Tuned Liquid Damper(TLD) in irregular building

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Abstract: *The project examines the efficiency of converting water tanks into tuned liquid dampers to mitigate seismic-induced vibrations in tall, slender, and irregular L-shaped buildings, complementing traditional dampers like tuned mass and viscous dampers.*

Experimental investigations were carried out on scaled models of L shaped three storey buildings using a shake table. Numerical investigation was carried out using ETABS to arrive at the dimension of the scaled model. The response of the structure with TLD is studied and the optimum depth of water is experimentally determined. The acceleration response was recorded using accelerometer sensors positioned at various locations in the model. Further, the response of the structure with different water levels on TLD for sinusoidal acceleration of 0.1g with 1Hz frequency was studied. The experiments were repeated with the optimum depth of water at different locations on the structure to identify the best location for TLD in the L shaped structure.

From the study, it was observed that TLDs are a good solution for mitigating vibrations in irregular buildings when the tank is positioned near the centre of gravity and when it is half filled. TLDs can perform better since the primary mode of vibration of irregular buildings will be torsional and the sloshing of water in both directions can be helpful in reducing the response in both directions.

KEYWORDS: Tuned liquid dampers, sloshing action, seismic damping, shake table.

1. General

Current trends in the construction industry demand taller and lighter structures, which are also more flexible and have quite low damping value. This increases failure possibilities and also, problems from serviceability point of view. The devastating earthquake around the world has made experts think about the response of structures during earthquake vibrations. Today one of the main challenges in structural engineering is to form innovative design concepts to protect structures along with its materials and occupants. Earlier concept of making a structure to resist earthquakes was to make the structure excessively stiff and strong. But this method has not been entertained in recent years as they are not economical. Currently designers focus on appropriately sizing the structure to be strong and ductile enough to survive the shaking with acceptable damage, to equipping it with base isolation or using structural vibration control technologies to minimise any forces and deformation. The other solution to resolve the problem of earthquake induced damage is to incorporate passive or active systems to control vibrations.

Tuned mass dampers was one such innovation introduced to reduce seismic effect. But these devices are large enough to reduce some of the occupant space (Tait et. al., 2008 & Lívio Pires et, al., 2019). They are usually placed at the top of structures. So, researchers began to investigate the scope of turning any of the structural components to passive vibration resisting structures. This has led them to convert existing water tanks as passive systems. A TLD (tuned liquid damper) is a passive control device on top of a structure that dissipates the input excitation energy through the liquid boundary layer friction, and wave breaking (Abd Elrahman et. al., 2015, Alberto Di Matteo et. al., 2022, K. Fujii et. al., 1990). A passive control system does not require an external power for operation and utilises the motion of the structure to develop the control forces. Systems in this category are very liable since they are unaffected by power outages which are common during earthquakes. Moreover, it requires low maintenance requirements (G. Hemalatha and K.P. Jaya, 2008).

2. Numerical study

The effect of optimum height of water and optimum position of water tank for L shaped building is studied numerically using ETABS 20.0.1. A reference structure of L shape in plan is modelled in ETABS and its mode of vibration and frequency is identified. Keeping it as a reference structure a scaled down model is created in ETABS. The model was scaled down by maintaining the same natural frequency and mode of vibration with the original building. Water in the water tank was modelled as a linear link element according to IS 1893 (part 2): 2014.

Spring for convective mass was modelled using a linear link element whose stiffness in X and Y direction is given as K/2, and its degree of freedom in Z direction was set as fixed. Spring for impulsive mass was also modelled using a linear link element, but its degree of freedom was set fixed in all directions.The plan dimension and the height of the story is scaled by a factor of 100 and the dimensions of the elements were modelled such that the frequency and mode of vibrations are same as the original reference structure.
The scaled down structure is provided with a water tank with different amounts of water. The investigation was also carried out using a water tank in various locations. The structures are subjected to sinusoidal acceleration of 0.1g. Frequency and acceleration of different models are plotted from ETABS. Identifying the ideal position and depth of water is made possible by comparing the acceleration and frequency of various models.

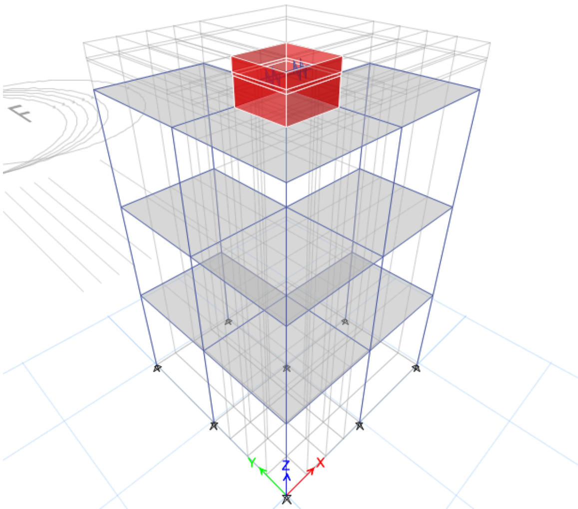

Figure 1: Scaled model with water in tank

3. Experimental study

The scaled down model is fabricated using aluminium columns and beams of size 10 X 10mm and a plywood slab of thickness 9mm attached with tuned liquid damper is subjected to sinusoidal excitation using a shake table. A shake table is a device used for shaking scaled structural models or building components. The test specimens are kept on a flat platform, often to the point of failure. The scaled down model is subjected to sinusoidal acceleration and the structure is excited with 1Hz frequency. The data is acquired using acceleration sensors placed at each storey of structure.

The setup consisted of a unidirectional shake table with a 1.5 m × 0.5 m sliding platform attached through a pulley system to a motor and can be used to create sinusoidal external excitation of different frequencies. Custom made acceleration sensors with a data acquisition system were used for recording data. The sensor array consists of four accelerometers and a hardware for acquiring data. A python-based software is used to acquire and save data on a computer.
The experimental study is conducted with 30mm, 40mm, 50mm, 60mm and 70mm water height. The experiment is repeated by placing tank at three different locations. The acceleration data obtained from each set of tests is compared to obtain optimum depth and optimum position.

Figure 2: Data extraction using sensors

Figure 3: Tank positioned at left corner

Figure 4: Tank positioned near centre

Figure 5: Tank positioned at middle corner

4. **Numerical Analysis**

The scaled down structure is modelled in ETABS. The frequency, acceleration and displacement plots are extracted after analysis. The three mode of frequency is tabulated in Table 1 below:

Table 1: Frequency for three mode of vibrations

Mode	Frequency (Hz) of reference structure	Frequency of scaled down structure (Hz)
Mode 1	9.1	9.2
Mode 2	9.2	9.3
Mode 3	11.25	11.75

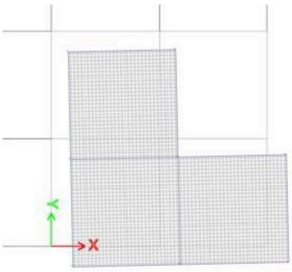

Figure 6: Mode shape 1

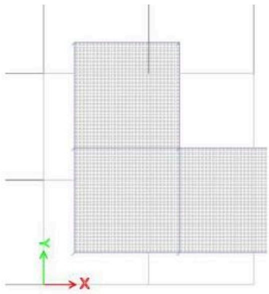

Figure 7: mode shape 2

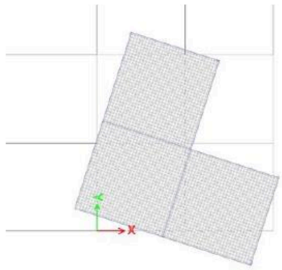

Figure 8: mode shape 3

Mode shape of scaled down structure for three mode of vibration is shown in Figure 6, Figure 7 and Figure 8 respectively:

4.1 Displacement Response

Figure 8 shows the acceleration response of the top storey of the structure with empty tank

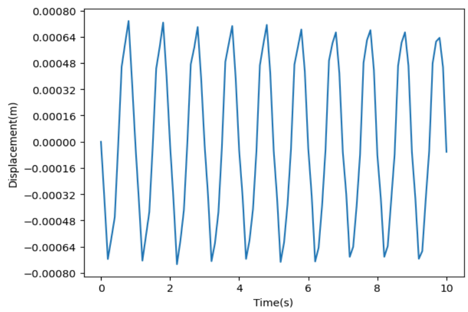

Figure 8: Time Vs displacement graph for structure with empty tank

Figure 9 shows time Vs displacement graph of top storey of structure with water tank having 40mm height water

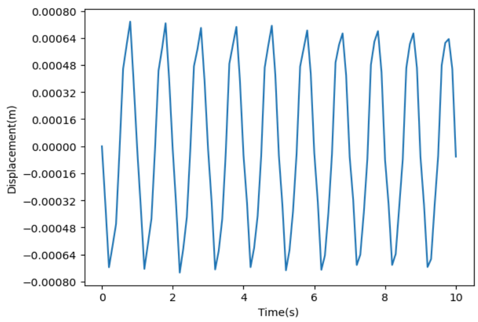

Figure 9: Time Vs displacement graph for structure with water at a depth of 40 mm

Figure 10 shows time Vs displacement graph of top storey of structure with water tank having 50mm height water

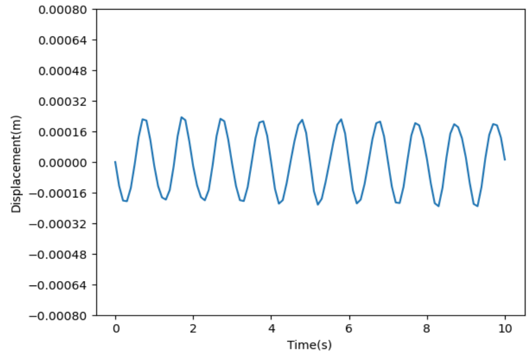

Figure 10: Time Vs displacement graph for structure with water at a depth of 50 mm

Figure 11 shows time Vs displacement graph of top storey of structure with water tank having 60mm height water.

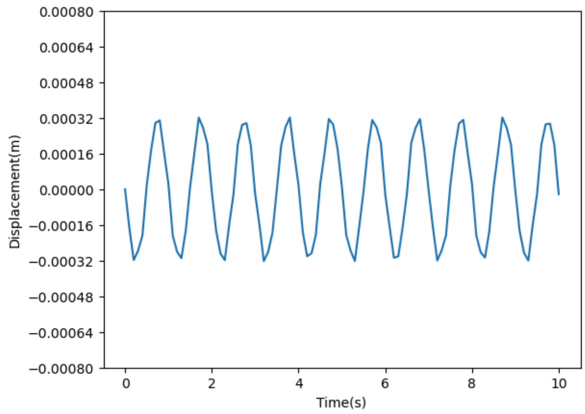

Figure 11: Time Vs displacement graph for structure with water at a depth of 60 mm

Table 6.2 depicts the displacement of each storey with different depths of water when subjected to sinusoidal acceleration of 0.1g.

Table 2: Displacement of structure under different water level

Depth of water (mm)	Storey	Displacement (mm)
Empty tank	3	0.71
	2	0.59
	1	0.34
40	3	0.73
	2	0.60
	1	0.35
50	3	0.23
	2	0.18
	1	0.10
60	3	0.32
	2	0.26
	1	0.16

Displacement Vs time graph for structure with different water levels is plotted. From the graph plotted, it is very evident that structures carrying 50 mm water showed minimum displacement.

4.2 Acceleration Response

The structure was modelled in ETABS. It is subjected to sinusoidal acceleration of 0.1g. The time Vs acceleration graph is plotted after analysis. The analysis is carried out for 40, 50, and 60mm. Figure 12 to figure 14 shows the acceleration response of the structure with water height of 40mm, 50mm and 60mm.

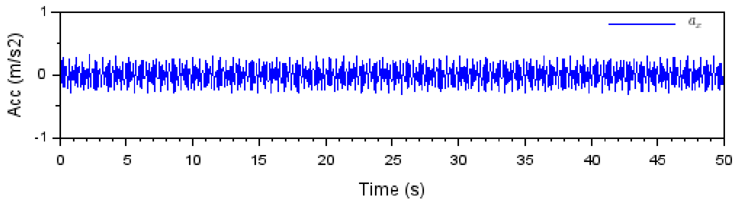

Figure 12: Time Vs acceleration graph for 40mm water

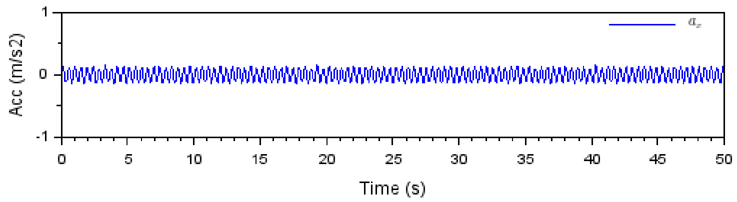

Figure 13: Time Vs acceleration graph for 50mm water

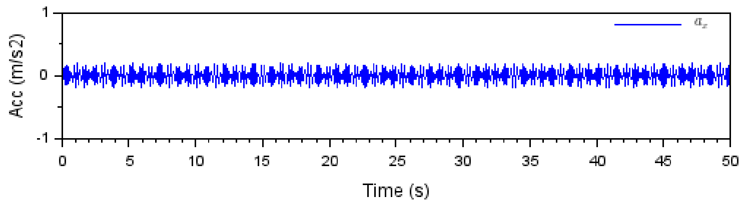

Figure 14: Time Vs acceleration graph for 60mm water

Table 3 shows the value of acceleration in x axis for scaled down structure with different height of water

Table 3: Acceleration in x axis extracted analytically

Water level mm	Acceleration in x axis (m/s^2)
40	0.3
50	0.2
60	0.25

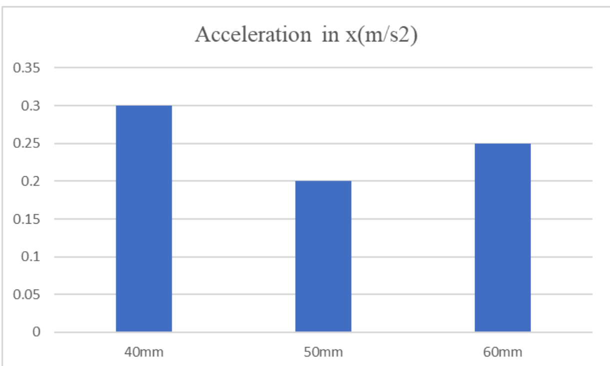

Figure 15: Acceleration in x axis for different water level

The time Vs acceleration graph of structure with three different water levels shows a significant reduction in acceleration at a water level of 50mm.

5. Experimental Analysis

Using sensors positioned at each level, the acceleration response of the tank is measured when it is put in different locations with varying water levels. When the tank was empty and kept at the left-hand corner of the structure, an acceleration study revealed acceleration of 1.8 m/s2 in the x direction and 1.5 m/s2 in the y direction. There was a 55.55% drop in acceleration with a 30 cm water level in the water tank. A further rise in water level to 40 cm revealed a percentage decline in acceleration of 66.66%. With 50 and 60 cm of water in the tank, acceleration is reduced by 77.77%. However, as the water level rose further to 70 cm, the acceleration decreased by 72.22%. With more water present, it was discovered that the acceleration reduction was slower. Hence, the acceleration reduction was slower with water content more than 60 cm. Therefore optimum water level for better performance of tld in irregular buildings is 60 cm. The acceleration response in y direction at a water level of 50cm was found to decrease acceleration to 33.33% compared with the tank at its empty condition.

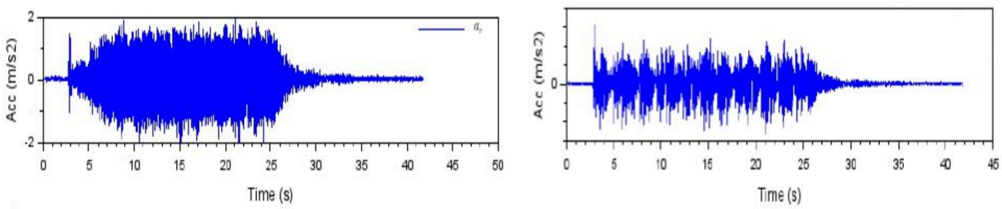

Figure 16: Time Vs acceleration plot for structure without water tank in x and y direction

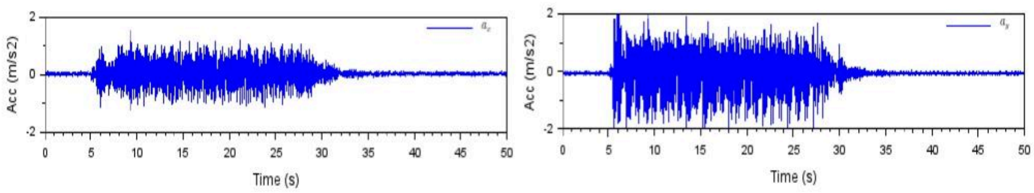

Figure 17: Time Vs acceleration plot for water at a depth of 30mm in x and y direction

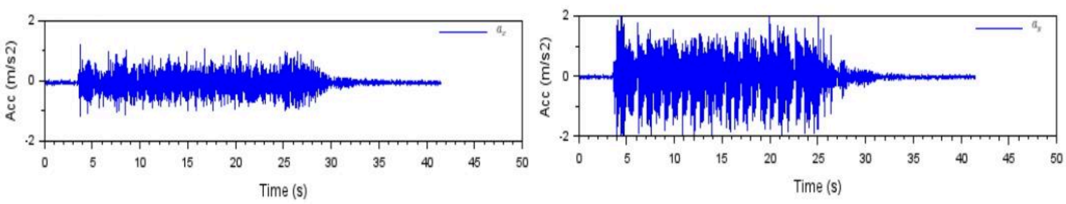

Figure 18: Time Vs acceleration plot for water at 40 mm depth in x and y direction

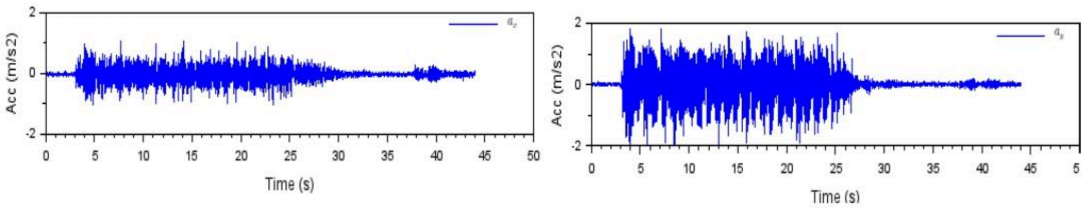

Figure 19: Time Vs acceleration plot for water at 50mm depth in x and y direction

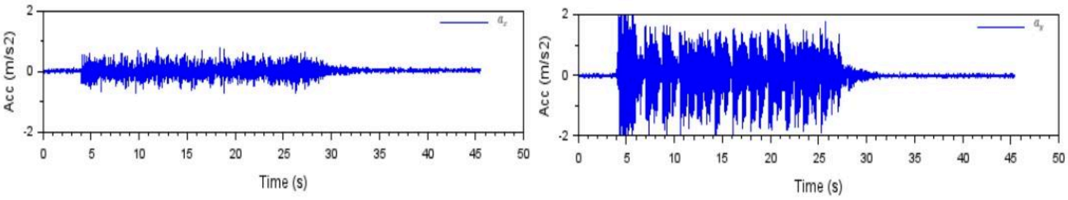

Figure 20: Time Vs acceleration plot for water at 60 mm depth in x and y direction

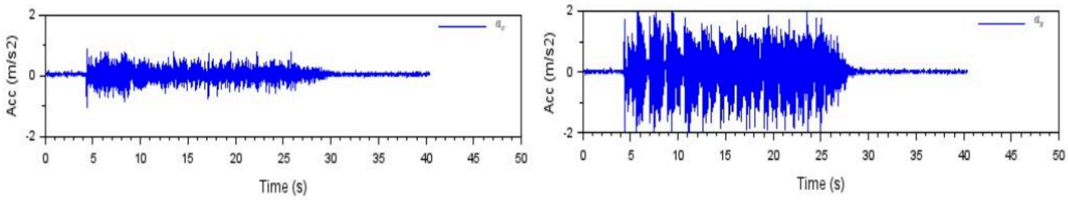

Figure 21: Time Vs acceleration plot for water at 70mm depth in x and y direction

The experiment is then carried out again with the tank placed close to the centre of gravity. When the tank is empty, the acceleration response is determined to be 1.5 m/s2 in the y axis and 1.8 m/s2 in the x axis. When the tank's water level reached 30 cm, the acceleration in the x axis fell by 55.55%. The acceleration has been further reduced to 72.22% by 40 cm of water depth. Further raising the water level to 50 cm resulted in a 77.77% x-axis acceleration decrease and a 46.67% y-axis acceleration decrease. However, further raising the water level has increased the percentage of acceleration in both the x and y directions. Thus, the highest drop in acceleration was seen at 50 cm of water.

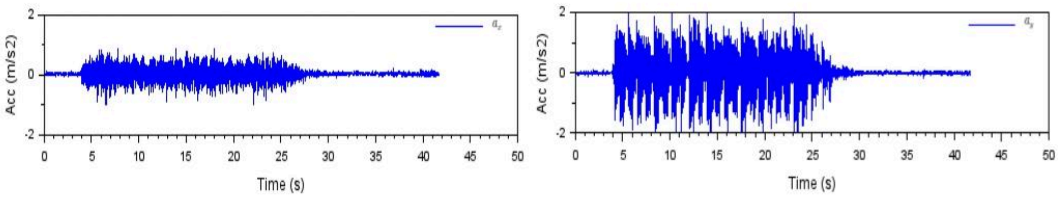

Figure 22: Time Vs acceleration plot for water at 30mm depth in x and y direction

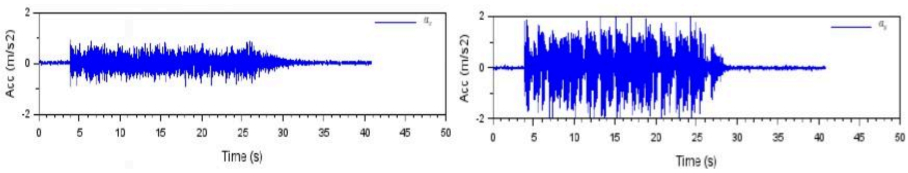

Figure 23: Time Vs acceleration plot for water at 40mm depth in x and y direction

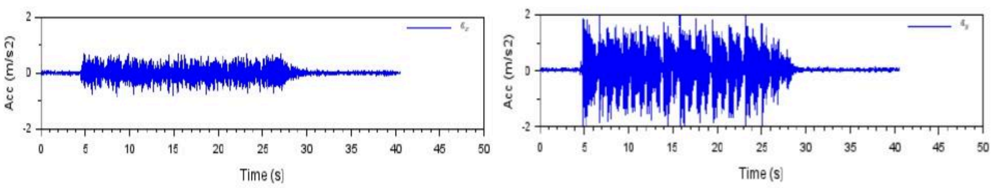

Fig 24: Time Vs acceleration plot for water at 50mm depth in x and y direction

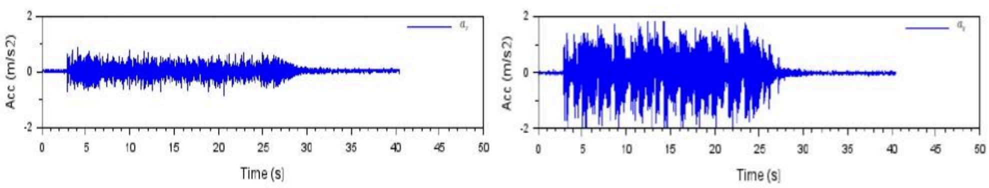

Figure 25: Time Vs acceleration plot for water at 60 mm depth in x and y direction

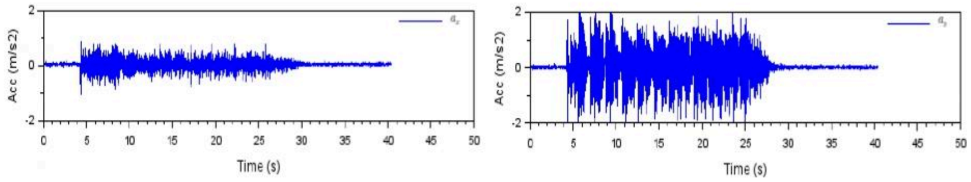

Figure 26: Time Vs acceleration plot for water at 70mm depth in x and y direction

The structure was tested with a tank positioned at the middle corner. When the structure was provided with 30 cm of water in the tank it showed a percentage decrease of 61.11% in acceleration. Further increase in water level to 50 cm showed a percentage decrease of 83.33% in acceleration. When water level is increased more than 50 cm increased percentage of acceleration.

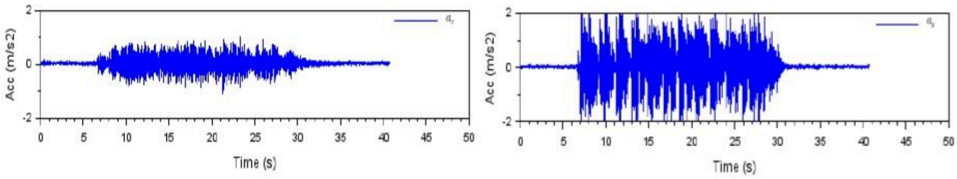

Figure 27: Acceleration Vs time plot for water at 30mm depth in x and y direction

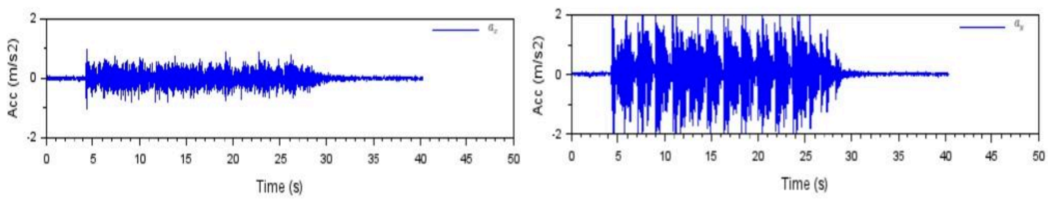

Figure 28: Acceleration Vs time plot for water at 40mm depth in x and y direction

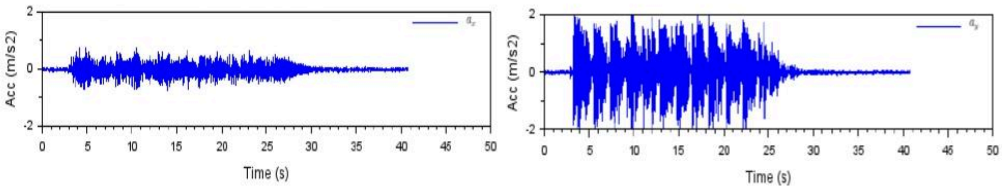

Figure 29: Acceleration Vs time plot for water at 50mm depth in x and y direction

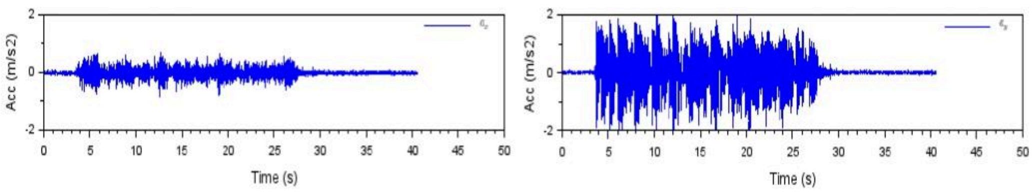

Figure 30: Acceleration Vs time plot for water at 60 mm depth in x and y direction

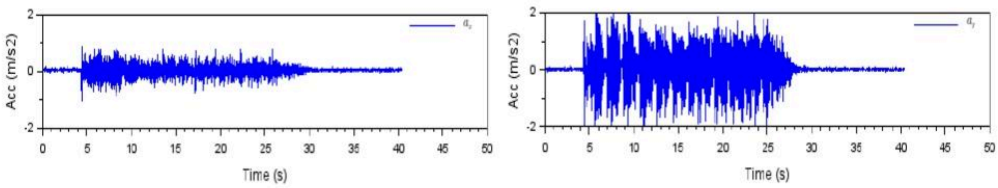

Figure 31: Acceleration Vs time plot for water at 70mm depth in x and y direction

From the analysis carried out on structures with different water levels in different locations of tank, 50 cm of water is found to be most effective. Tank with partially filled water placed at the middle corner is found to be most effective.

Table 3: Acceleration in x and y axis for different water level

Water level (mm)	Acceleration value when tank in left corner		Acceleration value when tank near centre of gravity		Acceleration value when tank in middle corner	
	X axis	Y axis	X axis	Y axis	X axis	Y axis
empty	1.8	1.5	1.8	1.5	1.8	1.5
30	0.8	1.2	0.8	1	0.7	1.5
40	0.6	1.1	0.5	0.8	0.5	1
50	0.4	1	0.4	0.8	0.3	0.5
60	0.4	1	0.45	1.2	0.3	1
70	0.5	1.2	0.5	1.2	0.4	1.2

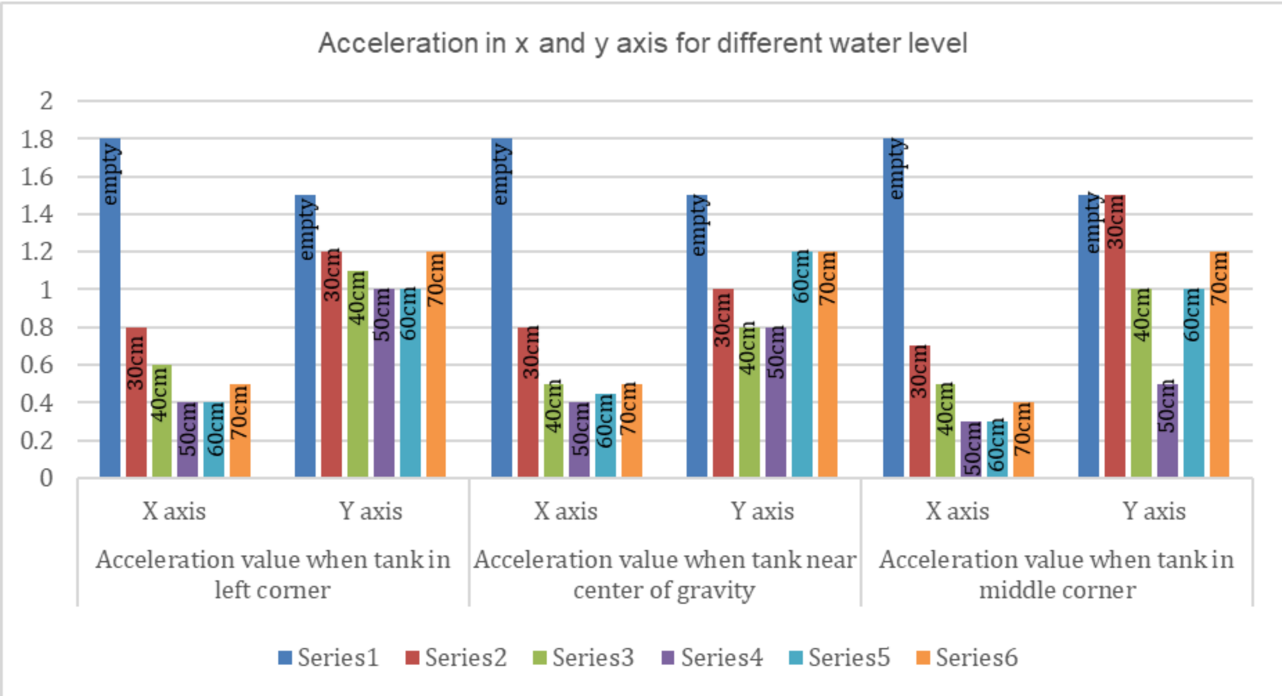

Figure 32: Acceleration in x and y axis for different water level

6. **Frequency Analysis of Forced Vibration**

Figure 33 to 37 shows the frequency response of the structure with water height of 30mm, 40mm, 50mm, 60mm and 70mm respectively when the structure is subjected to forced vibration of 1Hz frequency.

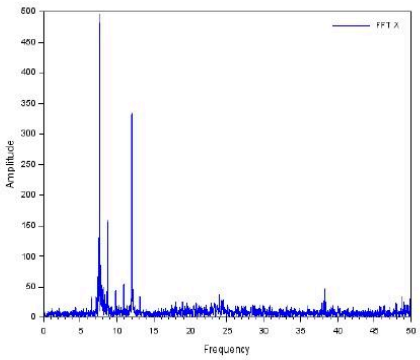

Figure 33: Frequency Vs amplitude plot for 30 mm water

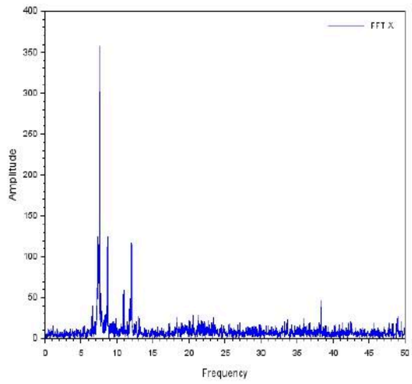

Figure 34: Frequency Vs amplitude plot for 40 mm water

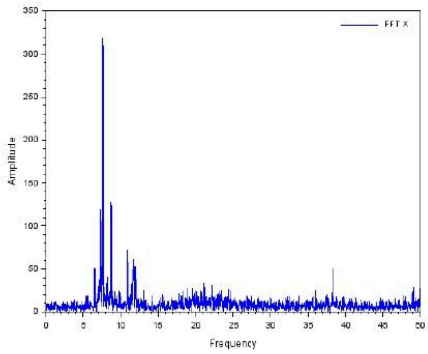

Figure 35: Frequency Vs amplitude plot for 50 mm water

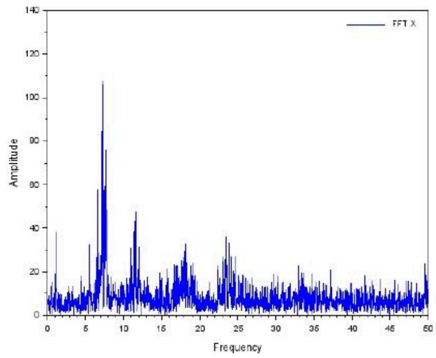

Figure 36: Frequency Vs amplitude plot for 60 mm water

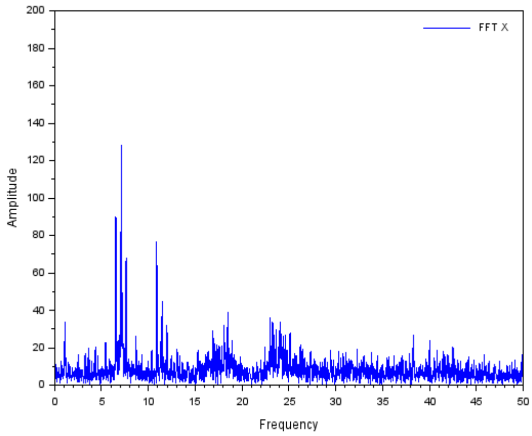

Figure 37: Frequency Vs amplitude plot for 70 mm water

Table 4 consolidates the frequency corresponding to different mode shapes when the water height is varied in the tank. The same is depicted in the chart given in figure 38. It can be observed that there is a decrease in frequency for increase in water content.

Table 4: Frequency of structure for different water levels.

Amount of water(mm)	Frequency		
	Mode 1	Mode 2	Mode 3
30	8	8.9	12
40	7.9	8.8	12
50	7.8	8.8	11
60	7.5	8	11
70	7	7.5	11

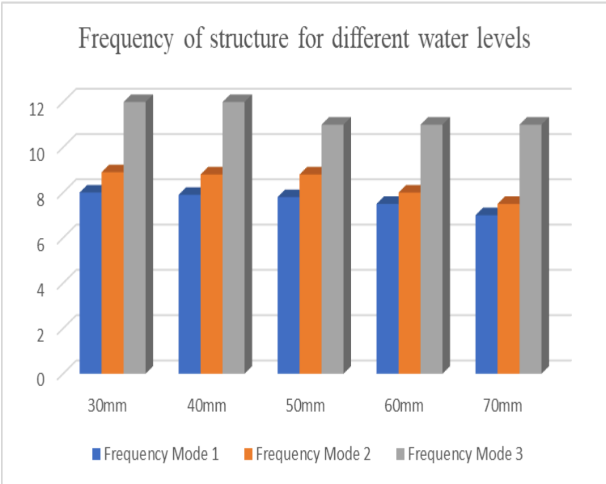

Figure 38: Frequency plot for different water levels.

7. Conclusion

In the present study, numerical and experimental study of the structure were performed. It is observed that the structural frequency determined numerically and experimentally is the same. The structure containing water at a 50 mm depth demonstrated the greatest reduction in seismic reaction, as observed from the time Vs acceleration graph obtained from experimental and analytical study. Thus, It can be concluded that irregular and regular structures with tanks that are partially filled with water can provide maximum reduction in response.

In this study, the structure is analysed with 30, 40, 50, 60 and 70 mm with different locations. The plot of acceleration reveals that the greatest response reduction is observed when the water depth is 50 mm. Better response was demonstrated by a structure that had a half full tank positioned in the middle corner, which is close to the centre of gravity of the structure. It is also observed that the structure frequency reduces as water level rises. During experiments, it was observed that the structure primarily experienced a torsional mode of vibration. This was evident from the acceleration response in both x and y directions. Finally, it can be concluded that TLDs are a good solution for mitigating vibrations in irregular buildings when the tank is positioned near the middle corner and when it is half filled. TLDs can perform better since the primary mode of vibration of irregular buildings will be torsional and the sloshing of water in both directions can be helpful in reducing the response in both directions.

8. **References**

Banerji, P., & Samanta, A. (2011). Earthquake vibration control of structures using hybrid mass liquid damper. *Engineering structures*, *33*(4), 1291-1301. https://doi.org/10.1016/j.engstruct.2011.01.006

Cammelli, S., Li, Y. F., & Mijorski, S. (2016). Mitigation of wind-induced accelerations using Tuned Liquid Column Dampers: Experimental and numerical studies. *Journal of Wind Engineering and Industrial Aerodynamics*, *155*, 174-181. https://doi.org/10.1016/j.jweia.2016.06.002

Chang, C. C., & Gu, M. (1999). Suppression of vortex-excited vibration of tall buildings using tuned liquid dampers. *Journal of Wind Engineering and Industrial Aerodynamics*, *83*(1-3), 225-237. https://doi.org/10.1016/S0167-6105(99)00074-4

Chen, B. F., & Yang, B. H. (2018). Experimental study of a hybrid TMD and TLD on structure motion reduction. *Ocean Engineering*, *165*, 538-549. https://doi.org/10.1016/j.oceaneng.2018.06.016

Chen, G., & Wu, J. (2001). Optimal placement of multiple tune mass dampers for seismic structures. *Journal of Structural Engineering*, *127*(9), 1054-1062. https://doi.org/10.1061/(ASCE)0733-9445(2001)127:9(1054)

Di Matteo, A., Masnata, C., Adam, C., & Pirrotta, A. (2022). Optimal design of tuned liquid column damper inerter for vibration control. *Mechanical Systems and Signal Processing*, *167*, 108553. https://doi.org/10.1016/j.ymssp.2021.108553

Fujii, K., Tamura, Y., Sato, T., & Wakahara, T. (1990). Wind-induced vibration of tower and practical applications of tuned sloshing damper. *Journal of Wind Engineering and Industrial Aerodynamics*, *33*(1-2), 263-272. https://doi.org/10.1016/0167-6105(90)90042-B

Furtmüller, T., Joas, G., & Adam, C. (2022). Control of pendulum oscillations by Tuned Liquid Dampers. *Journal of Fluids and Structures*, *114*, 103753. https://doi.org/10.1016/j.jfluidstructs.2022.103753

G. Hemalatha and K.P. Jaya (2008), “Water tank as passive tmd for seismically excited structures”, Asian journal of civil engineering (building and housing), 9, (4), 349-366

Kiran, N. K., Unni Kartha, G., & Nair, N. (2022). A Study on the Effect of Tank Shape on the Performance of Tuned Liquid Dampers. In *Recent Advances in Materials, Mechanics and Structures: Select Proceedings of ICMMS 2022* (pp. 237-244). Singapore: Springer Nature Singapore., https://doi.org/10.1007/978-981-19-3371-4_21

Novo, T., Varum, H., Teixeira-Dias, F., Rodrigues, H., Silva, M. F., Costa, A. C., & Guerreiro, L. (2014). Tuned liquid dampers simulation for earthquake response control of buildings. *Bulletin of earthquake engineering*, *12*, 1007-1024. https://doi.org/10.1007/s10518-013-9528-2

Pabarja, A., Vafaei, M., Alih, S. C., Yatim, M. Y. M., & Osman, S. A. (2019). Experimental study on the efficiency of tuned liquid dampers for vibration mitigation of a vertically irregular structure. *Mechanical Systems and Signal Processing*, *114*, 84-105. https://doi.org/10.1016/j.ymssp.2018.05.008

Roy, A., Ghosh, A. D., & Chatterjee, S. (2017). Influence of tuning of passive TLD on the seismic vibration control of elevated water tanks under various tank-full conditions. *Structural Control and Health Monitoring*, *24*(6), e1924. https://doi.org/10.1002/stc.1924

Tait, M. J., Isyumov, N., & El Damatty, A. A. (2008). Performance of tuned liquid dampers. *Journal of Engineering Mechanics*, *134*(5), 417-427. https://doi.org/10.1061/(ASCE)0733-9399(2008)134:5(417)

Vafaei, M., Pabarja, A., & Alih, S. C. (2021). An innovative tuned liquid damper for vibration mitigation of structures. *International Journal of Civil Engineering*, *19*, 1071-1090. https://doi.org/10.1007/s40999-021-00626-8

Zhang, A., Xie, Z., Zhang, Y., & Lin, H. (2021). Shaking table test of a prefabricated steel frame structure with all-bolted connections. *Engineering Structures*, *248*, 113273. https://doi.org/10.1016/j.engstruct.2021.113273