mass ratio (2%, 3%, 4% and 5%) with the depth ratio of 0.2. It has been observed that by increasing the mass ratio the overall displacement of the structure reduced gradually. But mass ratio greater than 4% would not be that effective as the dynamic motion of the water increases the response of the structure [10]. This can also be seen from the Table 5 and 6 and from Figure 4 and 7 that increasing the mass upto 4% there is an increase in percentage reduction of displacement and after 4% percentage reduction in displacement slightly reduces resulting in reduction of efficiency of TLD.

Table 5: Reduction in lateral Displacement from Response Spectrum for 10 storey

S.N	Mass ratio (%)	Displacement at top storey (mm)		
		Without TLD	With TLD	% Reduction
1	2	29.5	23.1	21.7
2	3	29.5	20.1	31.5
3	4	29.5	19.1	35.6
4	5	29.5	19.7	33.2

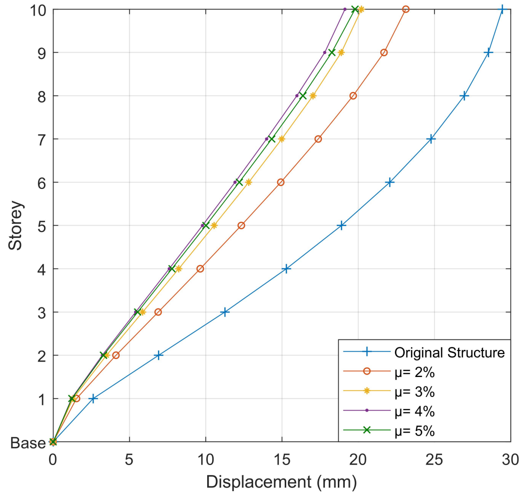

Figure 6: Lateral Displacement for Response Spectrum

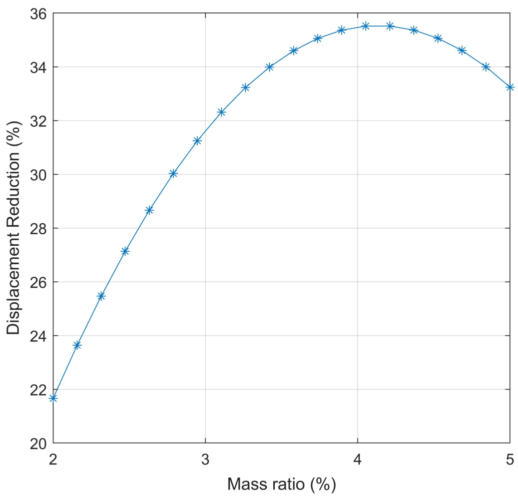

Figure 4: Displacement Reduction vs Mass Ratio

Table 6: Reduction in lateral Displacement from Response Spectrum for 15 storey

S.N	Mass ratio (%)	Displacement at top storey (mm)		
		Without TLD	With TLD	% Reduction
1	2	48.7	34.9	28.33
2	3	48.7	30.1	38.02
3	4	48.7	27.87	42.77
4	5	48.7	28.7	41.01

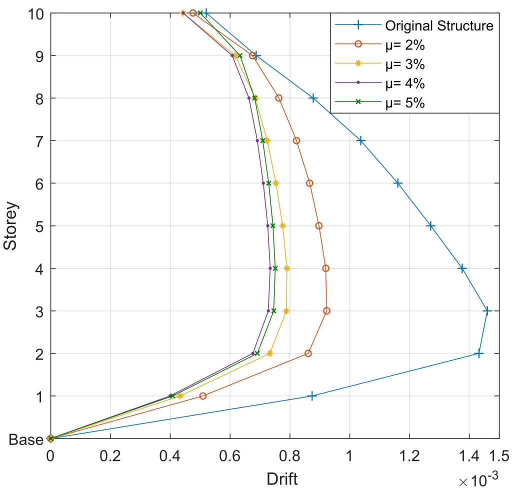

Figure 5: Drift for Response Spectrum

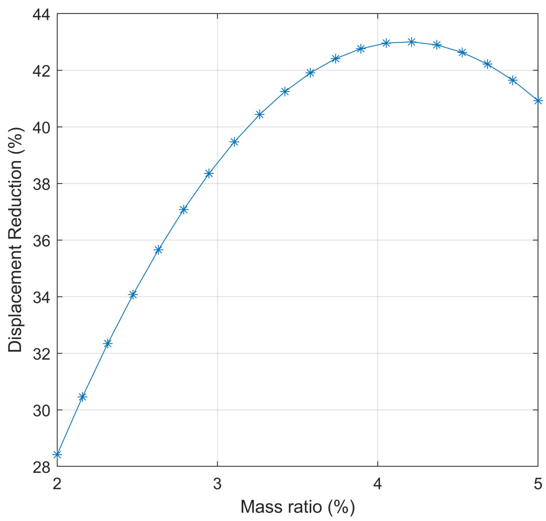

Figure 7: Displacement Reduction vs Mass Ratio

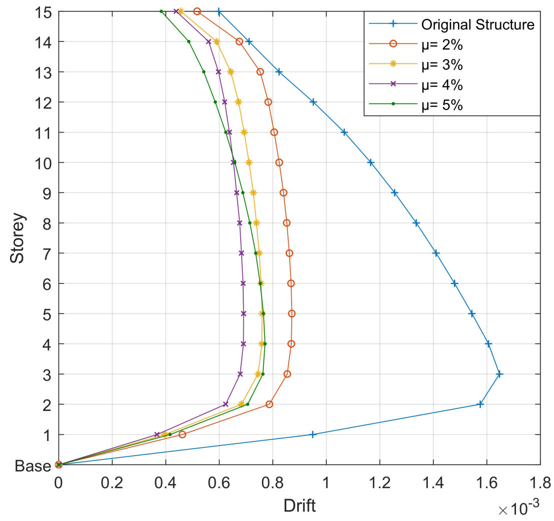

Figure 8: Drift for Response Spectrum

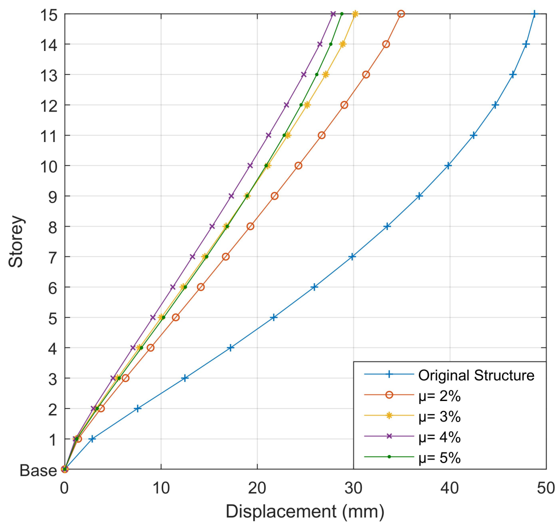

Figure 9: Lateral Displacement for Response Spectrum

While comparing the results, it shows that increasing the mass ratio of the TLD reduces the response of the building. This is due to the larger mass ratio will increase the sloshing mass (Convective mass) of the water in the tank which increases sloshing force in the tank. This sloshing force act opposite to the direction of movement of the structure's movement as fundamental frequency of structure and frequency of liquid in the tank was equated. This opposite acting force reduces the incomming lateral load resulting in reduced displacement.

Figure 4 and 7 we can see that percentage reduction in displacement increased with th increase in mass ratio till 4% and decreased after 4%. Ths is due to the dynamic motion of the water [10] which increases the response of the structure.So, we can say that the optimal mass ratio for the TLD to be effective is between 3% and 4%

3.2 Effect of storey on efficiency of TLD

TLD was modelled for two different storey level i.e, 10 storied and 15 storied level and the result was compared in term of percentage reduction in displacement of the top of the roof storey. From figure 10 we can say that the percentage reduction in displacement for 15 storied structure is greater than 10 storied structure for same mass ratio.

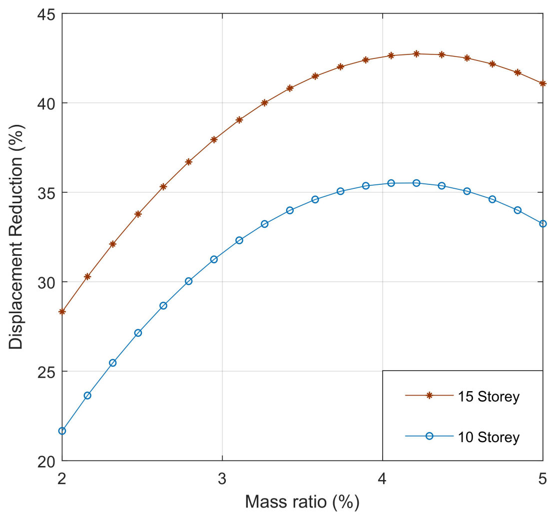

Figure 10: Percentage reduction in Displacement for different storey

Above Figure shows that reduction in displacement percentage increased with increase in the storey i.e., for same mass ratio (Mass of the water / Mass of the structure) the percentage in displacement reduction of 15 storey is greater than that of 10 storey building. We can see that for every mass ratio the percentage in displacement reduction increased with the increase in the storey of the structure. This is due to larger sloshing water mass participate in the tank as we increase the storey level resulting in greater displacement reduction.

4. Conclusion

A typical reinforced concrete public building has been considered for the study. The building is modelled in

Etabs 18. Eight different model was modeled for 10 storey and 15 storey structure with different mass ratio of 2%, 3%, 4% and 5% with the depth ratio of 0.2. Dynamic analysis of the building (Response spectrum) with and without TLD is carried out. Results are compared in terms of percentage reduction in displacement and optimum mass ratio was determined.

On the basis of the results obtained from the analysis, the following conclusions are made:

1. Lateral displacement and drift of the structure decreases after the use of TLD in the structure.
2. For same building, increasing mass ratio from 2% to 4% will increase the effectiveness of tuned liquid damper. For 10 storey structure, percentage reduction in displacement for mass ratio 2% was found to be 21.7% for 3% was 31.5% and for 4% was 35.6% and results were similar for 15 storied structure also.
3. The effectiveness of TLD increases with increase in the storey level. As the storey level increases the sloshing mass also increases resulting in more sloshing force which increases the effectiveness of TLD. For mass ratio of 2%, percentage reduction in displacement of 10 storey was found to be 21.7% whereas for 15 storey it was found to be 28.33%, similarly for 3%, 4% and 5% percentage reduction for 15 storey was found to be greater than 10 storey.
4. Optimum mass ratio for a building should be between 3% to 4%. Mass ratio greater than 4% would not be economically efiicient for the structure.

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