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Modelling and Assessing the Performance of Tuned Liquid Damper for Vibration Control

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Abstract: In this article, we explore innovative solutions in structural engineering, focusing on Tuned Liquid Dampers (TLDs) to mitigate structural vibrations induced by dynamic loads. Our meticulous analysis uncovers transformative insights, revealing a spectrum of dampening effectiveness across various TLD configurations. Each design, from flat base to arc bottom shape variants, contributes uniquely to the symphony of vibration control. This article utilizes Ansys Workbench for finite element modeling and fluid-structure interaction computations within a computational building model. Findings highlight the flat base TLD's effectiveness in reducing deformations. Sloped bottom TLDs enhance damping, while arc bottom TLDs excel in vibration reduction. Square Shape TLD, a versatile design, addresses seismic challenges from all angles, embodying innovation in structural resilience. The study illuminate geometric influences, paving the way for adaptable structural solutions. In conclusion, this thesis transcends academia, promising to revolutionize architecture. It envisions structures gracefully enduring dynamic forces, synthesizing geometry, fluid mechanics, and structural dynamics. The result is an era of adaptable, safe, and resilient built environments.

***Index Terms* - Tuned liquid damper, Finite element analysis, Structural vibrations, System coupling, Seismic response, Fluid-structure interaction**

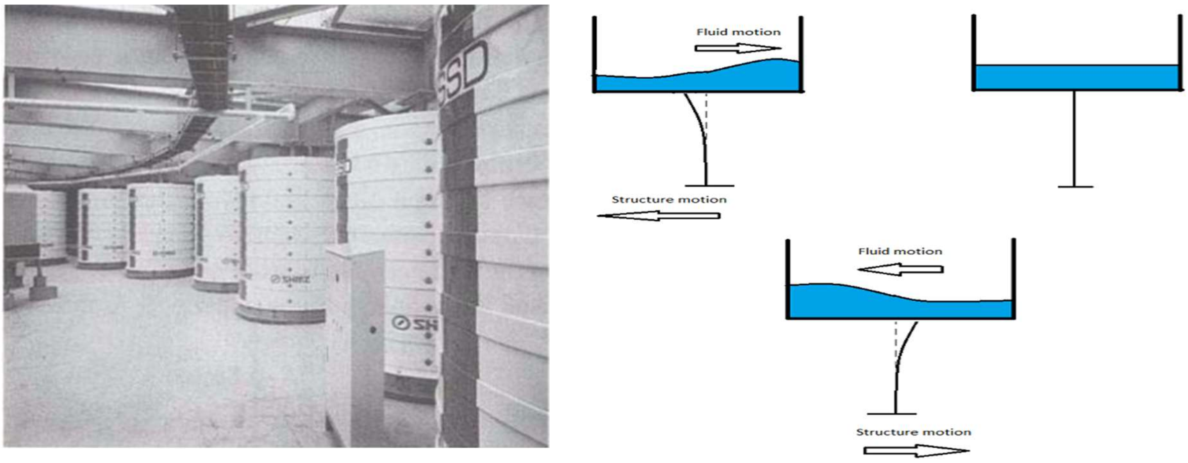
1. INTRODUCTION

Tall buildings play a crucial role in contemporary city development, positively impacting the economy, environment, and culture. Their ability to accommodate more individuals in limited space necessitates a focus on safety and security. However, tall structures are susceptible to dynamic loads like wind and seismic forces due to their flexibility and poor dampening. This can lead to structural issues such as resonance and fatigue failure. To counteract these problems, vibration reduction devices are essential.

Various devices, including Tuned Mass Damper and Fluid Viscous Damper, aim to control structural displacement. The Tuned Liquid Damper (TLD), a passive damper, stands out for its simplicity, cost-effectiveness, and ease of design and maintenance. A 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. Dating back to the 19th century, TLDs gained prominence in the latter half of the 20th century. They have been applied successfully in structures like the Nagasaki Airport Tower, Taipei 101, Storebaelt Bridge, and Shin Yokohama Prince Hotel, effectively reducing structural vibrations. The TLD's efficacy was demonstrated in Nagasaki, where it decreased RMS accelerations by 70% at 20 m/s wind speeds. Overall, TLDs offer a practical solution to enhance the stability and safety of tall buildings.

Research by Fujii et al. (1990) revealed a 50% reduction in vibrations in tall towers, like Yokohama Marine Tower and Nagasaki Airport Tower, upon installing wind-induced vibration dampers. Yozo Fujino and Limin Sun (1992) developed an effective analytical model for Tuned Liquid Dampers (TLD) based on shallow water wave theory, demonstrating accurate predictions even with breaking waves. Pacheco, Chaiseri, Sun (1992) established a structural model with prototype-sized circular containers, illustrating the importance of tuning liquid frequency to the structure's natural frequency for enhanced damping. Tamura, Modi (1992, 1995) found TLDs raised the damping ratio of Tokyo International Airport Tower by 7.6%, improving serviceability. Koh and Mahatma (1995) conducted simulations revealing the advantages of combining liquid dampers set to different frequencies in a multi-degree-of-freedom structure. Fujino and Koga (1995) developed a tuned liquid damper model for suppressing pitching motions, validated through shaking table tests. Abe and Fujino (1998) improved TLD performance using magnetic fluids activated by electromagnets, demonstrating superiority over passive TLD even when sloshing frequency is off-tuned. Wakahara (1999) designed an ideal TLD, reducing wind-induced response by half on the "Shin Yokohama Prince Hotel." Kaneko and Ishikawa (1999) proposed an analytical model showing that TLDs with submerged nets effectively minimize horizontal structural vibration. Banerji and Shah (2000) demonstrated that a higher depth ratio for TLD is more effective in seismic simulations, and Gardarsson and Reed (2001) found a sloped-bottom TLD to be most effective when adjusted slightly higher than the structure's fundamental response frequency.

In this present article 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.



(a) (b)

Figure 1. (a) TLDs installed in SYPH [2]; (b) Working principal of TLD

2. OBJECTIVE AND SCOPE

The goal of this thesis paper is to examine the efficiency of a Tuned Liquid Damper (TLD) 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.

This study focuses on the modelling and analysis of tuned liquid dampers in a 10-story building under seismic loading. It does not include any investigation of TCLD, TLD with baffle wall, slat screen or any other structural retrofit methods or the analysis of dynamic loading conditions other than earthquakes.

3. MATHEMATICAL FORMULATIONS

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 Equation (1)

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

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.

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. [3]** had suggested a formula to describe and create TLDs.

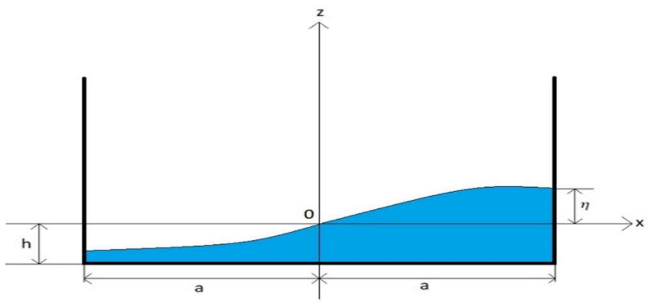


Figure 3.1. Schematic sketch of TLD for Horizontal motion

The following formulas are identified:

$$\frac{\partial \eta}{\partial t} + h\sigma \frac{\partial(\phi u)}{\partial x} = 0 \qquad (2)$$

$$\frac{\partial u}{\partial t} + (1-T_H^2)\, u\frac{\partial u}{\partial x} + C_{fr}^2 g \frac{\partial \eta}{\partial x} + gh\sigma\phi \frac{\partial^2 \eta}{\partial x^2}\frac{\partial \eta}{\partial x} = -C_{da}\lambda u - \ddot{x}_s \qquad (3)$$

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 (2) and (3) can be used to compute σ, ϕ and T_H as follows:

$$\sigma = \frac{\tanh(kh)}{kh} \qquad (4)$$

$$\phi = \frac{\tanh(kh+\eta)}{tanh(kh)} \qquad (5)$$

$$T_H = \tanh(kh+\eta) \qquad (6)$$

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

$$\lambda = \frac{1}{(h+\eta)}\frac{1}{\sqrt{2}}\sqrt{\omega_1 \upsilon}\left[1+\frac{2h}{b}+s\right] \qquad (7)$$

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 [1]** and detailed in **Eq. (8)** the fundamental sloshing frequency of TLD is calculated as:

$$f_n = \frac{1}{2}\sqrt{\frac{3.16}{L}\,tanh\left(\frac{3.16h}{L}\right)} \qquad (8)$$

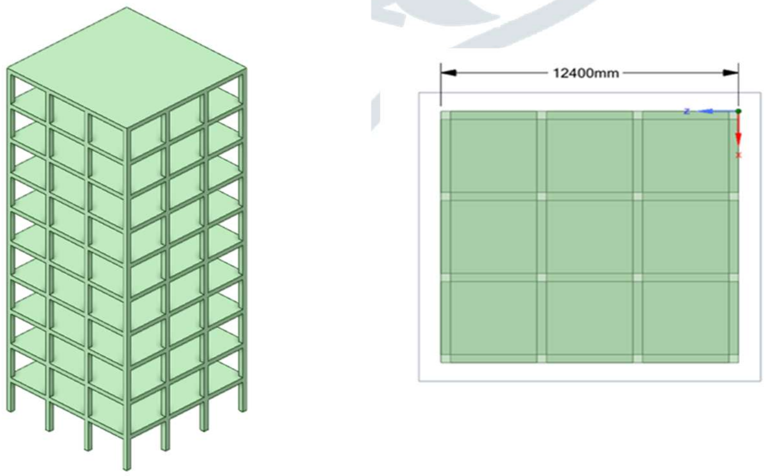
Where, h is the undisturbed water depth, L is the length of tank and g is acceleration due to gravity. When waves are unstable and break, the coefficients C_{fr} and C_{da} in equation 'x' are taken into account to adjust the water wave phase velocity and damping, respectively. When waves don't break, 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:

$$C_{da} = 0.57\sqrt{\frac{h^2\omega^1}{a\,\upsilon}(x_s)_{max}} \qquad (9)$$

4. METHODOLOGY

4.1. Building Model Creation

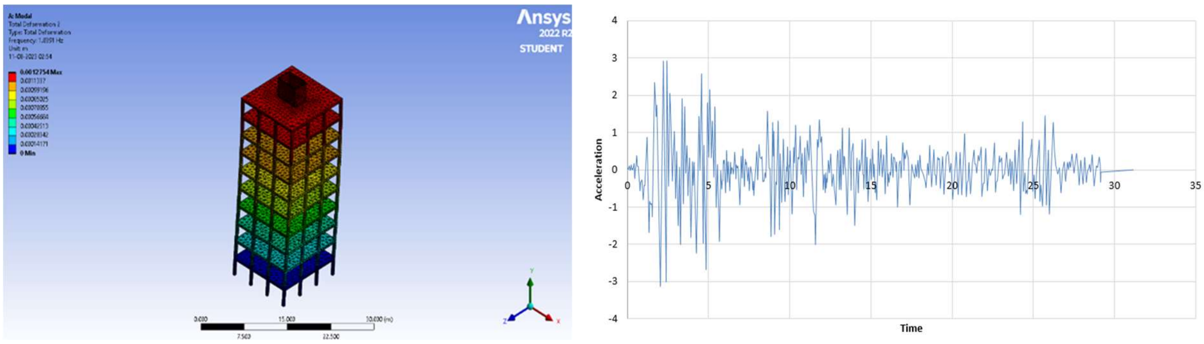
Here in this study the computational square shape building model is drawn in Ansys SpaceClaim. The total height of the superstructure is 35 m having columns of (400 x 400) mm^2 and beams of (400 x 450) mm^2. The thickness of slabs is 200 mm with 153760000 mm^2 surface area. The floor-to-floor height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



(a) (b)

Figure 4.1. (a) 3d Ansys model of the building; (b) Structure plan

Meshing and Load application is done in Transient structural. 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.



(a) (b)

Figure 4.2. (a) First mode shape of the building; (b) El Centro earthquake time history graph (NS component)

Table 1. Modal frequencies

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

4.2 TLD Model Creation

The rectangular tanks working as TLD have same material properties as the building model. The tanks are fixed on the top of the structure. **Eq. (8**) 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 article, three different kinds of rectangle bottom TLD’s and one kind of unique square bottom TLD are taken into account.

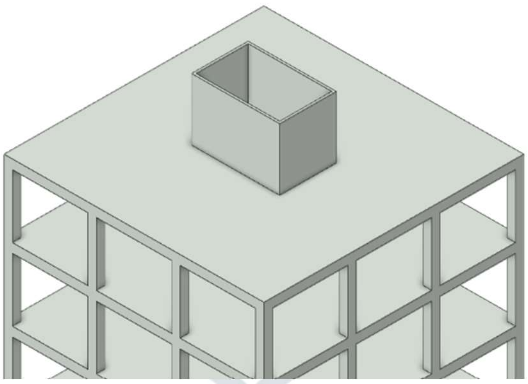
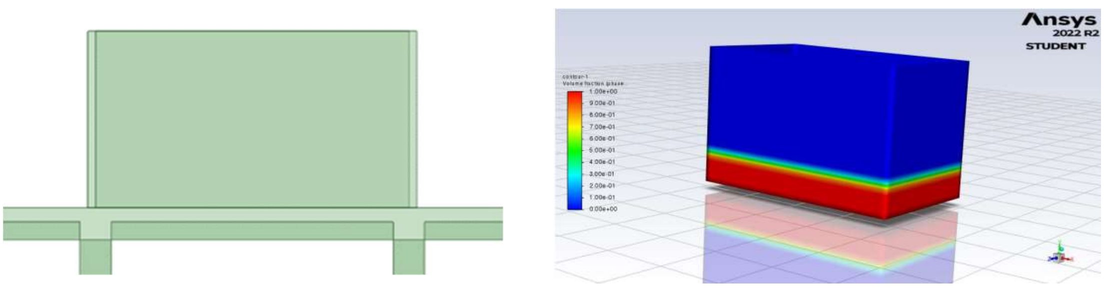
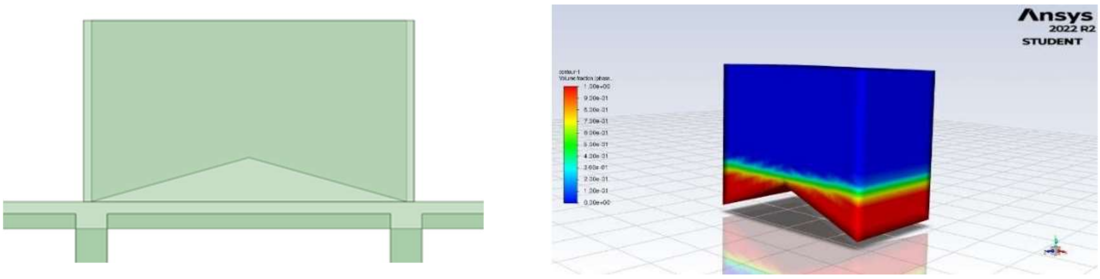


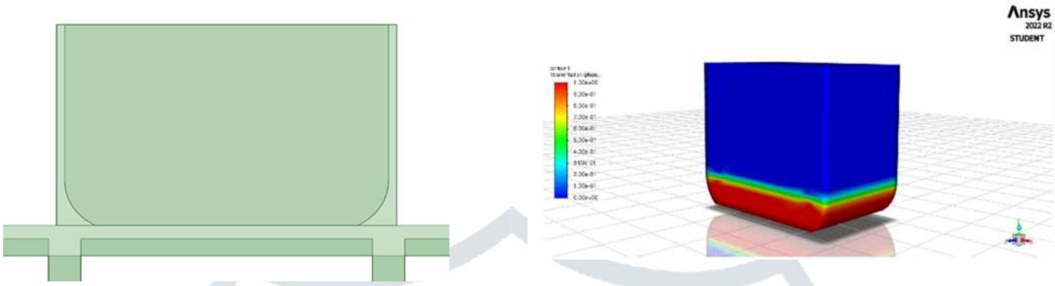
Figure 4.3. TLD position on the building



(a) (b)



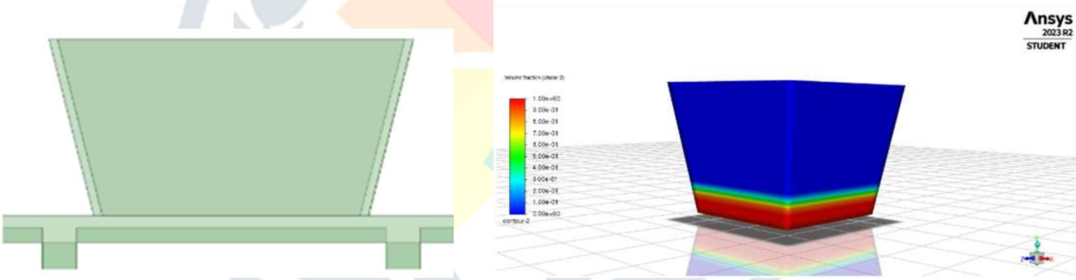
(c) (d)



(e) (f)

Figure 4.4. (a) Side view of flat bottom TLD; (b) Water contour of flat bottom TLD; (c) Side view of sloped bottom TLD; (d) Water contour of sloped bottom TLD; (e) Side view of arc bottom TLD; (f) Water contour of sloped bottom TLD

The pursuit of effective structural engineering solutions goes beyond theory, demanding adaptability to seismic challenges from any direction. The Multi-Directional Inclined-Wall Square TLD offers a good response, surpassing limitations of conventional designs. Unlike single-direction TLDs vulnerable to unforeseen ground motions, this square-shaped TLD excels in diverse seismic scenarios. Its innovative design, featuring sloped walls, enhances dampening by maximizing liquid-wall interaction, significantly reducing structural vibrations. This work introduces a versatile TLD configuration, ensuring adaptability and durability against dynamic forces, marking a transformative stride in seismic resilience.



(a) (b)

Figure 4.5. (a) Side view of 10- degree inclined wall square TLD; (b) Water contour of square TLD

Table 2. Details of tank

Tank type	Considered length of tank	Water height
Flat bottom TLD	4 m	0.56 m
Sloped bottom(20^0) TLD	4.25 m	0.63 m
Arc bottom TLD	4.8 m	0.8 m
Square shape TLD	3 m	0.3 m

4.3 System Coupling Procedure

The process of integrating and simulating interactions between various physical systems in Ansys is termed 'System Coupling' or multi-physics coupling. In this study, System Coupling combines the building model and the Tuned Liquid Damper model, assessing the TLD's effectiveness in controlling structural vibrations. It integrates Ansys Fluent's TLD model with Transient Structural's building model, allowing independent system functions while exchanging information through a predefined coupling interface. Dynamic loads on the structure generate forces on the TLD, influencing fluid motion within it, while the TLD's dynamic effect on building vibration control is captured through iterative modifications for convergence. The coupling interface facilitates the exchange of displacement, force, and fluid dynamics information, providing a comprehensive understanding of how the TLD reduces vibrations and enhances structural stability in this coupled system.

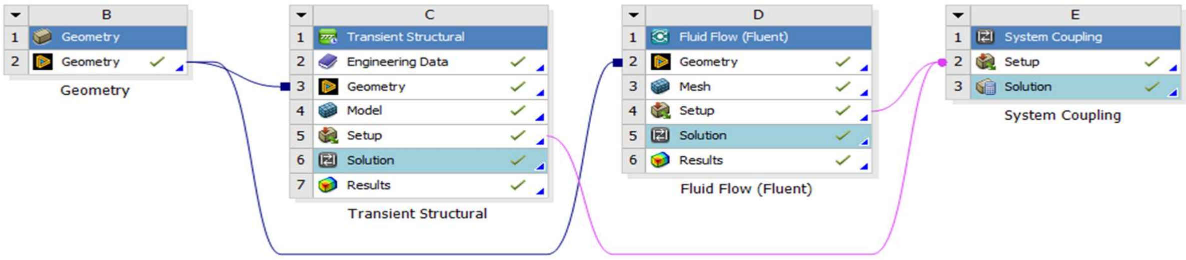
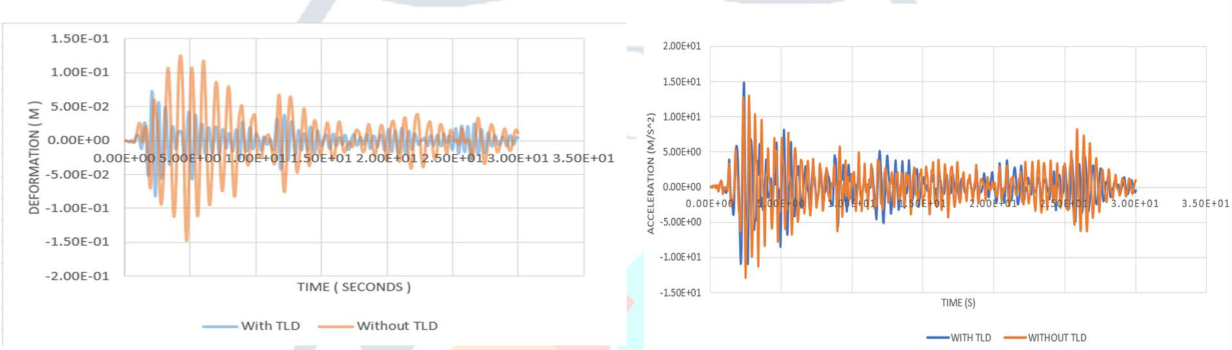


Figure 4.6. Flow chart of system coupling procedure in Ansys Workbench

5. RESULT AND DISCUSSIONS

5.1 Flat Bottom TLD

This section explores the unique dampening capacity provided by water in the flat base TLD, aiming to assess its impact on top floor deformation and acceleration. The baseline scenario involves a 10-story building experiencing dynamic stresses without TLDs, reaching a peak deformation of 147 mm. Introducing Flat Bottom Conventional TLDs results in a significant reduction, with peak deformation now at 84 mm. Beyond deformation, these TLDs showcase their effectiveness in lowering top-floor acceleration, highlighting their role in promoting a harmonious environment where structure and occupant comfort coexist peacefully.

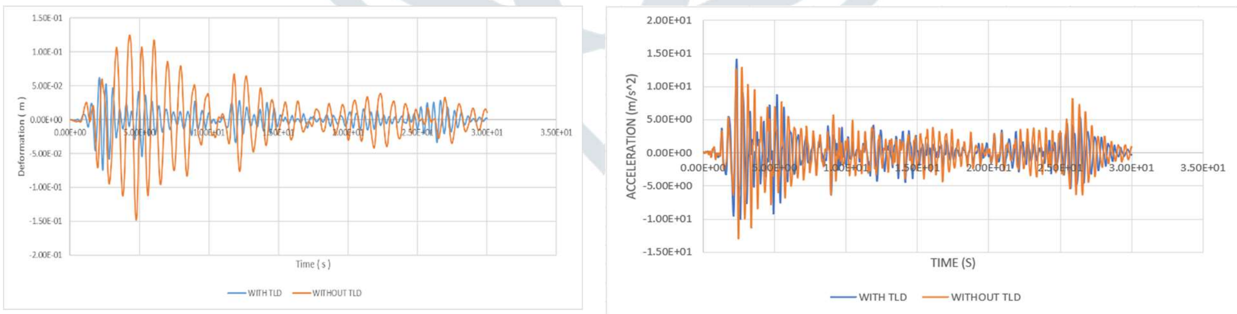


(a) (b)

Figure 5.1. (a) Top floor deformation with and without TLD; (b) Top floor acceleration with and without TLD

5.2 Sloped Bottom TLD

In this comparison, Sloped Bottom TLDs, featuring a 20-degree slope, effectively reduce building deformation and acceleration. Peak deformations, initially at 147 mm without TLDs, now reach 62 mm, showcasing the architectural prowess of Sloped Bottom TLDs in moderating structural responses. This design fosters an environment where structural resilience and occupant comfort coexist harmoniously.

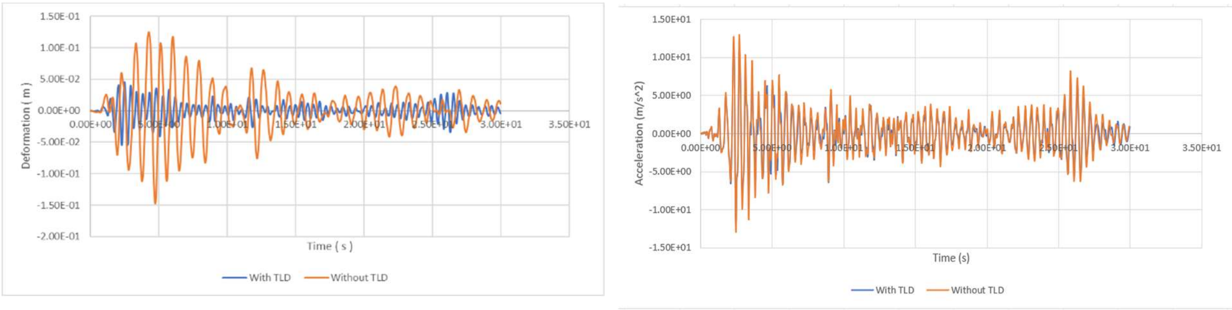


(a) (b)

Figure 5.2. (a) Top floor deformation with and without TLD; (b) Top floor acceleration with and without TLD

5.3 Arc Bottom TLD

Arc Bottom TLD outshines flat and sloped variants, offering superior vibration control by significantly reducing structural deformations. This section emphasizes the performance outcomes achieved through the implementation of Arc Bottom TLD in a 10-story building, showcasing a remarkable peak deformation reduction to 47 mm.

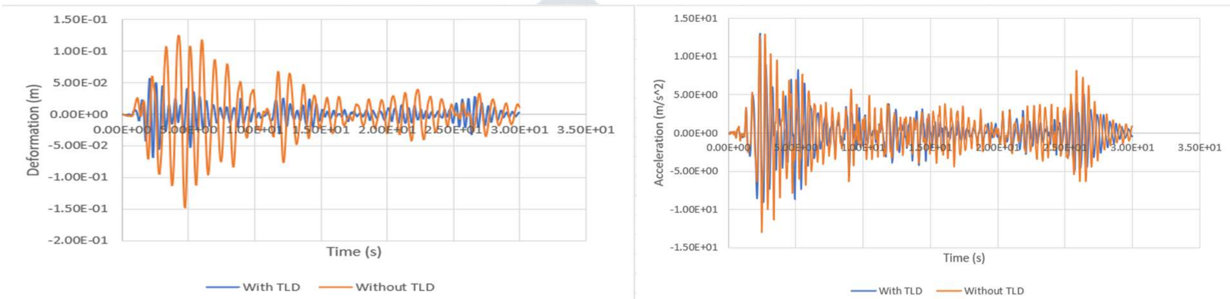


(a) (b)

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

5.4 Square Shape TLD

This section explores the transformative impact of Square Shape TLDs in mitigating structural deformations and top-floor accelerations. The 10-degree variant significantly reduces peak deformation from 147 mm to 51 mm. The TLD plays a crucial role in minimizing top-floor acceleration, fostering a harmonious coexistence of structural stability and occupant well-being.



(a) (b)

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

5.5 Comparative Analysis of Different TLD

This section serves as a pivotal crossroads in structural engineering, where innovation meets resilience. It's a stage where diverse TLD designs undergo meticulous scrutiny. The goal is to compare their performance and determine the most effective path toward creating secure and reliable built environments. From Square Shape TLDs showcasing transformative potential to the efficiency of Arc Bottom TLD and the dynamics of Sloped and Flat Bottom TLDs, our exploration has unveiled a spectrum of structural possibilities.

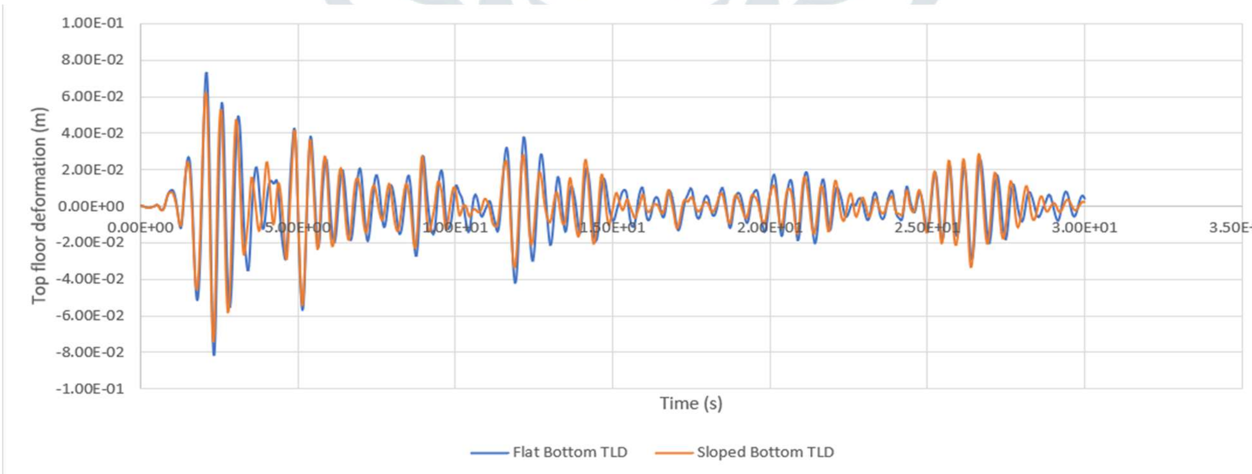


Figure 5.5. Comparison between Flat bottom and Sloped bottom TLD

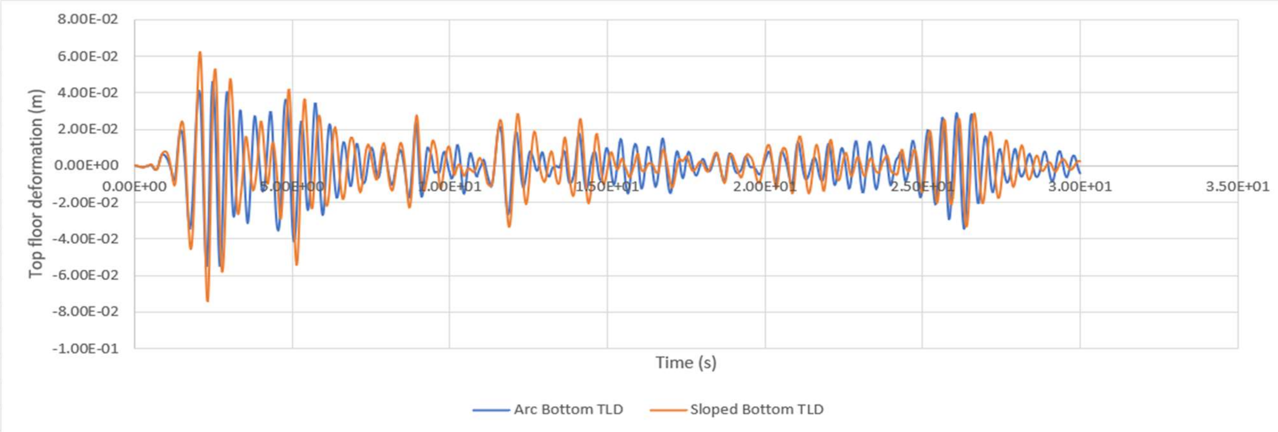


Figure 5.6. Comparison between Arc bottom and Sloped bottom TLD

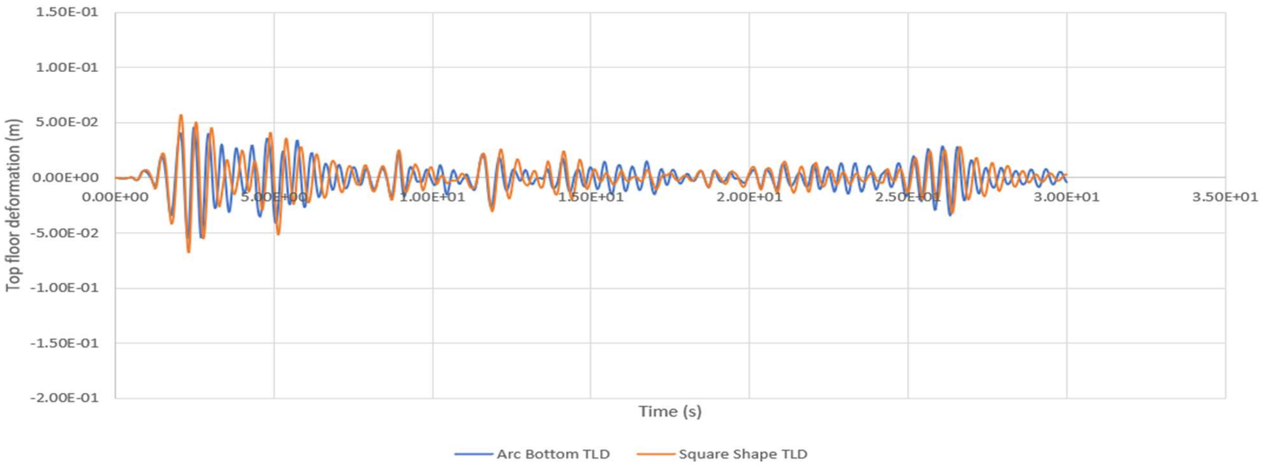


Figure 5.7. Comparison between Arc bottom and Square shape TLD

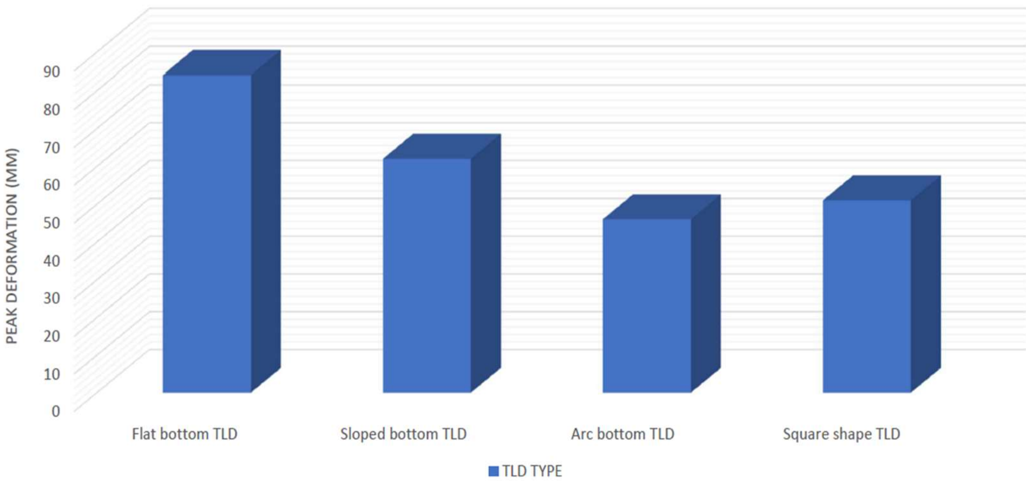


Figure 5.8. Comparative results of different TLDs

6. CONCLUSIONS AND FUTURE SCOPES

6.1 Conclusions

This article 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.
- The sloped bottom TLD with 20-degree slope performed better than the flat bottom TLD, highlighting the impact of even minor design differences on damping efficiency. The sloped TLD design was superior to the traditional flat base design due to its greater capacity to manage structural vibrations through dynamic interaction of liquid and sloped walls.
- The appeal of slopped TLD's 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 arc bottom TLDs 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 emphasizes its skill at suppressing vibrations, adding a new level of structural robustness to symmetrical structures.

This study's conclusion highlights the versatile potential of tunable 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 behavior, 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 characterized by adaptive structural stability.

6.2 Future Scopes

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.
- 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.

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.

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