ANALYTICAL SIMULATION OF TLD AND ASSESSING THE EFFECTS OF TLD ON THE RESIDUAL DISPLACEMENT

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Abstract: *Various control systems have been implemented to mitigate the effects of earthquakes on buildings, aiming to reduce the kinetic energy generated by dynamic activity caused by earthquakes and wind. Among these systems, Tuned Mass Dampers (TMD) and Tuned Liquid Dampers (TLD) serve as cost-effective and practical passive control mechanisms. TMD and TLD essentially operate on the same principle. In this operating principle, the period of the damper is equal to or in predetermined proportions close to the fundamental period of the building. TLD is more advantageous compared to TMD due to its cost-effectiveness and potential benefits in the event of a fire. When subjected to dynamic motion, such as wind and earthquake effects, the damper counteracts the movement of the building in the opposite direction. A damper with an optimal mass ratio relative to the building mass is selected and placed in the structure to achieve this motion. TLD can be also utilized to mitigate the residual displacement. The residual displacement value is crucial for a building after an earthquake because it directly affects whether the building is suitable for retrofitting or the cost of retrofitting. This paper investigates the effect of the TLD on the residual displacement of a 10-story reinforced concrete building in post-earthquake conditions. The building was modelled in SAP2000 and a validation procedure was implemented to determine the optimal mass ratio for the TLD, achieved through Nonlinear Time History Analysis (NLTHA) using 3 ground motion records. Subsequently, after the TLD selection process, the residual displacement demand of the building with and without the TLD was determined, and the relationship between the TLD and residual displacement was established. The result of this paper indicates that TLD significantly reduces the residual displacement value by assisting in the recentering of the building.*

1 Introduction

Earthquakes are the most effective natural disasters that cause loss of life and destruction. They also cause damage to buildings even in the absence of extensive devastation. The amount of damage left by the earthquake is crucial for the building since the repairability of a building depends on the damage. This repairability of buildings after an earthquake is directly related to the amount of residual displacement (Kawashima et al.,1998). Residual displacement represents the displacement of a structure or structural element compared to its initial state after the earthquake effect is removed. If this amount is excessive, the building cannot be repaired, or it is not economically feasible to repair it. According to Priestley (1993), residual displacement is more important than maximum displacement, as it determines the post-earthquake state of the structure. There have been many studies in the literature on how to reduce the residual displacement for structures. Qazi et al. (2006) found that the use of high-strength reinforcing steel in columns can prevent the formation of plastic joints in critical sections and significantly reduce the residual displacement after strong ground motions. Hoult and Almeida (2022) were able to reduce the residual displacement of reinforced concrete walls to permissible levels by utilizing shape memory alloy bars instead of standard reinforcing steel. Lobo et al. (2017) conducted a study to evaluate the effectiveness of various devices, including viscous dampers, steel hysteric dampers, and passive and semi-active shape memory alloys, in reducing the maximum peak displacement and residual displacement of a reinforced concrete building subjected to earthquake ground motions. The study found that semi-active devices and linear viscous dampers were similarly effective and more efficient than passive shape memory alloys in controlling displacements.

Control systems, including passive, active, semi-active, and hybrid types have been developed and implemented in structures to absorb earthquake-induced forces and decrease the residual displacement. Passive control systems, a specific type of these systems, do not require external power to operate and can protect structures from dynamic loads like earthquakes and wind. To ensure their effectiveness, these systems must be finely tuned to the specific structure (Saaed et al., 2015). Passive control systems are typically classified into two types: isolators and dampers. Rubber-based elastomer isolators and friction-based sliding isolators are common types of seismic isolators that are widely used today (Naeim and Kelly, 1999). Friction-type dampers, metallic dampers, viscoelastic dampers, viscous liquid dampers, Tuned Mass Dampers (TMD), and Tuned Liquid Dampers (TLD) are also types of passive control systems that can be applied to structures to reduce the effects of dynamic loads such as earthquakes and wind.

TLD serves as an exemplary passive control system, operating without the need for external power sources. During dynamic events like earthquakes, the water inside TLD tanks undergoes a sloshing motion opposite to the structure's movement. Water tanks of TLD can be rectangular or circular. The sloshing motion in TLD systems is inherently nonlinear, requiring the use of linear analytical models with specific assumptions to approximate this complexity of nonlinear liquid behaviour. These methods are detailed in studies by Housner (1957,1963), Malhotra (2000), and Eurocode-8.

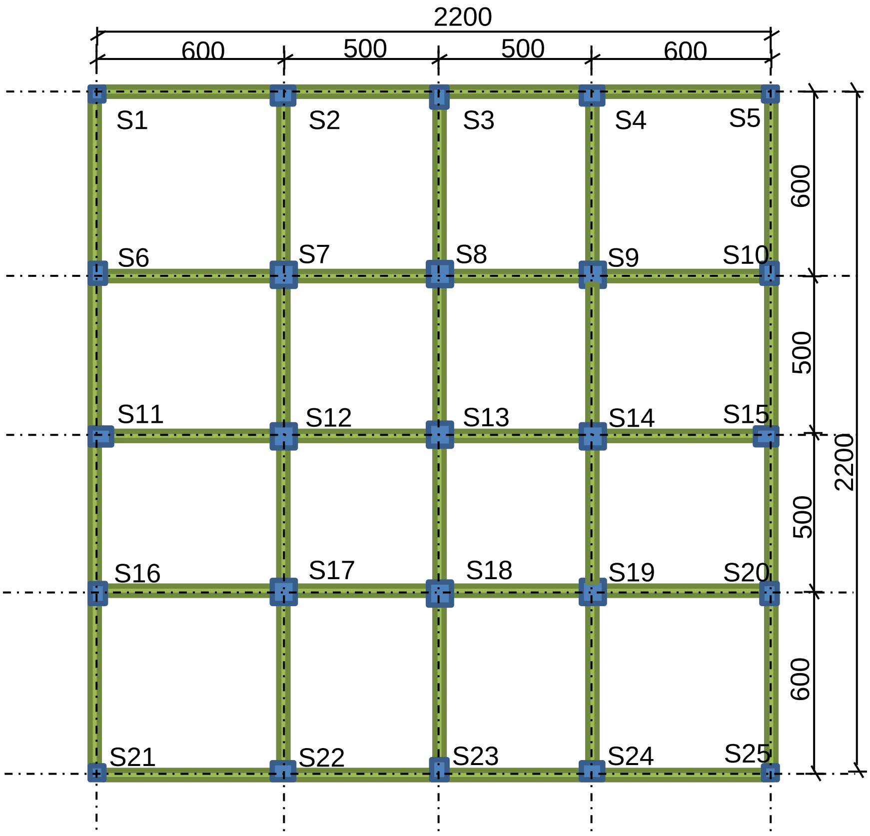
For better seismic behaviour, the TLD needs to be optimized in terms of mass ratio, frequency ratio, and water depth of the tank. This tuning phase has a crucial importance in the design process. According to Fujino et al. (1988), when the frequency of the TLD matches the dominant frequency of the structure, the TLD can effectively absorb the energy and reduce the vibrations of the structure. Tamura et al. (1992) found that when the mass ratio of TLD to structure is 1%, acceleration decreases by 55%, and peak displacement of the structure is also significantly reduced. Banerji et al. (2000) conducted numerical analyses and found that a water depth ratio of 0.15 can be considered shallow water, and the TLD with this depth ratio will provide the most effective results. The water depth ratio is defined as the ratio of the water height to the tank diameter if the tank is circular, or the ratio of the water height to the tank width if the tank is rectangular. In a study by Ashasi-Sorkhabi et al. (2017), it was found that the TLD is most efficient when the frequency ratio is between 1-1.2 and the mass ratio is 3%. They also found that TLDs work efficiently in structures with a hysteresis damping ratio of 2% or lower. Pabarja et al. (2019) designed TLDs based on the first and second dominant frequencies of a steel structure and placed them sequentially on each floor to determine the optimal frequency and location. They found that the maximum displacement reduction occurred when the TLD was placed on the top floor, and regardless of the placement floor, the TLD tuned to the second dominant frequency increased the structure's displacement. Yip et al. (2021) conducted an experiment to compare the effectiveness of using TLD versus not using TLD in a high-rise building simulation. They found that while the TLD system reduced the displacement demand on the ground floor by adding weight, it also increased the demand for peak displacement due to its mass and resulting inertia force. However, they also observed that the addition of TLD reduced the acceleration on the top floor.

This study aims to investigate the effectiveness of using TLD in reducing the post-earthquake residual displacement of RC buildings. For this purpose, a ten-storey reinforced concrete building representing the existing building stock in Turkey was modelled in SAP2000 and TLD tuning was conducted by comparing the residual displacement of the buildings with and without TLD. Since the building is symmetrical, it has the same period values in both directions. For this reason, the tanks to be used as TLDs were selected as circular tanks. NLTHAs were performed with 3 ground motion records and the effect of TLD on the residual displacement was estimated for different mass ratios.

2 Analytical Models and Method

2.1 The Building

The building has 10 stories, and all stories have the same height of 3 meters. It has a symmetrical design with 4 spans in both directions. The column cross-section sizes vary between the first five stories and the last five stories, decreasing in size towards the upper floors. The formwork plan of the building is shown in Figure 1.



Note: The units are in cm.

Figure 1. The formwork plan of the building

Similar columns and cross-sectional information on these columns are shown in Table 1. The beam sections are equal on all stories and have dimensions of 30x60 (cmxcm). The slab thickness was selected to be 12 cm. The concrete grade used is C14 for all elements and the steel grade is S220.

Table 1. Similar columns and dimensions

Similar Columns	Story	Dim. (cm×cm)
S1, S5, S21, S25	[1-5]	45x45
S2, S4, S22, S24	[1-5]	70x55
S3, S6, S10, S16, S20, S23	[1-5]	50x65
S7, S8, S9, S12, S13, S14, S17, S18, S19	[1-5]	75x75
S11, S15	[1-5]	70x50
S1, S5, S21, S25	[6-10]	40x40
S2, S4, S22, S24	[6-10]	70x35
S3, S6, S10, S16, S20, S23	[6-10]	30x65
S7, S8, S9, S12, S13, S14, S17, S18, S19	[6-10]	60x60
S11, S15	[6-10]	70x30

An analytical model of the building was prepared in SAP2000, by defining columns and beams with frame elements, and slabs with shell elements. Nonlinearity in columns and beams was ensured by assigning lumped plastic hinges to both ends of the elements. Elastoplastic moment-curvature relationships and P-M2-M3 interaction diagrams were defined to model the plastic hinges of beams and columns, respectively. A 3-D view of the SAP2000 model of the building is shown in Figure 2.

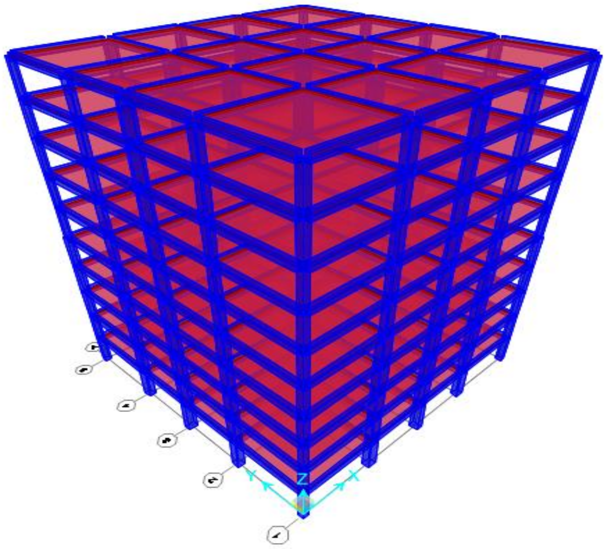


Figure 2. Analytical model of the building

2.2 Ground Motion Suite

NLTHA was applied based on the rules in the Turkish Seismic Code for Buildings (TSCB) 2018 by using 3 ground motions selected from a general search of the Pacific Earthquake Engineering Research Center (PEER) NGA ground motion database. The selection criteria of the ground motions are shear wave velocity in between 360 m/s and 760 m/s (soil class ZC), rupture distance higher than 20 km to minimize the near-fault effect, and source mechanism which is strike-slip. Ground motions were scaled to the target spectrum with the spectrum matching method in the SeismoMatch analysis program. The selected ground motions are listed in Table 2 and acceleration spectrums of scaled ground motions are represented in Figure 3 along with the 5% damped target spectrum.

Table 2. Earthquake data used in performance analysis of building with TLD

Earthquake	**Year**	**Station**	**Mag.**	**Mec.**	**$R_{jb(}$(km)**	**R_{rup}(km)**	**Vs_{30}(m/s)**
Landers	1992	Barstow	7.28	strike-slip	34.86	34.86	370.08
Kocaeli, Turkey	1999	Iznik	7.51	strike-slip	30.73	30.73	476.62
Hector Mine	1999	Amboy	7.13	strike-slip	41.81	43.05	382.93

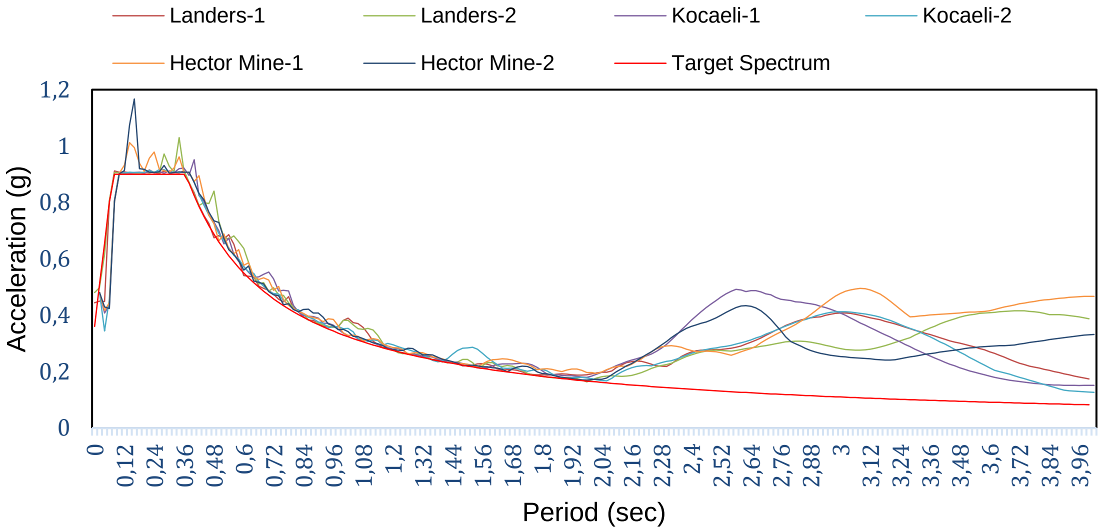


Figure 3. Acceleration spectrum of scaled ground motions

2.3 Tuned Liquid Dampers

In this study, TLD systems were represented as circular water tanks. The movement of the water inside a tank during seismic excitation is non-linear (Housner 1963). However, Housner (1963) proposed a method to transform the nonlinear motion of water into an equivalent linear one. For this purpose, Housner (1963) considered the moving water as two distinct masses as shown in Figure 4. During an oscillation, a certain part of the water moves in the same direction as the tank it is in, and this part is referred to as impulsive mass (m_i). The other part moves in the opposite direction of the tank's motion, and it is termed the "convective mass (m_c)". Unlike the impulsive mass, the convective mass possesses a certain level of lateral translational stiffness which is called k_c.

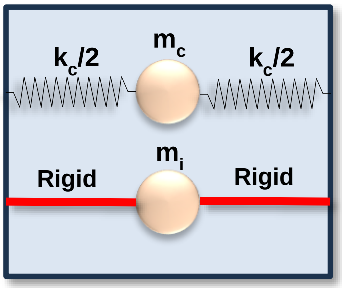


Figure 4. Simplification of TLD motion as two lumped masses

In this study, the selected frequency ratio is 1 (Fujina et al., 1988, Jin et al., 2007), while the water depth ratio is 0.15 (Banerji et al., 2000). Convective mass and impulsive mass are calculated using Eq. 1 and Eq. 2, respectively. Also, the translational stiffness of the convective mass is calculated using Eq. 3.

$$m_c = m_w 0.318 \frac{R}{h} tanh\left(1.84 \frac{h}{R}\right) \tag{1}$$

$$m_i = m_w \frac{tanh\left(\frac{1.74R}{h}\right)}{\left(\frac{1.74R}{h}\right)} \tag{2}$$

$$k_c = m_c \frac{g}{R} 1.84\, tanh\left(1.84 \frac{h}{R}\right) \tag{3}$$

R is the radius of the circular water tank and h is the water height. Eq. 4 expresses the circular frequency of the water tank used as TLD. As often stated in the literature, the circular frequency of the water tank is set equal to the fundamental frequency of the structure and the values of R and h are calculated by using this equation. Since the h/R ratio is 0.3 and the circular frequency of the TLD equals to the dominant frequency of the building, R can be calculated easily.

$$\omega^2 = \frac{g}{R} 1.84\, tanh\left(1.84 \frac{h}{R}\right) \tag{4}$$

Accordingly, the diameter of a water tank and the amount of water in it is shown in Figure 5. The given dimensions provide the optimal frequency tuning which is a unit frequency ratio.

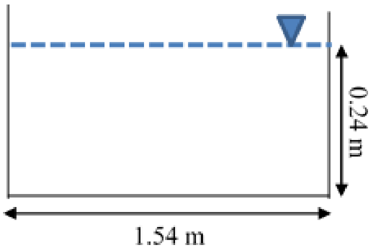


Figure 5. Dimension of a TLD

The TLD was modelled with an equal mass-spring mechanical system in SAP2000. The convective and impulsive masses of the TLD were modelled as separate masses. While the impulsive mass is connected to the building with a rigid element, the convective mass is connected to the building with a spring of which lateral translation stiffness was obtained according to Eq. 3.

To find the optimum mass ratio for TLD to be effective, models with many different mass ratios were prepared. Mass ratios of 3%, 5%, 10%, 15%, and 20% were determined and TLD systems were placed on the top floor of the building. The maximum displacement of the building were obtained for 3 ground motion records. Accordingly, the mass ratio that does not increase the maximum peak displacement of the building but at the same time reduces the residual displacement most effectively was selected as the most appropriate mass ratio. The relevant mass ratios and the required TLD information for these ratios are given in Table 3. TLD system elements are placed on the top story of the building in the required mass ratios. Figure 6 provides a three-dimensional view of the building to which the TLD was incorporated.

Table 3. TLD properties

Mass Ratio	**Water Mass (tons)**	**Required TLD**	**Number of rows**	**Σ $M_{impulsive}$ (ton)**	**Σ $M_{convective}$ (ton)**	**Σ k_c (kN/m)**
3%	158.7	355	2	28.4	83.9	988.6
5%	264.6	592	3	47.4	139.8	1648.5
10%	529.3	1184	6	94.8	279.7	3297.1
15%	793.5	1775	9	142.1	419.3	4942.8
20%	1058.1	2367	12	189.5	559.1	6591.4

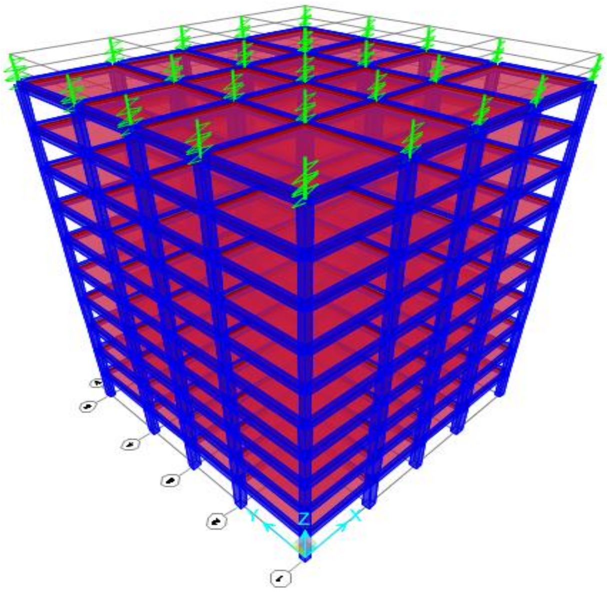


Figure 6. 3-D view of the building with TLD

3 Analysis Results

Scatter plots of the residual displacement in the X and Y directions are presented in Figures 7 and 8, respectively. According to the results of this study, the residual top displacement demand of the building without TLD is 0.60 m. It is evident that, on average, TLD significantly reduces the residual top displacement demand for all mass ratios. However, the variation in individual motions is greater in the X direction compared to the Y direction. The effect of TLD can be considered negligible in the Y direction in terms of the average value; however, this effect is not conservative for several individual motions. In general, since the demand value is in the X direction, it is worth noting that TLD is effective in reducing residual top displacement.

Nevertheless, it is not suitable to determine a mass ratio solely by evaluating the residual displacement demands. Tuning requires the evaluation of both the maximum top displacement during an earthquake motion and the residual displacement. For this purpose, the rate of change in maximum top displacement during an earthquake and residual displacement due to different TLD mass ratios are given in Figures 9 and 10.

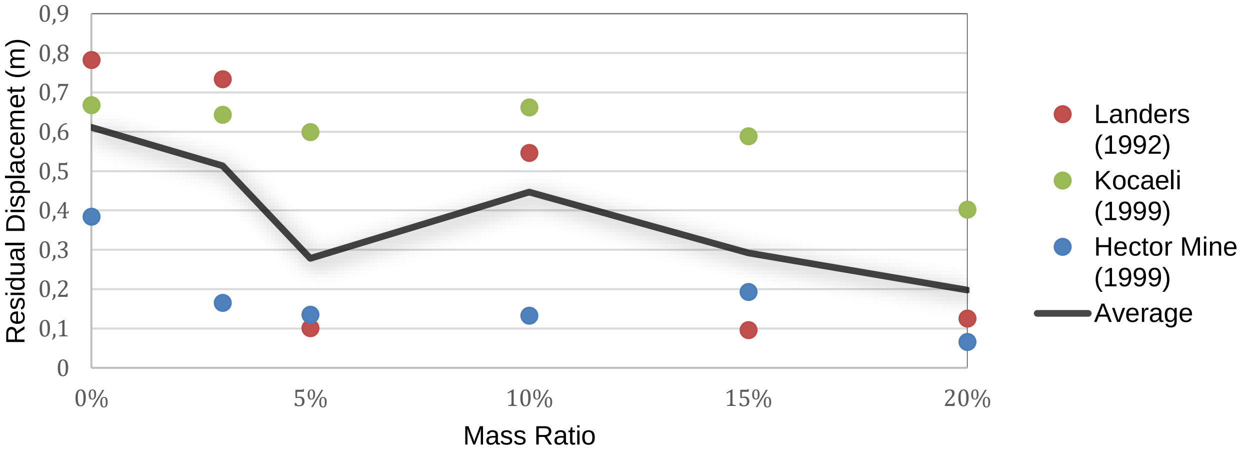


Figure 7. Residual displacement in X direction due to individual ground motions and their average

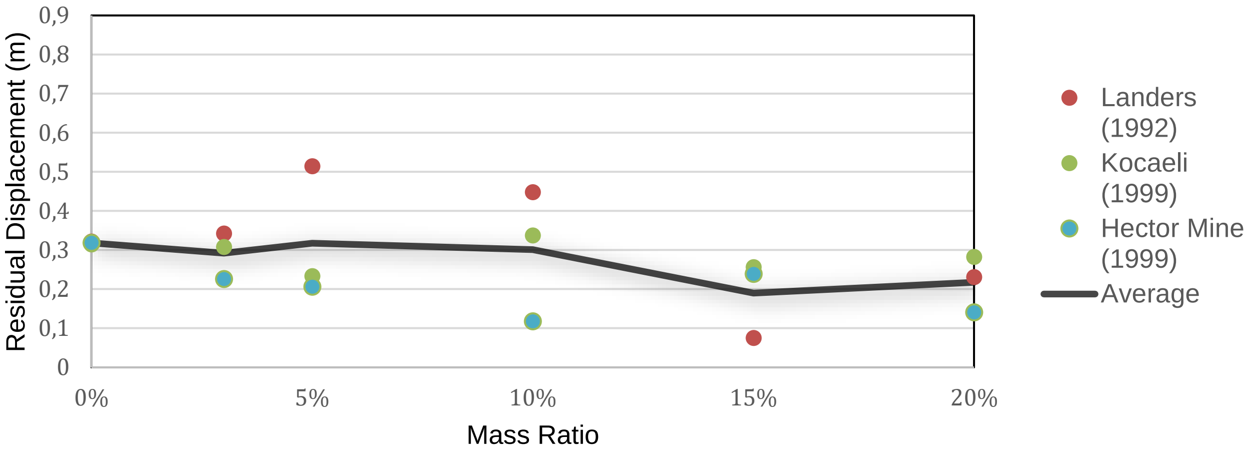
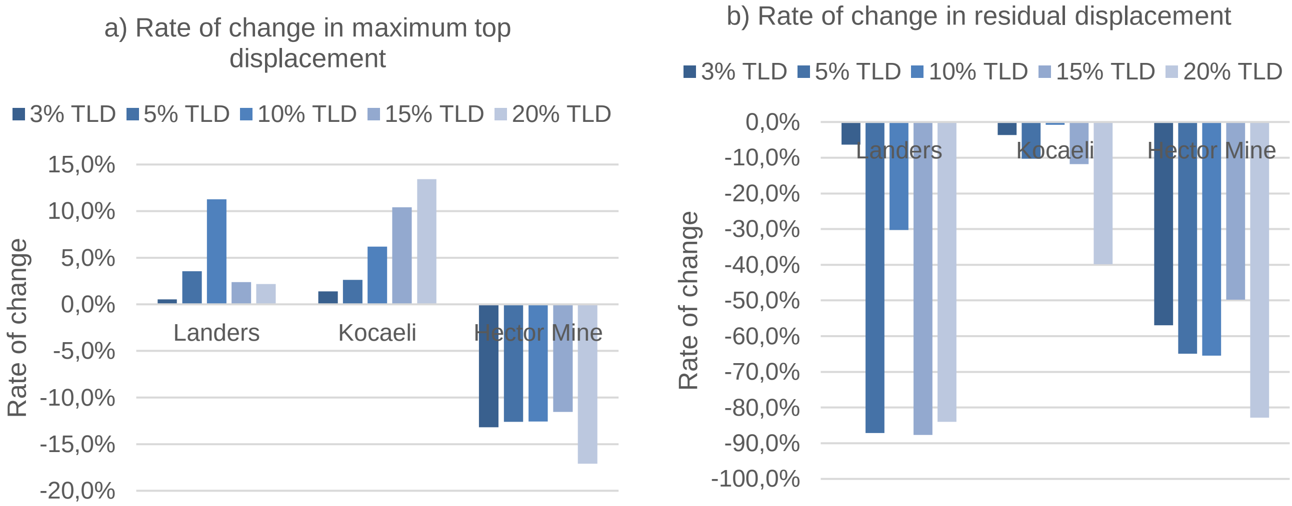
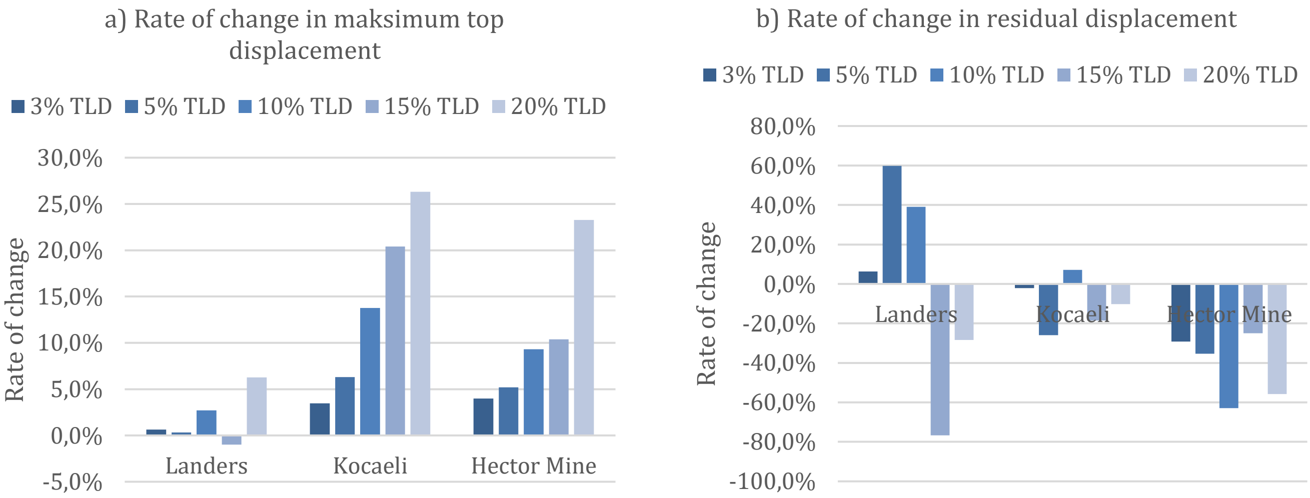


Figure 8. Residual displacement in Y direction due to individual ground motions and their average


a) Rate of change in maximum top displacement

b) Rate of change in residual displacement

Figure 9. Rate of change in top and residual displacements in X direction


a) Rate of change in maksimum top displacement

b) Rate of change in residual displacement

Figure 10. Rate of change in top and residual displacements in Y direction

The top displacement of the building mostly increases due to different TLD mass ratios compared to the top displacement of the existing building. This increase varies between 0.53% and 26.3%, and a 3% mass ratio causes the least increase, while a 20% mass ratio causes the greatest one. However, as can be seen from the plots, there is no linear correlation between the increase in displacement and the increase in mass ratio. Additionally, the individual motions have different trends in the effect of mass ratio on the peak top displacement. Also, it has been observed that tuned liquid dampers are highly effective in reducing the residual displacement of buildings after an earthquake. For the Landers earthquake, a 15% mass ratio reduces the residual displacement demand in the x and y directions by 87.72% and 76.74%, respectively, while a 5% mass ratio increases the residual displacement in the Y direction by 59.79%.

4 Conclusions and Discussions

Numerous control systems have been deployed to reduce residual displacement on buildings, among these systems, TLD systems have emerged as cost-effective and practical passive control mechanisms. When the building is subjected to dynamic movements, such as those induced by wind or earthquakes, the TLD works to counteract the building's motion in the opposite direction. To achieve this, a damper with an optimal mass ratio to the building's mass is selected and installed within the structure.

The effect of TLD on the residual top displacement of a 10-story reinforced concrete building was investigated within the scope of this study. The residual displacement demands for both the building without TLD and with TLD were simulated using the Nonlinear Time History Analysis (NLTHA) method with 3 ground motions records in the SAP2000 program. These analyses were repeated for the mass ratios of 3%, 5%, 10%, 15%, and 20% and TLD systems were placed on the top story of the building.

This study shows that TLD is considerably effective in reducing the average residual displacement of the building. However, this outcome is not valid for individual ground motions since the variation of the rate of the change of the residual displacement in individual ground motions is quite large. The optimal mass ratio should be selected in terms of displacement or deformation during a seismic event. As for the maximum displacement during a seismic event, the rate of the change of maximum top displacement due to TLD quite varies for different ground motion records. Thus, the effect of TLD on the maximum displacement substantially depends on the characteristics of ground motions. The most effective properties of the ground motion on the TLD behaviour need to be investigated to estimate adequate information in the tuning process. All in all, although an exact mass ratio highly depends on the considered ground motion records, it can be said that TLD helps to re-centring the building by reducing the residual displacement and, accordingly the cost of repair.

5 References

Ashasi-Sorkhabi, A., Malekghasemi, H., Ghaemmaghami, A., & Mercan, O. (2017). Experimental investigations of tuned liquid damper-structure interactions in resonance considering multiple parameters. *Journal of Sound and Vibration*, *388*, 141-153.

Banerji, P., Murudi, M., Shah, A. H., & Popplewell, N. (2000). Tuned liquid dampers for controlling earthquake response of structures. Earthquake engineering & structural dynamics, 29(5), 587-602.

Eurocode-8, 2003. Design of structures for earthquake resistance—Part 1. 1:General rules—Seismic action and general requirements for structures-Part 4: Silos, tanks, and pipelines. European Committee for Standardization, Final PT Draft.

Fujino, Y., Pacheco, B. M., Chaiseri, P., & Sun, L. M. (1988). Parametric studies on tuned liquid damper (TLD) using circular containers by free-oscillation experiments. *Doboku Gakkai Ronbunshu*, *1988*(398), 177-187.

Hoult, R. D., & de Almeida, J. P. (2022). Residual displacements of reinforced concrete walls detailed with conventional steel and shape memory alloy rebars. *Engineering Structures*, 256, 114002.

Housner, G. W. (1957). Dynamic pressures on accelerated fluid containers. *Bulletin of the Seismological Society of America*, *47*(1), 15-35.

Housner, G. W. (1963). The dynamic behaviour of water tanks. *Bulletin of the Seismological Society of America*, *53*(2), 381-387.

Jin, Q., Li, X., Sun, N., Zhou, J., & Guan, J. (2007). Experimental and numerical study on tuned liquid dampers for controlling earthquake response of jacket offshore platform. Marine Structures, 20(4), 238-254.

Kawashima, K., MacRae, G. A., Hoshikuma, J. I., & Nagaya, K. (1998). Residual displacement response spectrum. Journal of Structural Engineering, 124(5), 523-530.

Lobo, P. S., Almeida, J., & Guerreiro, L. (2017). Recentring and control of peak displacements of an RC frame using damping devices. *Soil Dynamics and Earthquake Engineering*, *94*, 66-74.

Malhotra, P. K., Wenk, T., & Wieland, M. (2000). Simple procedure for seismic analysis of liquid-storage tanks. *Structural Engineering International, 10(3)*, 197-201.

Naeim, F., & Kelly, J. M. (1999). Design of seismic isolated structures: from theory to practice. John Wiley & Sons.

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.

PEER, N.G.A. Strong Motion Database, <http://peer.berkeley.edu/nga>, 2010.

Priestley, M. N. (1993). Myths and fallacies in earthquake engineering: conflicts between design and reality*. Bulletin of the New Zealand Society for Earthquake Engineering, 26(3)*, 329-341.

Saaed, T. E., Nikolakopoulos, G., Jonasson, J. E., & Hedlund, H. (2015). A state-of-the-art review of structural control systems. *Journal of Vibration and Control*, *21*(5), 919-937.

SAP2000, Structural Analysis and Design, Computers and Structures Inc., California, USA.

Seismosoft, 2016. Seismomatch

Qazi, A. U., Ye, L., & Lu, X. (2006). Passive control reinforced concrete frame mechanism with high strength reinforcements and its potential benefits against earthquakes. *Tsinghua Science and Technology, 11(6),* 640-647.

Tamura, Y., Kousaka, R., & Modi, V. J. (1992). Practical application of nutation damper for suppressing wind-induced vibrations of airport towers. *Journal of Wind Engineering and Industrial Aerodynamics*, *43*(1-3), 1919-1930.

TSCB. (2018). Türkish Seismic Code for Buildings. (2018).18 Mart 2018.

Yip, C. C., Wong, J. Y., Ling, L., Goh, Y. L., & Ong, H. E. (2021). Dynamic response of scaled structure with one liquid tuned mass damper. *Case Studies in Construction Materials*, *14*, e00512.