ATTENUATION OF EARTHQUAKE INDUCED VIBRATION OF BUILDING STRUCTURE USING FLOATING SAND FILLED BALLS IN TUNED LIQUID COLUMN DAMPER

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ABSTRACT

The study concentrates on reducing the earthquake-induced vibration of building structures by modifying the Tuned Liquid Column Damper. The modification of the Tuned Liquid Column Damper (TLCD) is done by employing sand-filled floating balls in association with an elastic rubber band that is fixed to the tank bottom. The sand-filled floating balls behave as a barrier against the free sloshing of the liquid and dissipate the kinetic energy by creating a damping force. The dissipation effectively reduces the output displacement of the building structure. An experimental three-storied steel structure is used as a multi-degree-of-freedom system (MDOF) to perform the earthquake shake table experiment. This investigation is undertaken considering liquid height, free and fixed floating of the sand-filled balls, and the percent weight of sand filled in the hollow core of the balls. The comparisons of the uncontrolled and controlled data show that the displacements (mm) of the sand-filled floating balls in TLCD mitigate more structural vibration. The optimum percent weights of sand-filled balls and optimum liquid level heights for the experimental shaking time are presented for which the displacements decrease the most. From the outcomes, it is evident that modifying the Tuned Liquid Column Damper with sand-filled floating balls is more robust than the traditional TLCD.

Keywords: *tuned liquid column sand ball damper, multi-degree of freedom (MDOF), earthquake shake table, water sloshing, damping*

1. INTRODUCTION

Considering the lethal consequences of the earthquake, numerous kinds of research are being conducted on the Tuned Liquid Column Damper to signify an impeccable modification to reduce the earthquake-induced vibration on structures. Tuned Liquid Column Damper or TLCD is used as a passive device to mitigate the vibration of infrastructures due to wind or seismic activities (Ding, et al., 2023).

TLCD possesses notable advantages. It has a flexible damping ability, can be designed as per the characteristics of structures, also it is cost-effective (Ding, et al., 2023). Earlier, it has been studied for its effectiveness for high-rise buildings, bridges, stadiums, wind turbines, and also for harvesting energy (Hochrainer & M. J., 2005) (Ding, et al., 2023). In a recent study, a design guideline for TLCD in response to wind has been proposed by Jong-Cheng Wu (Wu, et al., 2005). The experiment was executed on a structure regarding it as a single-degree-of-freedom (SDOF) structure. The findings state that, for a certain mass ratio and horizontal length ratio, TLCD columns having uniform cross-sections perform the best. While Sakai (Sakai, et al., 1989) initially advocated for the use of TLCD, subsequent research revealed that the effectiveness of vibration attenuation depends on structural attributes, damping properties, and excitation characteristics (Balendra, et al., 1995). In the research done by Sakai (Sakai, et al., 1989), it was recommended that two TLCDs should be used for the shear type of buildings. Another research done by Mulyadi (Bur, et al., 2022) on a two DOF (two-degree-of-freedom) vibration system structure using a Tuned Mass Damper (TMD) along with TLCD showed that optimal mass for the TMD and optimal volume of liquid in the TLCD altogether significantly reduced the vibration of the experimental structure. Qinhua (Wang, et al., 2020) did parametric optimization of inerter-based TLCD or Tuned Liquid Column Damper Inerter (TLCDI) for research on SDOF structure. The modification was compared with the conventional TLCD by adopting the equivalent linearization method and was found effective. In a study of H. Gao (Gao, et al., 1999) on Multiple Tuned Liquid Column Damper (MTLCD) determined the application of MTLCD is more reliable than a single TLCD for the experimental structure. Changzhao Qian's research paper (Qian, et al., 2018) highlights that adjusting TLCD using different schemes leads to a more significant reduction in vibration percentages for structures in both SDOF and MDOF systems.

Muhammad Tanveer (Tanveer, et al., 2019) presented a Tuned Liquid Column Ball Damper or TLCBD. The experiment was done by employing steel balls of different diameters as a moving orifice and changing the diameters of the liquid-containing columns. Applying TLCBD on an MDOF system showed good results according to the study. Later on, Muhammad Tanveer (Tanveer, et al., 2020) worked on the optimization of materials of TLCBD by increasing the density of steel balls and the liquid. The optimization also provided a more productive outcome than before. Many more studies have shown the significance of the application of TLCBD on MDOF and sparked further research and optimization of it (Chen, et al., 2021) (Shah, et al., 2023).

Following all previous studies, it is understood that the optimization exploration of TLCD is needed to be more cost-effective. This is being initiated due to the gradual adoption of it in industrial practice and is increasing drastically. This study aims to modify the TLCD with floating sand-filled balls and assess the optimization for its effectiveness. In this research, the assessment of the Tuned Liquid Column Sand Ball Damper (TLCSBD) is done considering the multi-degree-of-freedom system (MDOF) system structure, which has been rarely done. The earthquake shake table experiment is conducted by inputting a prototype of El-Centro ground shaking for 15 seconds of vibration. The comparison is carried out only for output displacements and five different liquid heights of the liquid-containing column. The percent reduction of displacements of the experimental structure without TLCD, with TLCD and TLCSBD for a free and fixed position of movement of balls are thoroughly surveyed and illustrated here.

2. METHODOLOGY

In Figure 7, the experiment is conducted on a 3-storied simple steel structure of 54 inches a total height and 3 slabs of 18×18 square inches area as an MDOF structure. It is set up fixed on the earthquake shake table along with the total weight of 75 kg (25 kg of bag of sand on each slab excluding the bottom slab) on the structure. An experimental TLCD has been used and modified later considering 3 types of design: i) Traditional TLCD with no orifice, ii) TLCSBD (free movement of balls), and iii) TLCSBD (fixed base with a rubber band). Normal water has been used as the liquid inside of the TLCD.

The ground-shaking table was configured to mimic 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 used El-Centro earthquake data with varying cases over 15 and 20 seconds. The aim is to minimize structural response by utilizing the TLCSBD.

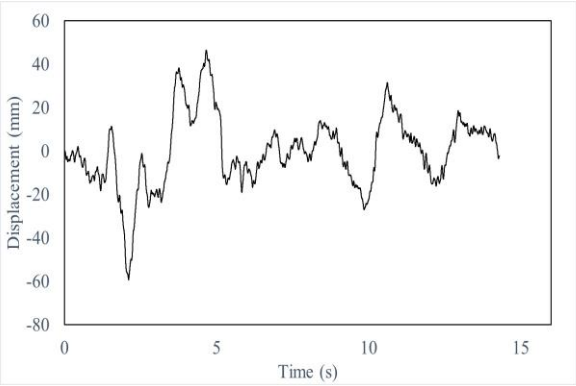

Figure 1: El-Centro prototype curve for 15s

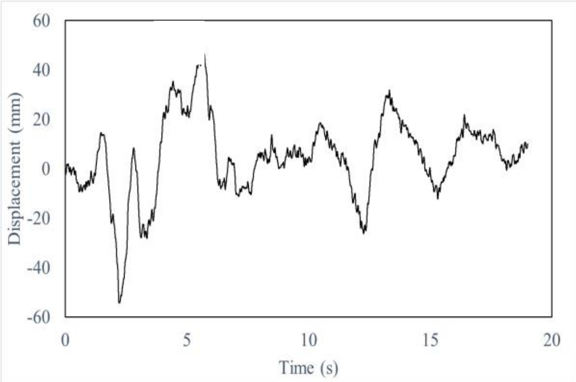

Figure 2 : El-Centro prototype curve for 20s

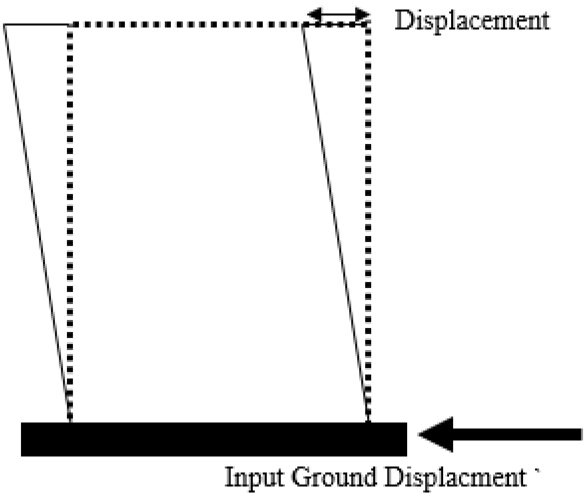

Figure 3 : Input and output displacement

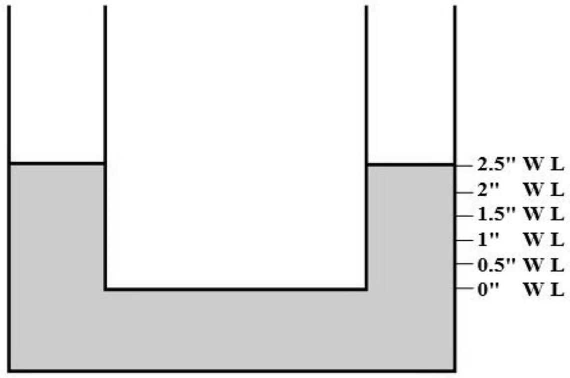

Figure 4 : TLCD

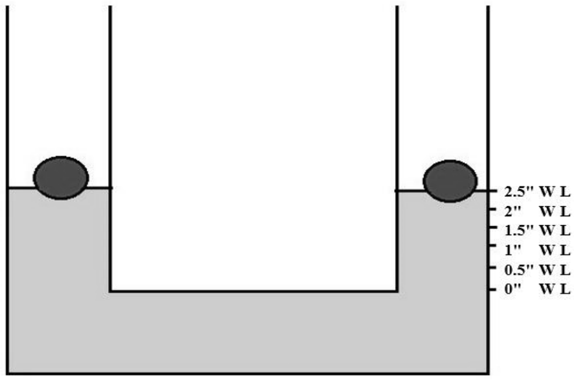

Figure 5 : TLCSBD Free

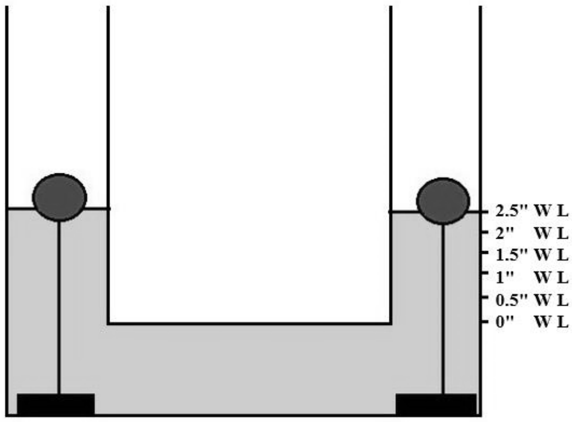

Figure 6 : TLCSBD Fixed

In Figures 4, 5, and 6, the effect of change in water height or level (WL) in the liquid-containing column has a crucial influence on the study. To investigate the impact, the output displacements of the structure for 5 WL consequently 0 inches, 0.5 inches, 1 inch, 1.5 inches, 2 inches, and 2.5 inches have been analyzed along with the changes made to the TLCD. The water level (WL) has been counted above the bottom channel of the TLCD referring to it as the base. For every 0.5 inches of WL increment, the difference in output data has been recorded.

In the experiment, sand-filled plastic balls moving freely with the sloshing of water is called free position movement (TLCSBD Free). On the other hand, keeping the floating position of these balls fixed by rubber elastic band loops with steel sheet plates is called fixed-based (TLCSBD Fixed). Each liquid-containing column contains 4 sand balls floating within the cross-sectional area.

In Figure 8, the experimental TLCSBD is modified using plastic hollow centered balls filled with sand. To ensure the floatation of these balls, the presence of air in association with the sand is required. The percent weight of sand here refers to the amount of sand relative to the weight of sand (g) filling the total volume of a plastic ball. To keep the buoyancy secured, the percent weight of sand used are 50%, 45%, and 35% respectively known as Case I, Case II, and Case III.

The output data of the structure without TLCD is here referred to as uncontrolled or Unc. Whereas, output data with TLCD, TLCSBD free, and TLCSBD fixed are controlled or Cn data. All these data are collected by time history analysis software through sensors. The comparison study is made for 15 sec and 20 sec of input data, based on 3 cases along with 2 floating types for SB (sand ball) of the TLCSBD and 5 successive WLs: i) 35% sand ball free vs fixed vs TLCD vs Unc: Case I ii) 45% sand ball free vs fixed vs TLCD vs Unc: Case II and iii) 50% sand ball free vs fixed vs TLCD vs Unc: Case III. It is of significance to mention, that the input data for all conditions and cases are the same.

Figure 7 : Experimental set up

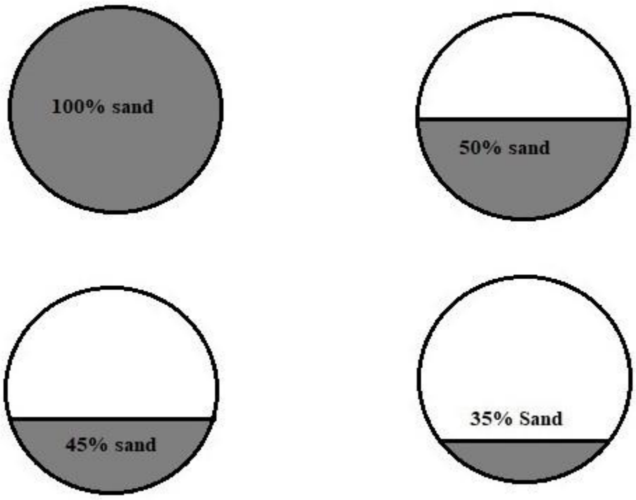

Figure 8 : Percent weight of sand (3 cases)

3. ILLUSTRATIONS

3.1 Graphs

The following graphs illustrated here for 15 seconds and 20 seconds represent the comparisons between the Uncontrolled data, controlled without ball data, controlled with the free ball, and controlled with fixed ball data of the top displacement for three cases mentioned earlier in the methodology of this paper. 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.

3.1.1 Case I: 35% Sand Filled Ball

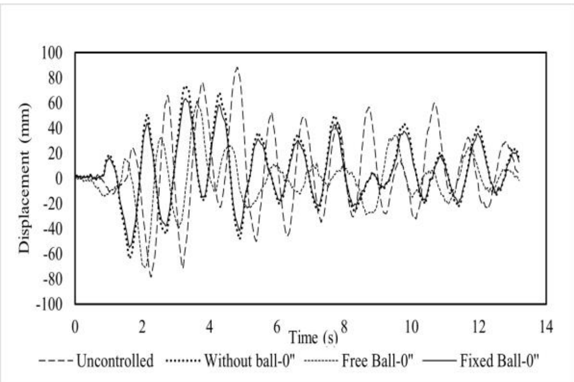

Figure 9 : Displacement vs Time at WL 0 inches

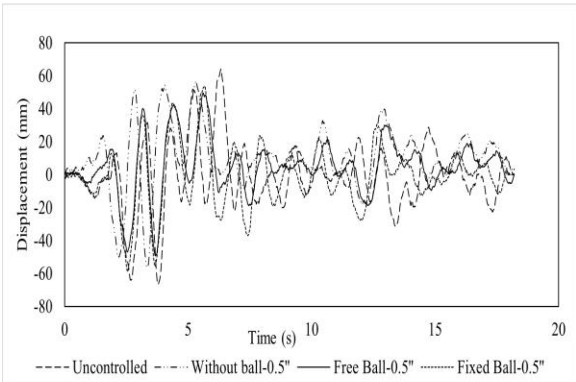

Figure 10: Displacement vs Time at WL 0.5 inches

Running time 15s : In Figure 9, the graph is shown for the optimum WL 0 inches at 15 seconds duration. In this graph, the highest displacement is seen at 88.2772mm. Which is the uncontrolled value. The conventional TLCD (Without ball 0 inches shows 73.690mm. However, TLCSBD (Free

Ball 0 inches) has a displacement of 70.705mm and (Fixed Ball 0 inches) 63.374mm. The lowest value is recorded for the fixed floating balls.

Running time 20s : Figure 10 illustrates that, for the optimum WL 0.5 inches, the uncontrolled value obtained in 20 seconds is 66.521mm. On the other hand, Without a ball, 0.5 inches shows 56.891mm, a lesser displacement. Whereas, the TLCSBD for Free Ball 0.5 inches has the least value, around 49.581mm. However, the Fixed Ball 0.5 inches gives 58.903mm displacement which is similar to the conventional TLCD.

3.1.2 Case II: 45 % Sand Filled Ball

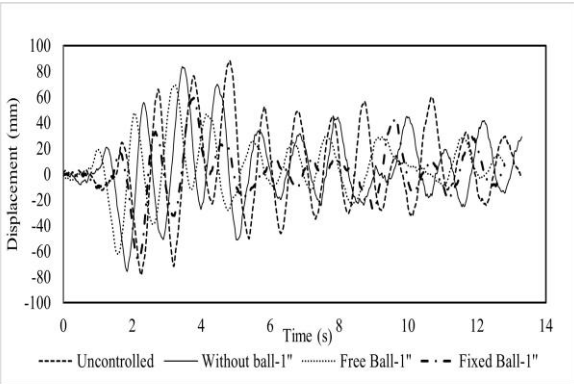

Figure 11 : Displacement vs Time at WL 1 inch

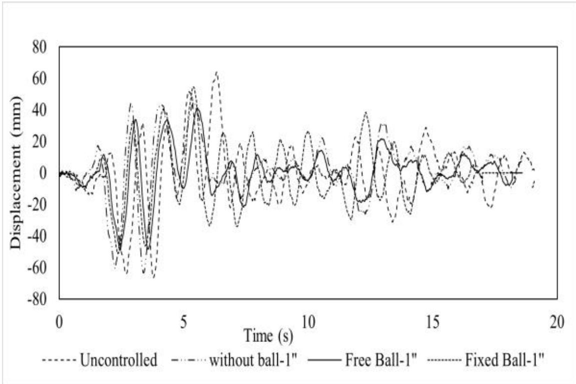

Figure 12 : Displacement vs Time at WL 1 inch

Running time 15s : In Figure 11, the graph is shown for the optimum WL 1 inch at 15 seconds duration. In this graph, the highest displacement is 88.2772mm, which is the uncontrolled value. The conventional TLCD (Without a ball 1 inch) shows around 76.953mm. However, TLCSBD (Free Ball 1 inch) has a displacement of 69.606mm and (Fixed Ball 1 inch) 66.606mm. The lowest value is recorded for the fixed floating balls.

Running time 20s : Figure 12 illustrates that, for the optimum WL 1 inch, the uncontrolled value obtained in 20 seconds is 66.521mm. On the other hand, Without a ball, 1 inch shows 63.472mm, a lesser displacement. Whereas, the TLCSBD for Free Ball 1 inch has the least value, which is 49.153mm. However, the Fixed Ball 1 inch gives 54.535mm displacement.

3.1.3 Case III: 50% Sand Filled Ball

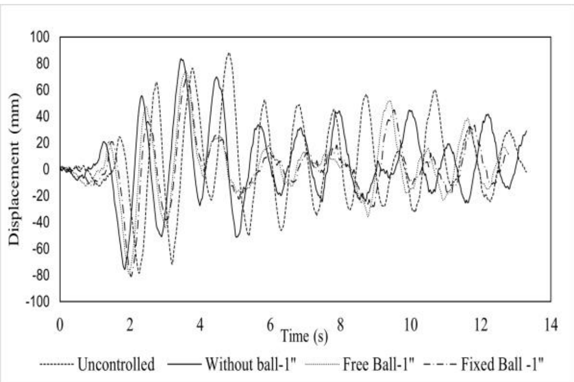

Figure 13 : Displacement vs Time at WL 1 inch

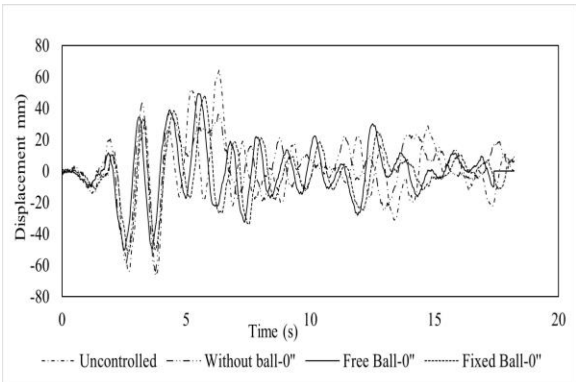

Figure 14 : Displacement vs Time at WL 0 inches

Running time 15s : In Figure 13, the graph is shown for the optimum WL 1 inch at 15 seconds duration. In this graph, the highest displacement is 88.2772mm, which is the uncontrolled value. The conventional TLCD (Without a ball 1 inch) shows around 76.953mm. However, TLCSBD (Free Ball 0 inches) has a displacement of 66.810mm and (Fixed Ball 1 inch) 68.778mm. The least value is recorded for the free-floating balls.

Running time 20s : Figure 12 illustrates that, for the optimum WL 0 inches, the uncontrolled value obtained in 20 seconds is 66.521mm. On the other hand, Without a ball, 0 inches shows 63.609mm, a lesser displacement. Whereas, the TLCSBD for Free Ball 0 inches has the least value, is around 50.140mm. However, the Fixed Ball 0 inches gives 52.851mm displacement.

3.2 Tables

3.2.1 Running Time 15 Seconds

From Table 1, the conventional TLCD gives a minimum displacement of 71.261mm for 2.5 inches WL at 15s. However, TLCSBD shows the least displacements than the TLCD in all the cases. In Case I, the displacement value 63.374mm is found for 0 inches WL. For Case II, 66.476mm displacement is gained for 1 inch WL. Furthermore, for Case III, 66.810mm is found for 1-inch WL. Among all the three cases and two floating conditions, the least displacement has been recorded in Case I, that is fixed sand-filled balls and the optimum WL is 0 inches.

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

Water level (inches)	Controlled By TLCD (Conventional)	Controlled by TLCSBD					
		CASE-I : 35% sand-filled ball		CASE-II : 45% sand filled ball		CASE-III : 50% sand-filled ball	
		Free	Fixed	Free	Fixed	Free	Fixed
0	73.690	70.705	**63.374**	70.432	69.945	67.447	**67.566**
0.5	74.296	69.584	66.032	72.103	69.940	69.298	69.556
1	76.953	68.467	68.419	69.606	**66.476**	**66.810**	68.778
1.5	75.919	**67.047**	68.002	**66.820**	71.795	68.897	68.372
2	78.842	73.734	68.883	70.364	73.657	68.761	69.792
2.5	**71.261**	69.410	69.028	67.792	69.459	68.226	72.011

To have a vivid understanding of the difference, Table 2 shows the maximum reduction percentages of all the minimum values received in different cases a their optimum heights in comparison to the uncontrolled data in Table 1. The conventional TLCD has only a 19.276% displacement reduction capacity for 2.5 inches WL at 15s. However, The maximum displacement reduction capacity is recorded in Case I: 35% fixed sand-filled balls at optimum WL 0 inches, which is 28.210% at 15s. It is 10% more effective than the conventional TLCD.

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	-	88.2772	-
Controlled by TLCD (conventional)	2.5	71.261	19.276
Case I : 35% sand-filled free ball	1.5	67.047	24.049
Case I : 35% sand-filled fixed ball	0	63.374	**28.210**
Case II : 45% sand-filled free ball	1.5	66.820	24.307

Case II : 45% sand-filled fixed ball	1	66.476	24.696
Case III : 50% sand-filled free ball	1	66.810	24.318
Case III : 50% sand-filled fixed ball	0	67.566	23.462

3.2.2 Running Time 20 Seconds

From Table 3, the conventional TLCD gives a minimum displacement of 56.891mm for 0.5 inches WL at 20s. However, TLCSBD shows the least displacements than the TLCD in most of the cases. In Case I, the displacement value 49.581mm is found for 0.5 inches WL. For Case II, 49.153mm displacement is gained for 1 inch WL. Furthermore, for Case III, 50.140mm is found for 0 inches WL. Among all the three cases and two floating conditions, the least displacement has been recorded in Case II, that is free sand-filled balls and the optimum WL is 1 inch.

Table 3 : Top displacements (mm) at different water levels of different conditions at the 20s

Water level (inches)	Controlled By TLCD (Conventional)	Controlled by TLCSBD					
		CASE-I : 35% sand-filled ball		CASE-II : 45% sand filled ball		CASE-III : 50% sand-filled ball	
		Free	Fixed	Free	Fixed	Free	Fixed
0	63.609	57.260	**58.260**	50.401	53.656	**50.140**	52.851
0.5	**56.891**	**49.581**	58.903	52.392	**52.601**	54.988	**52.153**
1	63.472	70.339	70.339	**49.153**	54.535	54.097	54.396
1.5	56.925	53.490	72.155	50.279	57.005	53.799	53.237
2	65.023	58.090	70.137	54.334	60.871	59.081	56.327
2.5	68.532	63.800	70.832	50.191	60.280	58.567	56.633

To have a clear understanding of the difference, Table 4 shows the maximum reduction percentages of all the minimum values received in different cases and their optimum heights in comparison to the uncontrolled data in Table 4. The conventional TLCD has only a 14.476% displacement reduction capacity for 0.5 inches WL at 20s. However, The maximum displacement reduction capacity is recorded in Case II: 45% free sand-filled balls at optimum WL 1 inch, which is 26.109% at the 20s. It is 12% more effective than the conventional TLCD.

Table 4 : Top displacements (mm) & maximum reduction percentages (%) for all conditions at 20s

Conditions	Water Level (inches)	Top displacement (mm)	Maximum Reduction Percentage (%)
Uncontrolled Structure	-	66.521	-
Controlled by TLCD (conventional)	0.5	56.891	14.476
Case I : 35% sand-filled free ball	0.5	49.581	25.466
Case I : 35% sand-filled fixed ball	0	58.260	12.419
Case II : 45% sand-filled free ball	1	49.153	**26.109**
Case II : 45% sand-filled fixed ball	0.5	52.601	20.925
Case III : 50% sand-filled free ball	0	50.140	24.625
Case III : 50% sand-filled fixed ball	0.5	52.153	21.598

3.3 Optimum Results

3.3.1 Optimum Graphs

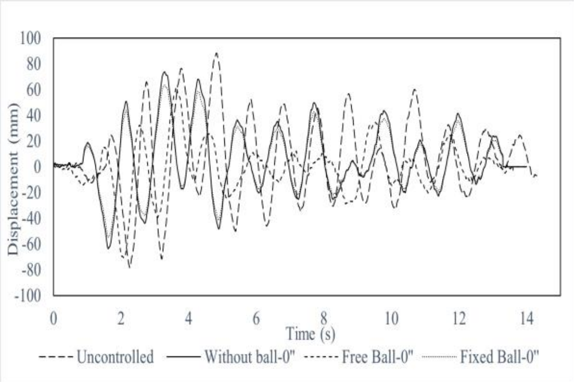

Figure 15 : Displacement vs Time at WL 0 inches

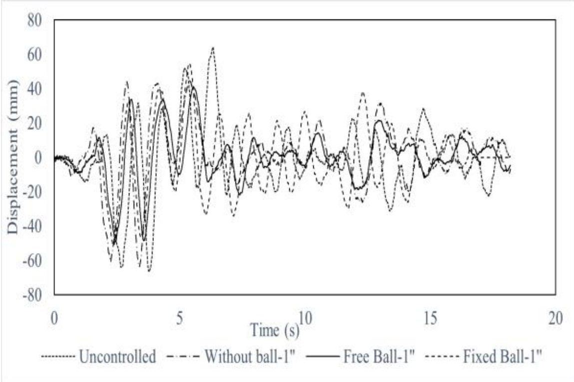

Figure 16 : Displacement vs Time at WL 1 inch

Running time 15s : Figure 15 is the graphical representation of the output data compared to all other cases for the optimum height of 0 inches WL in 15 seconds. Therefore, the highest reduction is recorded for 35% sand-filled TLCSBD (fixed floatation) at 0 inches WL.

Running time 20s: Figure 16 is the graphical representation of the output data compared to all other cases for 1 inch WL in 20 seconds. Therefore, the highest reduction is recorded for 45% sand-filled TLCSBD (free floatation) at 1 inch WL.

3.3.2 Optimum Table

Running time 15s : Table 5 exhibits a detailed variance influenced by the two floating conditions in Case I. At 0 inches WL, free-floating SB has a reduction percentage of 24.853%, lower than the fixed-floating sand-filled balls. The fixed-floating SB shows a 28.210% reduction capacity, 12% higher than the conventional TLCD for the same WL.

Table 5 : 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	-	88.2772	-
Controlled by TLCD (conventional)	0	73.69	16.524
Case I : 35% sand-filled free ball	0	70.705	24.853
Case I : 35% sand-filled Fixed ball	0	63.374	**28.210**

Running time 20s: Table 6 exhibits a detailed variance influenced by the two floating conditions in Case II. At 1 inch WL, free-floating SB has a reduction percentage of 26.109%, higher than the fixed-floating sand-filled balls. The fixed-floating SB shows 18.018% reduction capacity. The conventional TLCD for the same WL has a 4.583% reduction capacity which is around 22% lower than the free-floating SB.

Table 6 : Top displacement(mm) at optimum water level for all conditions at 20s

Conditions	Water Level (inches)	Top displacement (mm)	Reduction Percentage (%)
Uncontrolled Structure		66.521	-
Controlled by TLCD (conventional)	1	63.472	4.583
Case II : 35% sand-filled free ball	1	49.153	**26.109**

Case II : 35% sand-filled fixed ball	1	54.535	18.018

4. CONCLUSIONS

With the gradual increment of the adoption of TLCD in engineering structures including industrial sectors, it is becoming a vital need to research for a satisfactory optimization of the TLCD. However, by the time the optimization becomes cost-efficient oriented. The study on the vibration control of a Multi-Degree-of-Freedom (MDOF) structure by applying a Tuned Liquid Column Sand Ball Damper (TLCSBD) aims to ascertain the effectiveness of the applied modification and encourage further research for economic optimization. The analysis presents a detailed variance among two configurations: Uncontrolled (without TLCD), Controlled with TLCD, and TLCSBD. The floating method of sand-filled balls is also taken into consideration to figure out the distinction.

Analyzing the displacement data for the top portion of the structure for all the referred cases in the methodology of this paper, it is shown that, in response to the El-Centro prototype shaking generated by the earthquake shake table for a running time of 15 seconds and 20 seconds the optimum liquid heights are 0 inches and 1 inch in the liquid-containing columns successively. In these two cases, TLCSBD having 35% weight sand-filled balls with fixed floating position secured by rubber elastic band loop with steel plate decreases the top displacement of the structure significantly more than the free position floating of 45% weight sand-filled balls. The elastic rubber band loop contributed to obstructing the free sloshing of the liquid to dissipate the kinetic energy more.

In conclusion, the modification of the TLCD with sand-filled balls is more reliable than the conventional TLCD.

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