

Analysis of Tuned Liquid Damper (TLD) in Controlling Earthquake Response of a Building using SAP2000

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Abstract - This project aims to study the effectiveness of Tuned Liquid Dampers (TLD) in reducing the seismic vibration of a building when it is subjected to horizontal sinusoidal excitation. TLD is a water confined container, or simply a water tank, which uses the sloshing energy of water to reduce the dynamic response of a structure when it is subjected to excitation. In this study, a procedure for designing TLD for a building is suggested and a method is proposed to model the TLD in SAP2000 software. Then, multiple analyses have been carried out to analyse the effect of different parameters of TLD which may affect its performance. Analyses are conducted with varying mass ratio, tuning ratio, excitation ratio, number of storeys, position of TLD, etc. The structural response is compared based on maximum base shear, maximum relative acceleration and maximum displacement of top storey. With reference to the results from these analyses, conclusions are derived and recommendations are given for an optimal design of TLD.

Keywords: Tuned Liquid Damper, SAP2000, Earthquake Engineering, Modelling, Dampers, TLD

1 INTRODUCTION:

Earthquakes are perhaps the most disastrous and unpredictable among all the natural calamities. We have witnessed many high intensity earthquakes which have claimed numerous lives and have damaged an immeasurable amount of properties. They not only pose a threat to humans but also have a tremendous impact on the surrounding including the structures. In such cases where the structures lie in an earthquake prone area, the designers, architects and engineers have to take adequate precautions to safeguard the structures against the effect of earthquake. Many techniques are available to reduce the effect of earthquake on structures. This paper discusses and analyses the applicability of tuned liquid damper in reducing the earthquake effect on building.

1.1 Tuned Liquid Dampers (TLD)

When earthquake forces hit a structure it imparts energy to it which causes vibration, If by any means we can absorb the imparted energy, we can easily reduce the amplitude of vibration of the building. This is usually termed as “damping”. One way of doing this is by facilitating the structure with a “Tuned Liquid Damper (TLD)”. It was first introduced in the 1980s by Bauer and later installed in several other buildings, the recent being One Rincon Hill tower of San Francisco.

TLDs are basically a tank partially filled with water or sometimes with sugar solution usually installed on the top of the building. Buildings under earthquake forces starts vibrating at a particular frequency called natural frequency, TLDs are designed to have the same natural frequency so that sloshing of liquid in the tank under external excitation generates anti-phase to the building motion as shown in figure 1.

TLD acts as a passive energy dissipation device and has following advantages over other damping systems

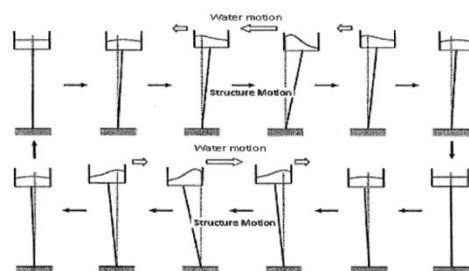


Figure 1.1: Principle of TLD working

- Low cost - installation as well as maintenance
- Easy installation in new as well as in existing buildings
- Non restriction to unidirectional vibration
- Easily adjustable natural frequency of the tank by simply adjusting the water depth.
- Water in tanks can be utilized during emergency such as during fire hazards.

Based on depth of water, shape and function, TLDs are classified into following categories:

TSD: Tuned Sloshing Damper; **TLCD:** Tuned Liquid Column Damper; **LCVA:** Liquid Column Vibration Absorber; **DTLCD:** Double Tuned Liquid Column Damper; **HTLCD:** Hybrid Tuned Liquid Column Damper; **PTLCD:** Pressurized Tuned Liquid Column Damper

1.2 Parameters affecting the behaviour of TLD

There are different parameters that affect the behaviour of TLD in building. These are natural frequency of building, excitation frequency ratio, mass ratio, depth ratio, tuning frequency ratio, shape of the tank and position of the tank on the building. All these are explained below.

Tuning ratio: Tuning ratio is the ratio of frequency of TLD to the frequency of the building. The damping effect of TLD is best when tuning ratio is 1, and is known to reduce sharply as it moves away from unity.

Mass ratio: Mass ratio is the ratio of the mass of the liquid in TLD to the mass of the building. The effect of damping often increases with the increase in mass ratio. This is because the increase in mass will mean the TLD will have more damping force or sloshing force to counter the earthquake force.

Depth ratio: Depth ratio is the ratio of the depth of the tank to the length of the tank in the direction of sloshing. Water mass may be divided into convective mass and impulsive mass out of which convective mass has the participation in sloshing mechanism. The ratio of convective mass to impulsive mass of water is inversely related to the depth ratio. So, higher depth ratio would mean lesser convective mass and thence, lesser participation in sloshing. Hence, a lower depth ratio is often preferred.

Shape of tank: The shape of the tank can be circular, rectangular, conical or geometrical shape. Different shape of tank depicts different sloshing behaviour. Often, it is the rectangular tank or circular tank that is used because of its simplicity. Even in design codes, such as IS1893:2002 part 2, the charts are available only for circular and rectangular tanks, so they are more preferred for the analysis purpose.

Position of tank: Position of the tank also affects the behaviour of the TLD. The position of TLD can be in some mid storey or somewhere at the top of building. The position can also be at the centre, edge or at the corner of the storey in which it is placed. Most literature shows that the best effect of TLD is obtained when it is placed on the terrace.

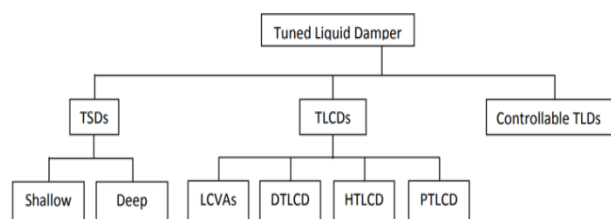


Figure 1.2: Types of TLD

2 LITERATUREREVIEW

Till date, TLD has been studied by several researchers. Some of them are given below.

(Soong, T.T; Dargush, Gary F., 1997) Provides reviews on the theoretical studies done on TLD system and various experiments conducted on different TLD designs. Factors controlling various design parameters are introduced. Comparative studies made on these factors were made to find optimum designs. Integration of different materials in buildings constructed are introduced and their performance statistics are shown. This book provides, for the first time, an

extensive exploration of the various types of energy dissipation that are currently available to structural designers. The book starts with a short chapter on structural dynamics and then goes straight into chapters that provide detailed discussions of various damping systems. All the standard damping systems are included such as "Metallic Dampers", "Friction Dampers", "Viscoelastic Dampers", "Viscous Fluid Dampers", "Tuned Mass Dampers" and "Tuned Liquid Dampers", and the book also includes a chapter on the more esoteric topic of "Smart Materials" which outlines how some innovative materials can be incorporated into damping elements

(Bauer, H. F., 1984) Was amongst the first researchers who applied TLDs to ground civil engineering structures by introducing a rectangular tank full of two immiscible liquids to decrease structural vibration.

(K. Fujii, Y. Tamura, T. Sato, T. Wakahara, 1990) Found that wind-induced vibrations of two buildings in Nagasaki and Yokohama, were reduced to about half upon installation of Tuned Sloshing Damper.

Wakahara carried out theoretical and experimental studies to design an optimum TLD and verified the TLD with a project in Yokohama. The interaction model considered by them was based on the Boundary Element Method for simulating liquid motion in a TLD container, and Multi-degrees of Freedom for the structure method. The TLD installation on the building could reduce the wind-induced response up to half the original value.

Tamura found that the damping ratio of 77.6m high Tokyo international Airport Tower increased to 7.6% from 1.0% by using Tuned liquid Damper.

(L.M. Sun, Y. Fujino, B.M.Pacheco , and P. Chaiseri, 1992) Explained a nonlinear model for rectangular Tuned Liquid Damper. This model utilizes shallow water wave theory with consideration of liquid damping effects. The model is further extended to account for the effect of breaking waves. Two empirical coefficients were identified experimentally and are introduced in the model. It was then experimentally verified that the model can well predict the response of structures installed with TLD's even when breaking waves occur.

(V.J. Modi, S.R. Munshi, 1998) Introduced a semi-circular obstacle in the damper to accelerate and enhance the liquid sloshing and to increase the energy dissipation. They conducted an experimental study to improve the TLD efficiency by introducing a two-dimensional obstacle. Then, they conducted a parametric study to obtain the optimum size and location of the obstacle. As per the results, up to 60% increase in energy dissipation was observed in the presence of the obstacle.

(F. Casciati, A.D. Stefano, E. Matta, 2003) Studied the use of frustum-conical TLD as an alternative to the traditional cylindrical tank. A linear model is presented which can interpret TLD's behaviour for small excitations. However, for larger amplitudes, the linear model is no longer valid because strong nonlinearities exist. Furthermore, to represent the frustum-cone TLD subjected to harmonic excitations, a tuned mass damper (TMD) analogy is established where TMD parameters vary with the excitation amplitude.

(Kim Y.M., You K.P., Cho J.E., Hong D.P., 2006) Conducted shake table experiments to investigate the characteristics of water sloshing motion in TLD (rectangular and circular) and TLCD. They found the parameters such as wave height, base shear force, and energy dissipation etc. from the experiment. It was found that the TLCD was more effective in controlling vibration than TLD.

(Shang C.Y., Zhao J.C., 2008) Presented a novel tuned liquid damper (TLD) rectangular tank with two angle-adjustable baffles. The numerical analysis was performed using the commercial code FLUENT. The standard kinetic energy and dissipation rate turbulent model was employed, which was solved using volume of fluid (VOF) method able to treat both the free surface motion and the viscous stresses over the rigid walls accurately. The relationship between the natural periods of water and the angles of its baffles was studied by numerical simulating of a case, and the changes of energy dissipations were investigated. The natural periods and dampers of the novel TLD can be changed in a wide range by adjusting the baffles' angle, thus it is more effective in controlling the vibration of structures in a wide frequency range.

(X.L. Xu, K.C.S. Kwok, B. Samali, 1992) Made an investigation on the possible application of tuned liquid column dampers (TLCD) and tuned liquid column/mass dampers (TLCMD) in reducing the cross-wind response of wind sensitive structures. The structure is modelled as a lumped mass multi-degree freedom system taking into account both bending and shears. The cross-wind wake excitation is modelled as a stochastic process which is stationary in time and non-homogeneous in space. A random vibration analysis utilising transfer matrix formulation is carried out to obtain response statistics. The non-linear damping term in the fundamental equation of the tuned liquid damper is treated by an equivalent linear technique. Numerical examples show that tuned liquid dampers, which have significant practical advantages, can

achieve the same motion reduction level as the traditional tuned mass dampers if the parameters of the liquid dampers are properly selected. However, excessive liquid motion in a tuned liquid column/mass damper may reduce the effectiveness of this damper and therefore a careful selection of the frequency tuning ratios of the damper is necessary.

(**Samanta A., Banerji P., 2008**) Designed a modified configuration of TL, in which the liquid tank, instead of being rigidly connected to the floor, was elevated using an appropriately designed torsion spring. Greater effectiveness was observed.

(**Housner G. W., 1963**) was the person to develop spring mass analogy for modelling water tanks. Here, we can find the formulas for calculating different parameters of the spring mass system like convective mass, impulsive mass and their respective heights like convective height and impulsive heights. He has done analytical analysis of TLD of rectangular as well as circular cross sections. Later, his work was adopted in building the IS1893 part 2 which is related to the earthquake resistant design of water tanks situated at ground as well as elevated circular and rectangular tanks.

(**N.S. Sebastian, 2017**) Modelled water tank in two parts namely convective mass and impulsive mass. The convective mass acts as a sloshing mass of water which is present above the impulsive mass which acts as fixed mass of water tank at the bottom portion. He has modelled the water tank using the mass spring system. He has done a linear static analysis and time history analysis of a framed structure. The buildings used were 3, 6, 9 and 12 storey buildings. He found 64% reduction in 3 storey building and 84% in 12 storey building. He found it increasing with increase in number of storey. He compared the results with tank and without tank and shape of tank being circular as well as rectangular.

(**T. Novo, H. Varum, F. Teixeira-Dias, H. Rodrigues, M. Falcao Silva, A. Campos Costa, L. Guerreiro, 2013**) Studied the behaviour of an isolated TLD, subjected to a sinusoidal excitation at its base, with different displacement amplitudes by finite element method. He concluded that for a sinusoidal cyclic loading, the behaviour of the TLD is globally efficient, significantly increasing the energy dissipation and causing a corresponding equivalent damping of the global system. The TLD is highly effective in reducing the structural demand for structures with a low natural period.

3 OBJECTIVE AND SCOPE:

The objective of this study is to develop a model of Tuned Liquid damper in SAP2000 and to carry out multiple analyses on it. In summary, the scope and objectives of this study can be listed out as follows:

- Modelling of a structure with TLD in SAP2000 and analysing the effect of TLD on the structure
- Re-affirming the different parameters of TLD which affects its performance and thus giving recommendations on it – mass ratio, depth ratio, excitation ratio and tuning ratio.
- Comparing the effect of TLD for buildings of different storeys / height.
- Study the effects of TLD on the building when it is placed at different locations on the terrace.

4 METHODOLOGY:

The entire procedure of making the model and conducting the analysis is broken down into a set of steps as given below.

- 1 Modelling of the structure using SAP2000
- 2 Designing the TLD for structure
- 3 Modelling of the TLD using SAP2000
- 4 Analysis

The set of steps used for designing and modelling structure and TLD is explained in this section using an example of a 20 storey building. Then, similar procedure was used for all other buildings used in the analysis and then the results were compared.

4.1 Modelling of the structure using SAP2000

First, the given structure is modelled in SAP2000. For this analysis, a simple 20 storey RC bare frame is considered with properties as given below.

4.1.1 Properties of the RC frame

Number of grid line in X direction = 6

Number of grid lines in Y direction = 6

Number of grid lines in Z direction = 21

Spacing in X direction = 4m

Spacing in Y direction = 4m

Spacing in Z direction = 3.5m

4.1.2 Defining material Properties

M50 concrete of Indian standard is defined.

HYSD rebars of Fe500 is defined.

4.1.3 Defining the frame sections

Column size of 0.6mX0.6m of M50 grade using Fe500 rebars is used.

Beam size of 0.6mX0.3m of M50 grade using Fe500 rebars is used.

4.1.4 Defining the slab section

The slab of 250 mm thickness of M30 material is used for modelling of a structure.

4.1.5 Assigning the support condition:

The base of the building in the plan the xy plane view is selected and fixed support condition was assigned.

4.1.6 Defining Load Pattern

Dead load, Live load (4 kN/m²), other load (Floor finish and Partition load = 2 kN/m²) and earthquake load of zone 5 with soil type II and 5 % damping conforming to IS1893:2002 with 1 scale factor.

4.1.7 Defining Time History Function

We used time history Sine function for the Time History Analysis. The time period of the function was made same as that of the building to have the maximum effect of earthquake on the structure. The scale factor used is $ZIS_a/2R$. So, for ordinary RC frame building of zone 5 in soft soil, scale factor with be: $0.36*1*(1.67/2)/2/3*9.81 = 0.491$. It can be seen in the figures 4.1 and 4.2.

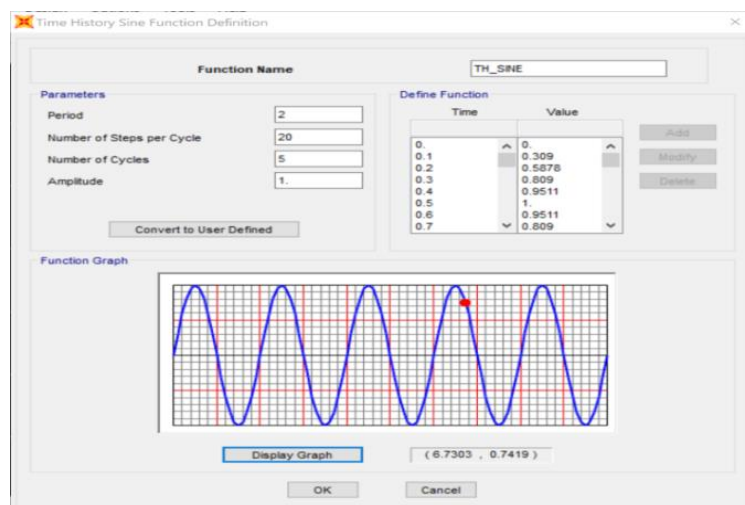


Figure 4.1: Defining sinusoidal time history function

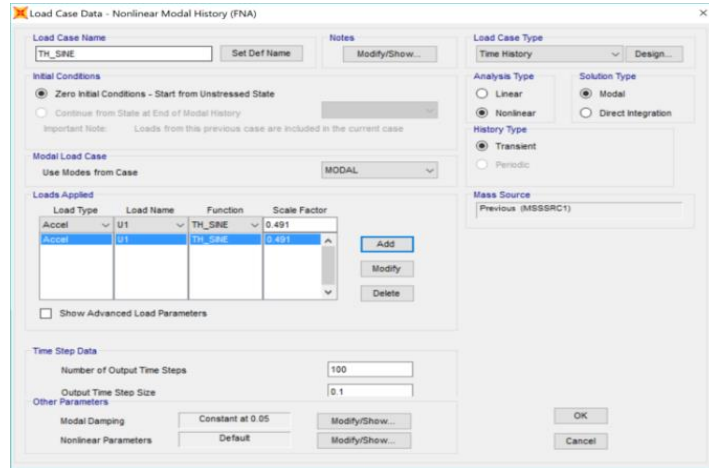


Figure 4.2: Defining sinusoidal time history load case

4.2 Designing the TLD for the structure

The TLD is designed such that its frequency is slightly lower than the fundamental frequency of the building under consideration. Here, the TLD is modelled as a spring mass system as specified in IS1893:2002 Indian code. The design curves present in the IS code are used for the design purpose. The steps for design are outlined below.

4.2.1 Selecting design parameters

Mass ratio ($m_r = 2\%$)

Depth ratio ($d_r = .2$)

Mass of building ($M' = 9425200\text{kg}$)

Fundamental frequency of the building ($f' = .5\text{Hz}$)

Maximum length of TLD specified for the building ($L' = 12\text{m}$)

4.2.2 Obtaining optimal tuning frequency

It is given by: $f = f' / (1 + m_r) = .49\text{Hz}$

4.2.3 Using IS 1893:2002 part 2 curves

For the given depth ratio, $d_r = 0.2$, we can obtain,

$$m_c/m = .77$$

$$h_i/h = 2$$

$$m_i/m = .23$$

$$h_c/h = 2.8$$

$$K_h/mg = .25$$

4.2.4 Obtaining dimension of each tank

Frequency of spring is given by:

$$f = 1/2\pi \sqrt{k/m_c}$$

Putting values of k and m_c from IS curves, we get,

$$f = 1/2\pi\sqrt{(.25*mg/h)/(.77m)}$$

$$\text{So, } h = 1/(2\pi f)^2 * .25g / .77 = .336\text{m}$$

$$\text{Length of liquid} = L = h/\text{depth ratio} = .131/.2 = 1.679\text{m}$$

Maximum height of sloshing can be obtained by IS code as:

$$h_s = Ah * R * L / 2$$

$$= (ZIS_a / 2Rg) * R * L / 2$$

$$= .075 * 2 * 1.679 / 2$$

$$= .126\text{m}$$

$$\text{So, inner height of tank required} = h + h_s = .336 + .126 = .462\text{m}$$

Assuming 150mm wall thickness,

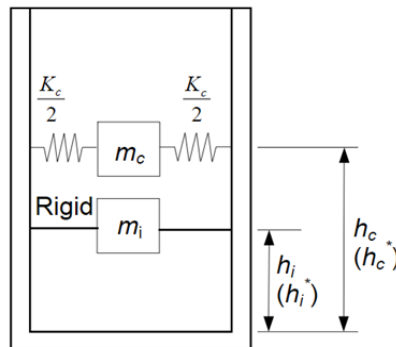


Figure 4.3: Spring mass analogy for TLD

Therefore, **Size of each tank = 1.979mX1.979mX.612 m**

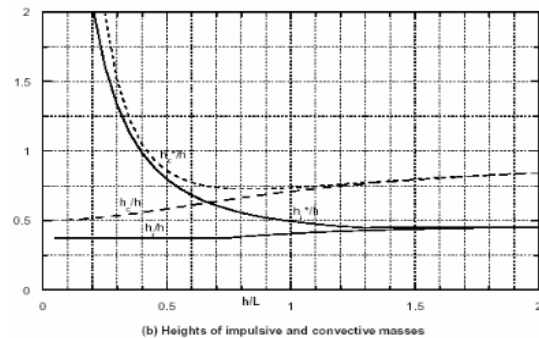
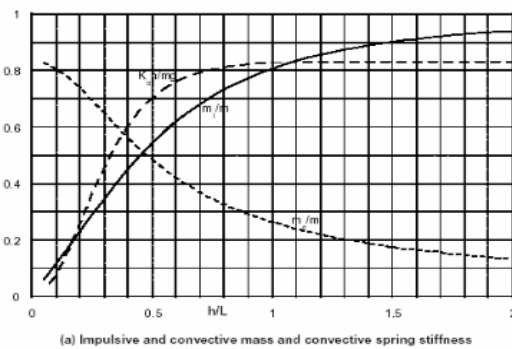


Figure 4.4: IS curves for parameters of the spring mass model for rectangular tank

4.2.5 Finding the number and arrangement of TLDs

Mass of each tank

$$m = L^2h * 1000 = 946\text{kg}$$

Number of tanks required,

$$n = m_r * M' / m = .02 * 9425200 / 946 = 200$$

If $L' = 12\text{m}$ length is given as TLD space in terrace, then,

Number of TLDs in each direction = $12/1.979 = 15.9 = 6$ no.

And, number of TLD layers required = $200/6/6 = 6$ no

Hence, no of TLDs provided = $6*6*6 = 216$

4.2.6 Obtaining parameters for each spring mass system

Mass of liquid in each tank, $m = 1000*L^2*h = 55.6\text{kg}$

$m_c/m = .77 \Rightarrow m_c = .77*946 = 728\text{kg}$

$m_i/m = .23; 77 \Rightarrow m_i = .23*946 = 218\text{kg}$

$K_h/mg = .25 \Rightarrow K = .25*946*9.8/.336 = 6904\text{N/m}$

$h_c/h = 2.8 \Rightarrow h_c = 2.8*946 = .94\text{m}$

$h_i/h = 2 \Rightarrow h_i = 2*946 = .672\text{m}$

4.2.7 Modelling the set of spring mass systems as a single equivalent spring mass system

The number of TLDs in each building is a very high number and modelling each one of them will be a tedious and an impractical task. So, in order to simplify the analysis, it is more intuitive to model the set of TLDs as a single equivalent spring mass system.

If 'n' be the no of TLDs in the entire system, the equivalent parameters for the equivalent system can be obtained as follows.

If 'f' be force applied by each tank then for 'n' tanks, the total force applied is nf. Let 'F' be equivalent force applied by the equivalent system. Let small letters k, m and h represent stiffness, masses and heights for each tank and capital letters K, M, and H represent corresponding parameters for the equivalent system. Then, here,

$$F = nf$$

$$Kx + Ma = n(kx + ma)$$

$$Kx + Ma = nkx + nma$$

Equating coefficients of x and a,

$$K = n*k = 1381\text{kN/m}$$

$$M = n*m = 189200\text{kg}$$

Similarly, we can write,

$$M_i = n*m_i = 43527\text{kg}$$

$$M_c = n*m_c = 145719\text{kg}$$

Height values can be obtained as the average height value of all the layers about the bottom. After simplifying, we get,

$$H_i = h_i + (\text{no of layers} - 1) * \text{height of tank} / 2 = 1.49\text{m}$$

$$H_c = h_c + (\text{no of layers} - 1) * \text{height of tank} / 2 = 1.76\text{m}$$

4.3 Modelling of the TLD using SAP2000

Tank frame is modelled using columns of same size as that of building which is then filled with concrete wall panels.

Spring for convective mass is modelled using “linear link” element whose stiffness in X and Y direction is given as $K/2$ and its DOF in Z direction is set as fixed. Spring for impulsive mass is also modelled using linear link element, but its DOF is set fixed in all direction.

“Joint mass” is assigned at the joint of the spring with values M_c and M_i in X and Y direction.

“Joint force” is assigned at the joint of the spring with values M_c and M_i in GRAVITY direction.

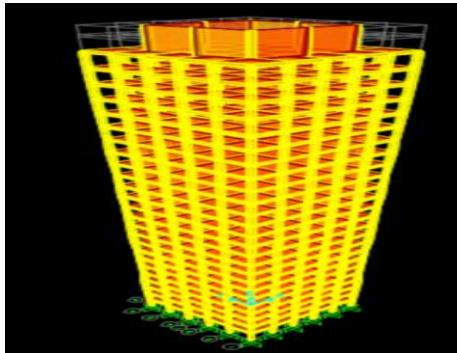


Figure 4.8: TLD model in the structure

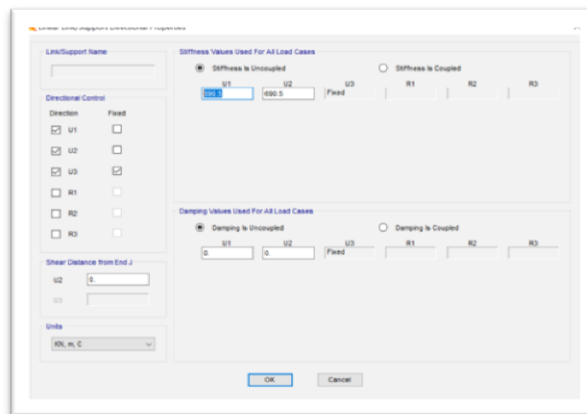


Figure 4.7: Assigning link properties to model

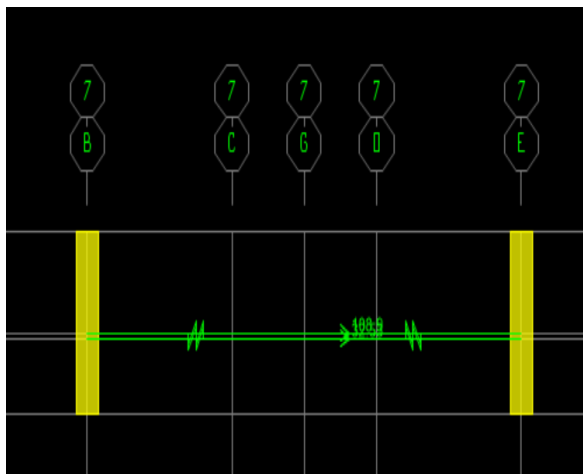


Figure 4.6: Assigning joint masses

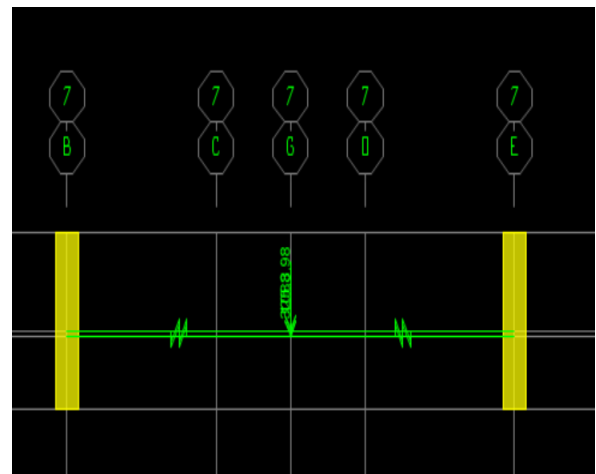


Figure 4.6: Assigning joint load

4.4 Analysis

The analysis was carried out by considering different parameters to understand the behaviour of TLD. A standard G+19 storey building with TLD was modelled and it was tested with different excitation frequency ratios, different depth ratio, different locations of TLD on the terrace and different mass ratios. While analysing one particular parameter, the other parameters and other components of the building were kept constant.

The tuning frequency of the building is the ratio of frequency of TLD to the frequency of the building. Tuning ratio was varied from 0.8 to 1.2 and analysis was done for the different tuning ratios

Depth ratio is the depth of water in TLD to the length of liquid in sloshing direction. The depth ratio was varied from 0.1 to 0.5 and comparative analysis was carried out.

Effect of TLD when placed at different locations of the terrace was analysed. The different locations on terrace considered in the study were centre, edge and corner.

The mass ratio is the ratio of mass of TLD to the mass of the building. The mass ratios varying from 1% to 5% were analysed.

The analysis for different storeys of building was also done. The number of storeys was varied from 10 storeys to 35 storeys.

The results were analysed on the basis of percentage reduction in maximum displacement and acceleration of a joint in the top storey of the building along with percentage reduction in base shear force after the implementation of TLD. The analysis carried out was time history analysis using sinusoidal wave whose peak acceleration was obtained from the equation given in IS code, given as $ZIS_a/2R$ in m/s^2 .

5 RESULTS:

The results obtained are given below under various topics.

- Standard TLD designed for a G+19 building
- TLDs at different excitation frequency ratios
- TLDs with different tuning ratios
- TLDs with different depth ratios
- TLDs with different mass ratios
- TLDs at different locations on the terrace
- TLDs for different number of storeys of building

5.1 Standard TLD designed for a G+19 building

Table 5.1: Results for Time History analysis for sine wave with time period same as time period of the structure

	Units	Values
Maxm joint accln in top storey without TLD	m/s ²	4.945
Maximum joint displacement in top storey without TLD	m	0.5252
Base shear without TLD	kN	37434
Maximum joint accln in top storey with TLD	m/s ²	2.915
Maximum joint displacement in top storey with TLD	m	0.2979
Base shear with TLD	kN	22140
% reduction in relative acceleration	%	41.100
% reduction in displacement	%	43.279
% reduction in base shear		40.856

Table 5.2: Results for Response Spectrum analysis

	Units	Values
Maxm joint accln in top storey without TLD	m/s ²	0.6561
Maximum joint displacement in top storey without TLD	m	0.04116
Base shear without TLD	kN	3409
Maximum joint accln in top storey with TLD	m/s ²	0.592
Maximum joint displacement in top storey with TLD	m	0.0335
Base shear with TLD	kN	2892
% reduction in relative acceleration	%	9.770
% reduction in displacement	%	18.610
% reduction in base shear	%	15.166

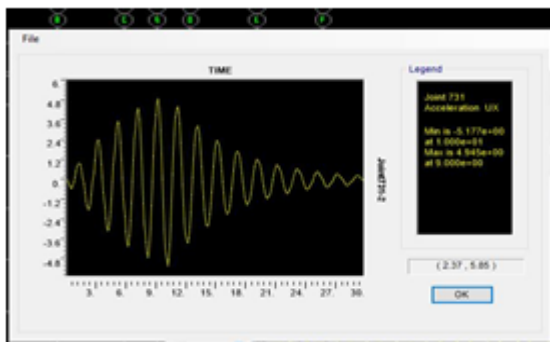


Figure 5.2 Acceleration vs. time of time history analysis without TLD of top storey

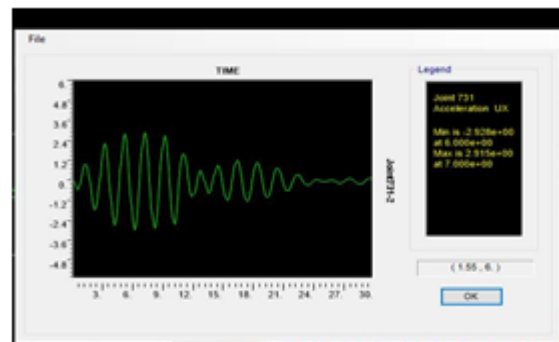


Figure 5.2 Acceleration vs. time of time history analysis with TLD of top storey

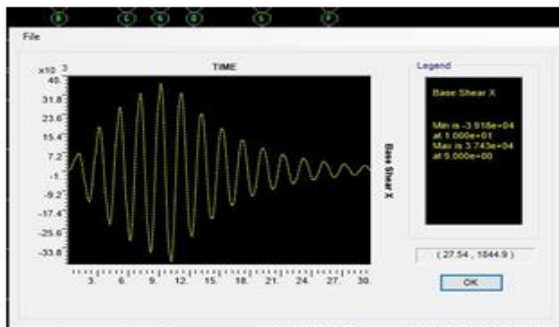


Figure 5.6: Base shear vs. time of time history analysis

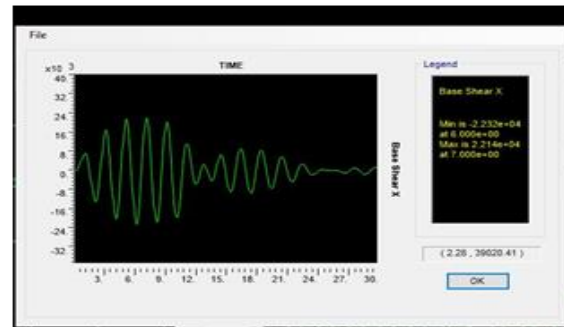


Figure 5.6: Base shear vs. time history analysis

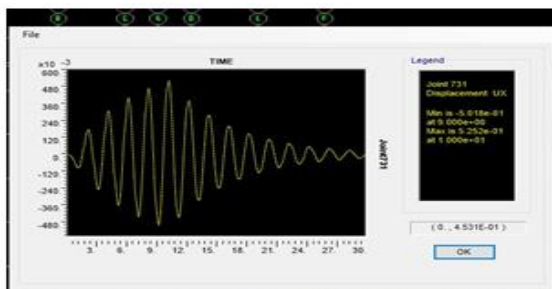


Figure 5.4 Displacement vs. time of time history analysis without TLD of top storey

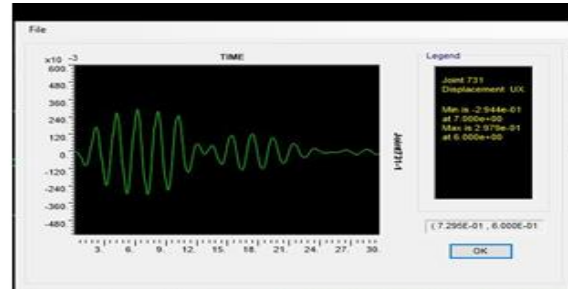


Figure 5.4 Displacement vs. time of time history analysis with TLD of top storey

5.2 XTLDs at different excitation frequency ratio

Table 5.2: Results for different excitation frequency ratios

Excitation ratio	Without TLD			With TLD		
	Base shear	Acceleration	Displacement	Base shear	Acceleration	Displacement
4.00	2171.574	0.53375	0.019018	2260.101	0.54466	0.017815
2.00	8619.194	0.37471	0.083142	8568.755	0.36254	0.083834
1.25	12677.107	2.47338	0.197561	11821.74	2.28712	0.172095
1.11	23693.538	3.86512	0.338255	19151.79	3.16936	0.27269
1.00	37434	4.945	0.525	22140	2.195	0.2979
0.91	30633.855	3.34837	0.395662	21776.76	2.38013	0.305505
0.83	21924.432	2.12303	0.26978	22487.33	2.15143	0.311321
0.67	12790.042	0.8883	0.161546	12664.67	0.80837	0.161645
0.50	9019.358	0.52469	0.099356	8960.604	0.51361	0.105082
0.40	8619.194	0.37471	0.083142	8568.755	0.36254	0.083834

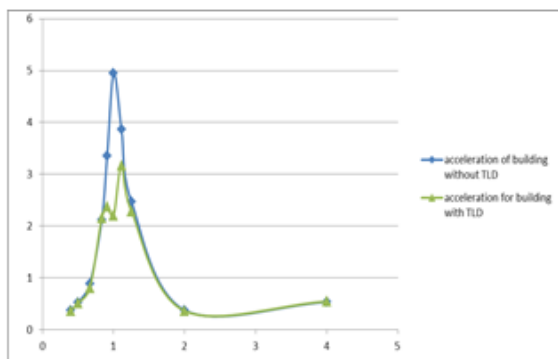


Figure 5.9: Acceleration vs. excitation frequency ratio of building with and without TLD

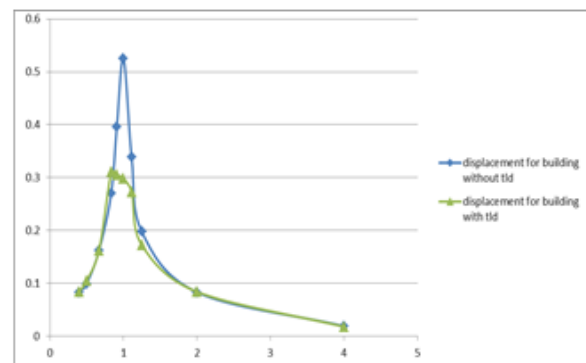


Figure 5.9: Displacement vs. excitation frequency ratio of building with and without TLD

5.3 TLDs with different tuning ratios

Table 5.3 Results for different tuning ratio

Tuning ratio	0.800	0.900	0.950	0.975	1.000	1.025	1.050	1.100	1.200
Maxm accln without TLD	4.955	4.957	4.902	4.958	4.958	4.948	4.866	4.935	4.864
Maxm disp. without TLD	0.5252	0.5259	0.5247	0.523	0.525	0.527	0.5223	0.526	0.5222
Base shear without TLD	37483	37488	37450	37300	3747	37570	37325	37508	37326
Maxm accln with TLD	4.289	3.478	3.024	2.937	2.877	2.849	2.895	3.265	4.15
Maxm disp. with TLD	0.456	0.3533	0.3018	0.298	0.298	0.2996	0.3058	0.3411	0.411
Base shear with TLD	33203	26846	23038	22128	2191	21882	21859	24058	30345
% reduction in accln	13.441	29.837	38.311	40.762	41.97	42.421	40.506	33.840	14.679

% reduction in disp.	13.176	32.820	42.481	43.021	43.27	43.150	41.451	35.152	21.295
% reduction in base shear	11.419	28.388	38.483	40.676	41.50	41.757	41.436	35.859	18.703

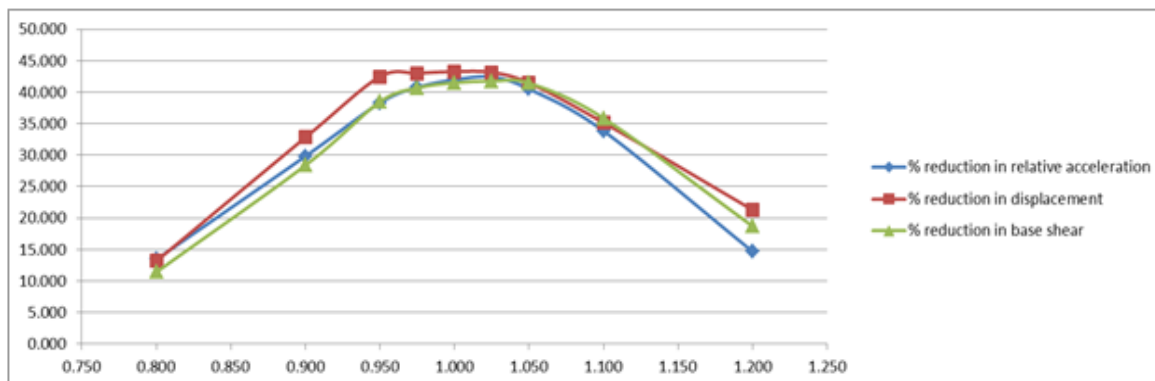


Figure 5.10: Percentage reduction in acceleration, displacement and base shear with different tuning ratio

5.4 TLDs with different depth ratios

Table 5.4: Results for different depth ratio

Depth ratio	0.10	0.20	0.30	0.40	0.50
Maxm joint accln without TLD	4.872	4.945	4.957	4.953	4.958
Maximum displacement without TLD	0.495	0.5252	0.5258	0.5255	0.5233
Base shear without TLD	37411	37434	37471	37495	37306
Maximum accln with TLD	2.702	2.195	3.107	3.119	3.426
Maximum displacement with TLD	0.2852	0.2979	0.3132	0.3139	0.3478
Base shear with TLD	20898	22140	23546	23601	25761
% reduction in relative acceleration	44.540	55.612	37.321	37.028	30.900
% reduction in displacement	42.384	43.279	40.434	40.266	33.537
% reduction in base shear	44.139	40.856	37.162	37.056	30.947

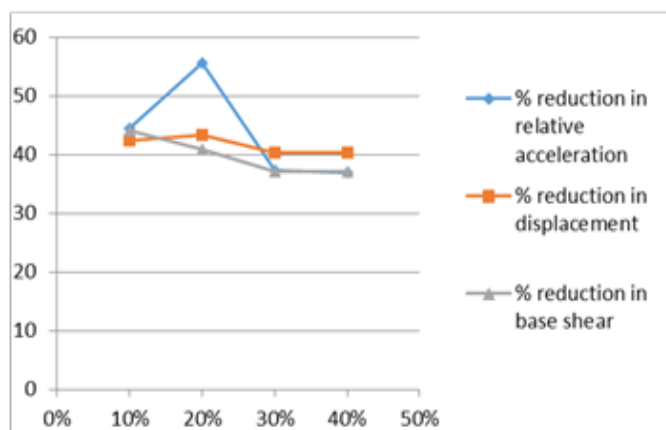


Figure: 5.12: Percentage reduction VS depth ratio

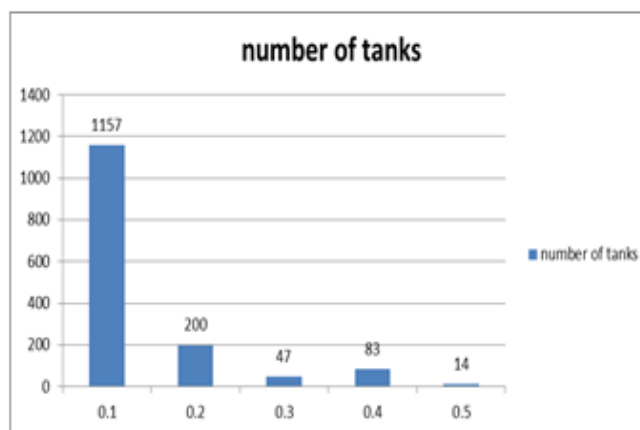


Figure: 5.12: Number of tanks vs. depth ratio

5.5 TLDs with different mass ratios

Table 5.5: Results of different mass ratio

Mass ratio	1.0%	1.5%	2.0%	2.5%	3.0%	5.0%
Maxm joint accln without TLD	4.98	4.895	5	4.956	4.821	4.859
Maximum displacement without TLD	0.514	0.522	0.53	0.526	0.509	0.548
Base shear without TLD	36879	37566	37426	37419	37006	37999
Maximum accln with TLD	3.716	3.189	2.38	2.696	2.416	2.1459
Maximum displacement with TLD	0.363	0.323	0.301	0.276	0.238	0.2275
Base shear with TLD	27430	24650	21701	20596	18547	16859
% reduction in relative acceleration	25.382	34.852	52.400	45.601	49.886	55.837
% reduction in displacement	29.377	38.123	43.208	47.529	53.242	58.485
% reduction in base shear	25.622	34.382	42.016	44.958	49.881	55.633

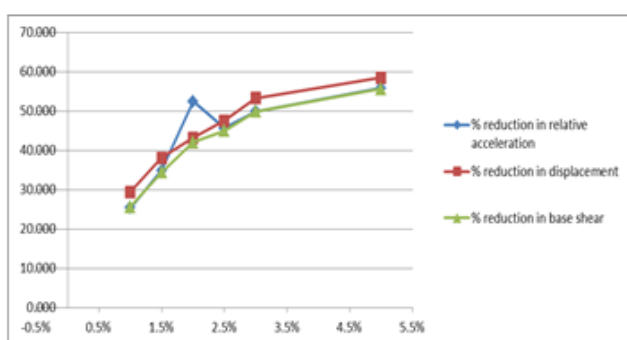


Figure 5.14: percentage reduction vs. mass ratio

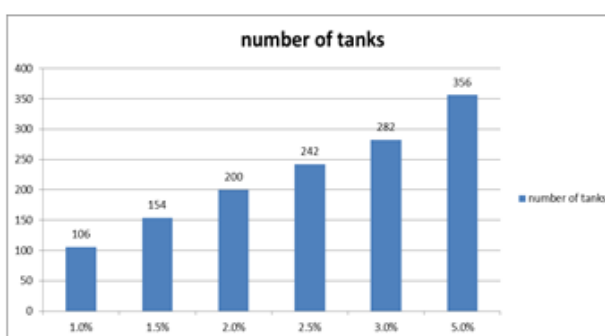


Figure 5.14 Number of tank vs. mass ratio

5.6 TLDs at different locations on the terrace

Table 5.6 Results of TLD at different locations on the terrace

Location	Center	Edge	Corner
Maxm joint accln without TLD	4.945	5.1052	4.8917
Maximum displacement without TLD	0.5252	0.5416	0.5189
Base shear without TLD	37434	37390	35873
Maximum accln with TLD	2.195	2.7593	2.741
Maximum displacement with TLD	0.2979	0.2882	0.2868
Base shear with TLD	22140	22142	22129
% reduction in relative acceleration	55.612	45.951	43.966
% reduction in displacement	43.279	46.787	44.729
% reduction in base shear	40.856	40.781	38.313

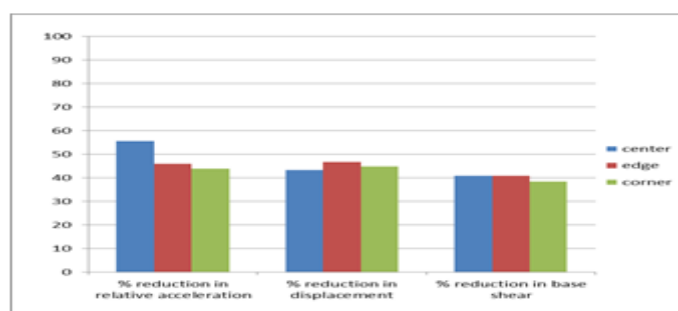


Figure 5.15 Percentage reduction vs. location of TLD

5.7 TLDs for different number of storeys of building

Table 5.7 Results for different number of storeys of building

Number of storeys	10 storey	15 storey	20 storey	25 storey	35 storey
Maxm accln without TLD	10.044	6.707	5	3.887	2.643
Maxm disp without TLD	0.2318	0.369	0.53	0.712	1.282
Base shear without TLD	39910	38933	37426	35786	34195
Maximum accln with TLD	6.136	4.055	2.38	2.234	1.445
Maxm disp with TLD	0.1367	0.214	0.3055	0.397	0.668
Base shear with TLD	25463	24127	21776	20550	18812
% Reduction in relative accln	38.909	39.541	52.400	42.526	45.327
% Reduction in disp	41.027	42.005	42.358	44.242	47.894
% Reduction in base shear	36.199	38.029	41.816	42.575	44.986

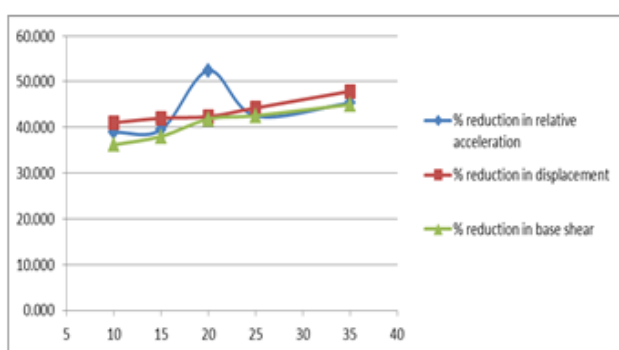


Figure 5.17: Number of storeys vs. response reduction graph

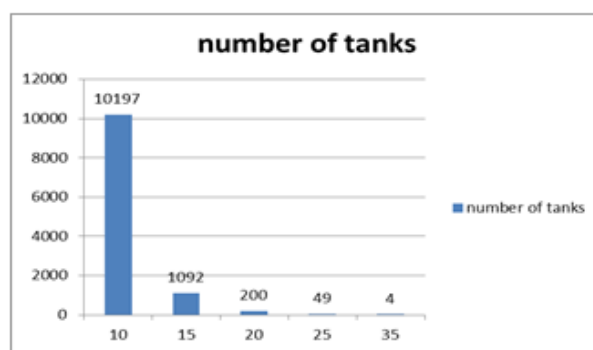


Figure 5.17: Number of storeys vs. number of tanks in TLD system

6 DISCUSSION:

Each analysis has been discussed separately under the following headings as given below.

1. Standard TLD designed for a G+19 building
2. TLDs at different excitation frequency ratios
3. TLDs with different tuning ratios
4. TLDs with different depth ratios
5. TLDs with different mass ratios
6. TLDs at different locations on the terrace
7. TLDs for different number of storeys of building

6.1 Standard TLD designed for a G +19 building

The detailed study done on G+19 building shows that the response of a building for an earthquake can be reduced by as much as 40-50% when the frequency of an earthquake matches with the natural frequency of the building (i.e.: resonance). This conclusion can be drawn from the results obtained by sinusoidal time history analysis.

However, results weren't as impressive when Response Spectrum analysis was conducted. Response spectrum analysis only showed a reduction by about 20%.

6.2 TLDs at different excitation frequency ratios

Excitation ratio is the ratio of frequency of sinusoidal wave to the fundamental frequency of the building. When the excitation ratio is 1 (i.e.: when the frequency matches), we see resonance and violent shaking of the building. At resonance, the response has magnified by about 5-10 times the normal response. However, when TLD has been introduced to the

building, the violent shaking has been stabilized. Although we still see peak values at resonance condition, this peak value is much lesser than the initial peak values. This shows the effectiveness of TLD in controlling earthquake response during resonance condition. However, it is to be noted that the difference TLD is making for response other than resonant response is minimal. This means the TLD has less or no effect for excitations other than the resonating frequencies.

6.3 TLDs with different tuning ratios

Tuning ratio is the ratio of the frequency of the TLD to the frequency of the building. The results show that the best response reduction is obtained when TLD is tuned perfectly to the frequency of the building. The results also show that the deviation in tuning by up to about 5% is acceptable. However, if deviation is beyond 5%, the TLD becomes less effective. When a TLD is designed, it is to be kept in mind that the added mass of tank would increase the natural time period of the building. So, it is best to design TLD for a tuning ratio of about .97 to .98. Literatures suggest the use of tuning ratio given by:

$$\text{Tuning ratio} = 1 / (1 + \text{mass_ratio})$$

The tuning ratio obtained by this method for 2% mass ratio turns out to be .98.

6.4 TLDs with different depth ratios

Depth ratio is the ratio of height of liquid in the tank to the length of liquid in the direction of motion. The ratio of convective mass of liquid to impulsive mass of liquid has an inversely dependent relationship with depth ratio. So, higher depth ratio indicates a lower convective mass, and hence, lesser response reduction during earthquakes. The results presented in this study are in agreement with this statement. As depth ratio has increased, correspondingly, response reduction has also reduced. However, it is to be kept in mind that a lower depth ratio necessitates high number of tanks which may be economically and practically infeasible. Seeing the results from this study, a depth ratio of 0.2 to 0.3 can be recommended.

6.5 TLDs with different mass ratios

Mass ratio is the ratio of mass of liquids in the tank to the mass of the entire structure. The results of analysis conducted in this study shows that the TLD system with higher mass ratio shows a higher reduction in response than a TLD system with a lower mass ratio. This is probably because the force exerted by the water mass depends on the mass of water itself.

However, it is to be kept in mind that a very high mass ratio would necessitate stronger structural design of the building and a very high number of tanks. This may be unfeasible. So, an optimal mass ratio of 2% is recommended by the results of this study.

6.6 TLDs at different locations on the terrace

3 analyses were carried out. One, by placing the TLD in the centre. Two, by placing the TLD at the edge. And three, by placing the TLD at the corner. The reduction in response was found to be maximum when the TLD was placed at the centre. However, the change in response shown by placing TLD in these three locations was very less. This means that the effect of position of TLD on a building has negligible effect in its response. But even so, more preference should be given for a central position.

6.7 TLDs for different number of storeys of building

The analysis was done for buildings with number of storeys varying from 10 to 35. From the results of this analysis, we see that the damping effect of TLD increases with the number of storeys. It is also to be noted that the size of tank increases with the increase in number of storeys. Because of this, lesser number of tanks becomes sufficient to provide the required damping effect. With this study, we find that TLDs are more effective and at the same time, more practical and feasible for taller structures than for shorter ones.

7 CONCLUSIONS

From this study, the following conclusions can be made.

- It has been found that TLD can be successfully modelled in SAP2000 even though there may be many numbers of tanks by using an equivalent spring mass system.
- Analyses on TLD showed that TLDs can be effectively used to reduce the response of a structure during earthquakes.

- The effect of TLD is found to be significant only in resonance zone. A reduction in response by as much as 45%-50% is obtained when earthquake's frequency matches building's natural frequency. In other words, TLD is found to be the most effective in reducing the violent shaking of building during resonance. However, during non-resonance, TLD doesn't have much effect.
- The effect of TLD is found to increase with an increase in mass ratio. The mass ratio for designing TLD was found to be optimal when it is about 2%.
- The effect of TLD is found to decrease with an increase in depth ratio. However, with regards to feasibility, a depth ratio of 0.2 to 0.3 is found to be the most optimal.
- The effect of tuning ratio is found to be critical in the design of TLD. A deviation in tuning by up to 5% is found acceptable. However, beyond this, a sharp reduction in effectiveness is found out. It is found out that it is best to tune the TLD to 98% of the building's natural frequency.
- The damping effect of TLD is found to be more pronounced for taller buildings with more number of storeys than for shorter buildings.
- Furthermore, TLD is also found to be more practical and economical for taller buildings. This is due to the fact that the size of each tank of TLD would be much higher for taller buildings and building such large tanks would be more practical than building many number of small tanks.

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