TRIBHUVAN UNIVERSITY
INSTITUTE OF ENGINEERING
PULCHOWK CAMPUS

**DEPARTMENT OF CIVIL ENGINEERING**
**M.Sc. Program in Structural Engineering**

**Thesis No: S00108**

# EFFECTIVENESS OF OVERHEAD TANK AS TUNED LIQUID DAMPER

**PREJU RAJBHANDARI**

**IOE, Pulchowk, January - 2007**

# COPYRIGHT

The author has agreed that the library, Department of Civil Engineering, Institute of Engineering, Pulchowk Campus, may make this thesis freely available for inspection.

Moreover, the author has agreed that permission for extensive copying of this thesis for scholarly purpose may be granted by the professor who supervised this thesis work recorded or, in his absence, by the head of Department or concerning M.Sc. programme coordinator or Dean of the institute in which the thesis work was done. It is understood that the recognition will be given to the author of this thesis and to the Department of Civil Engineering, Institute of Engineering Pulchowk Campus in any use of material of this thesis. Copying or publication or other use of this thesis for financial gain without approval of Department of Civil Engineering, Institute of Engineering Pulchowk Campus and author's written permission is prohibited.

Request for permission to copy or to make any use of the material in this thesis in whole or part should be addressed to:

Head of Department of Civil Engineering,
Institute of Engineering,
Pulchowk Campus,
Lalitpur,
Nepal.

# CERTIFICATE

This is to certify that the thesis "**Effectiveness of overhead tank as Tuned liquid damper"** being submitted by Miss Preju Rajbhandari (061/MSS/111), in partial fulfillment of the requirements for the award of degree of Master of Science in Structural Engineering at Institute of Engineering, Tribhuvan University, Nepal is as record of bonafide works carried out by her under my supervision and guidance and that no part of has been published or submitted for the award of any degree or diploma elsewhere.

Dr. P.N. Maskey
Professor
Department of Civil Engineering
Pulchowk Campus, Institute of Engineerig
Tribhuvan University, Lalitpur, Nepal

# ACKNOWLEDGEMENTS

I express my sincere thanks and gratitude to my thesis supervisor Dr. P.N. Maskey for his valuable guidance and suggestions. I am indebted to him for his moral and technical support and constant encouragement.

I would like to thank Dr. Roshan Tuladhar for his valuable suggestions.

The knowledge gained from my teachers right from the beginning of M.Sc. course has greatly helped in this research. So I wish to express deep appreciation to all the teachers and faculty of M.Sc. Structural Engineering who have helped me in various ways throughout the M.Sc. Course.

I would like to acknowledge my colleagues, classmates of M.Sc. Structure for their help.

Er. Preju Rajbhandari
061/MSS/111
January, 2007

# ABSTRACT

Tuned liquid damper has been very effective form of structural control device. Its working principle is same as tuned mass damper .The only difference is that the mass is replaced by liquid specially water. It dissipates vibration energy through sloshing. For high rise building the tuned mass damper and tuned liquid damper are very effective energy dissipating device.

Overhead water tank of a considerable capacity is needed for services of a public building. It is envisaged that such a large overhead tank if located and designed properly could act as an effective damping device. With this view present study is carried out to study the effectiveness of tuned liquid damper in a typical five storied public building prevalent in Nepal. By tuning the sloshing frequency with the fundamental frequency of the building, the configuration of tuned liquid damper has been determined. The tuned liquid damper has been modeled by using spring mass model. Response spectrum IS1893:2000 has been used for dynamic analysis. The building with empty overhead tank is analyzed to get the displacement of building. The building with tuned liquid damper is again analyzed and the displacement without tuned liquid damper and with tuned liquid damper is compared. From the study it is concluded that for a configuration of tuned liquid damper the reduction in displacement of the building decreases as the mass ratio and depth ratio increases. When the reduction in displacement is compared between two configurations of tuned liquid damper for same depth ratio, the larger sized tuned liquid damper is found to be more effective.

# TABLE OF CONTENTS

**Copyright** i

**Certificate** ii

**Acknowledgements** iii

**Abstract** iv

**Table of contents** v

**List of tables** vii

**List of figures** viii

**1. INTRODUCTION 1**
- 1.1 General 1
- 1.2 Problems and issues 2
- 1.3 Need of study 3
- 1.4 Objectives 3
- 1.5 Scope of work 4
- 1.6 Distribution of chapters 4

**2. LITERATURE REVIEW 6**
- 2.1 General 6
- 2.2 Tuned mass dampers 6
- 2.3 Tuned liquid dampers 7
- 2.4 Modeling tuned liquid damper 9

**3. PRINCIPLES OF TUNED LIQUID DAMPER 11**
- 3.1 General 11
- 3.2 Tuned liquid dampers 11
- 3.3 Sloshing frequency 14
- 3.4 Modeling of water 16

**4. PARAMETRIC STUDY 22**
- 4.1 Modeling of building 22
- 4.2 Determination of tank configuration 22
- 4.3 Determination of tuned liquid damper parameters 22
- 4.4 Modeling of water 24
- 4.5 Results and discussions 26

**5. CONCLUSIONS AND RECOMMENDATIONS** **37**
5.1 General 37
1.2 Major conclusions 37
1.3 Recommendations for extension of the work 38

**References** 39

# LIST OF TABLES

| Table | Title | Pages |
|---|---|---|
| 4.1 | Determination of the configuration of TLD | 28 |
| 4.2 | Determination of lump mass of water and its location | 29 |
| 4.3 | Percentage reduction in displacement of top storey | 30 |

# LIST OF FIGURES

| Figure | Title | Pages |
|---|---|---|
| 3.1 | Mathematical model of a single degree of freedom structure with rectangular TLD | 18 |
| 3.2 | Dimensions of the rectangular tuned liquid damper | 18 |
| 3.3 | Spring mass model | 19 |
| 3.4 | Impulsive and convective masses and convective spring stiffness | 20 |
| 3.5 | Heights of impulsive and convective masses | 21 |
| 4.4 | Displacements without and with TLD of size 0.2m by 0.2 m for different depth ratios | 31 |
| 4.5 | Displacements without and with TLD of size 0.25m by 0.25 m for different depth ratios | 32 |
| 4.6 | Displacements for various mass ratios at depth ratio 1 | 33 |
| 4.7 | Displacements for various mass ratios at depth ratio 1.6 | 34 |
| 4.8 | Displacements for various mass ratios at depth ratio 2 | 35 |
| 4.9 | Displacements for various mass ratios at depth ratio 2.2 | 36 |

# 1. INTRODUCTION

## 1.1 General

One of the most destructive phenomenons of nature is earthquake. It is difficult to predict the behavior of buildings under the effect of ground motion. The first step in preparing structures for shaking is to understand how buildings respond to ground motions. When the ground shakes, buildings respond to the accelerations transmitted from the ground through the structure's foundation. The inertia of the building can cause shearing of the structure which can concentrate stresses on the weak walls or joints in the structure resulting in failure or perhaps total collapse. The type of shaking and the frequency of shaking depend on the structure as well as soil characteristics. If the building rests on bed rock or hard soil, it experiences lower seismic waves dislike soft soils, as the seismic waves in soft soil highly amplifies and may cause huge damage of structures constructed over it. Hence predicting the precise behavior of buildings is complicated.

Nepal has a long history of destructive earthquakes. With a growing population of almost a million people, uncontrolled development, and building construction techniques that have changed little in the past century, Kathmandu Valley has becomes increasingly vulnerable to catastrophic earthquakes with each passing year. In addition to structural failure possibilities issues such as functional performance and human discomforts are major concerns. So to improve the structures performance, improvement in the ability of structure to dissipate the dynamic energy has become a great need of present day.  In past years people actually did not used to bother about all these things. But now a days people are showing there interest in constructing seismic resistant structures.

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

Tuned liquid damper is also a new type of passive mechanical damper and is a special case of tuned mass dampers in which mass is replaced by liquid, usually water. Since tuned liquid damper has some advantages over tuned mass dampers, such as low cost, easily adjustable natural frequency, suitability for temporary use, easy installation in the existing structures, efficiency in dissipation of vibration energy etc it has become the most popular vibration control device. It consists of rigid tank connected rigidly to the structure with partially filled water in it. This device dissipates vibration energy of the structures through the sloshing of the liquid. In addition the shear force caused by the inertia of the liquid mass, the structural response is improved.

The problem of shortage of water is growing day by day everywhere in Kathmandu valley. So people are compelled to use water tanks for the storage of water. But people are placing water tanks wherever they want and whatever size they need to fulfill their water demand. It is predicted that the precise calculation of location and size of tank including water depth not only fulfill the daily water demand but also improves the structural response during seismic excitation. Present study deals with the effectiveness of water tanks in buildings as the tuned liquid damper to reduce the earthquake effect. Main focus is given in the building displacement due to earthquake effect.

## 1.2 Problems and issues

Nepal lies in seismically vulnerable zone. Lots of damages have been suffered in Nepal due to past earthquakes. Moreover light weight materials are being used for construction purpose. These materials decrease the energy dissipating capacity of the structure. Therefore providing additional damping to the structure has become important. Nowadays we have lots of devices that can be used to provide additional damping to the structure. Among these the mass damper is much popular. But the current mass damper systems are not affordable. They are cumbersome, occupy lots of space and are difficult to install. A best alternative for mass damper is tuned liquid damper. Tuned liquid damper is much cheaper, occupies less space and is easy to install. Both mass dampers and tuned liquid damper have same principle. The main difference is that in tuned liquid damper the mass is replaced by liquid specially water. The problem of shortage of water is growing day by day everywhere in Kathmandu valley. So people here are bound to construct water tanks for water storage purpose. After the conduction of this thesis work if the result shows improvement in the structure response, the over head water tanks, apart from storing water, can also be used as energy dissipating device.

## 1.3 Need of study

Nepal has a long history of earthquake. Earthquake has destroyed lots of life and property. So, people are attracted towards the ways to make their house safe against earthquake.

There is shortage of water in Kathmandu valley. So people here construct separate water tank for storage purpose.

The over head water tanks, if with certain modifications, can be used as tuned liquid damper then we can get an economic solution to improve the energy dissipating capacity of buildings.

## 1.4 Objectives

The main objective of this work is to find the possibility of using overhead water storage tanks as tuned liquid dampers for which following sub-objectives are set:

1. To determine the seismic response of the building with empty overhead tank.

2. To identify the behavior of building with water in the tank for different combination of water levels and water mass in the tank.

3. To compare the lateral displacement of the structure with and without water in tank.

4. To determine the appropriate configuration of the tank for additional advantage of seismic response control.

### 1.5 Scope of Work

The research has been carried out for a typical reinforced concrete public building. The building is five storied, and is symmetric in both directions. In symmetric building the displacement in both directions will be same and also it will be easy to analyze the result. There are four bays in each direction in the building. Taking mass ratio one percent the mass of water required is determined. Based on this mass, size of a square tank is determined. This tank is divided into number of small tanks in such a way that the sloshing frequency of water is same as that of the natural vibrating frequency of the building. The tank is placed at the mid of the roof to maintain the symmetricity. The vertical slabs, dividing the tank into small tanks, have not been modeled. The water has been modeled as spring mass model. The spring mass model has been provided only in the direction of displacement because the water will slosh in that direction only. SAP 10 has been used as an analyzing tool. IS 1893:2002 response spectrum method has been used for dynamic analysis. The main focus of this thesis is to compare the displacement of the building without and with tuned liquid damper.

### 1.6 Distribution of chapters

This thesis has been divided into six different chapters.

The second chapter deals with the review of different literatures related with the present study. The survey of literature, for simplicity, is divided into four groups. These are related to general devices used for structural control, tuned mass damper, tuned liquid damper and modeling of tuned liquid damper. The review is mainly focused on the researches carried out on the respective working principles, modeling and analysis.

The third chapter deals with the principle of tuned liquid damper. It explains various theories that have to be applied on tuned liquid damper. This chapter has also been divided into four groups. In this part the equation of motion of the structure with tuned liquid damper, sloshing theories, methods to determine the sloshing frequency of liquid has been mentioned. It also deals with modeling of tuned liquid damper. It explains on how to determine the mass that participates on sloshing and how to determine the location to lump the water mass. It also suggests the way to determine the stiffness of the spring mass model.

The fourth chapter presents the parametric study part. In this part, how the study is preceded has been discussed. This chapter is divided into five groups. It explains on modeling of building elements, determination of configuration of overhead tank, determination of tuned liquid damper parameters, modeling of water, shows results followed by discussions. The results have been shown in terms of displacements.

The fifth chapter contains the major conclusions of the study. The principle conclusions include the efficiency of the overhead water tank in a building as tuned liquid damper. The displacement of the building is substantially reduced once the effect of tuned liquid damper is taken into consideration. The chapter also includes the recommendation for further works as extension of present study.

# 2. LITERATURE REVIEW

## 2.1 General

Due to extensive use of light weight construction material, the energy dissipating capacity of the building is decreasing. Researches are being carried out to find out the devices that could provide additional damping to the structure. These devices are called as structural control device. To enhance the safety and habitability of structures in general three types of structural control devices, namely passive, active and semi active devices are used. Viscoelatic dampers, base isolation systems, tuned mass damper and tuned liquid dampers are some examples of damping devices.

## 2.2 Tuned mass dampers

Sadek et al. (1996) carried out their study to find out the method of estimating parameters of tuned mass dampers for seismic application. They concluded that using the proposed tuned mass damper parameter reduces the displacement and acceleration responses significantly up to fifty percent. Their study showed that in order for a tuned mass damper to be effective, larger mass ratio must be used, especially for structure with higher damping ratios.

Deka et al. (2005) has shown that instead of installing separate tuned mass devices, the storage water tanks, if properly designed, can be used as device to reduce response of wind induced vibration. The study was conducted for ten storied reinforced office building. In the study the water tank at the roof has been modeled as tuned mass damper. The study revels that the effect of detuning of tuned mass damper may result in the increase of response, whereas if tuned mass damper is properly tuned to the first natural frequency of the structure, the response can be reduced effectively.

## 2.3 Tuned liquid dampers:

Frandsen (2004) developed a fully non linear two dimensional stress-transformed finite difference solver based on inviscid flow equations in rectangular tanks. The fluid equations are coupled to a linear elastic support structure. This solver is valid for deep water TLD. This numerical prediction showed that the coupling of liquid storage tank to a structure can change the behavior of the structure considerably; the optimum TLD- structural systems are herein discussed in terms of a) shift in eigenfrequency of dominating sloshing mode relative to structural natural frequency with nonmoving liquid, b) the reduction of system response due to liquid sloshing. This paper says that an effective tank- structural system displayed two distinct frequencies on the system displacement curves with reduced response, especially at the first system eigen frequency, due to large sloshing motion. The coupled system was effective to reduce the structural response when one of the dominating sloshing frequencies was near to the structure natural frequency. This effect was proportional to the mass ratio and decreases with $1/n^2$ for higher modes.

Banerji et al. (1999) carried out numerical simulation of a single degree of freedom structure rigidly supporting a tuned liquid damper and subjected to both real and artificially generated earthquake ground motion. The study concluded that TLD is more effective as the ground excitation level increases; a larger depth ratio is suitable for excitation levels expected in strong earthquake motions; effectiveness of TLD reduces as the structural damping increases; a larger mass ratio is required for a TLD to remain equally effective as structural damping increases, for TLD to be effective mass ratio has to be greater than 1%,

Damatty (2002) conducted an extensive research program to investigate the behavior of TLD system as a technique to up-grade the seismic resistance of structures at University of Western Ontario. The first study is carried out experimentally using shaking table device and a system test tower. This involved studying the behavior of Tuned liquid damper system and developing an equivalent simple model based on test result. The response of the structural model with and without tuned liquid damper attached to dynamic loading was recorded. The test revealed the great efficiency of tuned liquid damper system in damping the vibration of structural model. The second study involved developing software that can accurately predict the fluid motion in tank. The third study is conducted both analytically and experimentally. This study uses the finding of the two previous studies to investigate the earthquake response of the structure with a tuned liquid damper attached. It uses the concept of Tuned mass damper. This study concluded that the addition of Tuned liquid damper reduces the top displacement of structure by 60%.

Sun et al. (1992) carried out experiment to measure liquid motions in shallow tuned liquid dampers with rectangular, circular, and annular tanks, subjected to harmonic base excitation. Using single degree of freedom tuned mass damper analogy, equivalent mass, stiffness and damping of the TLD were calibrated from the experimental results. These parameters are function of the TLD base amplitude. Shaking table experiment was carried out to find out the behavior of TLD and following results obtained were: the wave form in the TLD changed depending upon the excitation frequency and amplitude of the shaking table. The natural frequency of liquid sloshing in rectangular tank increases as the excitation amplitude become large. Wave motion in circular tank TLD was found to be more complicated than rectangular one but in annular tank it was simpler than rectangular one. The investigation based on tuned mass damper analogy reveals that the effective mass of Tuned mass damper increases and reaches the value of mass of water as the excitation amplitude increases. The effective damping ratio also increases as the base excitation amplitude increases and exceeds 10% when breaking wave occurs. The effective natural frequency in shallow Tuned liquid damper increases as the base amplitude increases. The difference due to Tuned liquid damper tank shape for effective mass, frequency and damping occurs, but is not significant for engineering applications.

Sun et al. (1992) proposed non-linear analytical model for a TLD using rectangular tanks filled with shallow liquid under pitching vibration, utilizing a shallow water wave theory. The model includes the linear damping of the sloshing liquid which is an important parameter in the study of a TLD as it affects the efficiency of TLD. Shaking table experiments were conducted for verification, good agreement between analytical simulation and experimental results were observed in small excitation amplitude range. This study assumes the flow in the TLD to be potential (rotational), and then considers the relevant profiles in both horizontal and vertical direction. Since the liquid depth considered is very shallow, for simplicity the governing equations are integrated along the vertical direction. The liquid sloshing was described by two variables: the free surface elevation, and the horizontal velocity of the liquid particle in the free surface. The liquid damping was introduced semi theoretically in the basic equations. The pressure forces acting on side wall and the bottom of the TLD tank was calculated. These forces and moments due to liquid sloshing will act as interaction forces between the TLD and the structure to suppress structural vibration.

Ahsan (1990) proposed liquid sloshing model based on the non- linear shallow-water wave theory in two horizontal directions. According to this, the fluid sloshing system can be represented by an equivalent mechanical model in which the fluid is replaced by lumped fluid masses, springs and dashpots. The mechanical characteristics of the equivalent systems are established by using potential flow theory. His study concluded that sloshing damper can effectively reduce the motion of buildings when the fundamental sloshing and building frequencies are synchronized. The sloshing damper provides additional damping to system by modifying frequency response function of the structure thereby reducing the response.

IITK-GSDMA GUIDELINES (2005) for seismic design of liquid storage tanks (Indian institute of technology Kanpur) has suggested methods for determining the base shear at the base of tank, hydrodynamic force exerted by liquid on the tank wall , fundamental time period of the liquid sloshing etc.

### 2.4 Modeling tuned liquid damper

IITK-GSDMA GUIDELINES (2005) for seismic design of liquid storage tanks (Indian institute of technology Kanpur) says that when a tank containing liquid with a free surface is subjected to horizontal earthquake ground motion, tank wall and liquid are subjected to horizontal acceleration. The liquid in the lower region of tank behaves like a mass that is rigidly connected to tank wall which is termed as impulsive liquid mass. This mass accelerates along with the wall and induces impulsive hydrodynamic pressure on tank wall and on base. Liquid mass in the upper region of the tank undergoes sloshing motion. This mass is called as convective liquid mass and exerts convective hydrodynamic pressure on tank wall and on base. This guideline has suggested a spring mass model of tank-liquid system. This guideline has suggested expressions for determining the impulsive mass, convective mass and stiffness of the convective mass. It suggests lumping both masses at different height inside the tank and connecting the impulsive mass to the tank wall through rigid connection and convective mass to the tank wall by spring of its own stiffness.

Savyanvar (2005) carried out a dynamic analysis of liquid filled tank using the concept of generalized SDOF system. Hence linear analysis of sloshing in TLD can be carried out effectively by considering an equivalent tuned mass damper. The hydrodynamic theory of the TLD is somewhat complex and difficult to handle because of the intrinsic non linearity in the physical model. Water response on tank wall is modeled into two lumped masses: a fixed one known as “impulsive mass” representing the liquid mass moving with the acceleration of the structure rigidly connected to tank, and “connective mass” determining the sloshing effect which is responsible for energy absorption, connected to the tank by a spring and a damper.

Wilson (2002) explained that many different isotropic materials, which have a very low shear modulus compared to their bulk modulus, have fluid-like behavior. These materials are often referred to as nearly incompressible solids. For fluids, the bulk modulus is an independent constant, Poisson’s ratio is 0.5, and Young’s modulus and the shear modulus are zero.

# 3. PRINCIPLES OF TUNED LIQUID DAMPER

## 3.1 General

Damping is one of the most important parameters that limit the response of the structures during dynamic events. This property of the structure increases ability of the structure to dissipate a portion of energy released during a dynamic load event. Various passive structural control devices are prevalent for use in structures in connection with earthquake damage reduction. The tuned mass damper is one of such devices.

The tuned mass damper is a passive energy absorbing device consisting of a mass, a spring, and a viscous damper attached to a vibrating system to reduce undesirable vibrations. Its main purpose is to reduce the resonant component of the response by adding a force in opposite phase with respect to excitation, and achieved by tuning the additional vibrating mass to the frequency close to resonant frequency of the primary system. The tuned mass damper is very sensitive even to small offset in tuning ratio when it is optimally designed.

## 3.2 Tuned liquid dampers

Tuned liquid damper is a special case of tuned mass dampers in which mass is replaced by liquid, usually water. Since tuned liquid damper has some advantages over tuned mass dampers, such as low cost, easily adjustable natural frequency, suitability for temporary use, easy installation in the existing structures, efficiency in dissipation of vibration energy etc it has become the most popular vibration control device. It consists of rigid tank connected rigidly to the structure with partially filled liquid in it. This device dissipates vibration energy of the structures through the sloshing.

The basic principle involved in tuned liquid dampers is that the fundamental linear sloshing frequency of liquid is tuned to the structures natural frequency. Such a tuning causes large amount of sloshing and wave breaking at the resonant frequencies of the combined tuned liquid damper – structure system that dissipates a significant amount of energy.

A tuned liquid damper is characterized by three important parameters namely tuning ratio, mass ratio and depth ratio. Tuning ratio is the ratio of fundamental linear sloshing frequency of the liquid to the structural natural vibration frequency. Mass ratio is the ratio of mass of the liquid to the structural mass. Depth ratio is the ratio of depth of liquid in the tank to the tank length.

A research done by Sun et al. (1992) has found out that the effectiveness of a tuned liquid damper for suppressing the vibration depends not only on mass of liquid in tuned liquid damper but also on the configuration of the liquid, as well as the position where the tuned liquid damper is located. If the configuration of the liquid i.e. the liquid depth and tuned liquid dampers tank size is designed suitably, the tuned liquid dampers can be made more effective even with small mass of water. A research carried out by Banerji et al. (1999) has found out that the tuned liquid damper is more effective in reducing structural response as the ground excitation level increases. This is because it then dissipates more energy due to sloshing and wave breaking. A larger water-mass to structure-mass ratio is required for a tuned liquid damper to be equally effective as structural damping increases. This research done by Banerji et al. found out that the mass ratio should be more than one percent for the tuned liquid damper to be effective.

The mathematical model of a single degree of freedom (SDOF) structure with a tuned liquid damper attached to it and subjected to ground motion for SDOF structure is shown fig 3.1

The equation of motion for single degree of freedom system with a tuned liquid damper attached to it and subjected to ground motion as in fig 3.1 is as follows:

$$m_s\ddot{x}_s + c_s\dot{x}_s + k_s x_s = -m_s a_g + F_w$$

( 3.1)

Where,

$m_s$ = mass of the structure

$c_s$ = damping of the structure

$k_s$= stiffness of the structure

$x_s$= displacement of the structure relative to ground

$\dot{x}_s$= velocity of the structure

$\ddot{x}_s$= horizontal acceleration of the tank generated by the motion of the structure

$a_g$ = ground acceleration

$F_w$ = force developed by tuned liquid damper due to water sloshing

The force $F_w$ can be found out by integrating the pressure over the vertical walls. This force can be determined from the expression suggested by Banerji et al. (1999) (refer fig. 3.2):

$$F_w = \frac{\rho g b}{2}\left[(\eta_n + h)^2 - (\eta_o + h)^2\right]$$

(3.2)

Where

$\rho$ = mass density of water

b = tank width

$\eta_n$ = free surface elevation at right wall of tuned liquid damper

$\eta_o$ = free surface elevation at left wall of tuned liquid damper

h = undisturbed depth of water in tuned liquid damper

The liquid sloshes in opposite phase to the building. Therefore liquid in tuned liquid damper exerts sloshing force such that it reduces the response of the structure compared to the response when there was no tuned liquid damper. The energy dissipation in the structure with tuned liquid damper is more compared to structure without tuned liquid damper. This sloshing force depends on mass ratio and depth ratio. It seems that structural response should decrease with increasing mass ratio.

For multi degree of freedom system all the masses, responses, damping coefficients, stiffness, and forces will be in matrix form. To get the solution of such equation the free vibration equation is solved for fundamental frequencies. The free vibration equation is:

$$\left[k - \omega^2 m\right]\varphi = 0 \tag{3.3}$$

Where,

$k$ = stiffness matrix of the structure

$m$ = mass matrix of the structure

$\omega$ =Fundamental frequency matrix

$\varphi$ = mode shape matrix

After determining the fundamental frequencies, the mode shape is determined. This mode shape is multiplied by amplitude of displacement to get the displacement in each floor.

### 3.3 Sloshing frequency

Sloshing is a physical phenomenon characterized by the oscillation of unrestrained free surface of the liquid in a partially filled container due to external excitation. Depending on type of disturbance and container shape, the free liquid surface can experience different types of motion including simple planar, non planer, rotational etc. The basic problem of liquid sloshing involves the estimation of hydrodynamic pressure distribution, forces moments and natural frequencies of free water surface. These parameters have direct effect on the dynamic stability and performance the moving container. Generally the hydrodynamic pressure of liquid in moving rigid container has two distinct components. One component is directly proportional to the acceleration of the tank. This component is caused by the part of fluid moving with the same tank velocity. The second is known as convective pressure. The convective pressure is exerted by convective mass or sloshing mass of water.

Sloshing frequency is very important parameter for the effectiveness of tuned liquid damper. This frequency has to be tuned with the free vibration frequency of the structure. The sloshing frequency mainly depends on the configuration of tuned liquid damper and also on depth ratio.
Frandsen (2004) has suggested following expression for determining the linear sloshing frequency of liquid. (Refer fig. 3.2)

$$\omega_n^2 = gk_n \tanh\left(k_n h\right) \tag{3.4}$$

Where,
$\omega_n$ = natural frequency of n$^{th}$ sloshing mode
g = acceleration due to gravity
b = length of tank
h = undisturbed water depth
n = mode number
$k_n$ = the wave number and can be found our as
$k_n = \pi n/b$

Banerji et al. (1999) has also suggested similar expressions to find out the natural sloshing frequency

$$\mu = \sqrt{\frac{\Pi g \tanh(\Pi\Delta)}{b}} \tag{3.5}$$

Where

$\mu$ = liquid sloshing frequency

$\Delta$ = depth ratio

b = width of tuned liquid damper

IITK-GSDMA GUIDELINES (2005) for seismic design of liquid storage tanks has also suggested an expression for finding out the time period of sloshing mode as below:

$$T = 2\Pi\sqrt{\frac{m_c}{k_c}} \tag{3.6}$$

Where,

T= fundamental time period of convective mode

$m_c$= convective mass or sloshing mass of water

$k_c$ = convective stiffness

All the above equations for sloshing frequency yield the same result. As the length of tuned liquid damper increases the sloshing frequency decreases. Whereas the sloshing frequency increases with the increase in depth ratio until the depth ratio is one. When the depth ratio is more than one, the sloshing frequency becomes almost constant.

### 3.4 Modeling of water

Dynamic analysis of liquid containing tank is a complex problem. It involves problems related to fluid-structure interaction. Based on numerous analytical, numerical, and experimental studies,

IITK-GSDMA GUIDELINES (2005) for seismic design of liquid storage tanks has developed simple spring mass models of tank- liquid system to evaluate hydrodynamic forces. The whole mass of water is modeled as two lumped masses. The mass of lower portion of water is called as impulsive mass, which moves with the primary system. The upper part of the mass is called as sloshing mass or convective mass. These masses are determined from the expressions given in the guidelines as below:

$$m_i/m = (\tanh(0.866L/h))/(0.866L/h) \tag{3.7}$$

$$m_c/m = 0.264\tanh(3.16h/L)L/h \tag{3.8}$$

$$hi/h = 0.5-0.09375/(h/L) \text{ for } h/L>0.75 \tag{3.9}$$

$$hc/h = 1-((\cosh(3.16h/L)-1.0)/(3.16(h/L)\sinh(3.16h/L) \tag{3.10}$$

$$Kc = 0.833mg\tanh^2 (3.16h/L) \tag{3.11}$$

Where,

$m_c$= convective or sloshing mass of the structure

m= total mass of water

L= length of tank

h= depth of water in the tank

hi = height from base of the tank where the impulsive mass is lumped

hc = height from base of the tank where the convective mass is lumped

Kc = stiffness of the convective mass

Figure 3.3 presents the spring mass model of the tuned liquid damper.

The convective mass is connected to tank through a spring of stiffness Kc/2 on either side whereas the impulsive mass is connected to the tank by rigid link.

The charts developed using the above equations are shown in fig 3.4 and fig 3.5

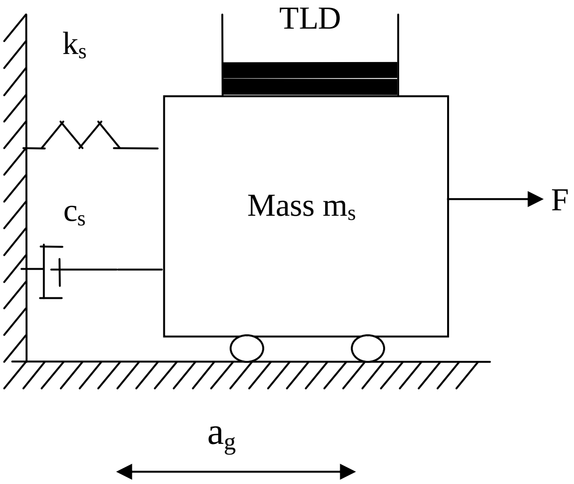

Fig. 3.1: Mathematical model of a single degree of freedom structure with rectangular TLD

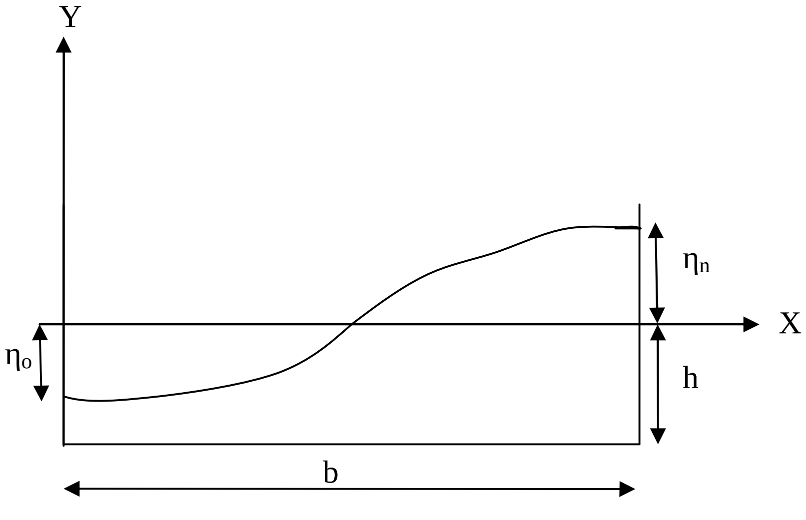

Fig. 3.2: Dimensions of the rectangular tuned liquid damper

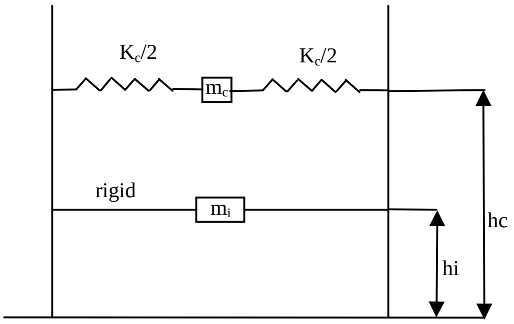

Fig.3.3: Spring mass model

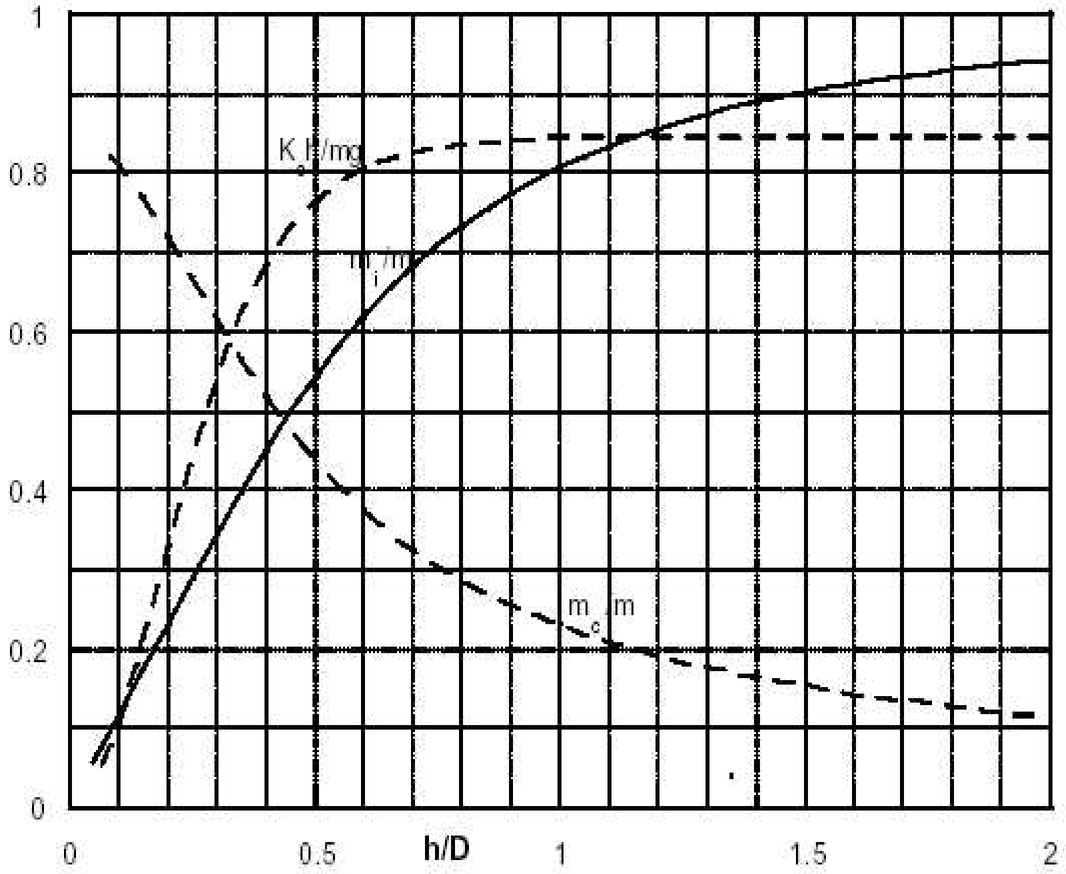

Fig. 3.4: Impulsive and convective masses and convective spring stiffness

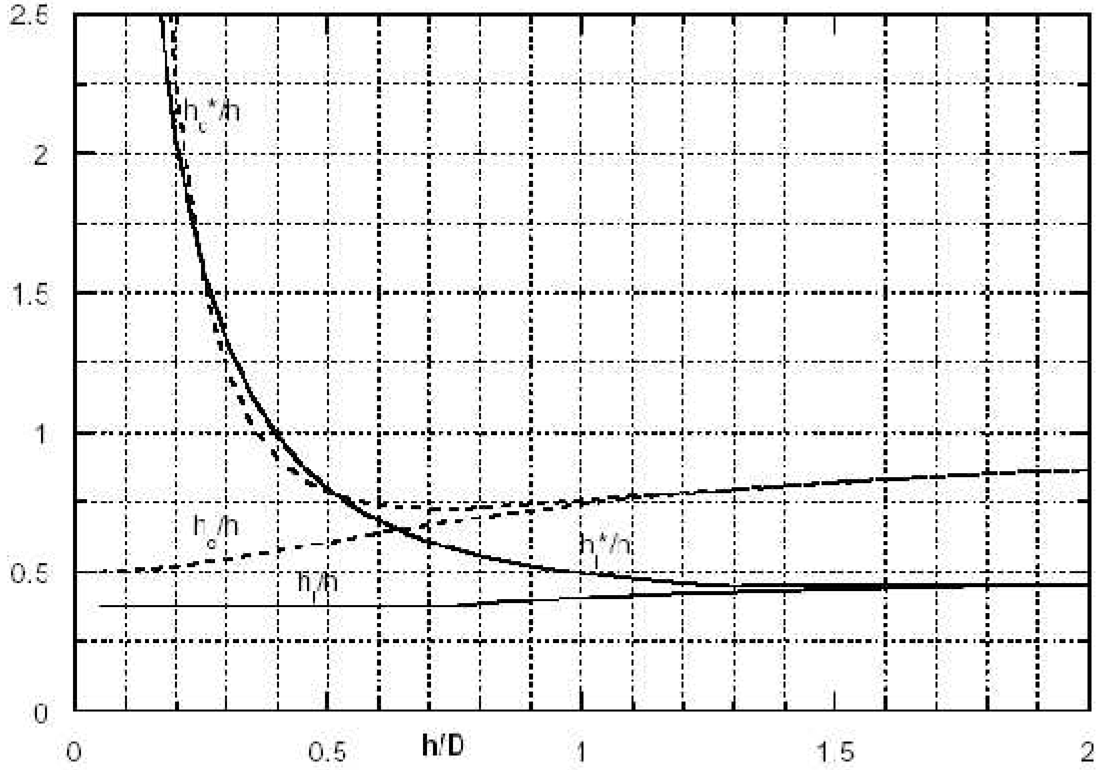

Fig. 3.5: Heights of impulsive and convective masses

# 4. PARAMETRIC STUDY

## 4.1 Modeling of building

A typical reinforced concrete public building has been taken. It is modeled as three dimensional frame in SAP 10. Its beams and columns are modeled as frame element and slabs are modeled as shell element. The building is symmetric in both directions. Displacement in such building is same in both directions and it is simpler to analyze them. The building is five storied, and has four bays in each direction. Each bay is five meters long and floor height is three meters. IS1893: 2002 response spectrum has been used for dynamic analysis. For this purpose the building is considered as special moment resisting frame. Soil type is considered as type II and the seismic zone as zone five. Since the building is symmetric, the dynamic load is applied along one direction.

## 4.2 Determination of tank configuration

To determine the configuration of tank, the volume of water that has to be stored in the tank is predicted as 25 cubic meters. After that the mass of whole building was calculated which is 1392074.41 Kg. A research carried out by Banerji et al. (1999) has found out that a larger water-mass to structure-mass ratio is required for a tuned liquid damper to be effective as structural damping increases. This research done by Banerji et al. found out that the mass ratio should be more than one percent for the tuned liquid damper to be effective. Therefore in our case taking mass ratio one percent the minimum mass of water required is 13920.7Kg. This mass of water occupies around 14 cubic meter volume. Therefore a square tank of size 10 *10*0.5 cubic meters was chosen. This tank is placed at the mid of roof to maintain the symmetricity. Its perimeter slabs are modeled as shell element.

## 4.3 Determination of Tuned liquid damper parameters

The time period of the building is determined from free vibration analysis, from which the natural vibrating frequency of the building is determined.

Time period of first mode of the building with empty overhead tank (Ts) = 0.568831 sec

The fundamental frequency is 11.045 rad/sec

According to Frandsen (2004) strong interaction between the primary and secondary system occurs in the first sloshing mode and the strength of interaction decays for higher modes. Therefore the natural frequency of first mode of the structure is tried to tune with the liner sloshing frequency of water.

In equation (3.4) the sloshing frequency is substituted by the structure natural frequency of first mode and then the length of tuned liquid damper and depth ratios are determined by hit and trial. From the expression for determining the natural sloshing frequency it is very clear that the tank length should be very small. Therefore water that can be accommodated in a tank would not be sufficient to meet the one percent requirement of mass ratio. So the number of such tanks required to make mass ratio one percent is calculated and it is also checked whether there is enough space for such requirement.

Assumed width of a tank (b) = 2m
$k_n = \pi n/b$
$= 1.57$ /m
$\omega_n^2 = gkn\tanh(k_nh)$
$= 4.6854$ rad$^2$/sec$^2$
$\omega = 2.164$ rad/sec

Since the sloshing frequency is not same as structure frequency, therefore another dimension of a tank is adopted

Assumed width of a tank (b) = 0.2m
$k_n = 15.707$/m

$\omega_n^2$= 9.81* 15.707*tanh (15.707*0.2)

$\omega_n$ = 12.389 rad/sec

$\omega_n$/ ωs =1.121 (tuned)

Therefore,

Length of a tank = 0.2m

Depth of water = 0.2m

Depth ratio = 0.2/0.2 = 1

Mass of water in one TLD = 8Kg

Number of such tanks in the 10m*10 m tank = 2500

Total mass of water = 20000Kg

Mass of structure with empty overhead tank = 1392074.41Kg

Mass ratio = 1.436 (>1) (ok)

Similar procedure has been carried out for determining other configuration of Tuned liquid tank and is presented in table.

The vertical slab of tuned liquid damper has not been modeled since increase in number of shell elements requires lots of memory.

### 4.4 Modeling of water

A square tank of size 10 m by 10 m is modeled as shell element and is rigidly connected to the roof the structure. Inside this tank small tanks of dimension as determined above should have been created, but this is not done because this results in increase in number of shell element and would create problem during analysis. Free vibration analysis for this structure with empty tank is carried out to determine its fundamental frequency. Then the size of a tank, and depth ratio was again revised for tuning ratio unity. From the modal analysis the displacement at different floor level of the building are recorded.

The water in a tank is modeled using spring mass model as suggested by IITK-GSDMA GUIDELINES for seismic design of liquid storage tanks. The whole mass of water is modeled as two lumped masses. The mass of lower portion of water is called as impulsive mass, which moves with the primary system. The upper part of the mass is called as sloshing mass or convective mass. These masses depend on the depth ratio and mass ratio. These masses, stiffness of the convective mass the height where they are to be lumped is determined from equations3.7 to 3.11 respectively. The water in the tank is modeled as in figure 3.3. Determination of these masses and their location has been presented in table 4.1 and 4.2.

Since there are number of such tanks within one bigger tank, water within each tank is modeled as shown in figure 3.3 and the connection between springs of adjacent masses was assigned as diaphragm which moves with the slab. Again the modal analysis is carried out for the structure with water in the tank. Then the deflection of the structure with empty tank and tank with water is compared.

Similar analysis is carried out for different depth ratios and mass ratios and results are compared.

### 4.5 Results and discussions

A typical, reinforced concrete, public building is considered for analysis purpose. The building is symmetric in both directions. The over head tank of size 10*10*0.5 cubic meters is placed at the mid of roof. The mass of the building with empty overhead tank is 1392074.41 Kg. Free vibration analysis is carried out for this building. The time period for this building is 0.568 seconds for which the fundamental frequency is 11.045rad/ sec. Response spectrum method is used for dynamic analysis. IS 1893:2002 response spectrum is used. The displacement at the top floor is found out.

By tuning the fundamental frequency of the building with that of the sloshing frequency, configuration of tuned liquid damper is determined. While tuning, it is observed that the sloshing frequency of water becomes almost constant after depth ratio one. Therefore if the tuning is not achieved even in depth ratio one, then the configuration can not be used as tuned liquid damper. Width of tuned liquid damper is also another important parameter that influences sloshing frequency. With the decrease in width, the sloshing frequency increases. Therefore, using over head tank in typical residential building may not be practical. Dynamic analysis is carried out for two sizes of tuned liquid damper. After providing the tuned liquid damper to the building, it is again analyzed to get displacement.

The displacements of the top storey without tuned liquid damper and with tuned liquid damper have been presented in table 4.3. It also shows the percentage reduction in the displacement. The first four results are for tuned liquid damper of size 0.2*0.2 square meters and the last four results are for tuned liquid damper of size 0.25*0.25 square meters.

The analysis has been carried out for four depth ratios for each configuration of tuned liquid damper. For one configuration of tuned liquid damper, the mass ratio and depth ratios are proportional to each other. That means if depth ratio increases mass ratio also increases. For one configuration as the mass ratio is increased, the percentage reduction in displacement decreases. This is because while increasing the mass ratio, there is no considerable increase in convective mass of water but the impulsive mass increases. The convective mass sloshes in opposite phase to the building whereas the impulsive mass of water vibrates in same phase as the building. For same depth ratio, if the percentage reduction is compared for two configurations, then this percentage is found to have increased for the 0.25 meters TLD. This is because in 0.25 meter TLD the sloshing mass is more than double of the sloshing mass in 0.2 meter TLD. The change in deflection with change in depth ratio for each configuration of TLD has been shown in fig. 4.4 and fig. 4.5. Fig 4.4 is for tuned liquid damper having size of 0.2m and fig. 4.5 is for the tuned liquid damper with size 0.25m. Fig 4.4 and fig 4.5 shows that as the depth ratio increases the displacement at top floor also increases, and hence the difference between the displacement without TLD and with TLD reduces. For same depth ratio this difference in displacement Without TLD and with TLD is more for 0.25m TLD compare to that with 0.2 m TLD. Fig 4.6 – 4.9 shows the displacements at the top storey for different mass ratios at constant depth ratio of 1, 1.6, 2 and 2.2 respectively. These figures show that as the mass ratio increases, the displacement reduces. This may be due to the reason that when the mass ratio increases for constant depth ratio, the sloshing mass increases.

Table 4.1: Determination of the configuration of TLD

| Length of TLD | Depth ratio | Depth of water | Sloshing frequency | Tuning ratio | Mass of water in one TLD | Number of TLDs | Total mass of water | Mass ratio |
|---|---|---|---|---|---|---|---|---|
| (m) | | (m) | | | (Kg) | | (Kg) | |
| 0.2 | 1 | 0.2 | 12.390 | 1.121 | 8 | 2500 | 20000 | 1.436 |
| 0.2 | 1.6 | 0.32 | 12.413 | 1.124 | 12.8 | 2500 | 32000 | 2.298 |
| 0.2 | 2 | 0.4 | 12.413 | 1.124 | 16 | 2500 | 40000 | 2.873 |
| 0.2 | 2.2 | 0.44 | 12.413 | 1.124 | 17.6 | 2500 | 44000 | 3.160 |
| 0.25 | 1 | 0.25 | 11.082 | 1.003 | 15.625 | 1600 | 25000 | 1.795 |
| 0.25 | 1.6 | 0.4 | 11.102 | 1.005 | 25 | 1600 | 40000 | 2.873 |
| 0.25 | 2 | 0.5 | 11.103 | 1.005 | 31.25 | 1600 | 50000 | 3.591 |
| 0.25 | 2.2 | 0.55 | 11.103 | 1.005 | 34.375 | 1600 | 55000 | 3.950 |

Table 4.2: determination of the lump mass of water and its location

| Mass of water in TLD | Depth ratio | Length of TLD | Depth of water in TLD | mi/m | mc/m | kch/mg | hi/h | hc/h | mi | mc | kc | hi | hc |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (Kg) | | (m) | (m) | | | | | | (Kg) | (Kg) | (N/m) | (m) | (m) |
| 8 | 1 | 0.2 | 0.2 | 0.8075 | 0.263 | 0.827 | 0.406 | 0.709 | 6.460 | 2.104 | 324.515 | 0.081 | 0.1418 |
| 12.8 | 1.6 | 0.2 | 0.32 | 0.9125 | 0.165 | 0.833 | 0.441 | 0.804 | 11.680 | 2.112 | 326.869 | 0.141 | 0.25728 |
| 16 | 2 | 0.2 | 0.4 | 0.942 | 0.132 | 0.833 | 0.453 | 0.842 | 15.072 | 2.112 | 326.869 | 0.181 | 0.3368 |
| 17.6 | 2.2 | 0.2 | 0.44 | 0.951 | 0.12 | 0.833 | 0.457 | 0.856 | 16.738 | 2.112 | 326.869 | 0.201 | 0.37664 |
| 15.625 | 1 | 0.25 | 0.25 | 0.807 | 0.263 | 0.827 | 0.406 | 0.709 | 12.609 | 4.109 | 507.054 | 0.102 | 0.17725 |
| 25 | 1.6 | 0.25 | 0.4 | 0.912 | 0.165 | 0.833 | 0.441 | 0.804 | 22.800 | 4.125 | 510.733 | 0.176 | 0.3216 |
| 31.25 | 2 | 0.25 | 0.5 | 0.941 | 0.132 | 0.833 | 0.453 | 0.842 | 29.406 | 4.125 | 510.733 | 0.227 | 0.421 |
| 34.375 | 2.2 | 0.25 | 0.55 | 0.951 | 0.12 | 0.833 | 0.457 | 0.856 | 32.691 | 4.125 | 510.733 | 0.251 | 0.4708 |

Table 4.3: Percentage reduction in displacement of top storey

| Depth ratio | Mass ratio | Tuning ratio | Displacement at top(mm) | | |
|---|---|---|---|---|---|
| | | | Without TLD | With TLD | % reduction |
| 1 | 1.436 | 1.121 | 13.834 | 12.992 | 6.086 |
| 1.6 | 2.298 | 1.124 | 13.837 | 13.249 | 4.249 |
| 2 | 2.873 | 1.124 | 13.838 | 13.395 | 3.201 |
| 2.2 | 3.16 | 1.124 | 13.835 | 13.465 | 2.674 |
| 1 | 1.795 | 1.003 | 13.837 | 9.11 | 34.162 |
| 1.6 | 2.873 | 1.005 | 13.841 | 10.07 | 27.245 |
| 2 | 3.591 | 1.005 | 13.842 | 10.582 | 23.552 |
| 2.2 | 3.95 | 1.005 | 13.844 | 10.82 | 21.843 |

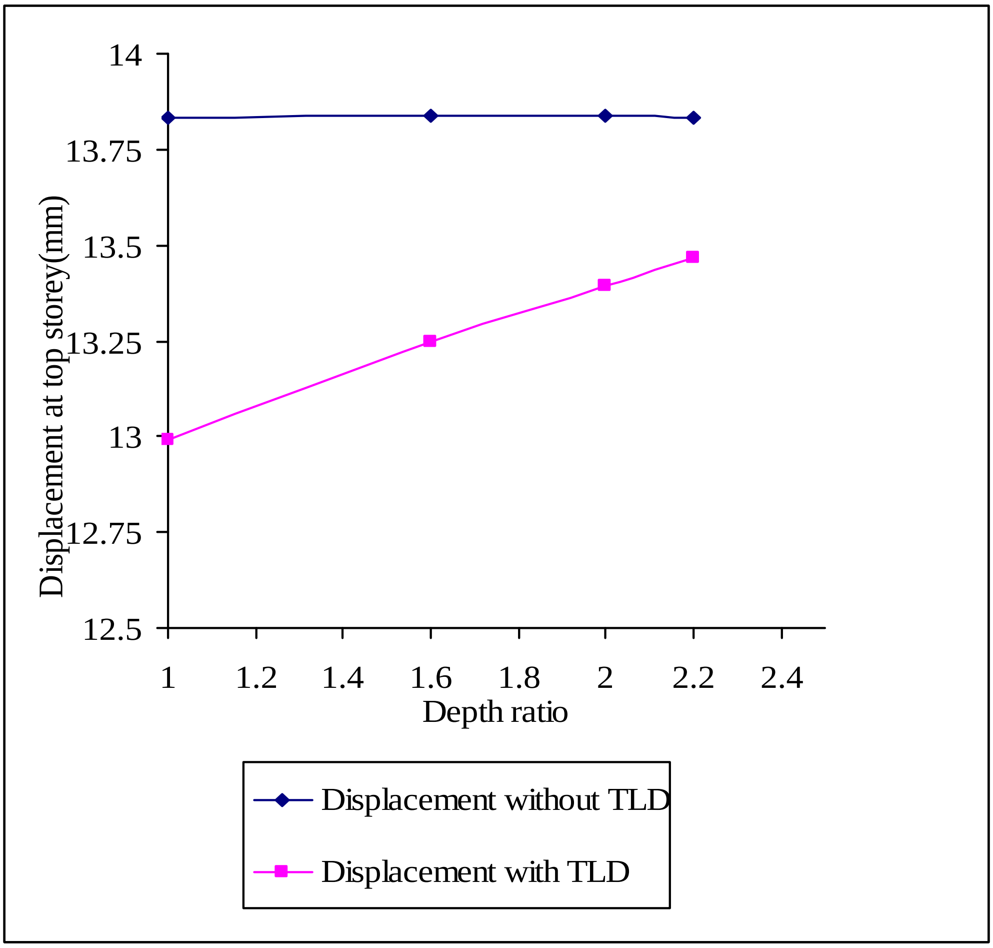

Fig. 4.4: Displacements without and with TLD of size 0.2m by 0.2 m for different depth ratios

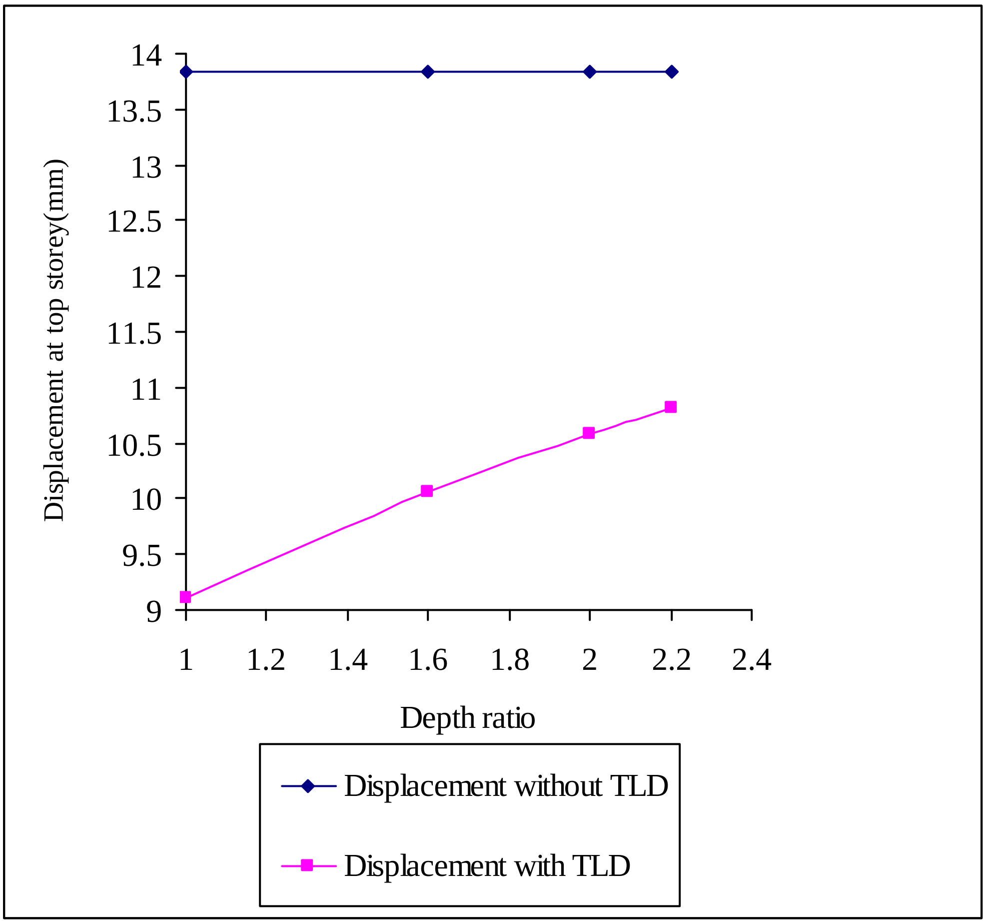

Fig. 4.5: Displacements without and with TLD of size 0.25 by 0.25m for different depth ratios

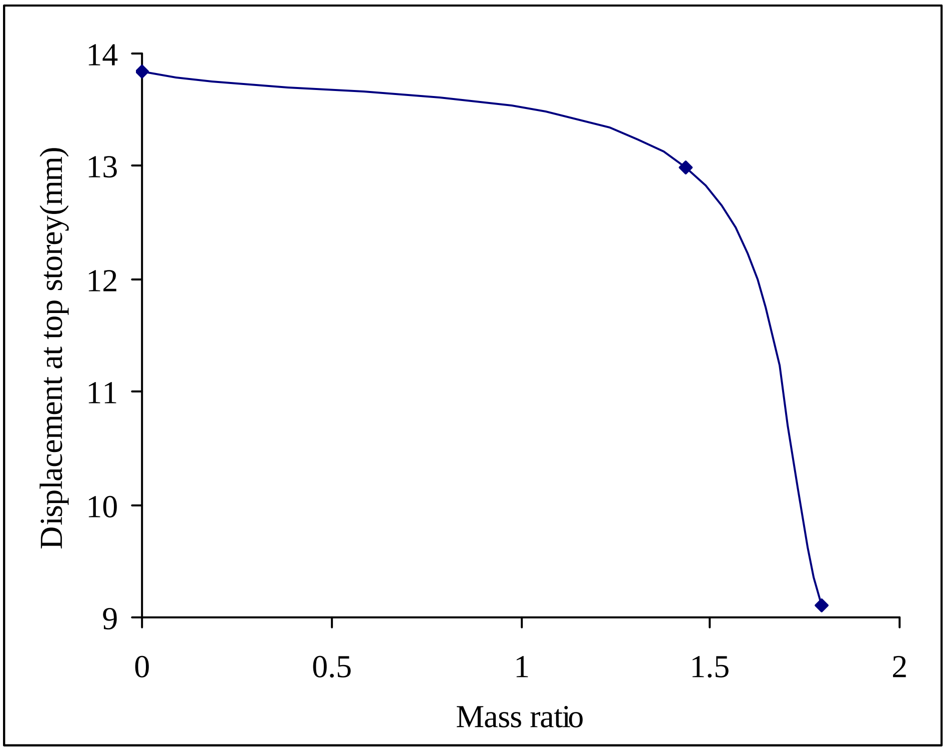

Fig. 4.6: Displacements for various mass ratios at depth ratio 1

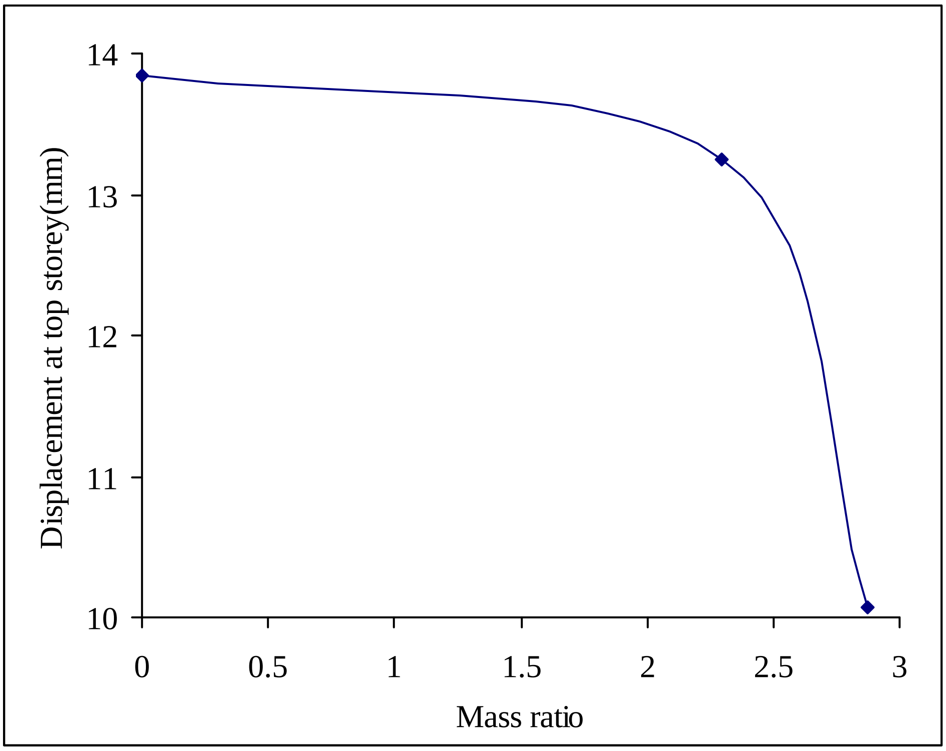

Fig. 4.7: Displacements for various mass ratios at depth ratio 1.6

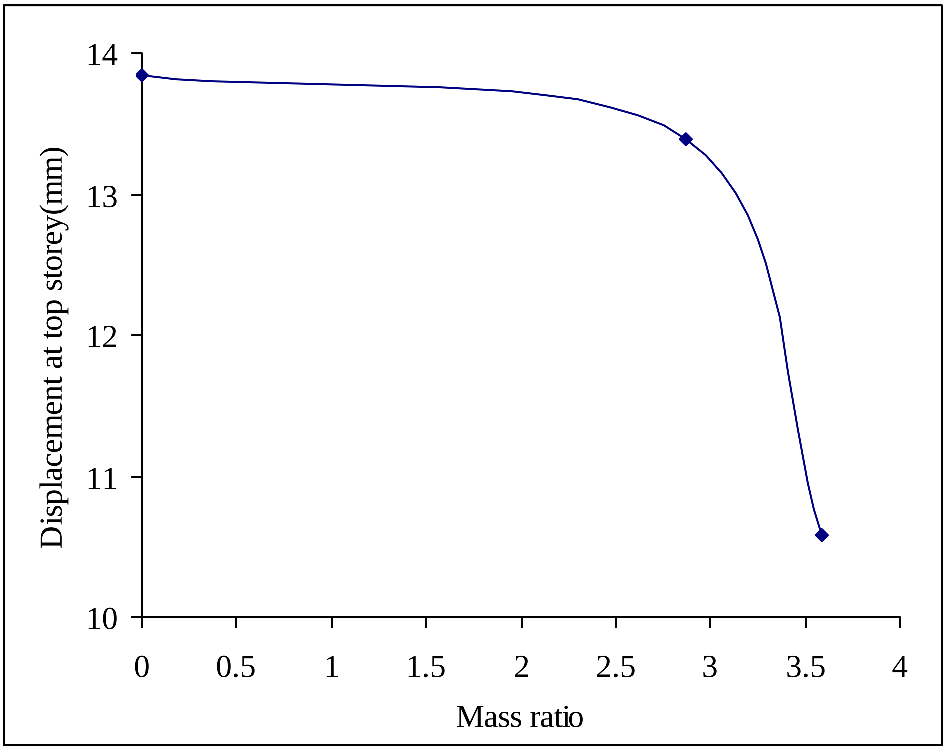

Fig. 4.8: Displacements for various mass ratios at depth ratio 2

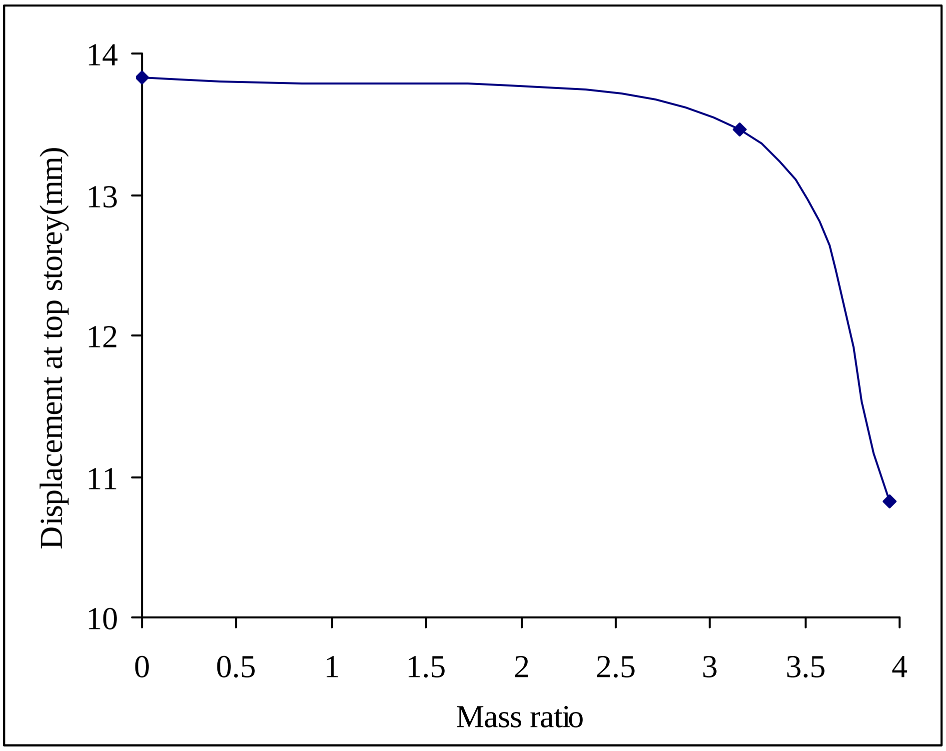

Fig. 4.9: Displacements for various mass ratios at depth ratio 2.2

# 5. CONCLUSIONS AND RECOMMENDATIONS

## 5.1 General

A typical reinforced concrete public building is considered for the study. This building is five storied, symmetric along both directions and has each bay five meters long. Floor height of the building is three meters. The building is modeled in SAP. Its beams and columns are modeled as frame element and slabs are modeled as shell elements. Then the configuration of overhead tank is determined, taking into account that it should contain at least one percent mass of water compared to mass of the building. This tank is placed at the mid of roof slab. The tank slabs are also modeled as shell elements. Dynamic analysis of the building is carried out. Response spectrum IS 1893:2000 is used for dynamic loading. The displacement of the top storey is recorded under such loading. After that by tuning the sloshing frequency of water with the natural frequency of first mode of the building, the configuration of tuned liquid damper is determined. The over head tank is divided into number of such tuned liquid damper. The water in each tuned liquid damper is modeled as spring mass model. The building with tuned liquid damper is again analyzed for same dynamic loading. The displacements of the top floor without and with tuned liquid damper are compared. The analysis is carried out for different depth ratios and mass ratios. Two different configurations, 0.2m by 0.2m and 0.25m by 0.25m, of tuned liquid damper are considered for the study.

## 5.2 Major conclusions

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

1. For each configuration of tuned liquid damper as the depth ratio increases, consequently mass ratio also increases. In such case the displacement of the building under dynamic loading also increases.

2. For the same depth ratio, the reduction in displacement of the building is more for 0.25 m tuned liquid damper compared to that for 0.2 m tuned liquid damper.

3. Tuned liquid damper may not be practical in residential buildings.

4. For a configuration of tuned liquid damper if tuning could not be obtained even in depth ratio one, then tuning cannot be obtained.

## 5.3 Recommendations for extension of the work

The following topics are recommended for study as extension of present work:

1. The effectiveness of Tuned liquid damper can be studied for unsymmetrical building.

2. The study can be carried out for higher buildings.

3. The effectiveness of circular overhead tanks as tuned liquid damper can be studied.

4. The study can be carried out for different location of overhead tank.

5. The effect of tuned liquid damper on the response of building when it is located at floor other than roof can be studied.

# REFRENCES

1. Sadek, Fahim , Mohraz, Bijan, Taylor, Andrew and Chung, Riley, (1996),' A method of estimating the parameters of tuned mass damper for seismic applications', Earthquake engineering and structural dynamics, vol. 26, 617-635(1997).

2. Deka . A and Talukdar .S (2005), ' Utilization of water storage tank at the roof of multistoried building as a tuned mass damper for controlling wind induced vibration', Structural dynamics, random vibrations and earthquake engineering, Conference proceedings, (2005)

3. Frandsen . J.B,(2004), 'Numerical prediction of Tuned liquid Tank structural systems', J. fluids and structures ,(2004)

4. Damatty, A.A EI, (2002), ‘Studies on the Application of Tuned liquid damper (TLD) to up-grade the seismic resistance of structures’, ICLR Research, paper series no. 17, (2002)

5. Sun, L.M., Fujino,Y., Chaiseri, P., , and Pacheco, B.M, (1992), ‘The properties of Tuned liquid dampers using TMD analogy’, Earthquake engineering and structural dynamics, vol. 24, 967-976 (1995)

6. Banerji Pradipta, Murudi Mohan, H. Shah Arvind and Popplewell Neil, (1999), ‘Tuned liquid dampers for controlling earthquake response of structures’, Earthquake engineering and structural dynamics, 2000; 29-587-602.

7. Sun, L.M., Fujino,Y., Koga, K., (1992), ‘A model of Tuned liquid damper for suppressing pitching motions of structures’, Earthquake engineering and structural dynamics, vol. 2.4, 625-636 (1995).

| | |
|---|---|
| 8. | Savayanavar, R.C., Parulekar, Y.M., Reddy G.R, Rama Rao, A., Kumar, P., Gosh,A.K., Vaze, K.K., Kushwaha, H.S., Chavan, S.P, (2005), ‘Seismic response control of structures using Tuned liquid dampers (TLD)’, Structural dynamics, random vibrations and earthquake engineering, Conference proceedings(2005) |
| 9. | IITK- GSDMA guidelines for seismic design of liquid storage tanks, Indian institute of technology Kanpur (2005) |
| 10. | Kareem Ahsan (1990), 'Reduction of wind induced motion utilizing a tuned sloshing damper', Journal of wind engineering and industrial Aerodynamics, 36 (1990) 725- 737. |