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Effect of Tuned Liquid Damper Mass Ratio on The Building Response

Hesham A. El-Gammal[1]*, M. Hamdy[1], Osama O. El-Mahdy[2], Maher Adam[2]

[1]Department of Civil Engineering, Faculty of Engineering and Technology , Badr University, Cairo, Egypt
[2] Department of Civil Engineering, Faculty of Engineering at Shoubra, Benha University, Cairo, Egypt
* Corresponding Author.
E-mail: Hesham-Ashraf@buc.edu.eg, Mohamed-hamdy@buc.edu.eg, Osama.alhenawy@feng.bu.edu.eg, Maher.adam@feng.bu.edu.eg

Abstract: The global propagation of tall building projects has occurred rapidly. Among the significant challenges encountered by tall buildings are the issue of structural vibrations. Therefore, damping, as a phenomenon leading to the gradual dissipation of system energy and subsequent reduction in structural vibrations, Various damping technologies have been developed to dissipate structural vibrations. These include passive damping systems such as tuned liquid dampers (TLDs), emerges as a crucial factor in safeguarding these structures from excessive oscillations. Damping tools have recently seen advancements in the form of Tuned Liquid Dampers (TLDs). Traditionally constructed as rigid tanks filled with a specific quantity of water, this tool employs the dynamics of sloshing water upon activation. The application this system in mitigating undesired structural vibrations holds practical significance. The current study aims to investigate the effectiveness of TLDs in reducing structural vibrations due to seismic excitations. This involves the numerical simulation of structures with different TLD mass ratios to determine the most effective mass ratio.

Keywords: Tuned Liquid Damper, structural dynamic, Response spectrum, Time domain analysis, base shear.

1. INTRODUCTION

When studying tall buildings, it's crucial to thoroughly assess the impact of lateral forces such as wind or earthquakes on them [1]. These structures might face resonance issues due to low-frequency signals in the seismic excitations. To prevent the negative effects of resonant vibrations, the initial solution is enhancing the structure's damping capacity. Various earthquake-resistant building designs and technologies have been created to minimize the impact of earthquakes on structures. Different types of reduction measures are employed such as seismic isolation, active and passive control systems, and semi-active control systems [2]. Tuned mass dampers (TMD) and tuned liquid dampers (TLD) are newer technologies. in this field that are gaining popularity [3]. The TLD is a simple device consisting of a tank and liquid that helps reduce structural responses. Its effectiveness comes from tuning the liquid's sloshing frequency to resonate with the main structures in an out-of-phase mode, reducing the impact [4]. TLDs were initially used to steady ships and satellites, but now they're being used to reduce the movement of tall buildings. Bhattacharjee et al. [5] studied a one-way tuned liquid damper that depends on the movement of a shallow liquid in a rigid tank. They performed experiments on a scaled model of a structure with tuned liquid damper systems to explore sloshing in both rectangular and square tanks. Saha and Debbarma [6] investigated the performance of multiple tuned liquid damper (MTLD) in attenuating the response of a structure under dynamic loading. Tuong and Huynh [7] presented two numerical methods to control the responses of a frame under dynamic loadings: the lumped mass method for quickly designing the TLDs, and finite volume method/finite element method (FVM/FEM) for analyzing the fluid and solid domains of the TLDs, in a single computational 3D model. Saingam and Petchsasithon [8] analyzed the potential of utilizing a water tank as a Tuned Mass Damper (TMD) by conducting a study evaluating 3D reinforced concrete buildings of four, eight, and twelve stories with a water tank placed on the roof. Kartha and Ritzy [9] investigated the efficiency of TLD in reducing seismic vibration of a two-story steel frame subjected to earthquake excitations, and Numerical study of the undamped frame was conducted using ANSYS computer program. Pabarja et al. [10] studied the efficiency of TLDs in mitigating dynamic response of structures having vertical irregularity. A three-story steel structure was experimentally tested under free and forced vibration [7]. Tuned liquid dampers (TLDs) have many advantages in controlling building vibrations, among which multi-tuned liquid dampers (MTLDs) appear to have better stability and effectiveness [11]. Application of TLD in controlling the unwanted vibration of the structure has practical importance Fan Yang, et al. [12] review of the structural vibration suppression using tuned mass damper technology mainly focused on the tuned mass damper technology and its modifications. Abd-Elhamed et al. [13] investigated the potential of using a tuned liquid damper TLD as a mitigation measure to reduce the seismic responses of structures on soft soil. The current study aims to investigate the effectiveness of TLDs in reducing structure vibrations due to seismic excitations. This involves the numerical simulation of structure with different TLDs mass ratio to determine the most effective mass ratio of TLDs. CSI-SAP2000V20 commercial software [14] was utilized for the numerical analysis.

2.VERIFICATION NUMERICAL MODELINGS

The experimental work conducted by Bhattacharjee et al. [5] served as a verification case study. They developed a physical model to predict the motion of liquid in a rectangular tank under sinusoidal excitation. Their findings indicated that the effectiveness of dampers depends on the frequency content of the earthquake spectrum and the positions where the dampers are installed. this study primarily focused on large-amplitude excitations, revealing that the response of a Tuned Liquid Damper (TLD) to large-amplitude excitations The verification process involved the adoption of a finite element model in CSI-SAP2000V20 commercial software [14].

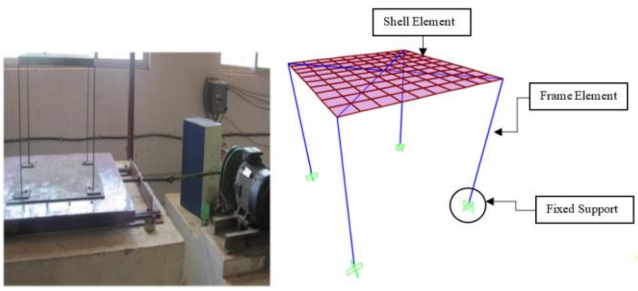


Fig 1 Experimental set-up of the Structure without TLD [5] and the FEM

To displace the structure horizontally, a table with dimensions 1m × 1m, table weight approximately 140 kg is utilized. It has a displacement capacity of up to ±100 mm and can operate within a maximum frequency range of 0 to 10 Hz. The TLD tanks are fabricated from 4-mm-thick acrylic sheets for the sidewalls and base plate, as illustrated in Figure (1). The structural model, composed of mild steel plate, ensures a robust floor supported by four 6×6×500mm high-tensile steel rods. Load from the slab is transmitted to the columns via two cross beams of identical size. The columns are welded to the slab and base plates. The natural frequency of the structural model without the tank is 1.9 Hz. The structure undergoes harmonic motion, with control over the amplitude and frequency of the oscillations. It is subjected to sinusoidal external excitation to study the effects of various parameters, including the excitation frequency ratio, which denotes the ratio of excitation frequency to the natural frequency of the structure.

The experimental study focused on different situations, including three cases, the first case is without a TLD, and the other two cases with a TLD having depth to length ratios of 20% and 30%. The research examined excitation frequency ratio which mean the ratio between the earthquake frequency and the natural frequency of the structure (ranging from 0.8 to 1.2). The finite elements based on commercial software CSI-SAP2000V20 [14] was utilized to model the structure and TLD, representing the water using two different types; convective and impulsive mass, each characterized by height and mass. The representation of convective mass and impulsive mass in the finite element model as spring element with stiffness which obtained as guidelines from the Egyptian Code for Loads on structures ECP201 [15].

The steel plate is simulated using shell element with plate bending capability with a suitable thickness matching its weight of 140 kilograms. The steel rod column is modeled as a frame element with a height of 500 mm and a cross-section of (6x6) mm having a density equal to 7.85 tons per cubic meter according to ECP203 [16]. The beam sections are also modeled as frame elements with the same dimensions of the columns as depicted in Figure (1). To simulate the welded connections, the boundary condition is set to a fixed support. Figure (2) shows simulation of structure with TLD, the water dynamic motion effect inside the tank is divided into two types: convective and impulsive mass, each defined by its height and mass. In the finite element model, the convective mass and impulsive mass are represented as a spring element with stiffness, based on guidelines outlined in the Egyptian Code for Loads on Structures, ECP201 [15]. The input function is represented using a time history function, specifically a harmonic motion function as mentioned by Bhattacharjee et al. [5]. The natural frequency obtained from the CSI-SAP2000V20 model of the structure without TLD is equal to 1.921 Hz, which aligns well with the experimental natural frequency.

The numerical results obtained are compared with the experimental ones as shown in Figures (3) through (5), demonstrating a very good agreement between both sets of results. The following remarks could be made based on the obtained results:

The maximum displacement of the structure without TLD at a frequency ratio of 1.0 is termed ‘resonance’. In Figure (3) the higher value of displacement was equal to 28mm occurred when the excitation frequency ratio of 1.0 showing a resonance phenomenon. However, when TLD with depth ratios of 20% and 30% are employed, it was observed that the maximum displacements are reduced. In Figure (4) the maximum displacement is. damped to be equal to 15mm at frequency ratio of 0.85 revealing the shift of the natural frequency of structure due to the existence of TLD. Similarly, in Figure (5) the maximum displacement damped to be equal to 12.5mm at frequency ratio of 0.85 because of the shifting of the natural frequency of structure with TLD.

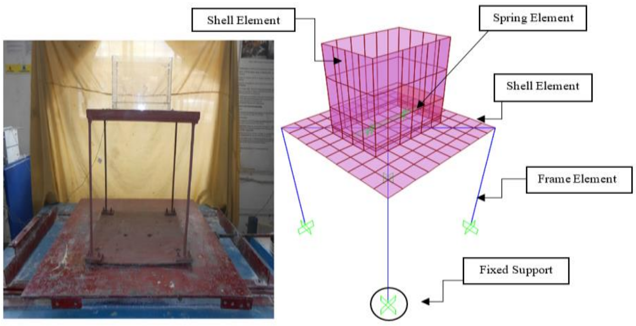


Fig 2 Experimental Set-Up of the Structure with TLD [5] and the FEM

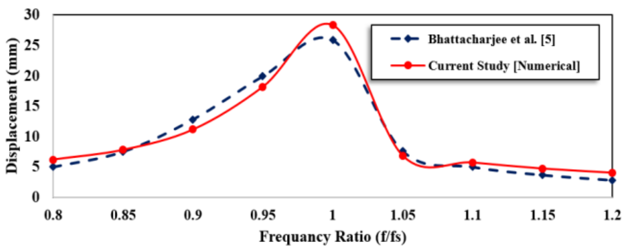


Fig 3 Numerical and Experimental Results of structure without TLD

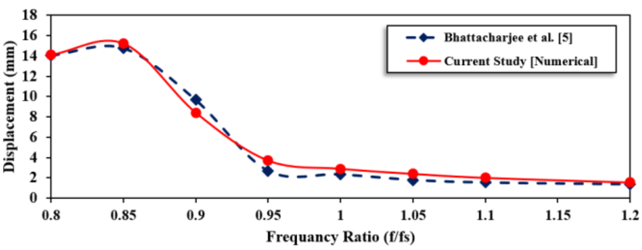


Fig 4 Numerical and Experimental Results of structure with TLD with depth ratio (20%)

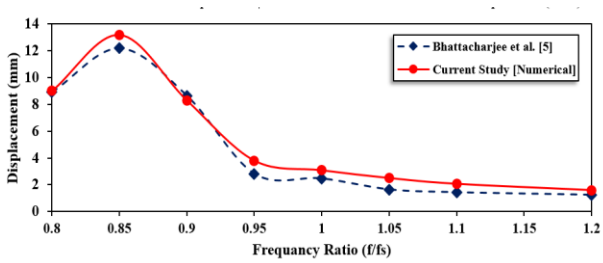
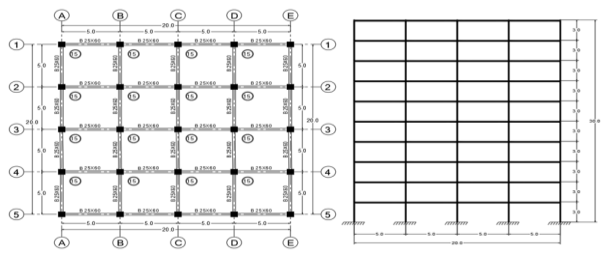


Fig 5 Numerical and Experimental Results of structure with TLD with depth ratio (30%).

3.DESCRIPTION OF THE CASE STUDY

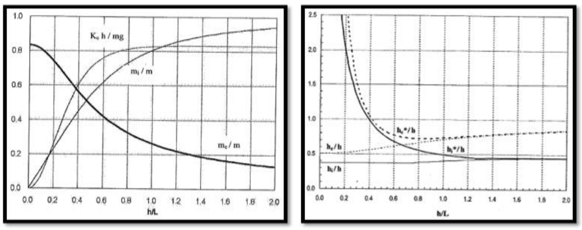
A ten-story reinforced concrete structure with plan dimensions of 20m x 20m is divided into four equal bays in both directions. The structure's height is 30m, with typical floor height of 3.0m. The floor slab thickness is 150 mm, and the beam section dimensions are (250x600) mm. All columns have a square cross-section of (600x600) mm. It is assumed that the concrete has a characteristic compressive strength (fcu) of 30 MPa, and the modulus of elasticity of concrete (Ec) calculated as Ec = $4400\sqrt{Fcu}$ [16]. The live load and floor cover are equal to 2 kN/m^2 and 1.5 kN/m^2 respectively.

Figure (6) shows the plan view and elevation of the building structure, detailing concrete dimensions, floor-to-floor height, and total building height. additionally, the three-dimensional modeling of the structure, where floor slabs are discretized using area elements of shell type, while beams and columns are modeled using frame elements in CSI-SAP2000V20 [14], are illustrated in Figure (9). The tuned liquid damper walls are modeled using area element with shell type, featuring a thickness of 300 mm made of concrete material. The water dynamic motion inside the tank is categorized using two different modeling type: convective and impulsive mass, each characterized by height and mass. The representation of convective mass in the finite element model is depicted as a “linear Link” element whose stiffness in X-direction (direction of motion) is given as K/2, and with fixed degree of freedom in other directions. The stiffness obtained from the provided guidelines by the Egyptian Code for Loads on structures, ECP201 [15]. and the impulsive mass modeled as a rigid link with fixed degree of freedom in all directions[17]



a) Plan View **b) Elevation**

Fig6 Plan View and Elevation of Building Structure with concrete dimension and heights



a) impulsive and convective mass and convective stiffness **b) heights of impulsive and convective mass**

Fig 7 curves for parameters of the spring mass model for rectangular tank due to ECP201 [15].

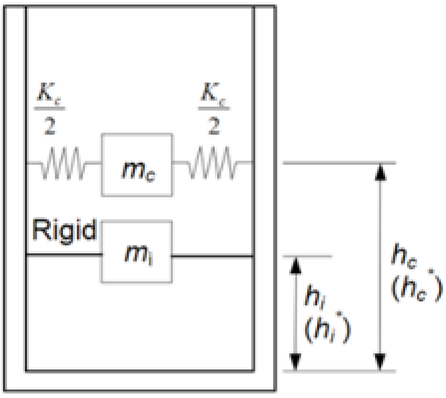
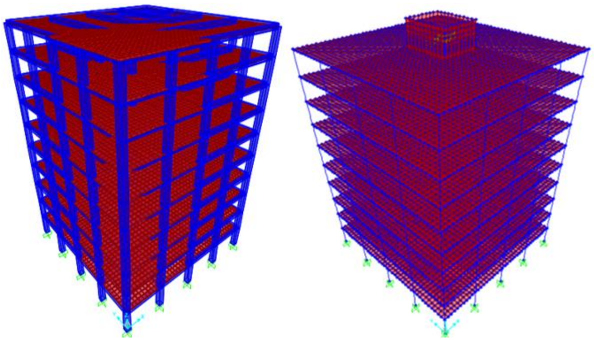


Fig 8 Spring mass analogy for TLD [15]



a) Without (TLD) **b) With (TLD)**

Fig 9 Three-dimensional FEM of the structure: a) without TLD, b) With TLD.

4.DESCRIPTION OF INPUT MOTION

One of the most convenient tools in the dynamic analysis is the time domain approach, which can easily account for input motion time history, nonlinear material properties, and element characteristics. The Great Hanshin earthquake, which struck the Kansai Region of Japan on January 16, 1995, stands out as one of the most catastrophic seismic events in history. The aftermath left the loss of over 6,000 lives and displacing more than 45,000 individuals. The economic ramifications were significant, with estimated losses surpassing $100 billion USD, Commonly referred to as the Kobe Earthquake [18], it was documented by the Centre of Earthquake Strong Motion Database, CESMD [19]. It is documented as having its epicenter situated on the northern end of Awaji Island, 20 km away from Kobe City center, Osaka Bay. The earthquake measured a moment magnitude of (Mw) 6.9 and occurred at a focal depth of 17 km. According to CESMD[19]. Figure (10) illustrates the time histories of acceleration, velocity, and displacement that obtained from data recorded at the seismic station of the Kobe Japan Meteorological Agency (KJMA), which is located close to the epicenter recording a total duration of approximately 20.02 seconds. The peak ground acceleration (PGA) observed during the Kobe Earthquake is approximately 0.821g, (where "g" is the acceleration of gravity) occurring at 5.56 second [20]. The Kobe Earthquake is characterized as an intermediate event with a crucial frequency of 1.45 Hz [21] . This seismic record serves as the input motion for the studied building, with input data such as the time history function utilized in CSI-SAP2000V20 [14], as illustrated in Figure (11).

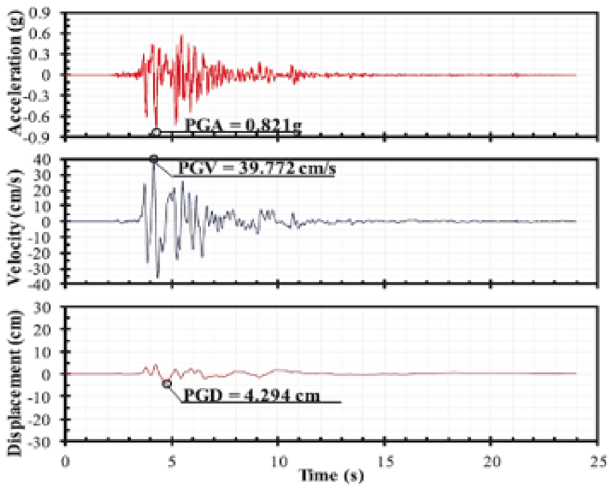


Fig 10 Recorded ground motions during the Mw 6.9 Kobe Earthquake at (KJMA) Station. [20]

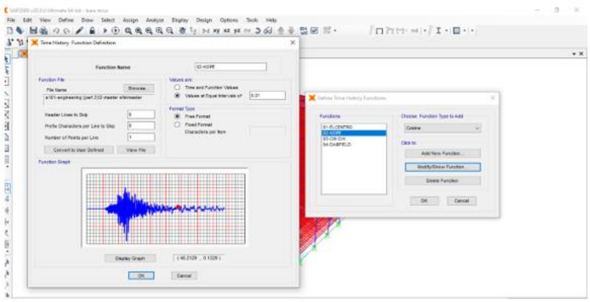


Fig 11 Kobe earthquake Record Using Time History Function on CSI-SAP2000V20 [14]

5.RESULTS AND DISCUSSION

The obtained results from the numerical study reveal significant insights into the influence of different mass ratios of tuned liquid dampers (TLDs) on the vibration behavior of the building. Specifically, the investigation focuses on displacement, inter-story drift, and base shear as key indicators of the structural response. The building mass is 44100 kN, and various tank dimensions and water quantities are adjusted in each case to achieve the desired mass ratio. The depth ratio, representing the ratio of water height to the tank length in the direction of motion, remains fixed at 50% across all scenarios. Five cases with mass ratios of 1%, 2%, 3%, 5%, and 10% to determine the most effective mass ratio, providing valuable insights for TLD design. Table (1) presents case numbers with assumed mass ratios for each study case. Case (M1) refers to the scenario with a mass ratio of 1%, while case number (M2) denotes a mass ratio of 2%, and so on. Additionally, case (M0) indicates the scenario without (TLD). The tank dimensions are selected to correspond with the desired depth ratio and mass ratio, as indicated in Table (1). The Egyptian Code for loads [15] and Figure (7) are employed to establish the relationship between the Impulsive mass(mi), Convective mass(mc), water height, and water spring stiffness(k), as summarized in Table (2).

TABLE 1 Water tank dimensions and water height considered for the studied cases.

Case Number	M0	M1	M2	M3	M5	M10
Mass Ratio	0	1%	2%	3%	5%	10%
Mass of structure (kN)	44100	44100	44100	44100	44100	44100
Mass of water (kN)	0	40	875	1260	2205	4500
Tank Dimension						
Tank Length (m)	---	4	5	6	7	10
Tank Width (m)	---	5	7	7	9	9
Tank Height (m)	---	3	3	4	4	6
Water Height (m)	---	2	2.5	3	3.5	5

TABLE 2 Convective and impulsive mass, height, and stiffness of water for each cases [15]

Model Number	M1	M2	M3	M5	M10
h/L	0.5	0.5	0.5	0.5	0.5
m_i / m	0.53	0.53	0.53	0.53	0.53
m_c / m	0.48	0.48	0.48	0.48	0.48
K_c*h / m*g	0.7	0.7	0.7	0.7	0.7
Mass of water (kN)	481	875	1262	2205	4501
m_i (kN)	254	463	667	1168	2385
m_c (kN)	231	421	605	1058	2161
K_c (kN/m)	168	245	294	441	630
h_i / h	0.39	0.39	0.39	0.39	0.39
h_c / h	0.6	0.6	0.6	0.6	0.6
Water Height (m)	2	2.5	3	3.5	5
h_i (m)	0.78	0.97	1.17	1.37	1.95
h_c (m)	1.2	1.5	1.8	2.1	3

TABLE 3 The resulted story displacements for the studied cases.

Lateral Displacements at each story in (mm)						
STORY	**M0**	**M1**	**M2**	**M3**	**M5**	**M10**
1	4.36	3.86	3.57	3.74	3.48	3.21
2	11.75	10.38	9.45	10.06	9.41	8.74
3	19.27	16.99	15.21	16.49	15.52	14.59
4	25.97	22.84	20.15	22.22	21.05	20.2
5	31.45	27.58	24.13	26.94	26.27	25.33
6	35.68	31.17	27.17	31.35	31.55	31.73
7	38.83	33.82	29.39	35.9	36.1	37.71
8	42.74	37.22	32.33	39.57	39.84	42.93
9	45.79	39.87	34.8	42.33	42.7	47.1
10	47.77	41.61	36.36	44.16	44.64	50.05

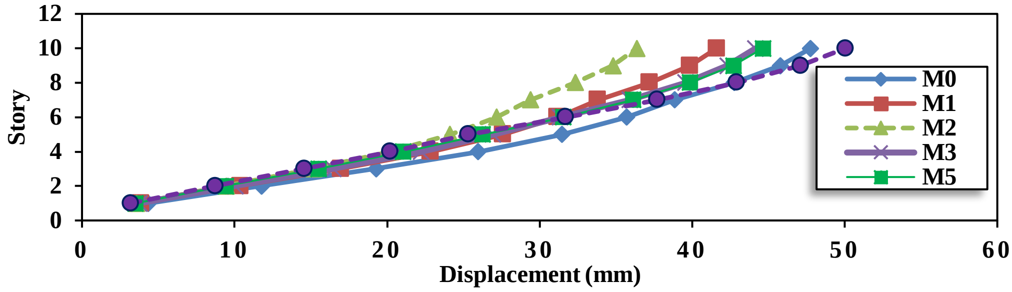


Fig 12 Top Displacements for M0, M1, M2, M3, M5, and M10

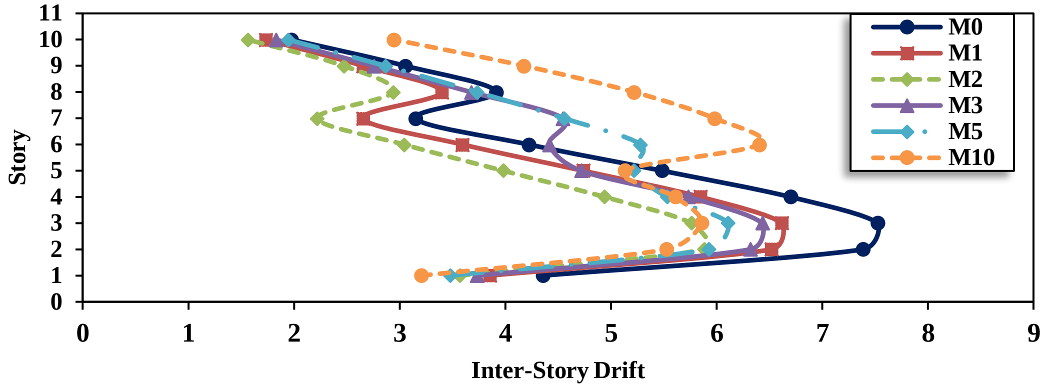


Fig 13 Inter story Drift for M0, M1, M2, M3, M5, and M10

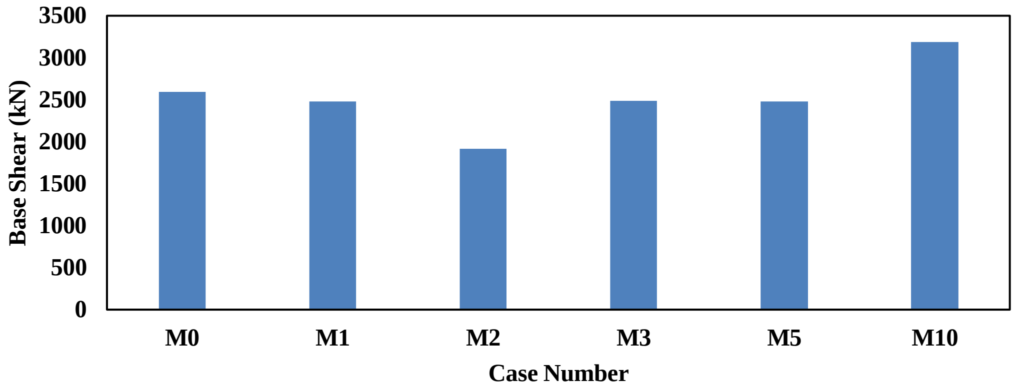


Fig 14 Base Shear results for M0, M1, M2, M3, M5, and M10

TABLE 4 Inter story Drift for M0, M1, M2, M3, M5, and M10

Inter Story Drift Results						
STORY	**M0**	**M1**	**M2**	**M3**	**M5**	**M10**
1	4.35	3.85	3.57	3.73	3.47	3.20
2	7.38	6.52	5.88	6.32	5.92	5.52
3	7.52	6.61	5.76	6.43	6.10	5.85
4	6.69	5.84	4.94	5.73	5.53	5.60
5	5.48	4.73	3.98	4.71	5.21	5.12
6	4.22	3.59	3.04	4.41	5.27	6.40
7	3.15	2.65	2.22	4.54	4.55	5.97
8	3.91	3.39	2.94	3.67	3.73	5.21
9	3.05	2.65	2.47	2.75	2.86	4.17
10	1.97	1.73	1.56	1.82	1.94	2.94

TABLE 5 Base Shear results for M0, M1, M2, M3, M5, and M10

Base Shear results with Mass Ratio				
Case No	Base Shear (kN)	Weight (kN)	Base Shear / Weight (%)	Base shear reduction (%)
M0	2595	37250	6.97	---
M1	2480	37587	6.6	4.46
M2	1918	37700	5.09	26.11
M3	2483	37900	6.55	4.43
M5	2480	38050	6.52	4.46
M10	3184	38675	8.23	-22.65 (increasing)

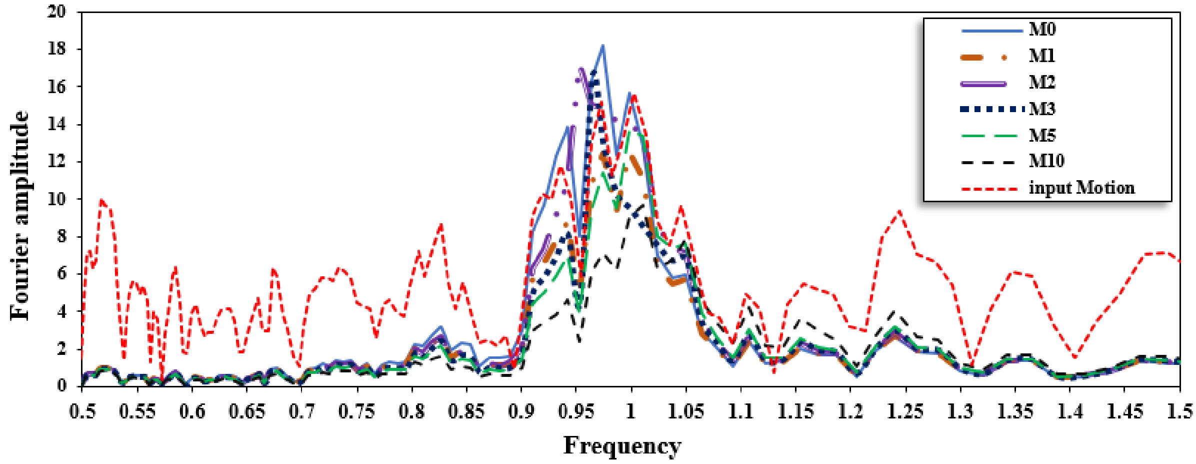


Fig 15 comparison between Fourier amplitude in studied cases M0, M1, M2, M3, M5, and M10 with input motion

Where:
(h): Water height inside the tank, (L): the tank length in sloshing direction, (m_i): impulsive mass of water, (m_c) : Convective mass of water, (K_c): water stiffness, (h_i): Height of impulsive mass, (h_c): height of convective mass.

The displacement results indicate that the addition of a Tuned Liquid Damper (TLD) system to the structures leads to relative alteration in the behavior of the structure against vibrations and seismic loads, as listed in Table (3). It is observed that an increase in the mass ratio leads to relative decrease of displacements, drift, and base shear, indicating the system's efficiency for the studied mass ratios 1%, 2%, 3%, and 5% as depicted in Figures (12) through (14). The correlation between mass ratio and performance is critical, as depicted in the displacement results. It underscores the balance between added mass and system efficacy, as demonstrated in Figure (12). Although higher mass ratios initially enhance performance, there is a diminishing return, and excessive mass can result in adverse effects, as listed in Table (3). Therefore, a significant increase in the mass ratio yields undesirable and counterproductive outcomes, as observed in the case of (M10). In the initial scenario (M1), the displacement on the top floor decreased by approximately 13% compared to the (M0) control case. Transitioning to the subsequent scenario (M2), the displacement decreased by 24% compared to the (M0), as depicted in Figure (10). Thus, upon analyzing these initial two scenarios, it was found that higher mass ratios effectively decrease building displacements. In the third scenario (M3), there was an approximate 8% decrease in the displacement of the top floor. Additionally, the fourth case (M5) exhibited a 6.5% reduction in displacement, as illustrated in Figure (12). The fifth scenario (M10) was examined, revealing a 4.7% increase in displacement, indicating that the system has transitioned from a solution to a problem, causing more displacement than (M0) control case.

It was observed that the presence of (TLD) significantly influences the values of displacement between successive floors (inter-story drift). In the case of (M0), the maximum drift was noted on the third floor, amounting to 7.52, as listed in Table (4). Similarly, the maximum inter-story drift value in the case of (M1) was 6.61, indicating a 12.1% reduction. In the case of (M2), the maximum inter-story drift value shifted to the second floor due to the effect of the (TLD) presence, with a reduced value of 5.88, representing a 21.8% decrease compared to the (M0) condition, as depicted in Figure (13). Furthermore, it was observed that in case (M10), the largest value shifted to the sixth floor, registering a value of 6.4, as listed in Table (4).

It has been observed that the presence of Tuned Liquid Dampers (TLD) results in a reduction of the base shear, as summarized in Table (5), due to the water-induced sloshing force it generates. This force acts in the opposite direction to the earthquake force, aiding in the dissipation of energy. In case (M2), the base shear is reduced by 4.46% compared to case (M1) and by 26.11% compared to the initial condition (M0), as listed in Table (5) and shown in Figure (14), respectively.

After analyzing various cases using the Fast Fourier Transform method to compare their frequency content with that of the Kobe earthquake which obtained from (KJMA), according to CESMD[19], the goal is to identify a case that avoids resonance when subjected to the earthquake frequency. It was observed that case (M2) exhibits the farthest frequency from the earthquake, followed by case (M3), as depicted in Figure (15). Additionally, it was noted that there is a shifting of the frequency content of the structure based on the mass ratio of the (TLD).

6.CONCLUSIONS

This paper presents a numerical investigation into the seismic response of a multi-story building equipped with a Tuned Liquid Damper (TLD). The study employs the time history analysis method and utilizes data from the 1995 Kobe earthquake. The analysis is conducted using the CSI-SAP2000V20 software.

Five different mass ratio scenarios were explored: 1%, 2%, 3%, 5%, and 10%, while keeping other parameters influencing (TLD) behavior constant. Analysis revealed that the water to building mass ratio significantly affects displacements, inter story drift, and base shear, underscoring its importance in (TLD) design. Furthermore, it was observed that while increasing water to building mass ratio can improve seismic performance, there exists a threshold beyond which further increases may be counterproductive. Based on the obtained results, the following conclusions can be stated:

1. The ratio of water mass to building mass is a significant factor in managing seismic energy and regulating building displacements. It directly influences the effectiveness of the Tuned Liquid Damper (TLD) system in reducing the impact of seismic forces on the structure.
2. The findings indicate that the water-to-building mass ratio for maximum dissipation of displacements in the building is 2%. This suggests that at this ratio, the TLD system is most efficient in mitigating the effects of seismic activity, resulting in the highest level of displacement reduction.
3. Similarly, the study reveals that the lowest inter-story drift, which is crucial for maintaining structural stability and integrity during seismic events, is achieved when the water-to-building mass ratio equals 2%. This underscores the importance of selecting an appropriate mass ratio to minimize structural deformation and ensure the safety of the building occupants.
4. The study highlights that the maximum dissipation of base shear, which is a critical parameter reflecting the lateral forces exerted on a building's foundation, is achieved when the mass ratio ranges between 2% to 3%.
5. The presence of Tuned Liquid Dampers (TLD) in a building's structural system can indeed lead to a shift in the frequency content of the structure. This shift occurs due to the dynamic interaction between the building and the TLD system.
6. Utilizing a water-to-building mass ratio of 5%, it leads to displacements and inter story drift results higher than those observed in the 2% case.
7. Using a water to building mass ratio of 10% leads to unfavorable outcomes in the building's behavior, resulting in increased displacements, and drift compared to scenarios of building without (TLD).

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