APPLICATION OF FIXED WOODEN PLATE WITH A DESIGNED OPENING IN A TUNED LIQUID COLUMN DAMPER FOR SEISMIC VIBRATION CONTROL OF BUILDING STRUCTURES

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ABSTRACT

This study seeks to address the issue of earthquake-induced vibrations in building structures by introducing a novel approach called the Tuned Liquid Column Wooden Plate Damper (TLCWPD), which is a modification of the traditional Tuned Liquid Column Damper (TLCD). The innovation involves incorporating fixed wooden plates with designed openings at the base of the damper, creating barriers that restrict the movement of the liquid within. These plates generate a damping force that efficiently dissipates kinetic energy, resulting in a substantial reduction in displacement in the upper levels of the building. To validate this approach, an experimental setup using a three-story steel Multi-Degree-of-Freedom System Structure (MDOF) is employed. Simulated earthquake conditions are applied through base displacement on a shake table. The displacement data is then categorized into "uncontrolled" scenarios (without TLCWPD) and "controlled" scenarios (with TLCWPD) at the top of the building. Various parameters such as time, liquid height, the arrangement of designed wooden plates, and the diameters of the TLCWPD pipes are systematically varied. A comparison of these scenarios demonstrates a notable reduction in displacements when the designed opening of plates within the pipe TLCD is incorporated, as opposed to traditional TLCD or no dampers. Optimal configurations, including the size of the wooden plate openings, water level heights, and pipe TLCWPD diameters, are identified for different earthquake durations, highlighting significant displacement reduction. The Modified TLCWPD outperforms conventional TLCD, enhancing the resilience of the damper system and presenting a promising solution for mitigating earthquake-induced vibrations in buildings. This innovative approach has the potential to substantially improve structural safety.

Keywords: *fixed wooden plates with designed openings, damping force, Liquid Column Wooden Plate Damper (TLCWPD), displacement reduction, Multi-Degree-of-Freedom (MDOF)*

1. INTRODUCTION

Considering earthquakes can turn extremely devastating, the threat they represent to buildings and other structures has received a lot of attention recently. Ensuring the safety and structural integrity of buildings necessitates the mitigation of seismic forces (Islam, et al., 2016). Using tuned liquid column dampers (TLCDs) is one method that has gained popularity in earthquake engineering. These gadgets have demonstrated the potential to lessen the vibrational effects of earthquakes on building structures (Kavand & Zahrai, 2006).

As lightweight high-rise structures become more prevalent, the significance of vibration control has grown. Tuned liquid column dampers (TLCDs) offer an energy-efficient solution for damping forces in these structures. Altering the column geometry of TLCDs semi-actively adjusts their natural frequency, enhancing control performance. However, this modification introduces strong nonlinearities and challenging controller design. This contribution proposes a model-based controller considering the nonlinear dynamics of a coupled system—a multi-story structure with a semi-active TLCD. A hierarchical nonlinear model predictive controller (NMPC) with a multi-start strategy is formulated to address diverse system dynamics. An extrapolation algorithm predicts the future trajectory of the induced excitation load on the structure, incorporated into the NMPC framework. Validation on a 20-story benchmark structure with a semi-active TLCD is conducted through simulation, comparing results with passive vibration control (Zimmer, et al., 2022).

The traditional 2-degrees-of-freedom (2-DOF) paradigm in terms of a single particular structural mode typically the resonant mode-is the foundation for the ideal calibration of a TLCD for damping structural vibration. This suggests that additional non-resonant modes' background flexibility contribution is ignored for flexible multi-degree-of-freedom (MDOF) structures, leading to an imbalance in the frequency response of the flexible structure-TLCD coupled system (Chen, et al., 2021). Much research works on passive dampers such as Dynamic Vibration Absorber(DVA) has been conducted in recent years. Among passive DVA, a Tuned Liquid Column Damper(TLCD) is of great interest for some of its characteristics such as easy implementation, low cost of construction and maintenance, and no need to add mass to the structure if the liquid is used as water supply (Son, 2016). The tuned liquid column damper (TLCD), like other passive vibration control devices, is an energy-absorbing device that runs without the need for an external power source. The hydrodynamic head losses that occur when the liquid moves inside the TLCD provide the damping effect (Min, et al., 2015).

The results of this study may have a major impact on the creation of more reliable and effective methods for designing and constructing earthquake-resistant buildings. Furthermore, the findings can provide engineers with insightful direction on how to incorporate efficient earthquake mitigation techniques into building designs. This study is a major step in assuring the safety of residents and infrastructure and improving the resilience of structures in earthquake-prone areas (Ghosh, 2023).

This research explores a novel approach for mitigating seismic vibrations in building structures through the integration of a fixed wooden plate on the base of a Tuned Liquid Column Damper (TLCD), featuring a designed opening within a modified structure termed Tuned Liquid Column Wooden Plate Damper (TLCWPD). The primary objective of the study is to assess the efficacy of this innovative method in reducing structural vibrations induced by earthquakes. The investigation specifically examines the impact of different wooden plate designs, denoted as cases I, II, and III, along with variations in TLCWPD sizes characterized by pipe diameters of 4 inches, 3 inches, and 2 inches.

The study investigates the vibration of a structure induced by the water sloshing inside a fixed wooden plate with a designed opening inside the Tuned Liquid Column Wooden Plate Damper (TLCWPD) column at different water heights. Measurements are taken at six distinct water levels: 0 inches (base), 1 inch, 2 inches, 3 inches, 4 inches, and 5 inches. By systematically exploring these characteristics, the research aims to provide valuable insights into the effectiveness of the earthquake vibration mitigation strategy.

In this research, we provide a comprehensive analysis of the experimental setup, methodology, and results. We aim to elucidate the potential of the proposed fixed wooden opening plate in the TLCWPD damper as a promising solution for earthquake vibration control in building structures. The comprehensive assessment of the various parameters will provide a holistic understanding of the performance and effectiveness of this innovative approach in seismic engineering.

2. METHODOLOGY

The experimental investigation took place in a meticulously controlled laboratory environment, equipped with all necessary tools for testing and documenting water sloshing within a fixed wooden plate featuring a designed opening within modified Tuned Liquid Column Wooden Plate Dampers (TLCWPD). The study incorporated three distinct pipe diameters: 4 inches, 3 inches, and 2 inches represented by TLCWPDs denoted as TLCWPD 4 inches, TLCWPD 3 inches, and TLCWPD 2 inches, respectively. The base of the modified Tuned Liquid Column Damper's (TLCWPD) orifice was positioned at the same height as the diameter of the pipe.

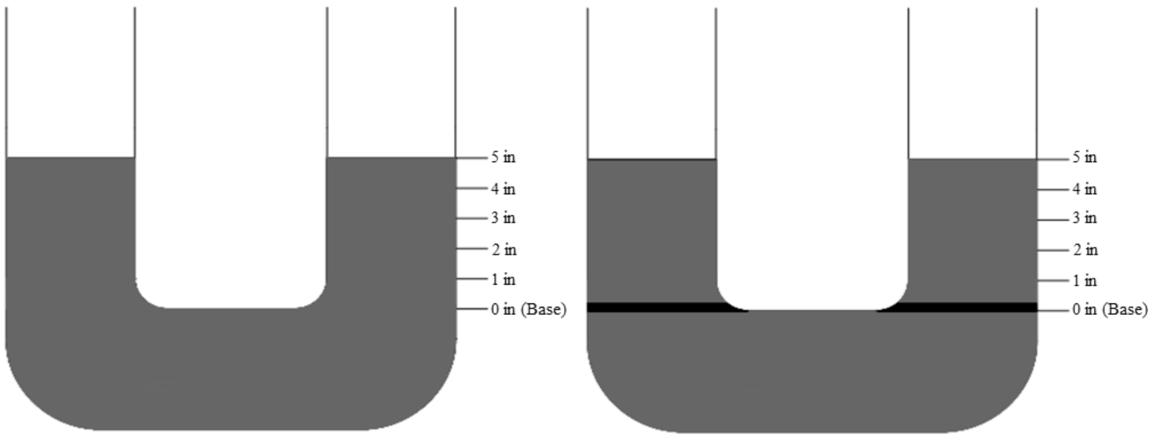

Figure 1 : TLCWPD with only water and TLCWPD with fixed wooden plate

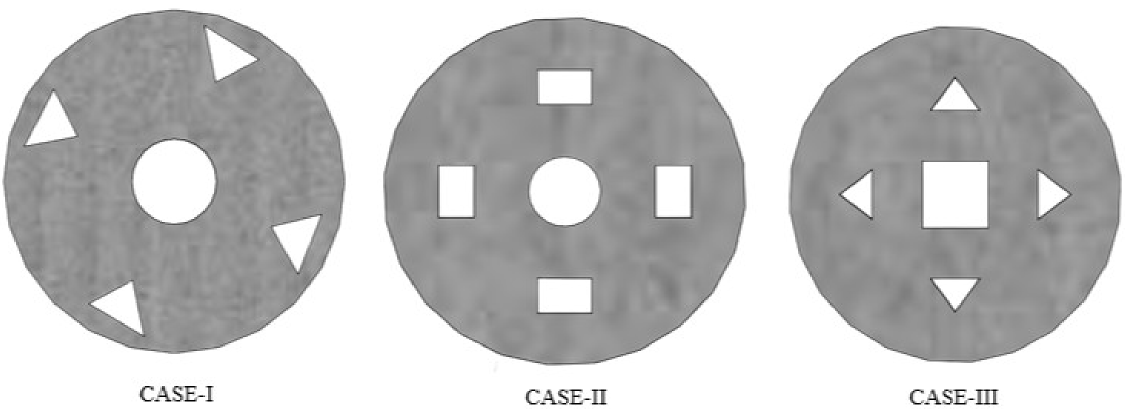

Figure 2 : Different cases of designed wooden plate

Furthermore, for comparative analysis with each TLCWPD, three distinct wooden plate designs (case-I, case-II, and case-III) were employed. Case-I, the wooden plate featured a central circle surrounded by four triangles. Case II, a similar wooden plate with a central circle was accompanied by four rectangles positioned away from the center circle. Case III, the wooden plate showcased a central square surrounded by four triangles. The adjustment of the wooden plate design was executed by the TLCWPD pipe diameter, and it was positioned at the base of the TLCWPD.

3. Building Specification

The experiment featured in Figure 3 involved a 3-story steel structure with a total weight of 15 kg. Each story had an additional 12 kg load, resulting in a cumulative structure weight of 51 kg. The dimensions of each story were 18 inches in height, length, and width. All beams and columns were circular with a diameter of 0.37 inches. The structure was made of ASTM A615 Steel, grade 60. It was fixed on the base plate of the ground-shaking table for support. The natural frequency of the structure was measured to be 1.78 hertz.

Figure 3 : Experimental setup

4. TLCD design

Utilizing numerical optimization, optimal design parameters were determined, emphasizing the consistent achievement of peak performance by maintaining a uniform cross-section for all columns, tailored to specific mass and horizontal length ratios. Subsequently, a predictive model was developed by conducting property tests on a Tuned Liquid Column Damper (TLCD), employing free vibration and harmonic forced vibration techniques on a shake table. The TLCD design adheres to the guidelines established by Jong-Cheng Wu (Wu et al., 2005), as illustrated in Figure 4, incorporating a 3-inch pipe TLCD with a 1-inch water height and a 7-inch horizontal length. In this context, symbols such as υ denote the section ratio (set to 1), Le represents the effective length of the liquid column (12 inches), Lv signifies the vertical column height of the TLCD (2.5 inches), and Lh indicates the horizontal column length of the TLCD (7 inches). The damper's natural period, they are denoted as Td, measured 0.678 seconds, while the structure's natural period, denoted as Ts, was 0.56 seconds. Ultimately, the Frequency ratio η was determined to be 0.71.

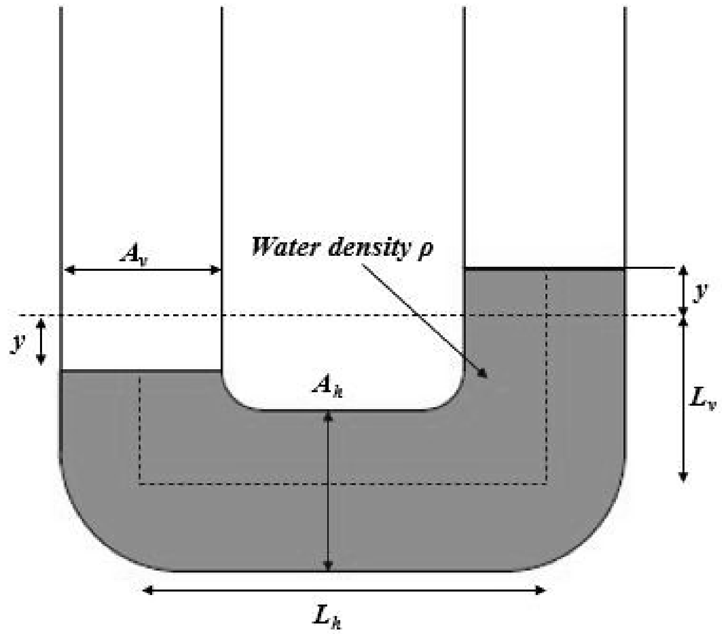

Figure 4 : TLCD design diagram

Essential equations for designing a Tuned Liquid Column Damper (TLCD):

$$\upsilon = A_v/A_h \tag{1}$$

$$L_e = L = 2L_v + L_h \tag{2}$$

$$T_d = 2\pi \sqrt{(L_e/2g)} \tag{3}$$

$$\eta = T_s/T_d \tag{4}$$

5. Input displacement

In Figure 5, the ground-shaking table was configured to replicate the characteristics of a prototype El-Centro seismic graph. Input displacement data was applied at the base of the structure, and the resulting displacements (measured in mm) of the top floor were recorded for all test scenarios. These tests utilized El-Centro earthquake data with varying cases over 15 seconds, aiming to minimize structural response through the utilization of the TLCWPD. The maximum displacement was 68.2852mm at the top of the structure in 3.62 seconds during ground shaking.

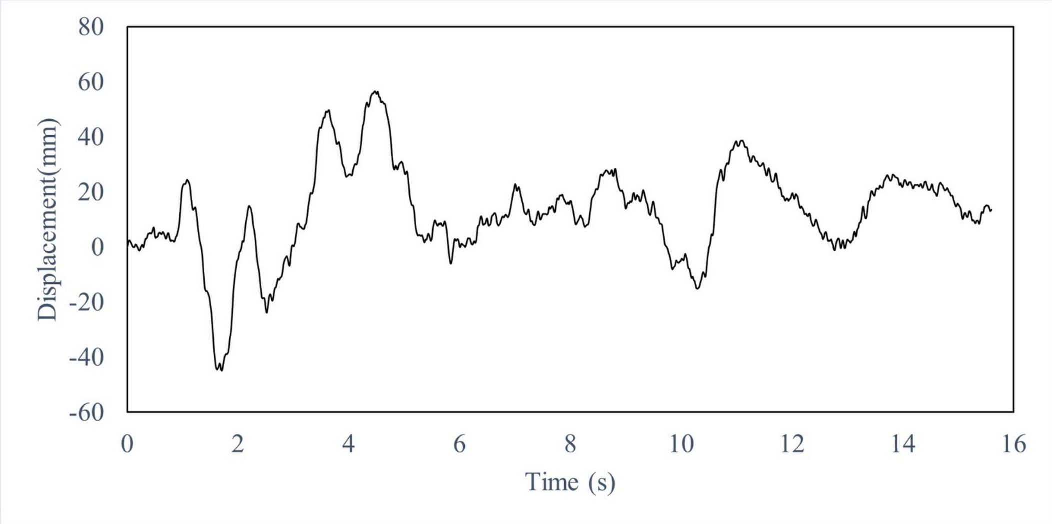

Figure 5: El-Centro prototype curve for 15s

6. Data Reporting

Initially, we gathered uncontrolled data, signifying the absence of Tuned Liquid Column Wooden Plate Dampers (TLCWPD) on our structure. The experiments were systematically conducted at six different water levels within each TLCWPD column (TLCDWP 4 inches, TLCDWP 3 inches, and TLCDWP 2 inches) specifically, at the base (0 inches), 1 inch, 2 inches, 3 inches, 4 inches, and 5 inches. These experiments were carried out for both scenarios: exclusively with water in TLCWPD and with the addition of wooden plates, all while being exposed to 15 seconds of earthquake shaking. Throughout the experiment, meticulous attention was dedicated to maintaining and monitoring each water level, ensuring precision and consistency in the data collection process.

7. ILLUSTRATIONS

8. Graphs

The following graphs illustrated here for 15 seconds represent the comparisons between the Uncontrolled data, controlled without a wooden plate, and controlled with the Tuned Liquid Column Wooden Plate Dampers (TLCWPD) data of the top displacement for three cases mentioned earlier in the methodology of this research. The X-axis conveys time (s) and the Y-axis exhibits displacements (mm). The cases are investigated for the changes in liquid height level in the liquid-containing columns.

9. Four Inches Diameter Pipe TLCWPD

In Figure 6, in Case III, the tuned liquid column with a four-inch diameter and a designed plate (TLCWPD) demonstrated effectiveness by achieving a maximum displacement of 55.071 mm at a water height of 0 inches in 2.564 seconds, which represented the minimum displacement among all cases. This displacement, compared to the uncontrolled scenario (68.285 mm) occurring in 3.62 seconds, outperformed other cases: 65.493 mm at 0 inches (Case-I) in 1.035 seconds, 66.824 mm at 0 inches (water only) in 5.157 seconds, and 55.839 mm at 0 inches (Case-II) in 1.809 seconds. Case III with the TLCWPD showcased superior performance in minimizing displacement compared to both the uncontrolled setup and alternative configurations.

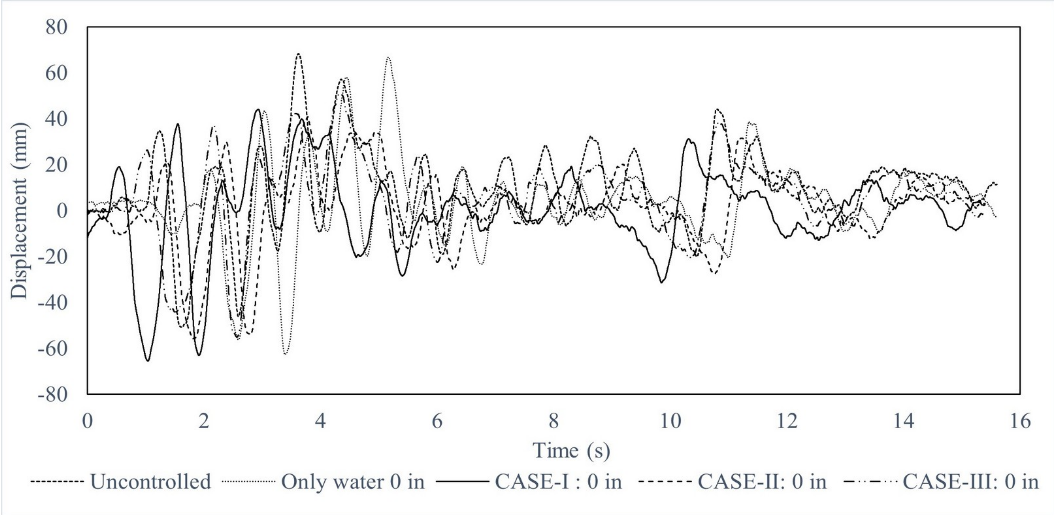

Figure 6 : Displacement vs Time at water level 0 inches

10. Three Inches Diameter Pipe TLCWPD

In Figure 7, in Case-I, the tuned liquid column with a three-inch diameter and a designed plate (TLCWPD) effectively minimized displacement, achieving a minimum of 50.088 mm at a 1-inch water height in 1.532 seconds. This performance surpassed the uncontrolled scenario (68.285 mm) in 3.62 seconds and other cases: 57.925 mm at 1 inch (Case-II) in 1.358 seconds, 59.159 mm at 1 inch (water only) in 3.206 seconds, and 56.623 mm at 1 inch (Case-III) in 2.128 seconds. Case-I with the TLCWPD demonstrated superior displacement reduction compared to both the uncontrolled setup and alternative configurations.

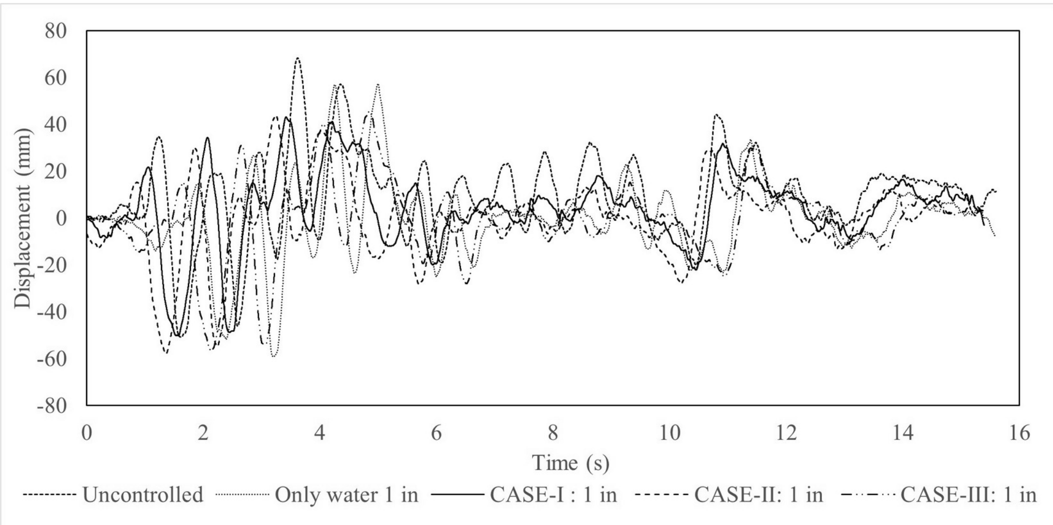

Figure 7 : Displacement vs Time at water level 1 inch

11. Two Inches Diameter Pipe TLCWPD

In Figure 8, in Case-I, the tuned liquid column with a 2-inch diameter and a specially designed plate (TLCWPD) effectively minimized displacement, achieving a minimum of 53.623 mm with a 2-inch water height within 3.648 seconds. This performance outperformed the uncontrolled scenario, which recorded a displacement of 68.285 mm in 3.62 seconds, as well as other cases: 57.925 mm at 2 inches (Case-II) in 3.648 seconds, 62.471 mm at 2 inches (water only) in 3.648 seconds, and 56.893 mm at 2 inches (Case-III) in 3.648 seconds. Case-I, employing the TLCWPD, demonstrated superior displacement reduction compared to both the uncontrolled setup and alternative configurations.

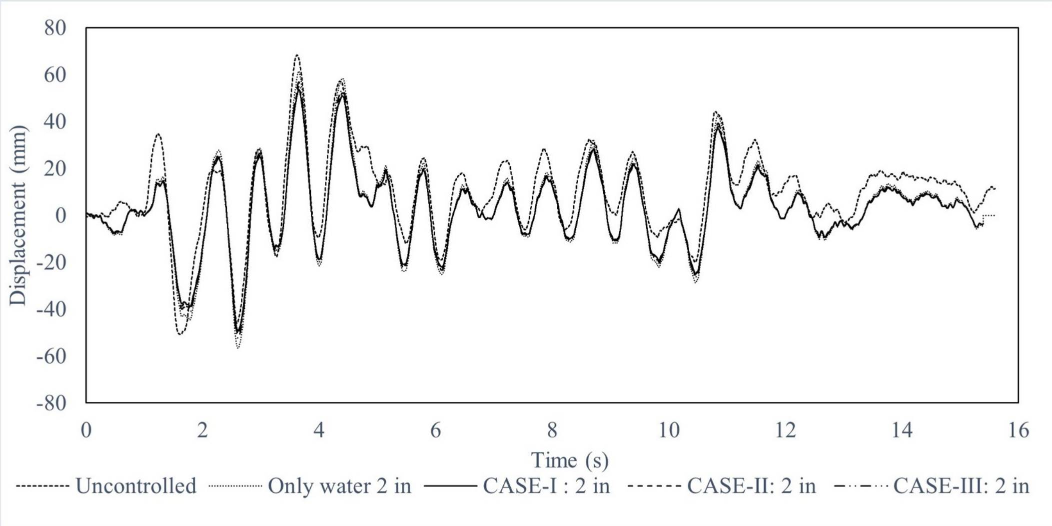

Figure 8 : Displacement vs Time at water level 2 inches

12. Tables

13. Four Inches Diameter Pipe TLCWPD

Table 1 illustrates the minimum top displacement in millimeters for three scenarios: controlled without a wooden plate, represented as the conventional Tuned Liquid Column Damper (TLCD), and controlled by the Tuned Liquid Column Damper with Wooden Plate Damping (TLCWPD) in three distinct cases.

Table 1: Top displacement (mm) at different water levels for 3 cases at 15s

Water level (inches)	Controlled By TLCD (Conventional)	Controlled by TLCWPD		
		CASE-I	CASE-II	CASE-III
0	66.824	65.493	**55.839**	**55.071**
1	**62.458**	**56.349**	62.752	59.483
2	63.759	57.059	65.742	57.069
3	72.018	64.218	61.560	61.673
4	73.956	65.288	56.684	60.448
5	77.701	69.040	65.016	67.697

Table 2 presents the minimum top displacement of the structure when controlled by the conventional Tuned Liquid Column Damper (TLCD) at 1-inch water height, Case-I at 1-inch water height, Case-II at 0-inch water height, and Case-III at 1-inch water height. Subsequently, a comparison is made with the uncontrolled structure to determine the maximum displacement reduction percentage.

Table 2: Top displacements (mm) & maximum reduction percentages (%) for all conditions at 15s

Conditions	Water Level (inches)	Top displacement (mm)	Maximum Reduction Percentage (%)
Uncontrolled Structure	-	68.285	-
Controlled by TLCD (conventional)	1	62.458	8.53
Case-I	1	56.349	17.48

Case-II	0	55.839	18.23
Case-III	0	55.071	**19.35**

Table 3 illustrates the comparisons of optimal displacement for a four inches diameter pipe TLCD, specifically in Case-III, in contrast to an Uncontrolled Structure, structures Controlled by the conventional Tuned Liquid Column Damper (TLCD), Case-I and Case-II. The reduction percentage for Case III is reported to be 19.35%.

Table 3: Top displacement (mm) & reduction percentage (%) at optimum water level from all conditions at 15s

Conditions	**Water Level (inches)**	**Top displacement (mm)**	**Reduction Percentage (%)**
Uncontrolled Structure	-	68.285	-
Controlled by TLCD (conventional)	0	66.824	2.14
Case-I	0	65.493	4.09
Case-II	0	55.839	18.23
Case-III	0	55.071	**19.35**

14. Three Inches Diameter Pipe TLCWPD

Table 4 displays the minimum top displacement in millimeters under three conditions: controlled without a wooden plate, referred to as the conventional Tuned Liquid Column Damper (TLCD), and controlled by the Tuned Liquid Column Damper with Wooden Plate Damping (TLCWPD) in three different scenarios.

Table 4: Top displacement (mm) at different water levels for 3 cases at 15s

Water level (inches)	**Controlled By TLCD (Conventional)**	**Controlled by TLCWPD**		
		CASE-I	**CASE-II**	**CASE-III**
0	60.492	58.216	**51.544**	**52.423**
1	**59.159**	**50.088**	57.925	56.623
2	61.003	51.719	61.685	54.325
3	63.256	57.083	56.824	58.756
4	68.720	58.034	52.324	57.542
5	69.511	61.369	60.015	64.442

Table 5 illustrates the minimum top displacement of the structure under various conditions: controlled by the conventional Tuned Liquid Column Damper (TLCD) at 1-inch water height, Case-I at 1-inch water height, Case-II at 0 inches water height, and Case-III at 1-inch water height. Following this, a comparison is conducted with the uncontrolled structure to ascertain the maximum displacement reduction percentage.

Table 5: Top displacements (mm) & maximum reduction percentages (%) for all conditions at 15s

Conditions	**Water Level (inches)**	**Top displacement (mm)**	**Maximum Reduction Percentage (%)**
Uncontrolled Structure	-	68.285	-
Controlled by TLCD (conventional)	1	59.159	13.36
Case-I	1	50.088	**26.65**
Case-II	0	51.544	24.52
Case-III	0	52.423	23.23

Table 6 presents the comparisons of optimal displacement for a three-inch diameter pipe equipped with a Tuned Liquid Column Damper (TLCD), particularly in Case I. This is compared against an Uncontrolled Structure, structures controlled by the conventional Tuned Liquid Column Damper (TLCD), Case-II and Case-III. The reduction percentage for Case III is documented as 26.65%.

Table 6: Top displacement (mm) & reduction percentage (%) at optimum water level from all conditions at 15s

Conditions	**Water Level (inches)**	**Top displacement (mm)**	**Reduction Percentage (%)**
Uncontrolled Structure	-	68.285	-
Controlled by TLCD (conventional)	1	59.159	13.36
Case-I	1	50.088	**26.65**
Case-II	1	57.925	15.17
Case-III	1	56.623	17.08

15. Two Inches Diameter Pipe TLCWPD

Table 7 illustrates the minimum top displacement in millimeters under three conditions: controlled without a wooden plate, referred to as the conventional Tuned Liquid Column Damper (TLCD), and controlled by the Tuned Liquid Column Damper with Wooden Plate Damping (TLCWPD) in three different scenarios.

Table 7: Top displacement (mm) at different water levels for 3 cases at 15s

Water level (inches)	**Controlled By TLCD (Conventional)**	**Controlled by TLCWPD**		
		CASE-I	**CASE-II**	**CASE-III**
0	63.795	54.779	56.115	58.119
1	68.186	59.482	60.933	63.109
2	62.471	**53.623**	54.931	**56.893**
3	65.897	56.740	57.100	59.139
4	64.709	55.576	56.931	57.964
5	**61.413**	54.573	**54.880**	56.840

Table 8 illustrates the minimum top displacement of the structure under various conditions: controlled by the conventional Tuned Liquid Column Damper (TLCD) at 5 inches water height, Case-I at 2 inches water height, Case-II at 5 inches water height, and Case-III at 2 inches water height. Following this, a comparison is conducted with the uncontrolled structure to ascertain the maximum displacement reduction percentage.

Table 8: Top displacements (mm) & maximum reduction percentages (%) for all conditions at 15s

Conditions	**Water Level (inches)**	**Top displacement (mm)**	**Maximum Reduction Percentage (%)**
Uncontrolled Structure	-	68.285	-
Controlled by TLCD (conventional)	5	61.413	10.06
Case-I	2	53.623	**21.47**
Case-II	5	54.880	19.63
Case-III	2	56.893	16.68

Table 9 presents the comparisons of optimal displacement for a two-inch diameter pipe equipped with a Tuned Liquid Column Damper (TLCD), particularly in Case I. This is compared against an

Uncontrolled Structure, structures controlled by the conventional Tuned Liquid Column Damper (TLCD), Case-II and Case-III. The reduction percentage for Case III is documented as 21.47%.

Table 9: Top displacement (mm) & reduction percentage (%) at optimum water level from all conditions at 15s

Conditions	Water Level (inches)	Top displacement (mm)	Reduction Percentage (%)
Uncontrolled Structure	-	68.285	-
Controlled by TLCD (conventional)	2	62.471	8.51
Case-I	2	53.623	**21.47**
Case-II	2	54.931	19.56
Case-III	2	56.893	16.68

16. Optimum Result from All Study

17. Optimum Graph

Figure 8 illustrates a comparison of optimal results at the same water level with other cases. Specifically, it highlights the optimal outcomes obtained from a three-inch pipe Tuned Liquid Column Wooden Plate Damper (TLCWPD) in Case-I at a 1-inch water level. These results are then juxtaposed with TLCDs of two and four-inch diameters in Case I.

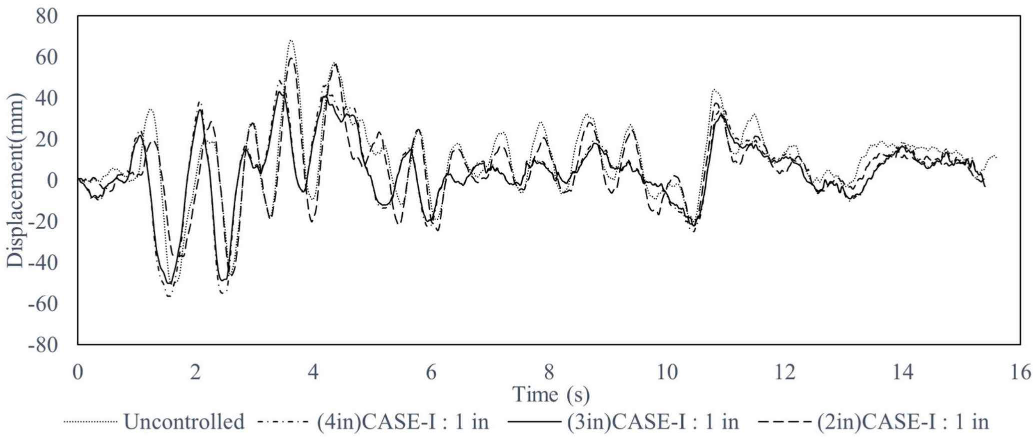

Figure 9 : Displacement vs Time at water level 1 in

18. Optimum Table

Table 10 displays the reduction percentages in optimum top displacements from the comprehensive study. The minimum top displacement recorded was 50.088 mm, with the highest reduction percentage observed at 26.65%, achieved by the TLCWPD with a three-inch diameter in Case-I.

Table 10: Top displacement (mm) & reduction percentage (%) at optimum water level from all studies at 15s

Conditions	TLCWPD Diameter (inches)	Water Level (inch)	Top displacement (mm)	Reduction Percentage (%)
Uncontrolled Structure	-	-	68.285	-
Case-I	4	1	56.349	17.48
Case-I	3	1	50.088	**26.65**
Case-I	2	1	59.482	12.89

19.CONCLUSIONS

With the increasing adoption of Tuned Liquid Column Dampers (TLCD) in engineering structures, particularly within industrial sectors, there is a growing necessity to focus on optimizing TLCDs in a cost-efficient manner. The research direction is shifting towards achieving satisfactory optimization, especially considering economic considerations. This study explores the vibration control of a Multi-Degree-of-Freedom (MDOF) structure through the application of a Tuned Liquid Column Wooden Plate Damper (TLCWPD). The objective is to evaluate the effectiveness of this modification and encourage further research toward economic optimization. The analysis delves into a detailed comparison among three configurations: Uncontrolled (without TLCD), Controlled with TLCD, and TLCWPD. The study also considers the fixed method of the wooden plate in different diameters of TLCWPD to discern any distinctions.

Upon analyzing the displacement data for the top portion of the structure in all referenced cases outlined in this paper's methodology, it is evident that, in response to the El-Centro prototype shaking generated by the earthquake shake table over a running time of 15 seconds, the optimal liquid heights are 1 inch in the liquid-containing columns consecutively. In this context, TLCWPD with a three-inch diameter in Case-I demonstrates a more substantial reduction in the top displacement of the structure compared to other diameters and cases. The introduction of specifically designed opening fixed wooden plates appears to effectively impede the free sloshing of the liquid, facilitating better dissipation of kinetic energy.

In conclusion, the modification of TLCD with designed opening fixed wooden plates proves to be more reliable than the conventional TLCD in terms of controlling vibrations and optimizing performance.

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