MODELLING AND ASSESSING THE PERFORMANCE OF TUNED LIQUID DAMPER FOR VIBRATION CONTROL

A Thesis

Submitted by

SOURAV MANDAL

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PROF. INDRAJIT BARUA

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DEPARTMENT OF CIVIL ENGINEERING

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Thesis Supervisor:

……………………

Indrajit Barua

Assistant Professor

Department of Civil Engineering

JADAVPUR UNIVERSITY

Countersigned by

……………………………….   …………………………..

Head of Department   ***DEAN***

Civil Engineering Department   *Faculty of Engineering and Technology*

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Date:

SOURAV MANDAL

Roll No. – 002110402029

Exam Roll No. – M4CIV23006

Department of Civil Engineering

Jadavpur University

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SYNOPSIS

In an era defined by the pursuit of safer and more resilient structures, this thesis stands as a testament to the power of innovation in structural engineering. Focused on the pivotal challenge of mitigating structural vibrations induced by dynamic loads, our investigation delves into the transformative potential of Tuned Liquid Dampers (TLDs). Through meticulous analysis and simulation, we unveil a set of findings that redefine the theory of vibration control. The voyage begins with a thorough investigation of several TLD configurations, each intended to reveal characteristics of their dampening effectiveness. From the straightforwardness of flat base TLD's to the complexity of arc bottom shape variants, a symphony of designs emerges. These TLD's geometrical details are not just for cosmetic purposes; they also have significant effects on how well they can control vibrations.

The finite element simulations were conducted using ANSYS software with its intuitive GUI for model setup. Among the findings that emerge, the flat base TLD asserts its prowess in effectively reducing structural deformations. However, this study delves further, embracing the dynamic interplay between fluid and structure. Sloped bottom TLDs enter the stage, offering enhanced damping capabilities and a glimpse into the harmonious fusion of form and function. The arc bottom shape TLDs emerge as the true prime mover, each showcasing its unique signature. The Circular Arc TLDs, elegant in their simplicity, engage in a dance with liquid dynamics to curtail vibrations. Yet, it is the Parabolic Arc TLDs that steal the spotlight, exhibiting unparalleled performance in vibration reduction. This discovery reignites the dialogue on geometric influence and paves the way for versatile structural solutions. Amidst these revelations, the Square Shape TLD emerges as a indicator of adaptability. Offering respite from the limitations of single-directional seismic scenarios, this design bridges the gap between aesthetics and function. The symmetrical geometry embraces seismic threats from all angles, epitomizing innovation's potential to reshape structural resilience.

In conclusion, this thesis transcends the realm of academic inquiry. It holds the promise of revolutionizing architectural practices, steering us toward structures that endure dynamic forces with grace. We embark on a journey beyond, where the synthesis of geometry, fluid mechanics, and structural dynamics propels us toward an era defined by adaptable, safe, and resilient built environments.

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LIST OF ABBREVIATIONS

1. TLD - Tuned Liquid Damper
2. DVTLD – Density Variable Tuned Liquid Damper
3. GUI - Graphical User Interface
4. FEM - Finite Element Model
5. FEA – Finite Element Analysis
6. FVA - Finite Volume Method
7. BEM – Boundary Element Method
8. FSI - Fluid-Structure Interaction
9. CFD - Computational Fluid Dynamics
10. RMS – Root Mean Square
11. SDOF - Single Degree of Freedom
12. ADINA - Automatic Dynamic Incremental Nonlinear Analysis

LIST OF SYMBOLS

1. m = Mass
2. k = Stiffness
3. c = Structure damping
4. ν = Displacement
5. F = Base shear
6. a_g = Acceleration time history
7. ω = Natural circular frequency
8. ξ = Damping ratio
9. f_n = Fundamental sloshing frequency
10. h = Undisturbed water height
11. a = Half length of the tank
12. η = Free surface elevation
13. $\ddot{x}$ = Base acceleration
14. λ = Damping factor
15. L = Length of tank
16. υ = Kinematic viscosity of water
17. g = Acceleration due to gravity
18. S = Surface contamination factor
19. ϕ = Potential function
20. Δt = Time step

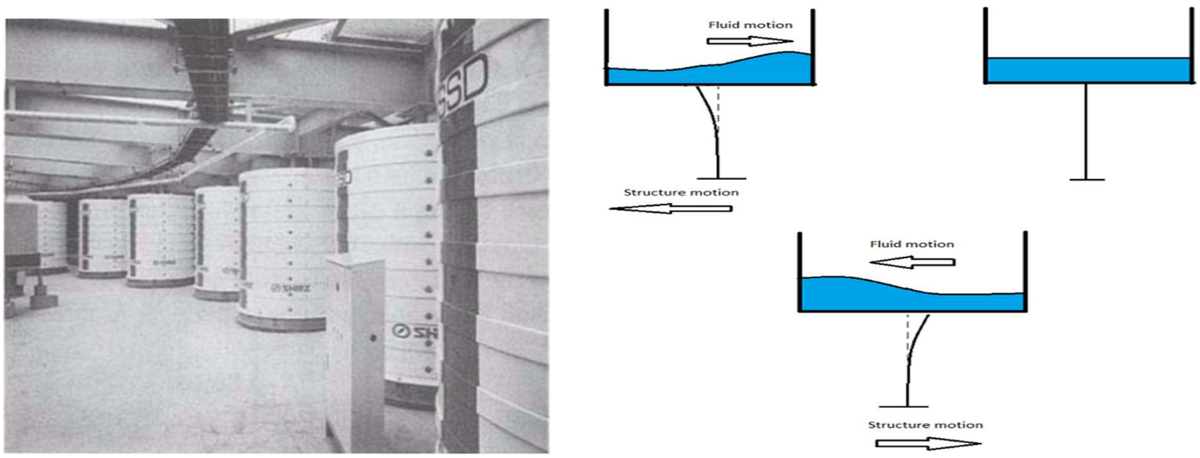
CHAPTER 1

INTRODUCTION

Tall buildings are essential to the growth and development of contemporary cities and can have positive effects on the economy, the environment, and even culture and society. More individuals can fit in the same amount of space. Structures that are safe and secure are therefore crucial. Tall buildings are especially vulnerable to dynamic loads, like wind and seismic loads, whose magnitude and direction change over time. This is because tall buildings have high structural flexibility and poor structural dampening. These dynamic loads could lead to a number of structural issues, including resonance, lateral displacement, and fatigue failure. To prevent unfavourable structural displacements, vibration reduction devices are therefore crucial.

There are several devices available that can be used to control the displacement of tall buildings such as Tuned mass damper, Tuned liquid damper, Fluid viscous damper, Friction dampers etc. A Tuned liquid damper (TLD) consists of a container partly filled with water or other liquids, that is designed to slosh in that tank in opposition of the motion of structure. The TLD’s oscillation frequency is tuned to match the structural natural frequency which causes a large amount of sloshing and dissipates a significant amount of energy. This tuning is achieved by adjusting the length or changing the water height of TLD. As it is a passive damper, TLD presents several advantages over other damping devices. They are relatively simple to design, construct and have a low initial and maintenance cost compared to other active and semi active damping devices.

The history of tuned liquid dampers dates back to the 19th century when the phenomenon of liquid sloshing inside containers was observed. However, the systematic study and application of tuned liquid dampers to engineering problems gained momentum in the latter half of the 20th century. In numerous practical applications, tuned liquid dampers (TLDs) have been used to reduce structural vibration and oscillation. Here are a few instances of TLDs being used: Its initial installation, which was only temporary, took place in the 42-meter-high Nagasaki Airport Tower in Nagasaki, Japan, in 1987. This installation was done to test the TLD's ability to lessen structural vibration. The Taipei 101 tower in Taiwan, for instance, features a TLD system that includes a large water tank near its top to dampen vibrations caused by typhoons and earthquakes, the Storebaelt Bridge in Denmark incorporates tuned liquid dampers to minimize vibrations caused by high-speed trains. The Shin Yokohama Prince Hotel (SYPH) in Yokohama, Japan, has a number of TLDs installed. The TLD system called for a multi-layer stack of nine circular containers, each measuring 2 metres in diameter and 22 centimetres high, for a total height of 2 metres. At wind speeds of 20 m/s, it was discovered that the TLD reduced the RMS accelerations in each direction to 70%.



(a) (b)

Figure 1. - (a) TLDs installed in SYPH [6], b) Working principal of TLD

In this present study finite element software 'Ansys Workbench' is used to create a computational building model, modal analysis and compute the fluid structure interaction between the liquid and structure. Performance comparison between conventional flat base TLD and non-conventional (Sloped bottom, Arc bottom, Square shape) TLD is shown in this study. Also, effectiveness of TLD consists of other liquid (except water) is shown here.

CHAPTER 2

GENERAL

TLD has been researched by numerous academics up to this point. These publications covered a range of TLD-related topics, such as experimental research, numerical analyses, and optimization methods, as well as their use in controlling seismic and wind-induced vibrations. A summary of past works on TLD is provided here.

2.1 LITERATURE REVIEW

Fujii (1990) et. al. discovered that installing wind-induced vibration dampers reduced the vibrations of two real tall towers, the Yokohama Marine Tower and the 42-meter Nagasaki Airport Tower, by about half.

Yozo Fujino, Limin Sun (1992) et. al. had successfully established an analytical model for TLD based on shallow water wave theory, which proved to be quite effective, and modified this model to account for the effect of breaking waves by introducing two empirical coefficients determined empirically. The model's ability to accurately forecast how structures fitted with TLDs will react even in the presence of breaking waves has been demonstrated through experimentation.

Pacheco, Chaiseri, Sun (1992) et. al. developed a single-degree-of-freedom structural model with a natural period of 2 seconds which was attached to circular containers that were prototype size and had diameters of 40 cm and 60 cm. The containers were partially filled with water. It is seen that tuning the liquid frequency to the natural frequency of the structure is important to achieve significant extra damping, particularly at low to moderate vibration amplitude. Prior to any potential energy dissipation by wave breaking, this improves energy absorption by the TLD.

Tamura, Modi (1992) et. al. had discovered that the use of tuned liquid dampers boosted the damping ratio of the Tokyo International Airport Tower. Additionally, they claimed that a damper holding water with a 1% mass ratio of floating particles might lower acceleration response by 55%, hence enhancing the towers' serviceability. **Tamura (1995)** discovered that utilising Tuned Liquid Damper raised the damping ratio of the 77.6-meter-high Tokyo International Airport Tower from 1.0% to 7.6%.

Koh, Mahatma (1995) et. al. conducted numerical simulations to examine the effect of combining liquid dampers set to different frequencies of a multi-degree-of-freedom structure. The results demonstrate that using dampers designed to different vibration modes of the structure is advantageous.

Fujino, Koga (1995) et. al. had developed a model of tuned liquid damper for suppressing pitching motions of structures. For validation, shaking table tests were performed, and in a narrow range of excitation amplitudes, good agreement between the analytical simulations and the practical data was seen. Additionally, it has been discovered that a TLD's ability to suppress pitching vibration depends not only on the mass of liquid it contains, but also on the liquid's composition and the location of the TLD.

Abe, Fujino (1998) et. al. improved the performance of TLD by using magnetic fluids activated by electromagnets. Even when the TLD sloshing frequency is off-tuned to the structural natural frequency, active TLD performs better than passive TLD.

Wakahara (1999) et. al. designed an ideal TLD using theoretical and experimental research, and then tested it by applying it to a real high-rise hotel, the "Shin Yokohama Prince (SYP) Hotel" in Yokohama. Their interaction model for simulating liquid movements in a TLD container was based on the BEM. The wind-induced response might be cut in half thanks to the TLD installation on the building.

Kaneko and **Ishikawa (1999)** proposed an analytical model to explain how well-tuned liquid dampers (TLD's) with submerged nets perform to prevent structures from vibrating horizontally. They used a liquid model based on nonlinear shallow water wave theory. The effect of the hydraulic resistance produced by the nets was investigated. They theoretically confirmed the experimental results of dissipation energy. They discovered that TLD's with submerged nets are more successful at minimizing structural vibration than TLD's without nets.

Banerji, Shah (2000) et. al. conducted seismic ground motion simulations using numerical models of a single-degree-of-freedom (SDOF) structure rigidly supporting a TLD. A higher depth ratio of 0.15 for a TLD, which is closer to the limit of the shallow water assumption, was proven to be more effective for large excitation amplitudes expected in significant earthquake ground motions. The effectiveness of a TLD is also found to rise with rising structural base excitation level, as energy dissipation due to sloshing increases.

Gardarsson, Reed (2001) et. al. investigated the experimental results of a tuned liquid damper with a sloped bottom at a 30° angle with the horizontal. The sloped-bottom TLD is most effective when adjusted somewhat higher than the structure's fundamental response frequency. The sloped-bottom TLD responds with a larger sloshing force than the similar box-shaped TLD with the same water mass.

Damatty (2002) investigated the way a TLD system behaves as a method of improving a structure's ability to withstand earthquakes. For instance, when a TLD system was connected to an eight-storey steel building, the vibrations caused by an actual pre-recorded earthquake were reduced by around 60%.

Li, Li Q.S (2002) et. al. provided a numerical model in which the dynamic characteristics of shallow liquid in rectangular containers exposed to forced horizontal oscillations are directly analysed from the continuity and momentum equations of fluid. They constructed the nonlinear partial differential equations that describe the wave movement of shallow liquid in rectangular containers under some reasonable assumptions, and they then proposed a numerical technique based on the finite element method for solving these equations.

Banerji (2004) had founded that the ability of a TLD to govern structural response to large amplitude base excitations is significantly influenced by the TLD-to-structure mass ratio and the depth ratio. A TLD is best suited to broad-banded ground motion at 4% mass ratio and 0.15 depth ratio.

Kim, You (2006) et. al. investigated the characteristics of the water sloshing motion in TLCD and TLD (rectangular and circular) by conducting shaking table experiments. From the experiment, they discovered the characteristics, including wave height, base shear force, and energy dissipation, among others. It was discovered that the TLCD was superior to the TLD at controlling vibration.

Han, Liu (2006) et. al. analysed the seismic response of fluid-structure interaction in the high-rise frame structure under TLD control using the ADINA software. They came to the conclusion that the larger the mass ratio, the better the damping effect when the frequency ratio is the same.

Xin, Qiao (2007) et. al. had investigated the viability of controlling the earthquake reaction of the jacket platform using TLD's. Experiments with liquid sloshing in a cylinder tank reveal that the sloshing is larger when the frequency of the external excitation is close to the fundamental frequency of the liquid.

Tait, Damatty (2007) investigated the performance of shallow water wave theory-based nonlinear numerical models for tuned liquid dampers under random stimulation for both unidirectional and bidirectional TLD's. Over a range of excitation amplitudes, the model was compared to experimental findings, and good agreement was found in every instance.

Shang & Zhao (2008) examined the effect of two angle-adjustable baffles in a rectangular TLD. By changing the baffle angles, the damper's fundamental natural periods can be varied widely, increasing its ability to control the vibration of structures across a wider frequency range. The angles of the baffles may have an impact on the amount of eddies. They discovered that the TLD tank is significantly more successful than a typical rectangular TLD tank of the same size at reducing the earthquake responses of structures.

Tait (2008) created an analogous linear mechanical model that takes the energy lost by the damping screens into account. He created formulas for equal damping ratio expressions for random and sinusoidal excitation. He went on to explain an early rapid preliminary design procedure. Initial damping screen design and TLD size for a TLD with damping screens.

Ding, Chen (2009) et. al. examined the Seismic performance of a large scale TLD Model with sloped bottoms. To investigate the seismic performance of a large scale TLD with three types of bottoms (V, W, and Arc shape), a three-story steel frame model was put to the test on a shaking table. They had discovered that the water-acrylic mixture utilised in the TLD tank is more efficient than the water-sand mixture, and the seismic performance of Arc-shape TLD is superior to V and W shape bottoms.

Xin, Chen (2009) et. al. used a shake table to conduct an experimental investigation of the seismic performance of a DVTLD with a sloping bottom. The suppression of story drift and floor acceleration of the structure had been shown to be more effective and durable with the density-variable control system than its comparable conventional tuned liquid damper.

Marivani and Hamed (2009) established a numerical model that integrates fluid and structural to simulate the response of an SDOF system with a TLD. The fluid flow model was a non-linear, two-dimensional model. His approach was successfully evaluated utilising three fluid flow issues. The fluid-structure model was also put to the test, and the findings demonstrate that it accurately captured the expected dampening impact of the TLD on the structure response.

Banerji, Samanta (2010) increased the liquid sloshing by using a modified TLD configuration. Instead of being permanently attached to the floor in this case, the TLD is raised using a stiff rod that is torsionally connected to the floor. In comparison to the traditional arrangement, where the TLD is rigidly connected to the structure, it has been discovered that this modified configuration is a more effective structural control device. Clearly, the stiffness of the rotational spring affects its performance.

Shad, Adnan (2013) analysed an SDOF system with a TLD added, both numerically and experimentally. The acceleration reactions of structure-TLD systems were measured using a shaking table and finite element analysis software. When the findings of experimental and FEM work were compared, there was a fair amount of agreement. The tuning ratio and mass ratio were discovered to have had a substantial impact on the responsiveness of the Structure-TLD system.

Bhattacharjee, Halder (2013) et. al. investigated two TLDs (one square and one rectangular) with different water depth ratios. According to the study, there is an ideal water depth for each TLD that correlates to the smallest response amplitude and provides the greatest level of vibration control. Additionally, it has been discovered that for the controlling response of the structure, the square TLD performs less well than the rectangle TLD.

Mondal, Nimmala (2014) et. al. used MATLAB to solve equations and simulate how the building would behave with and without TLD. First, an experiment was conducted, and then a building model was created using the spring mass formula. The experiment demonstrated the effectiveness of TLD. It can cut down vibration by 80%. Though successful in simulating the behaviour of the building, the theoretical model failed to accurately simulate the behaviour of water.

Roshni, Ritzy (2015) had demonstrated the efficiency of TLD in lowering seismic vibration of a two-story structure frame under horizontal excitations. Using the software ANSYS WORKBENCH, the undamped frame was studied analytically. The displacement of the structure is used to calculate the TLD's effectiveness.

Kuriakose (2016) et. al. used ANSYS WORKBENCH to model a 40-storeyed building. To determine the natural frequency of the building, eigen value analysis was used. It has been discovered that TLD can effectively control the structure's vibration. The ideal mass ratio was known. A 28.73% amplitude reduction was found.

Das, Maity, Bhattacharyya (2022) investigated the value of putting deep liquid storage tanks (DLTs) on the roofs of high-rise structures with irregular plans. For the numerical evaluation, a 20-story, 70 m tall, asymmetrical reinforced concrete building is taken into consideration. The structure fluid coupled dynamics are investigated using ANSYS Workbench's "System Coupling" feature. The ANSYS "Transient Structural" module uses FEA to solve the structure component, whereas "ANSYS (FLUENT)" uses the FVM to solve the fluid part. The combined CFD-FEA computational framework results in a response reduction of about 79% for TLD.

2.2 OBJECTIVE AND SCOPE OF WORK

The goal of this thesis paper is to examine the efficiency of a Tuned Liquid Damper in reducing the structural response of a 10-storeyed computational building that has been subjected to seismic excitation. The study intends to assess the effects of various TLD configurations, such as a flat bottom TLD and alternative TLD designs, as well as the effects of other liquid kind inside the TLD tank. With El Centro earthquake data as the seismic input, the main objective is to compare the building deformation and acceleration responses with and without taking the existence of the TLD into account.

The scope of work for this thesis includes the following:

- By using ANSYS software, create a 3D computational model of a 10-story structure. For the building model, consider acceptable structural features, material attributes, and realistic boundary conditions.
- Using the 'El Centro' earthquake data as input, simulate the seismic response of the computational building model. Without taking the presence of the TLD into account, evaluate the building's deformation, acceleration, and other relevant response statistics.
- Incorporating the flat bottom TLD into the computational building model using ANSYS software. Evaluate the effect of the TLD on the building's deformation, acceleration, and other reaction characteristics. Compare the results to the analysis performed without the TLD to establish the TLD's efficiency in decreasing structural vibrations.
- Creating various TLD configurations and compare their performance to the flat bottom TLD by analysing the building's response to seismic stimulation. Assess their efficiency in decreasing structural vibrations and see whether any improvements are made over the flat bottom TLD.
- Within the computational simulations, use different liquid, such silicon oil, in the TLD tank. Evaluate and compare the reaction of the building to seismic stimulation for other liquid kind in the TLD.
- Interpret the findings to establish the TLD's efficiency in minimising structural vibrations and to compare the various TLD configurations and liquid kind.

CHAPTER 3

MATHEMATICAL FORMULATIONS

The theoretical framework for analysing the behaviour of the building and the tuned liquid damper is provided by the mathematical formulation. Understanding how the two components interact and operate depends on the laws of motion guiding their dynamics.

3.1 STRUCTURAL DYNAMICS MODEL

The structure-fluid combined system's equation of motion for the ground acceleration time history, denoted by 'a_g' provided in Eq. (1)

$$m_s\ddot{v}_s + c_s\dot{v}_s + k_s v_s = -m_s a_g + F\text{…………...(1)}$$

where m_s, k_s and c_s stand for the structure's mass, stiffness, and damping respectively. Additionally, v_s stands for the structure's displacement with respect to the ground, and F represents the shear force generated by water sloshing at the base of the TLD. Equation (2) is represented as when it is normalized in relation to the structural mass

$$\ddot{v}_s + 2\boldsymbol{\xi}_s\boldsymbol{\omega}_s\dot{v}_s + \omega_S^2 v_s = -a_g + \frac{F}{m_s}\text{…………….(2)}$$

Where 'ω_s =2πf$_s$' and ξ are the structure's natural circular frequency and damping ratio, respectively and f_s denotes natural frequency.

3.2 TLD FORMULATIONS

The rigid rectangular TLD tank, which is seen in Fig. 3.1. has a depth of undisturbed water of *h* as well as dimensions of *2a* in length and *b* in breadth. It experiences the same excitation, x_s , as the top of the structure on the lateral base. Given that the water depth is assumed to be shallow, the equations for the motion of the water inside the tank can be stated in terms of free surface motion. The impacts of wave breaking should be accounted for in the equations of motion since intense earthquake ground motion typically produces critical amplitude TLD excitation. **Sun et al.** had suggested a formula to describe and create TLDs.

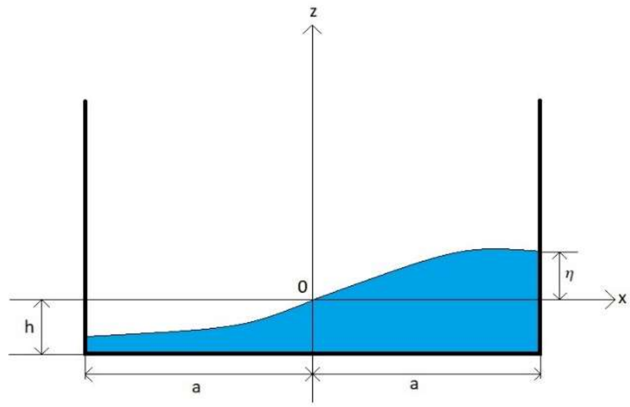


Figure 3.1 Schematic sketch of TLD for Horizontal motion

The following formulas are identified:

$$\frac{\partial \eta}{\partial t} + h\sigma \frac{\partial(\phi u)}{\partial x} = 0 \ldots\ldots\ldots\ldots\ldots\ldots..(4)$$

$$\frac{\partial u}{\partial t} + (1\text{-}T_H^2)\, u\frac{\partial u}{\partial x} + C_{fr}^2 g \frac{\partial \eta}{\partial x} + gh\sigma\phi \frac{\partial^2 \eta}{\partial x^2} \frac{\partial \eta}{\partial x} = -C_{da}\lambda u\text{-}\ddot{x}_s \ldots\ldots\ldots\ldots\ldots\ldots(5)$$

where $\eta(x,t)$ and $u(x, \eta, t)$ are independent variables, corresponding to the height of the free surface of undistributed water and the particle velocity of the free surface, respectively. Base shear force acceleration and TLD's base acceleration are equivalent ($\ddot{x}_s$) while base g is the acceleration of gravity.

Equations (4) and can be used to compute σ, ϕ and T_H as follows:

$$\sigma = \frac{\tanh(kh)}{kh} \ldots\ldots\ldots\ldots\ldots\ldots..\ldots.(6)$$

$$\phi = \frac{\tanh(kh+\eta)}{tanh(kh)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(7)$$

$$T_H = \tanh(kh + \eta) \ldots\ldots\ldots\ldots(8)$$

Where 'k' denotes the number of waves and 'λ' denotes the damping factor based on the boundary layer through the tank's bottom, side walls, and water-free surface contaminants. 'λ' can be written as:

$$\lambda = \frac{1}{(h+\eta)}\frac{1}{\sqrt{2}}\sqrt{\omega_1 \upsilon}\left[1 + \frac{2h}{b} + s\right] \text{.............}(9)$$

where 'ω_1' represents the fundamental linear sloshing frequency of the water in the tank, 'υ' stands for the kinematic viscosity of water, and 's' stands for a surface contamination factor that can be interpreted as unity. Using the equation provided by **Housner** and detailed in eq. (10), the fundamental sloshing frequency of TLD is calculated as

$$f_n = \frac{1}{2}\sqrt{\frac{3.16g}{L}tanh\left(\frac{3.16h}{L}\right)} \text{.................}(10)$$

Where, h is the undisturbed water depth, L is the length of tank and g is acceleration due to gravity. When waves are unstable and break, the coefficients C_{fr} and C_{da} in equation (5) are taken into account to adjust the water wave phase velocity and damping, respectively. When waves don't break, these coefficients have a unit value. In contrast, it is discovered that C_{fr} has a constant value of 1.05 when waves break, whereas C_{da} has a value that depends on the amplitude, $(x_s)_{max}$, of motion of the structure's top when a TLD is not attached to it. This value for C_{da} is supplied as

$$C_{da} = 0.57\sqrt{\frac{h^2\omega^1}{a\,\upsilon}(x_s)_{max}} \text{....................}(11)$$

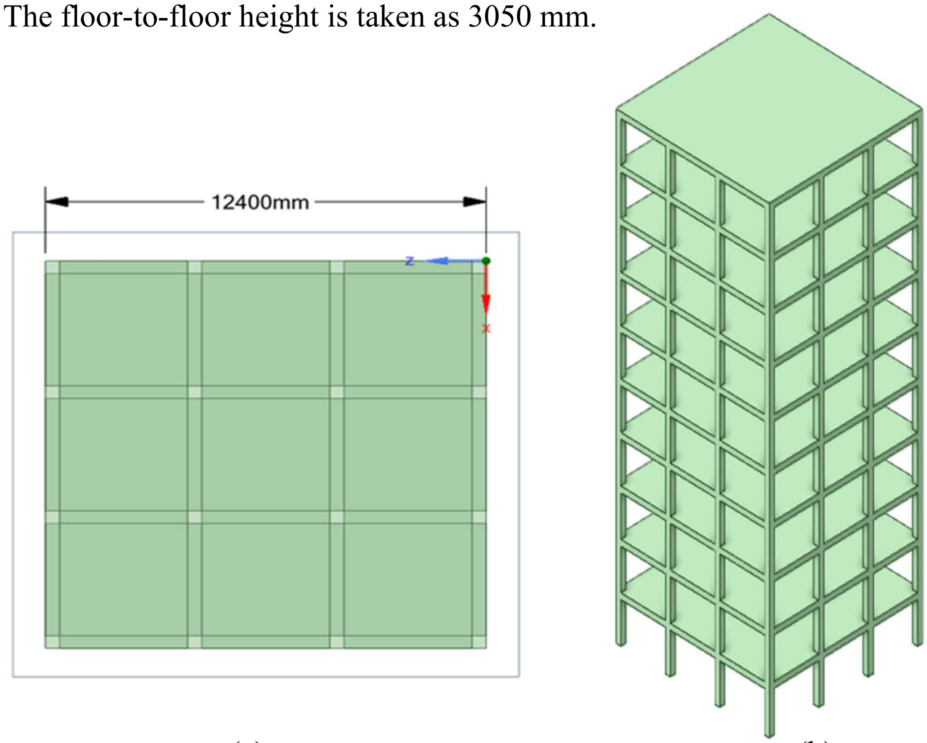
CHAPTER 4

METHODOLOGY

The key objective of this study is to determine whether a tuned liquid damper can effectively reduce structural vibrations in a 10-storeyed computational building model. The challenge comes from the requirement to strengthen the structure's resistance to dynamic stresses, such as seismic activity and wind-induced vibrations, which may threaten the structural integrity and comfort of the occupants. The significance of establishing efficient vibration control techniques grows as tall constructions become more prevalent.

4.1 ANSYS BUILDING MODEL CREATION

Here in this study the computational square shape building model is drawn in Ansys Space Claim. The total height of the superstructure is 35 m having columns of (400 x 400) mm^2 and beams of (400 x 450) mm^2. The thickness of slabs is 200 mm with 153760000 mm² surface area. The floor-to-floor height is taken as 3050 mm.



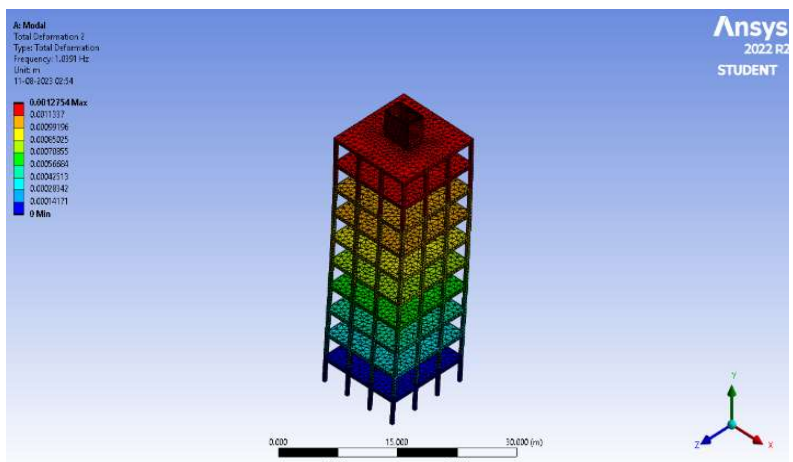
(a) (b)

Figure 4.1 – (a) Structure plan, (b) 3d Ansys model of the building

Here concrete is taken as default solid material as available in Engineering Data option. Material data considered for this concrete are; density – 2804.17 kg/m^3, young's modulus – 38729 MPa, Poisson's ratio – 0.15. Designing a 10-story building without any reinforcement, relying solely on high-strength concrete, especially when considering the use of TLDs, involves a careful balance of engineering considerations. The choice of high-strength concrete with a Young's modulus of 38729 MPa is instrumental. High-strength concrete possesses enhanced load-bearing capacity and better resistance to compression forces. This property makes it suitable for taller structures as it can withstand the vertical loads exerted by the building's own weight. On the other hand, the absence of reinforcement in the model could be attributed to the need for a simplified structural model for the research. The aim is to isolate and analyse the influence of TLDs specifically, without the added complexity introduced by reinforcing materials such as steel bars. A simplified model allows for a more focused study of the TLDs' impact on the building's vibration control. Material damping is taken as 5 % as per Indian Standard. Modal analysis is done by using Ansys Modal and first six natural frequencies are calculated.

Table 1.- Modal Frequencies

Mode	Frequency (Hz)
1	1.0351
2	1.0401
3	1.285
4	3.1554
5	3.1681
6	3.8765



(a)

Figure 4.2.- (a) First mode shape of the building

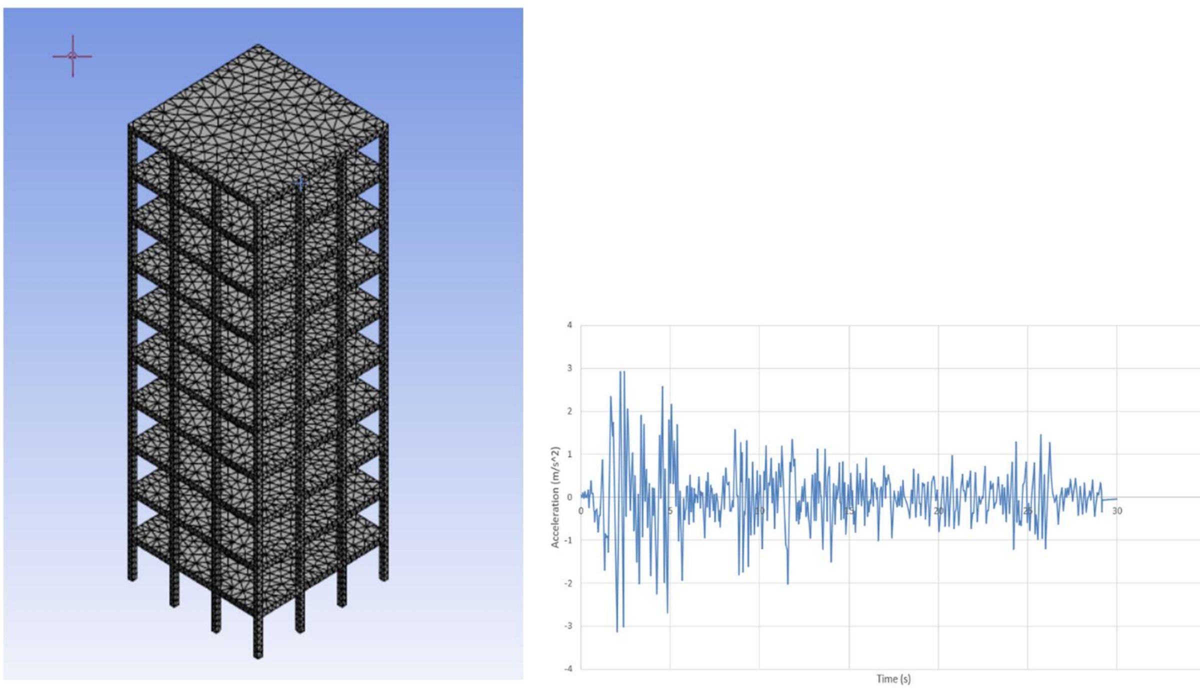
For finding the damping coefficients the following formulas are used;

Stiffness coefficient, $\delta = \frac{2\xi}{\omega_1+\omega_2}$……………(12)

Mass coefficient, $\eta = \omega_1 * \omega_2 * \delta$……………...(13)

Where $\boldsymbol{\xi} = 0.05$, $\omega_1 = 6.49$ rad/s and $\omega_2 = 19.78$ rad/s. Values of δ and η are used as direct input under Analysis settings tab.

Meshing and Load application is done in Transient structural. Element size of 0.5 m is taken and the mesh is created. This chosen mesh size is capturing the important features of the simulation accurately. This mesh consists of elements with good quality, meaning they are not distorted or highly skewed. In case of load application, standard earth gravity ($g = 9.81$ m/s^2) and El Centro earthquake data of 30 seconds with 0.02 seconds time step is applied in x direction. Fixed support is assigned to the bottom face of 16 columns.



(a) (b)

Figure 4.3.- (a) Meshing of the building, (b) Acceleration time history of El-centro Eq., NS component

4.2 TUNED LIQUID DAMPER MODELLING

The rectangular tanks working as TLD have same material properties as the building model. The tanks are fixed on the top of the structure. Equation (10) is used to calculate the length of the tank and the height of the water as the liquid slosh is tuned with the building's first natural frequency. Different TLD models are integrated into the building, and their efficiency in reducing structure vibration is evaluated. In this study, three different kinds of rectangle bottom TLD's and one kind of unique square bottom TLD are taken into account.

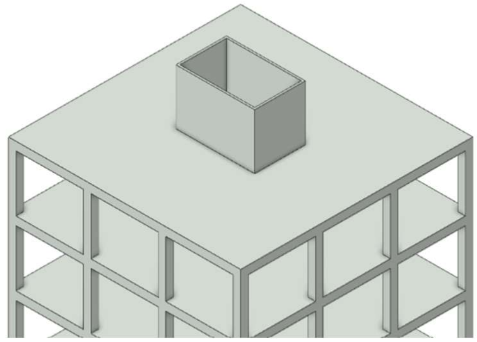
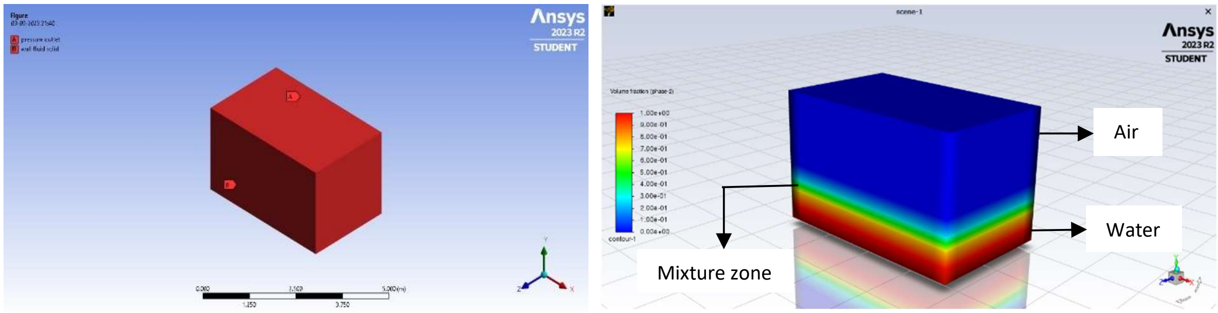


Figure 4.4.- TLD position on the building

The TLD model is created in Ansys Fluid Flow (Fluent) , with the following options configured.

- The model is meshed as shown in Figure 4.5 and the container parts are named (pressure outlet, wall fluid).
- The scale is set to the appropriate unit, and the mesh quality is tested.
- The pressure-based solver is employed, the velocity formulation is absolute, time is transient, and gravity is enabled in the vertical direction.
- The explicit formulation and the multiphase model with VOF model are employed. The viscous model is k-ε
- The materials used are air and water, which are both immiscible fluids. The phases are configured as follows: air as the primary phase and water as the secondary phase. The cell zone state is set to fluid.
- The water region is created by using cell register option. Initially, the water is static, and the container boundaries are marked by non-slip walls. The dynamic mesh is turned on.
- The water is placed in the registered region's container and then patched with water.

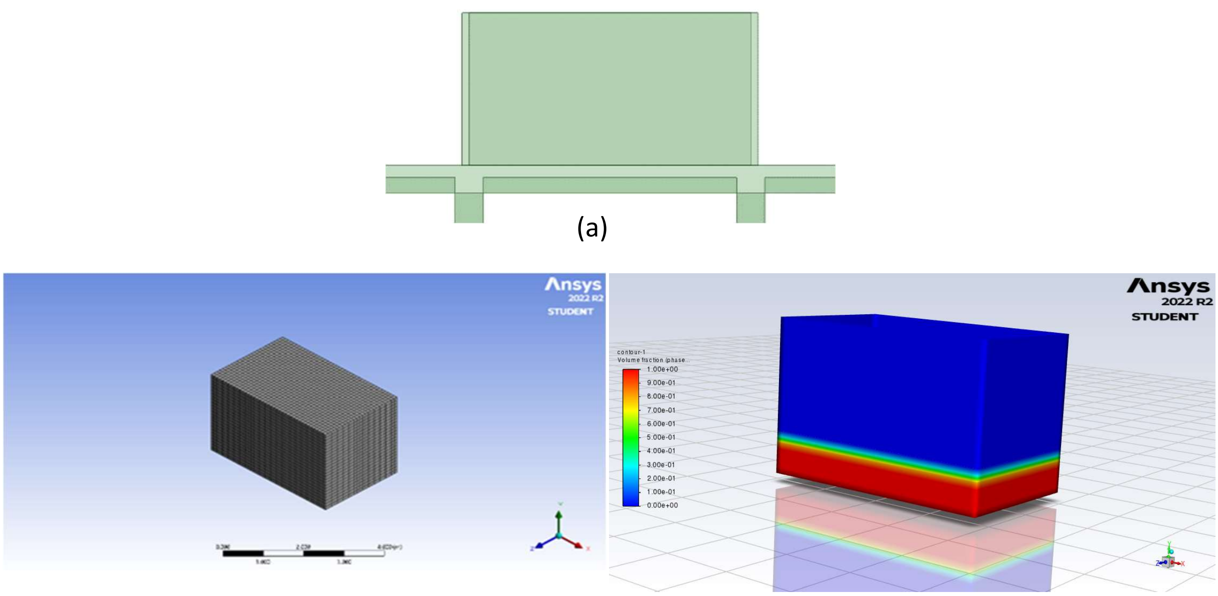


(a) (b)

Figure 4.5. – (a) Fluid part named selection, (b) Tank filled with air and water

4.2.1 RECTANGULAR TLD

Rectangular TLD have a width of 2.5 m and a length of 4 m in the loading direction(x). Rectangular TLD have a width of 2.5 m and a length of 4 m in the loading direction. The walls of the rectangular TLD's are 100 mm thick and have a 3 m height. Ansys Fluent is used to mesh and configure the fluid component inside the tank. In this case, water is treated as a liquid. The **Housner Equation** is used to calculate the height of water.

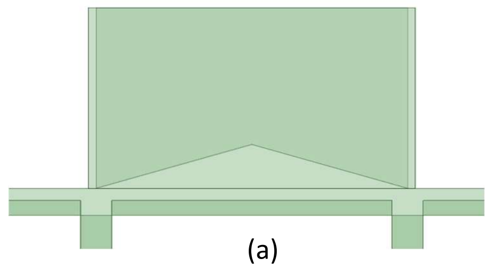


(b) (c)

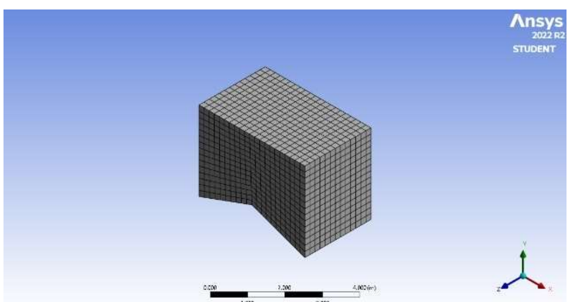
Figure 4.6. – Rec. TLD (a) side view of tank, (b) meshing of the fluid part (air and water), (c) water contour

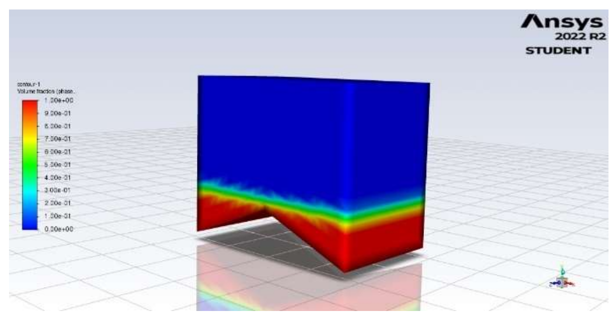
4.2.2 SLOPED BOTTOM TLD

The 20-degree sloped bottom TLD is the next area of focus. This specific configuration carries within its subtle inclination a promise of transformative capabilities in the realm of vibration control. TLD size and material characteristics are the same as flat bottom TLD. The tank's bottom is sloping in this instance.



(a)





(b) (c)

Figure 4.7.- Sloped bottom TLD (a) side view of sloped tank, (b) meshing of the fluid part (air and water), (c) water contour

4.2.3 ARC BOTTOM TLD

This section explores the realm of TLD with an arc bottom shape. It is intriguing to note that we examine the Circular Arc and the Parabolic Arc, two different arc shapes. The circular arc bottom has radius of 484 mm and arc angle of 90 degrees. On the other hand, parabolic arc TLD have an angle of 60 degrees with 755.174 mm radius.

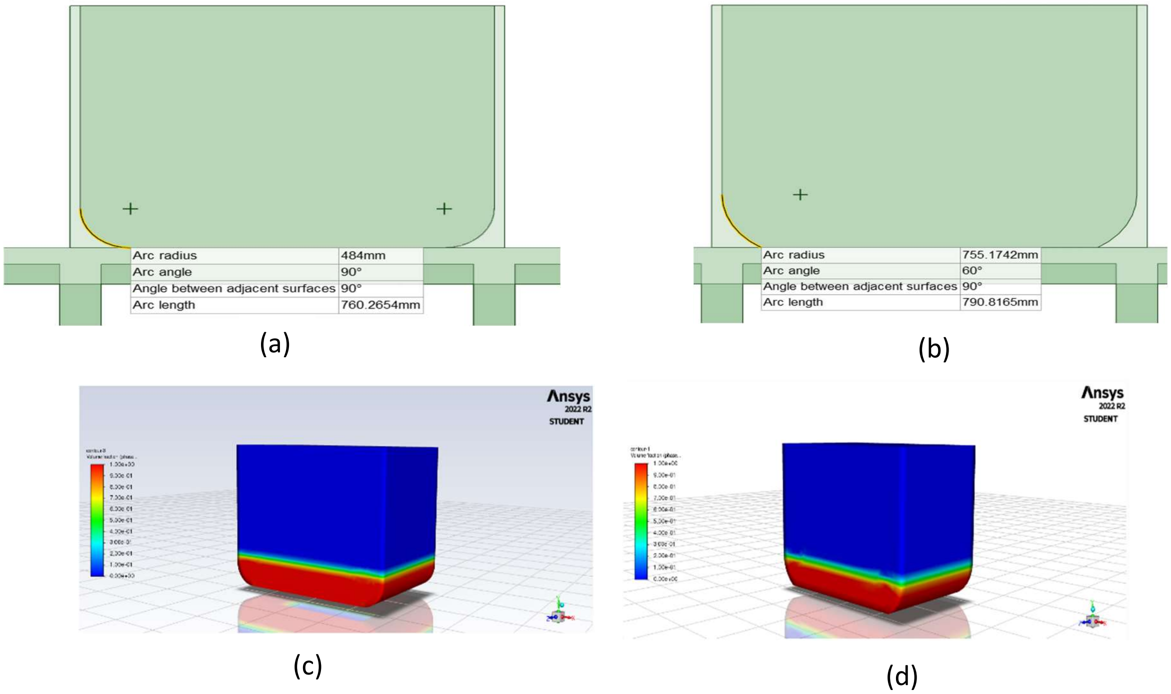


Figure 4.8.- (a) & (b): Arc bottom shapes TLD, (c) & (d): Water contours of respective TLDs

4.2.4 A SPECIAL TYPE OF TLD

The search for ideal solutions in the field of structural engineering goes beyond just theoretical considerations. A practical strategy necessitates the development of adaptable structures that go beyond the limitations of particular orientations because seismic events can occur from any angle. The Multi-Directional Inclined-Wall Square TLD, a ground-breaking solution to the dynamic problems caused by earthquakes, emerges in this setting. Structures that are built using conventional TLD designs, which are only suitable for one seismic direction, may unintentionally become vulnerable to unforeseen ground motions. Our work has delved into the realm of a square-shaped TLD, which is intended to give adaptation and durability across diverse seismic scenarios, in recognition of this intrinsic constraint.

This innovative TLD configuration not only meets the dynamic needs of earthquakes coming from any angle, but it also makes use of sloped walls to increase its dampening capability. This combined strategy takes use of the increased liquid-wall interaction, which boosts energy dissipation and, as a result, the ability to reduce structural vibrations.

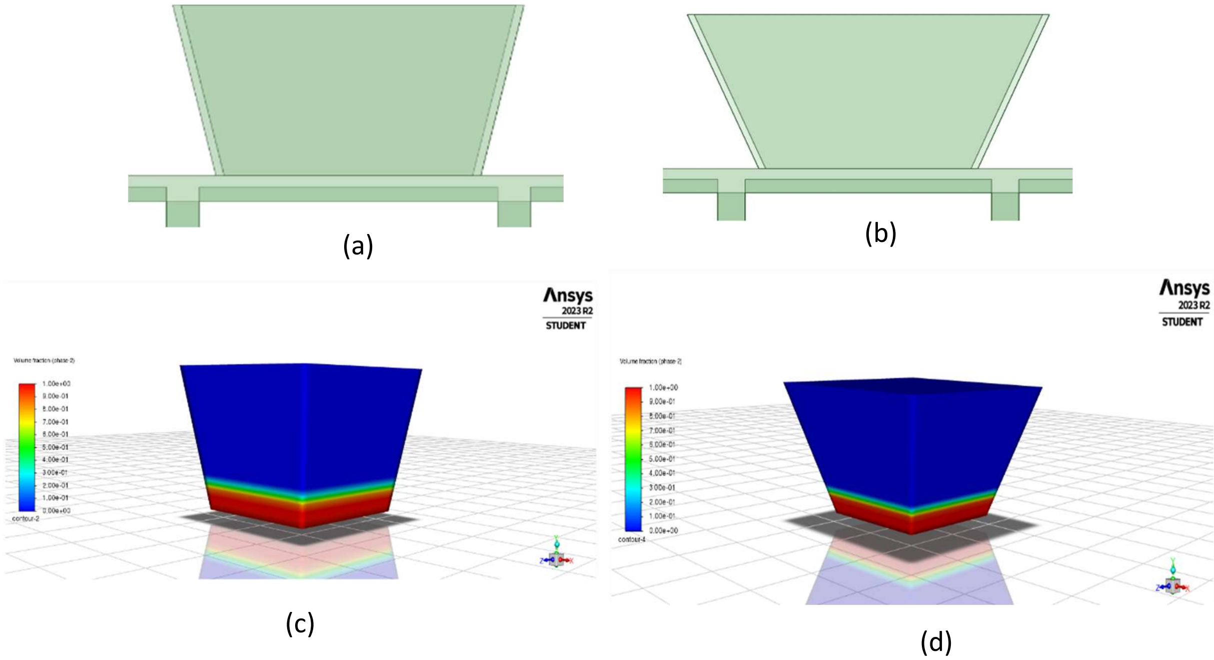


Figure 4.9.- (a) & (c) 10-degree Inclined TLD and its water contour, (b) & (d) 20- degree Inclined TLD and its water contour

Table 2.- Details of tanks

Tank type	Considered Length of tank	Water height
Flat base TLD	4 m	0.56 m
Sloped bottom (20^0) TLD	4.25 m	0.63 m
Arc bottom TLD	Parabolic Arc bottom: 4.8 m	0.8 m
	Circular Arc bottom: 4.6 m	0.76 m
Square TLD	10° Inclined TLD: 3 m	0.3 m
	20° Inclined TLD: 3 m	0.3 m

4.3 SYSTEM COUPLING PROCEDURE

In Ansys the process of integrating and simulating the interactions between various physical systems inside a single analysis framework is referred to as 'System Coupling', also known as multi-physics coupling or co-simulation. In the context of this study on the TLD, system coupling involves combining the building model and the TLD model to simulate their dynamic interaction and assess the TLD's effectiveness in controlling structural vibrations.

System coupling involves integrating the TLD model from Ansys Fluent with the building model from Transient Structural to simulate their interactions. Each system functions independently while exchanging information through a predefined coupling interface using a co-simulation technique. Dynamic loads create forces on the TLD as the structure is subjected to them, generating fluid motion within it. On the other hand, through the coupling interface, the fluid movement in the TLD influences the response of the building. The dynamic effect of the TLD on the building's vibration control is captured in this two-way exchange. Iterative modifications are necessary for this coupling process to reach convergence and dependability. The coupling interface, which enables the interchange of displacement, force, and fluid dynamics information at certain time intervals, facilitates the connection between Transient Structural and Fluent. This unique method offers a thorough understanding of how the TLD reduces vibrations and improves structural stability, mirroring the actual dynamics of this coupled system.

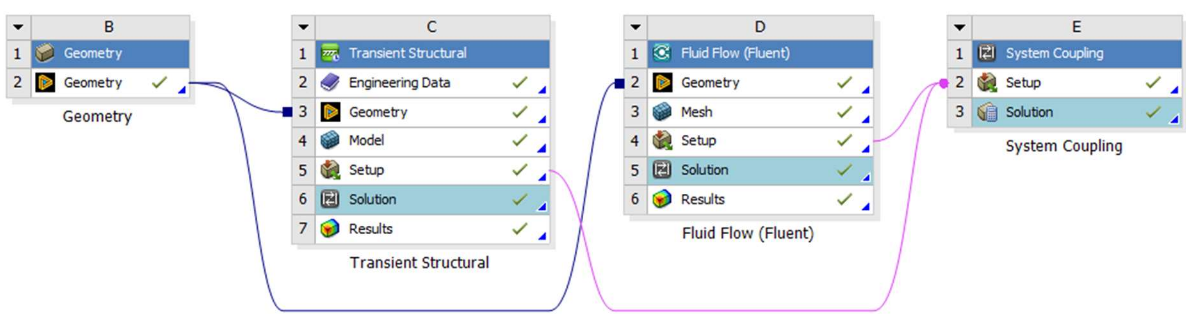


Figure 4.10.- Flow chart of system coupling procedure in Ansys Workbench

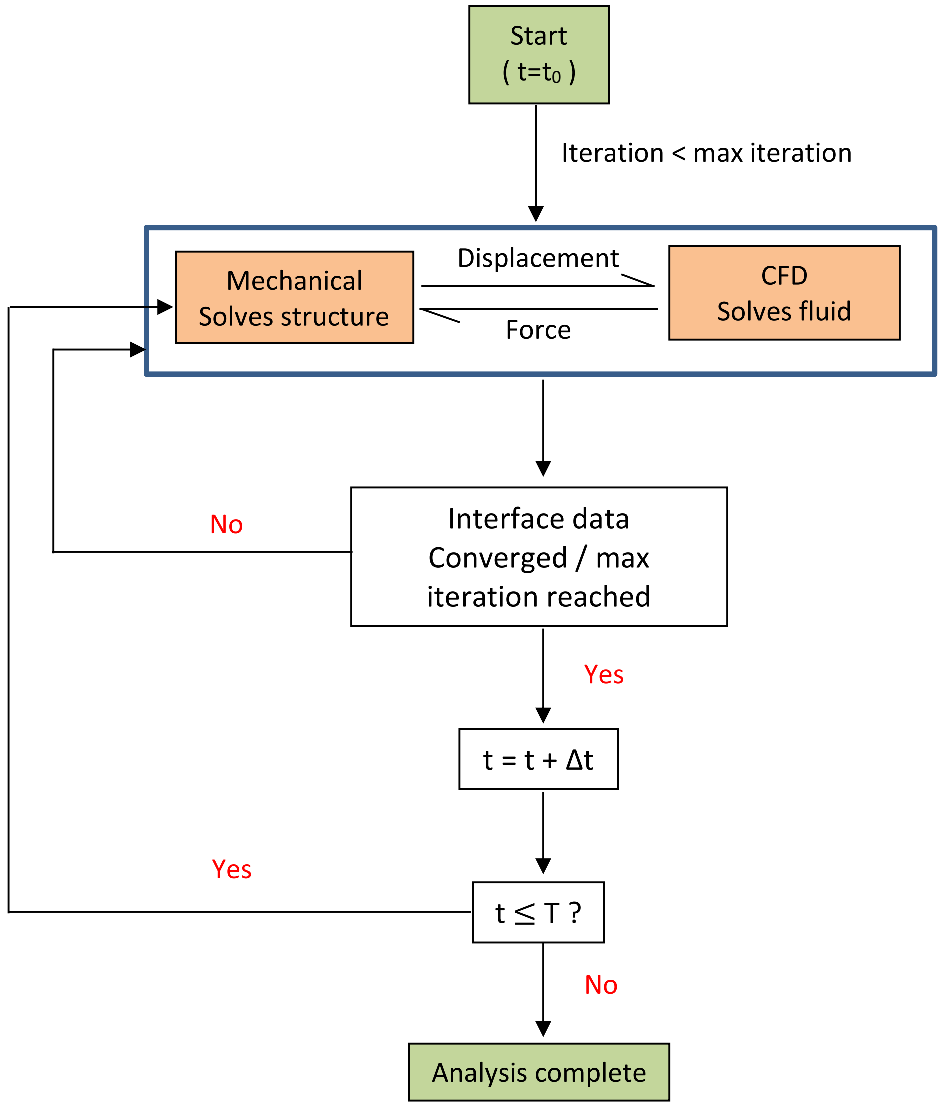


Figure 4.11.- Flow chart for two-way fluid–structure coupling procedure. [32]

CHAPTER 5

RESULTS AND DISCUSSIONS

This section discusses the findings of the application of TLDs to the field of structural vibration control. The dynamic behaviour of various TLD configurations and their significant influence on the decrease of acceleration and top-floor deformation are shown through rigorous analysis and modelling. Here, the structure's response is studied both with and without taking the effect of liquid into account.

5.1 VALIDATION OF PROPOSED METHOD

This section aims to validate the effectiveness of a modelled tuned liquid damper by comparing its response to an experimental analysis conducted by **Ersin Aydin et al.** In their research, Aydin et al. investigated the performance of a TLD integrated into a three-story steel frame structure. The TLD was subjected to controlled shake table experiments, simulating real-world dynamic conditions, with a focus on a fundamental natural frequency that matches that of the building model. Specifically, a 3 mm amplitude and 1.5 Hz frequency were selected to mimic the building's fundamental natural frequency. Additionally, 12 seconds harmonic load was applied to both the three-story model with the TLD and the one without, allowing a direct comparison of their deformation responses. By aligning our modelled results with the findings presented by Aydin et al., this validation process seeks to reinforce the reliability and accuracy of the developed tuned liquid damper model.

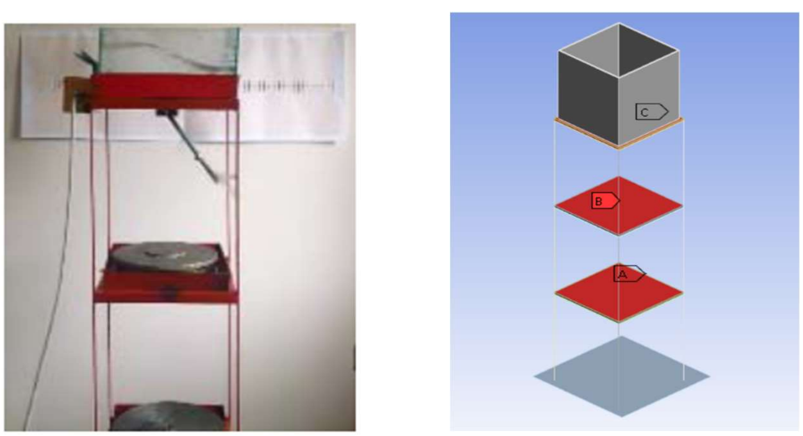


Figure 5.1. - (a) Actual model of the structure (b) FEM model of the structure

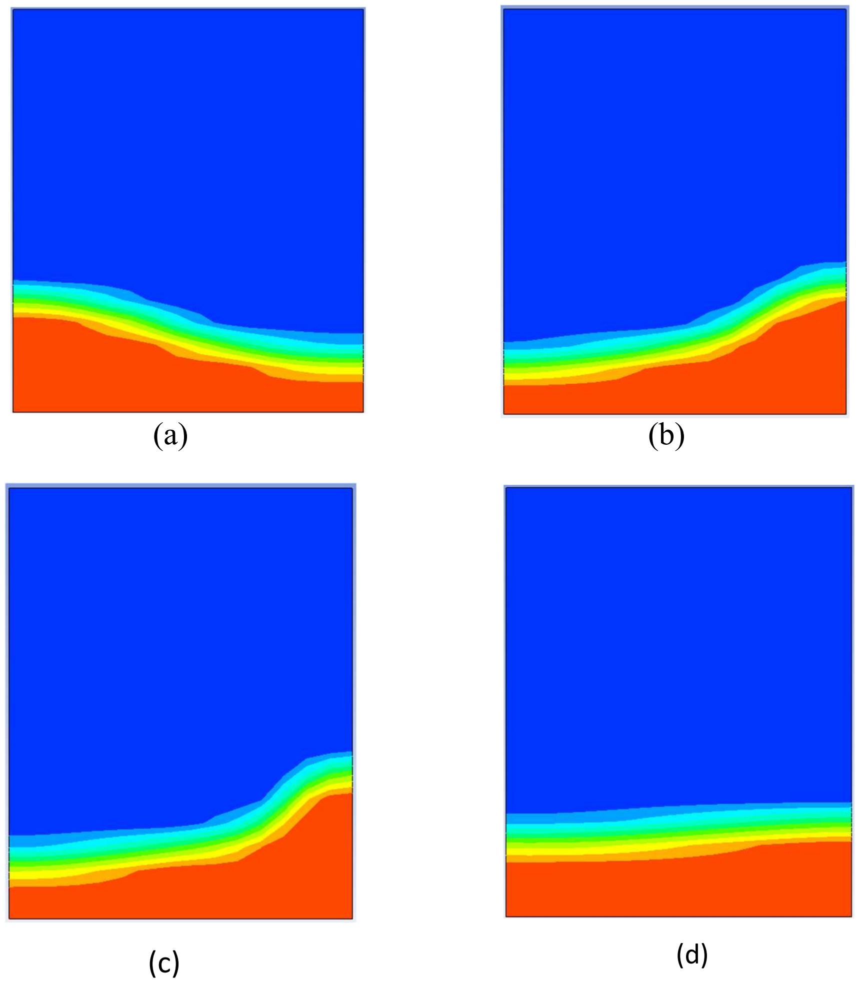


Figure 5.2. - water contours at (a) 1.245 seconds, (b) 1.52 seconds, (c) 2.82 seconds, (d) 11 seconds

Table 3.- Comparison between Experimental and Analytical values

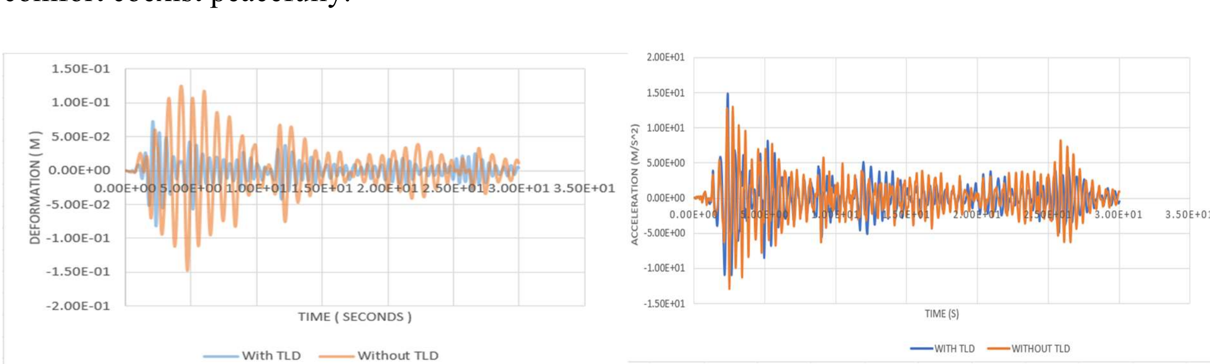
Structure model	First mode natural frequency
Actual model (experimental)	1.5 Hz
Ansys FEM model (analytical)	1.48 Hz

Structure model	First floor peak displacement	Second floor peak displacement
Actual model	0.66 cm	0.5 cm
Ansys FEM model	0.68258 cm	0.44554 cm

5.2 RESULTS

5.2.1 FLAT BOTTOM TLD

This section examines how the water in the flat base TLD gives the system a unique layer of dampening capacity. This initial investigation aims to determine whether this ostensibly little change could actually cause a noticeable decrease in top floor deformation and acceleration. The baseline scenario, which involves a 10-story building coping with dynamic stresses without the assistance of TLD and experiencing a peak deformation of 122 mm, is at the core of our investigation. The Flat Bottom Conventional TLD enter the picture in this situation and have the potential to reshape the trajectory of structural performance. The peak deformation, once a formidable 122 mm, now stands at 84 mm—an impactful reduction, shedding light on the proven capabilities of Flat Bottom Conventional TLDs. In order to delve further into the topic of occupant safety, we look at how TLD affect top-floor acceleration. Even though they are straightforward, the Flat Bottom Conventional TLD demonstrate its skill in this situation by successfully lowering acceleration and fostering an atmosphere where structure and occupant comfort coexist peacefully.



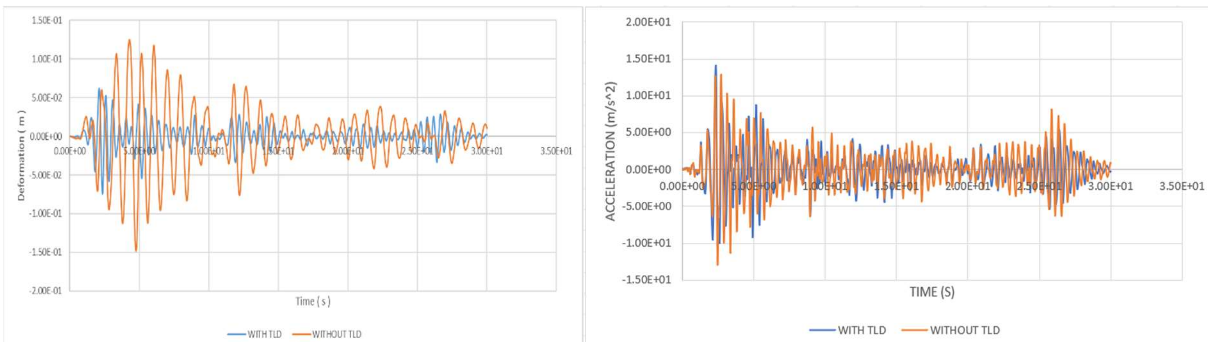
(a) (b)

Figure 5.3. (a) Top floor deformation with and without TLD, (b) Top floor acceleration with and without TLD

5.2.2 SLOPED BOTTOM TLD

Here, we compare the building answer with and without TLD. Additionally, it can successfully lessen the acceleration and deformation response of the building. Here, sloping bottoms of 20 degree is taken into account. The efficiency of this TLD is represented by the following figures. Peak deformations, once dominant at 122 mm without TLD, now bow to the influence of Sloped

Bottom TLD, reaching 62 mm. While this reduction may not be as dramatic as some of the more intricate TLD designs, it underscores the unique impact of Sloped Bottom TLD on structural deformations. The Sloped Bottom TLD demonstrate their architectural prowess in this situation by successfully moderating acceleration and fostering a setting where structural resilience and occupant comfort coexist peacefully.

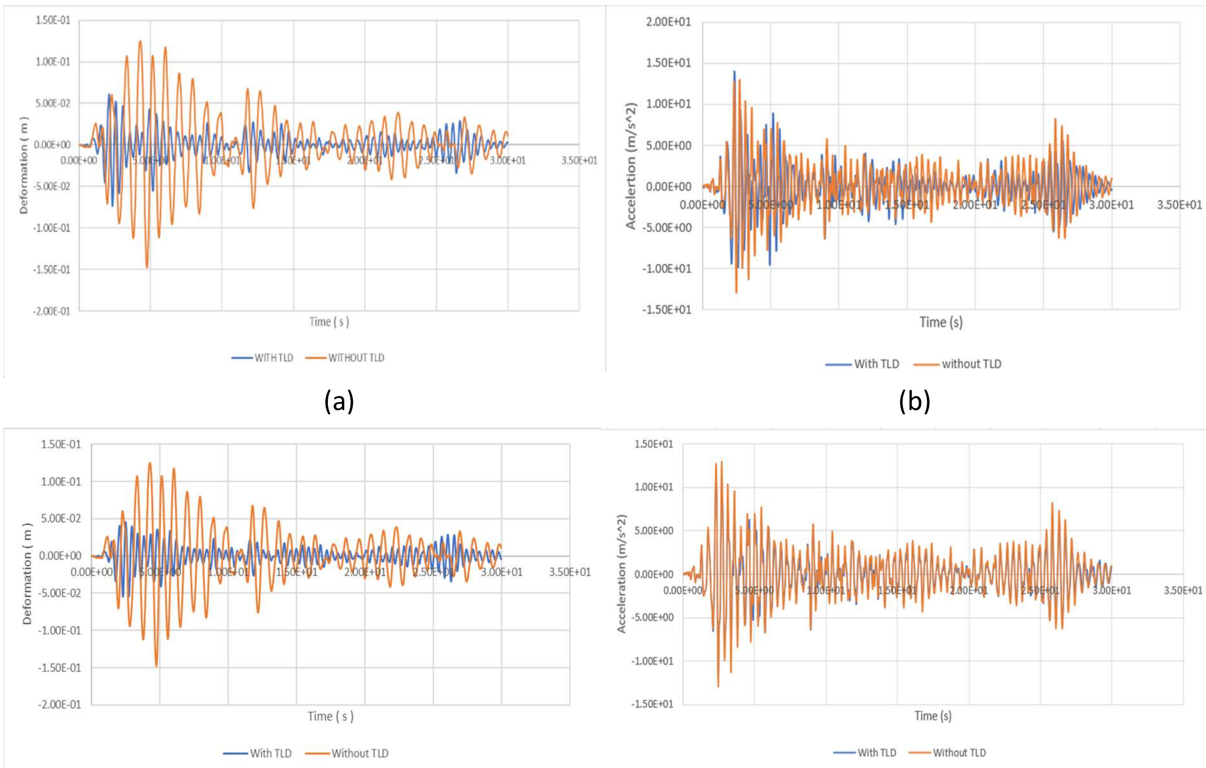


(a) (b)

Figure 5.4.- (a) Top floor deformation with and without TLD, (b) Top floor acceleration with and without TLD

5.2.3 ARC BOTTOM TLD

The best vibration control is provided by arc bottom TLD when compared to flat, sloped, TLD. It effectively lessens the structure's distortion. Within the structural narrative of resilience and innovation, this section casts a spotlight on the performance outcomes achieved through the implementation of Arc Bottom TLDs. Our central quest centres on the evaluation of Arc Bottom TLDs, including Circular Arc and Parabolic Arc configurations, and their profound impact on structural deformations and accelerations within a 10-story building. With the introduction of Circular Arc TLDs, the peak deformation dramatically diminishes to 52 mm. Similarly, the Parabolic Arc TLDs yield transformative results, reducing the peak deformation to a mere 46 mm.



(a) (b)

(c) (d)

Figure 5.5.- (a) & (b) Top floor deformation and acceleration of circular arc bottom TLD, (c) & (d) Top floor deformation and acceleration of parabolic arc bottom TLD

5.2.4 SQUARE SHAPE TLD

This section delves into the transformative outcomes yielded by Square Shape TLDs. The central inquiry centres on the performance of these Square Shape TLDs in reducing structural deformations and curbing accelerations at the top floor of the 10-story building. Its peak deformation reaching an initial high of 122 mm in the absence of TLD. With the introduction of 10-degree Square Shape TLDs, the peak deformation plunges to 51 mm. A parallel journey with 20-degree Square Shape TLDs reveals a comparable transformation, with the peak deformation reduced to 56 mm. TLDs influence on top-floor acceleration is profound, effectively reducing it and ensuring a harmonious relationship between structure and occupant well-being.

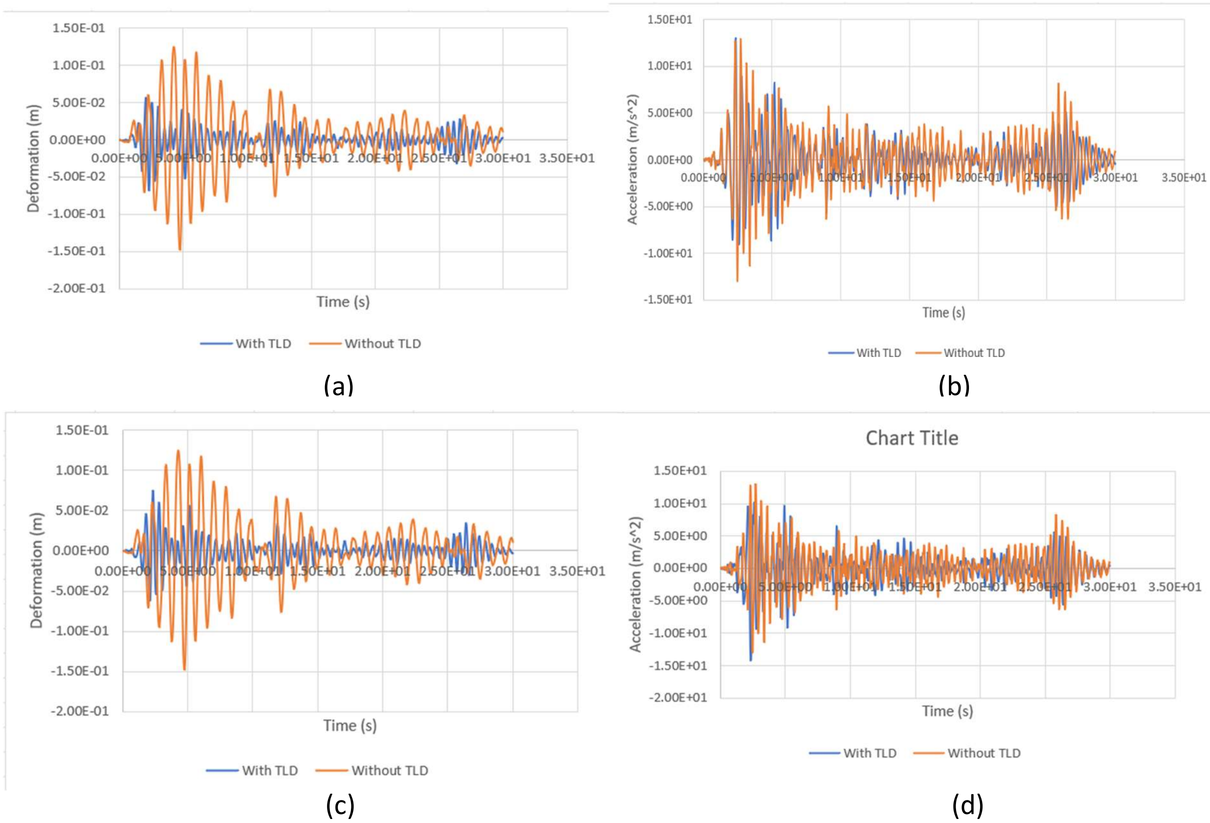


Figure 5.6.- (a) & (b) Top floor deformation and acceleration of 10-degree TLD, (c) & (d) Top floor deformation and acceleration of 20-degree TLD

This section focuses on a particularly intriguing area: a comparison of **Silicon Oil**- and water-based TLDs that reveals the subtle dynamics of liquid selection in TLD performance. The viscosity is taken as 1 kg/m-s and density is taken as 1050 kg/m^3. The effect of liquid type on TLD efficiency is the primary question driving our investigation. The sturdy water-based TLD, a well-known competitor with a peak deformation of 51 mm, is in one corner. It has proven its ability to minimise structural deformations. We introduce the silicon oil-based counterpart in the opposite corner that, intriguingly, shows a peak deformation decreased to 58 mm. The results that are about to provide paint a picture of how the liquid that is selected for a TLD can have a modest but real impact on structural response. As we proceed through this comparative investigation, we hope to identify the variables that contributed to the somewhat lower performance of the silicon oil-based TLD and, in doing so, discover new areas for future research.

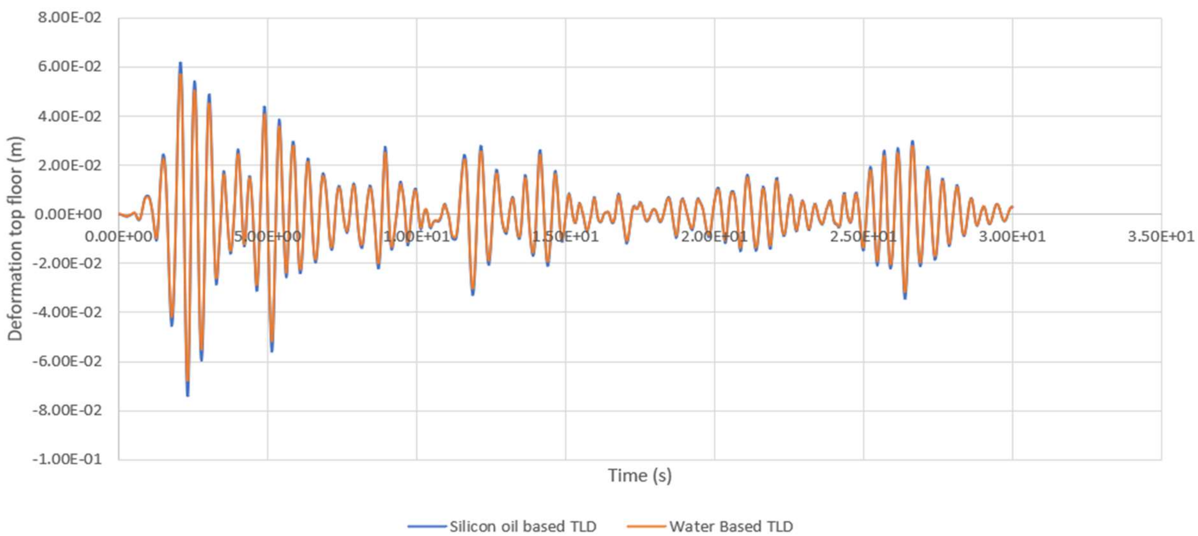


Figure 5.7.- Comparison of response between Silicon based and Water based TLD

5.2.5 COMPARATIVE ANALYSIS OF DIFFERENT TLDs

This section serves as a crucial intersection in the complex world of structural engineering, where the need for innovation collides with the requirements for resilience. It is a place where some TLD designs come together under close examination. Our goal is to compare the performance of various TLD variants in order to show the best way to create built environments that are more reliable and secure. The diverse cast of TLDs, each bearing its unique geometry and design, has graced our journey thus far. We have explored the transformative potential of Square Shape TLDs, the efficiency of Arc Bottom TLDs, and delved into the dynamics of Sloped Bottom and Flat Bottom TLD.

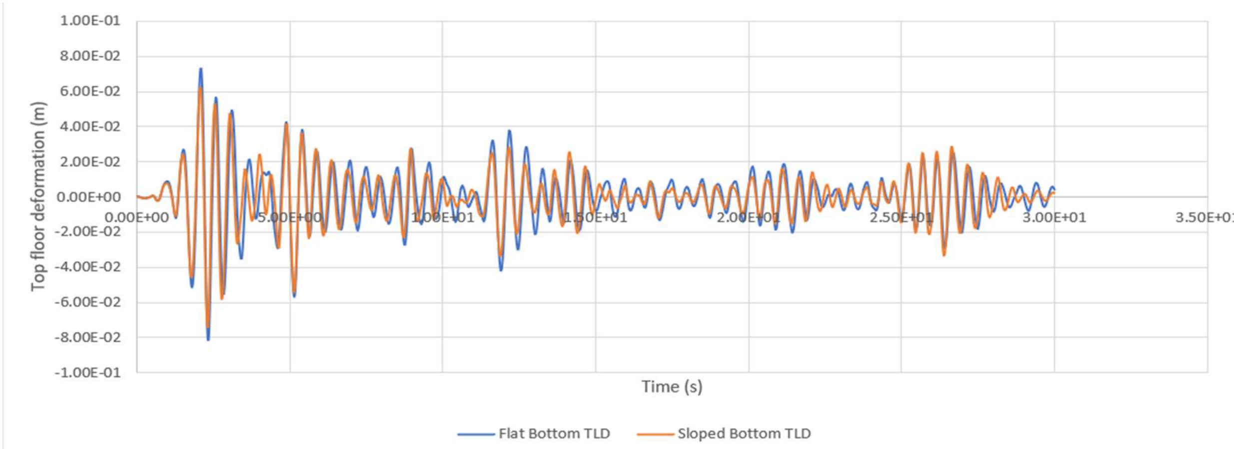


Figure 5.8.- Comparison between Flat bottom and Sloped bottom TLD

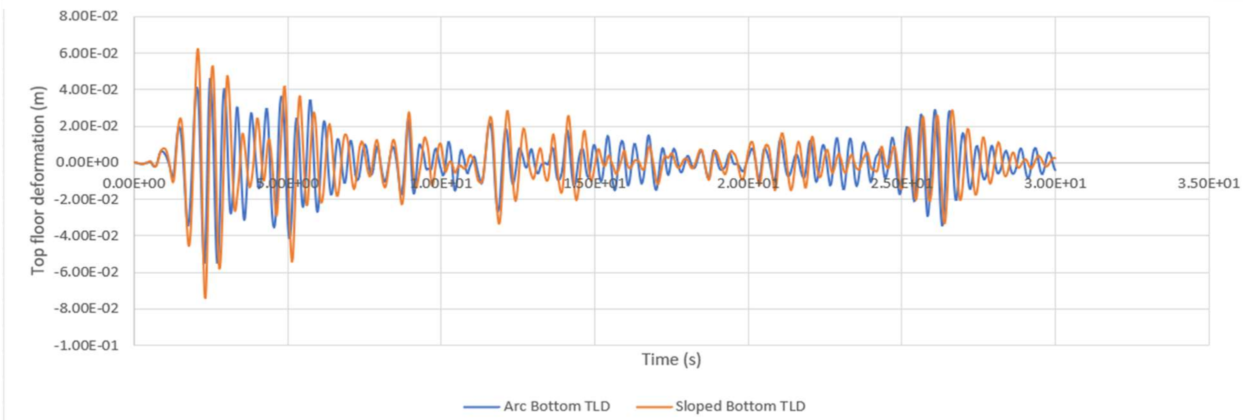


Figure 5.9.- Comparison between Arc bottom and Sloped bottom TLD

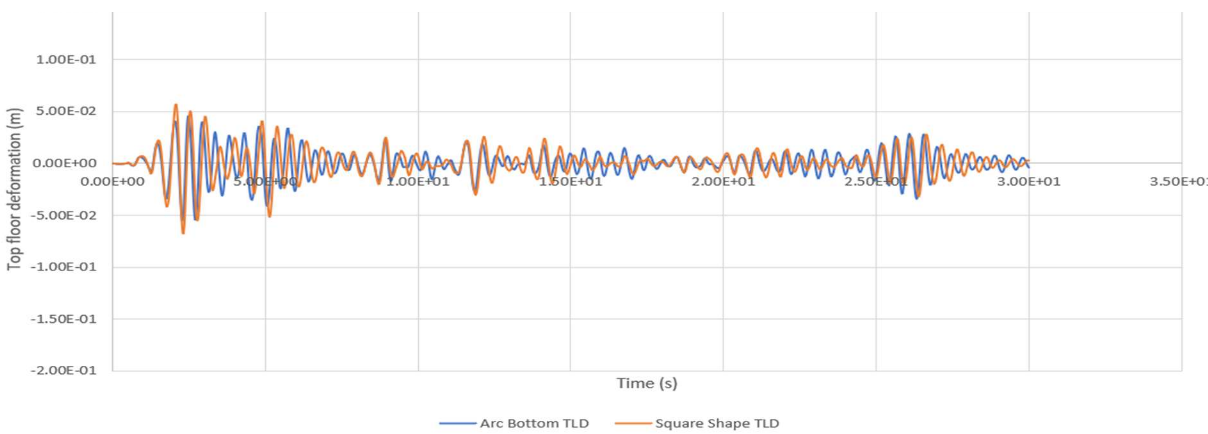


Figure 5.10.- Comparison between Arc bottom and 10-degree Square shape TLD

Table 4.- Comparative results of different TLDs

Sl. No.	TLD Type	Top Floor Peak Displacement
1	Flat Base TLD	84 mm
2	Sloped Base TLD	62 mm
3	Arc Bottom TLD	Circular Arc- 52 mm
		Parabolic Arc- 46 mm
5	Square Shape TLD	10-degree inclined – 51 mm
		20-degree inclined – 56 mm

CHAPTER 6

CONCLUSIONS AND SUGGESTION FOR FUTURE SCOPE OF WORK

6.1 CONCLUSIONS

This thesis has shown a range of insights that redefine our understanding of vibration control in the aim of improving structural stability through creative dampening techniques. We conclude this investigation by summarizing the principal findings that have resulted from our extensive investigation:

- Effectiveness of Flat Base TLD: The examination into the performance of various TLD configurations revealed that the flat base TLD is a strong contender for minimizing structural deformation. Its ability to successfully reduce vibrations highlights its potential to improve building performance.
- Performance of Sloped Bottom TLD: Sloped bottom TLD, with 20-degree slope is shown here. Notably, results from the 20-degree sloped TLD were better than those from flat bottom version. This subtle distinction emphasizes the significance of even minute design differences and their bearing on damping efficacy.
- The appeal of sloped TLD outweighed the traditional flat base design, which makes them superior. These arrangements have a greater capacity to manage structural vibrations thanks to the dynamic interaction between liquid and sloped walls, providing a glimpse into a time when architectural beauty and practical usefulness coexist peacefully.
- Arc Bottom TLD Improvements: The parabolic arc bottom TLD analysed stood out as a top performer. This design outperformed both flat base and sloped base TLD’s in terms of vibration reduction capabilities. Its success in reducing deformations makes it a promising method for reducing seismic vibration.
- Versatility of Square Shape TLD: The novel square shape TLD came into being as a versatile answer, outperforming sloped bottom TLDs in terms of performance. Its capacity to deal with earthquakes coming from different directions further emphasises

its skill at suppressing vibrations, adding a new level of structural robustness to symmetrical structures.

This study's conclusion highlights the versatile potential of tuneable liquid dampers as structural improvement tools. The findings highlight the significance of minor design details in redefining damping efficiency. Future vibration control will be built on the dynamic interaction of TLD geometry and liquid contact. These results add up to a comprehensive understanding of TLD behaviour, paving the way for improvements in structural engineering and safer, more resilient constructed environments. As we welcome the futures that these findings open up, we usher in a time when innovation and practical application converge effortlessly, advancing us towards a world characterised by adaptive structural stability.

6.2 FUTURE SCOPE OF THIS WORK

The approach taken in this thesis offers up a wide range of prospective directions for ongoing research and development in the fields of structural vibration control and TLD design. The potential directions for expanding and advancing the scope of this work include the following:

- Advanced TLD Designs: Future study can examine even more complex TLD designs by building on the knowledge gleaned from the many TLD combinations investigated. To further improve damping capabilities and efficacy, researchers are looking towards hybrid systems that combine various damping methods.
- Experimental Validation: While simulations provide incredibly insightful information, experimental validation of the different TLD configurations can close the gap between theoretical understanding and practical use. Physical tests on scaled models can produce empirical data that supports the simulation results and confirms their application in the real world.
- Real-Time Adaptive Control: Investigating real-time adaptive control strategies for TLDs presents an exciting direction. Incorporating sensors and control algorithms to adjust TLD parameters in response to changing environmental conditions can optimize damping performance under varying loads and seismic events.

- Numerical Parametric Studies: Conducting extensive parametric studies can shed light on the robustness and versatility of the TLD configurations explored. Varying parameters such as building height, base stiffness, and TLD placement can provide insights into the broader applicability of the identified optimal designs.
- Comparative Performance in Complex Structures: Extending the analysis to more complex building geometries and configurations can provide a broader understanding of TLD performance. Exploring how different TLDs fare in irregular buildings or structures with varying stiffness profiles adds depth to the study's applicability.
- Alternative liquid capabilities: While this thesis has explored the utilization of silicon oil as an alternative to water within TLDs, the realm of alternative damping liquids remains rich with unexplored potential. To further enhance the performance of TLDs and expand their applicability in structural vibration control

In conclusion, this thesis lays the groundwork for an engaging line of further research. Researchers and practitioners may advance the subject of structural vibration control by stepping into the future scope described above. By doing so, they can find creative solutions that rethink the resilience, stability, cost effectiveness and safety of our built environment.

CHAPTER 7

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