Multiple Tuned Mass Dampers and Double Tuned Mass Dampers for Soft Story Structures: A Comparative Study

FARAH ALNAYHOUM
Civil Engineering Department
Istanbul University-Cerrahpaşa
34320 Avcılar, Istanbul
TURKEY

IBRAHIMA KALIL CAMARA
Civil Engineering Department
Istanbul University-Cerrahpaşa
34320 Avcılar, Istanbul
TURKEY

SİNAN MELİH NİGDELİ
Civil Engineering Department
Istanbul University-Cerrahpaşa
34320 Avcılar, Istanbul
TURKEY

GEBRAİL BEKDAŞ
Civil Engineering Department
Istanbul University-Cerrahpaşa
34320 Avcılar, Istanbul
TURKEY

Abstract: Recent seismic events have highlighted the vulnerability of reinforced concrete buildings, especially soft-story structures, to damage and collapse during strong earthquakes due to the ground's vibrational response. This study aims to mitigate these adverse vibrations using passive control mechanisms, particularly tuned mass dampers (TMDs). Conventional TMDs require a substantial mass to effectively influence the structure's lateral reactions. The research explores the use of multi-tuned mass dampers (MTMDs) and double-tuned mass dampers (DTMDs) in a soft-story building. The study uses MATLAB to estimate TMD parameters and subject the models to seismic loading. The comparative assessment of these models reveals the potential benefits of using MTMD and DTMD systems to enhance the seismic resilience of soft-story structures.

Key-Words: Den Hartog, multiple TMD, Double TMD, soft story structures, passive control, optimum design.

Received: June 24, 2022. Revised: August 24, 2023. Accepted: October 11, 2023. Published: November 14, 2023.

1 Introduction

Rapid population growth in major cities worldwide has led to the construction of tall buildings and closely spaced structures to accommodate the increasing population. However, natural disturbances like earthquakes and severe winds can lead to excessive structural vibrations, affecting people's comfort. [1]

To maintain safety and technological competitiveness, structural designers have implemented vibration control technologies to control excessive vibrations and reduce their impact on structural response. These measures are particularly aimed at keeping structures within acceptable limits, especially during unpredictable events like earthquakes or winds. [2] Earthquakes have shown that some reinforced concrete buildings are vulnerable to damage or collapse, particularly soft-story buildings or flexible-story buildings, which are approximately 70% less rigid than other floors. [3,4]

Various vibration control technologies have been implemented to reduce damage and alter structural performance, including dampers, vibration isolators, control of excitation forces, and vibration absorbers.[5] Vibration absorbers like tuned mass dampers (TMD), Active Mass Dampers (AMD), Semi-Active Mass Dampers (SAMD), and Hybrid Mass Dampers (HBD)[5,6] have been studied and installed in skyscrapers to control the behavior of structures under vibration forces. [5]

In the realm of structural engineering, it is imperative to acknowledge that the initial methodologies employed to address environmental challenges, including base isolations and tuned mass dampers (TMDs), predominantly employed passive control mechanisms.[7,8] To further enhance the management of structural vibrations, the optimization of various parameters, such as mass, stiffness, and damping, has emerged as a viable strategy. With the progression of scientific knowledge, the successful implementation of specific control methods and practices has significantly contributed to the heightened effectiveness of vibration control in this context.[9] The placement of these dampers in civil engineering structures is carefully done to avoid causing harm to the structure.[6]

This study delves into the application of passive vibration control systems, particularly emphasizing the utilization of multiple-tuned mass dampers (MTMDs) and double-tuned mass dampers (DTMDs) as viable solutions for minimizing vibrations in structures subjected to dynamic loads.

The MTMD system is characterized by the incorporation of multiple smaller dampers strategically distributed within the structure, with distribution patterns, whether uniform, linearly varying, or designer-assessed. Each damper within the MTMD system is meticulously tuned to a specific frequency, tailored to mitigate vibrations occurring at that particular frequency. In contrast, tuned mass dampers (TMDs) are meticulously tuned to the natural frequency of the host structure.[7,10,11,12]

The central objective of the DTMD system is to introduce effective damping mechanisms into the primary structure, thereby significantly reducing structural oscillations.[13] The configuration comprises two TMDs: a larger undamped unit (TMD1) and a smaller, conventionally tuned unit (TMD2). Notably, TMD1 is strategically deployed to suppress vibrations within the primary structure, while TMD2 is dedicated to addressing vibrations within TMD1. [13,14]

For this study, the optimization and design of TMD systems are achieved through the application of the Den-Hartog equation. Den-Hartog technique is an enduring yet highly effective method in TMD system design. Over the years, the Den-Hartog technique has served as an efficient analytical approach, frequently employed to create and fine-tune TMD systems, all while maintaining structural integrity by not introducing additional damping into the primary structure.[15,16]

The principal objective of this study is to assess the effectiveness and response of both multiple-tuned mass dampers (MTMDs) and double-tuned mass dampers (DTMDs) when applied in soft-story buildings under seismic loading conditions. This research involves the application of MTMD and DTMD systems to a soft-story building, with a focus on determining the optimal parameters for the tuned mass dampers, including mode shapes, period, and frequency. The analysis will be executed through the utilization of a two-story model: in the MTMD case, each story is equipped with a single-tuned mass damper, while in the DTMD case; a double-tuned mass damper will be placed on the top story. Subsequently, these models will be subjected to the El Centro earthquake and analyzed using the Den-Hartog equation in conjunction with MATLAB. The study will conclude with a comparative assessment of the models featuring soft-story configurations and those without, shedding light on the potential advantages of employing MTMD and DTMD systems to enhance seismic resilience.

2 Problem Formulation

The present investigation focuses on the dynamic response analysis of a two-story shear building subjected to El-Centro seismic excitation. This study encompasses two main cases; the first case examines a system that does not consist of a soft story, while the second case consists of a soft story as a second story. Both cases will be examined twice. The first will be a system featuring multiple-tuned mass dampers (TMDs) installed on each story, while the second case explores a system with double TMDs located on the top story, as shown in Figure 1.

In this analysis, the structural parameters are represented by (***m, k, c***) denoting the mass, stiffness, and damping coefficients, respectively. Simultaneously, the TMD parameters are expressed as (m_{di}, k_{di}, c_{di}) representing the mass, stiffness, and damping coefficients of the TMDs. The structural responses are characterized by (x_i) indicating the displacement of each story concerning the ground, and ($\ddot{x}_g$) representing the ground acceleration. Similarly, the TMD responses are denoted as (x_{di}) signifying the displacement of the TMDs relative to the ground.

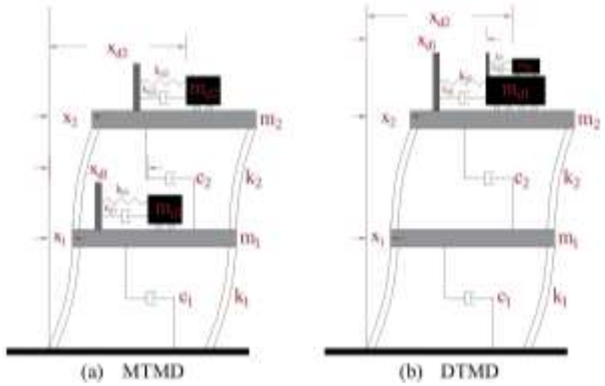


Fig. 1 Shear structure model.

The governing equations of motion for both scenarios are derived based on the principle of equilibrium of forces at each degree of freedom, as illustrated in Equation (1):

$$M\ddot{x}_{(t)} + C\dot{x}_{(t)} Kx_{(t)} = -M\,\{1\}\ddot{x}_{g(t)} \tag{1}$$

In Equation (1), the symbols M, C, and K correspond to the mass, damping, and stiffness matrices for both the structure and the tuned mass damper (TMD). Specifically, the term "$-M\{1\}\ddot{x}_{g(t)}$" represents the inertial forces arising from ground accelerations.

In the current study, the Den-Hartog equation was employed as a foundational framework. The design characteristics of the TMDs encompass their optimal damping ratio, frequency, mass, and stiffness. These design parameters are determined using the following equations:

$$f_{opt} = \frac{1}{1+\mu} \tag{2}$$

$$\xi_{d,opt} = \sqrt{\frac{3\mu}{8(1+\mu)}} \tag{3}$$

Within this context, the symbols "$\boldsymbol{f_{opt}}, \boldsymbol{\mu}, \boldsymbol{\xi_{d,opt}}$" stand for the optimal frequency, mass ratio, and optimum damping ratio, respectively.

For the scenario where a tuned mass damper (TMD) is not employed, the system's M_s, K_s, and C_s matrices, which pertain to mass, stiffness, and damping, are expressed as follows:

$$M_s = \begin{bmatrix} m_1 & & & \\ & m_2 & & \\ & & \ddots & \\ & & & m_N \end{bmatrix} \quad (4)$$

$$K_s = \begin{bmatrix} k_1+k_2 & -k_2 & & \\ -k_2 & k_2+k_3 & -k_3 & \\ & -k_3 & \ddots & -k_N \\ & & -k_N & k_N \end{bmatrix} \quad (5)$$

$$C_s = \begin{bmatrix} c_1+c_2 & -c_2 & & \\ -c_2 & c_2+c_3 & -c_3 & \\ & -c_3 & \ddots & -c_N \\ & & -c_N & c_N \end{bmatrix} \quad (6)$$

For systems with multi TMDs, $\boldsymbol{M_m}$, $\boldsymbol{K_m}$, and $\boldsymbol{C_m}$ matrices of the system are shown as:

$$M_m = \begin{bmatrix} M_s & 0 \\ 0 & M_d \end{bmatrix} \quad (7)$$

$$M_d = \begin{bmatrix} m_{d1} & 0 \\ 0 & m_{d2} \end{bmatrix}$$
(8)

$$K_m = \begin{bmatrix} K_s+K_d & -K_d \\ -K_d & K_d \end{bmatrix} \quad (9)$$

$$K_d = \begin{bmatrix} k_{d1} & 0 \\ 0 & k_{d2} \end{bmatrix} \quad (10)$$

$$C_m = \begin{bmatrix} C_s+C_d & -C_d \\ -C_d & C_d \end{bmatrix} \quad (11)$$

$$C_d = \begin{bmatrix} c_{d1} & 0 \\ 0 & c_{d2} \end{bmatrix} \quad (12)$$

For systems with double TMDs, $\boldsymbol{M_{db}}$, $\boldsymbol{K_{db}}$, and $\boldsymbol{C_{db}}$ matrices of the system are shown as:

$$M_{db} = \begin{bmatrix} M_s & 0 \\ 0 & M_d \end{bmatrix} \quad (13)$$

$$K_{db} = \begin{bmatrix} k_1+k_2 & -k_2 & & & & \\ -k_2 & k_2+k_3 & -k_3 & & & \\ & -k_3 & \ddots & -k_N & & \\ & & -k_N & k_N+k_{d1} & -k_{d1} & \\ & & & -k_{d1} & k_{d1}+k_{d2} & -k_{d2} \\ & & & & -k_{d2} & k_{d2} \end{bmatrix} \quad (14)$$

$$C_{db} = \begin{bmatrix} c_1+c_2 & -c_2 & & & & \\ -c_2 & c_2+c_3 & -c_3 & & & \\ & -c_3 & \ddots & -c_N & & \\ & & -c_N & c_N+c_{d1} & -c_{d1} & \\ & & & -c_{d1} & c_{d1}+c_{d2} & -c_{d2} \\ & & & & -c_{d2} & c_{d2} \end{bmatrix} \quad (15)$$

2.1 Case study

2.1.1 Case 1

A structure subjected to El Centro earthquake load was evaluated in this example. The structure is made up of two stories, each having equal masses connected to it, equivalent damping coefficients, and equal stiffness. In the present case:
(a) Multi-tuned mass dampers (MTMDs) were placed at each story of the structure.
(b) Double-tuned mass dampers (DTMDs) were placed at the top of the structure.
Both cases (a) and (b) result in the structure acting as a 4DOF system. The Den-Hartog approach was used to derive the TMD parameters based on the structure's initial mode. TMD was considered to have a mass ratio of 5% of the structure's two masses.

2.1.2 Case 2

The same structure with the same characteristics but with different stiffness values was evaluated. In this case:
(a) Multi-tuned mass dampers (MTMDs) were placed at each story of the structure.
(b) Double-tuned mass dampers (DTMDs) were placed at the top of the structure.
By assuming the same mass ratio of 5% and by using the Den-Hartog technique TMD parameters have been evaluated. The structure characteristics are shown in Table 1.

Table 1. Characteristics of structures

Case	Story	m (kg)	k (N/m)	C (Ns/m)
1	1	2924	1390000	1581
	2	2924	1390000	1581
2	1	2924	1390000	1581
	2	2924	2780000	1581

3 Problem Solution

The mass, stiffness, and damping matrices were successfully derived. The optimum values of the TMDs were listed in Table 2, Table 3, Table 4, and Table 5. Derived values have been used to calculate the frequencies and periods, which are presented in Table 6 and Table 7. Additionally, the mode shapes for both cases were extracted and are visualized in Figure 2 and Figure 3. With normalized values detailed in Table 8, Table 9, Table 10, and Table 11. Furthermore, the simulation results for roof displacement and total acceleration are depicted in Figure 4 and Figure 5, with maximum values of displacement and acceleration detailed in Table 12 and Table 13. These findings constitute an integral part of the study's results, providing insights into the structural behavior and response under the applied seismic loading conditions.

Table 2. TMD values for case 1. a

Case 1. a With Multiple TMD					
$\mu = 5\%$					
f_{opt}	$\xi_{d,opt}$	$\omega_{d,opt}$	$C_{d,opt}$	$m_{d,opt}$	$k_{d,opt}$
0.952	0.133	12.833	501.44	146.2	24078.58
0.952	0.133	33.598	1312.8	146.2	165037.06

Table 3. TMD values for case 1. b

Case 1. b With Double TMD					
$\mu = 5\%$					
f_{opt}	$\xi_{d,opt}$	$\omega_{d,opt}$	$C_{d,opt}$	$m_{d,opt}$	$k_{d,opt}$
0.952	0.133	12.833	501.44	146.2	24078.58
0.952	0.133	33.598	1312.8	146.2	165037.06

Table 4. TMD values for case 2. a

Case 2. a With Multiple TMD					
$\mu = 5\%$					
f_{opt}	$\xi_{d,opt}$	$\omega_{d,opt}$	$C_{d,opt}$	$m_{d,opt}$	$k_{d,opt}$
0.952	0.133	13.749	537.24	146.2	27639.07
0.952	0.133	44.349	1732.88	146.2	287553.66

Table 5. TMD values for case 2. b

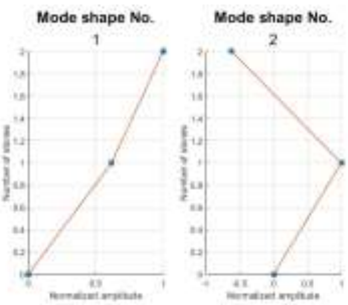
Case 2. b With Double TMD					
$\mu = 5\%$					
f_{opt}	$\xi_{d,opt}$	$\omega_{d,opt}$	$C_{d,opt}$	$m_{d,opt}$	$k_{d,opt}$
0.952	0.133	13.749	537.24	146.2	27639.07
0.952	0.133	44.349	1732.88	146.2	287553.66

Table 6. Frequency and period values for case 1

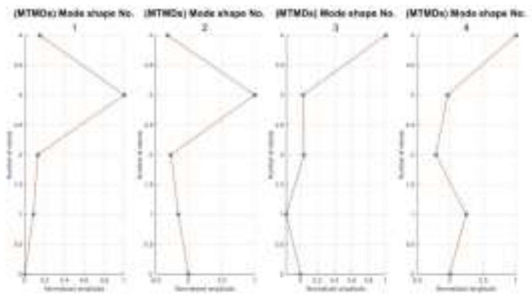
Without TMD		Case 1. a Multiple TMD		Case 1. b Double TMD	
Frequency (Hz)	Period (s)	Frequency (Hz)	Period (s)	Frequency (Hz)	Period (s)
2.1446	0.4662	1.9513	0.5124	1.3797	0.7247
5.6146	0.1781	2.1917	0.4562	2.2014	0.4542
		5.2324	0.1911	5.6197	0.1779
		5.8769	0.1701	7.7045	0.1297

Table 7. Frequency and period values for case 2

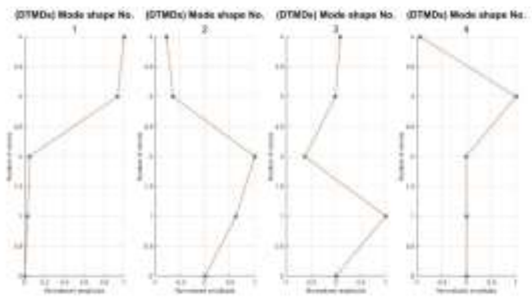
Without TMD		Case 2. a Multiple TMD		Case 2. b Double TMD	
Frequency (Hz)	Period (s)	Frequency (Hz)	Period (s)	Frequency (Hz)	Period (s)
2.2977	0.4352	2.0751	0.4818	1.4923	0.6700
7.4113	0.1349	2.3782	0.4204	2.3515	0.4252
		6.8194	0.1466	7.4173	0.1348
		7.8154	0.1279	10.1045	0.0989



(a) Without TMD



(b) MTMD



(c) DTMD

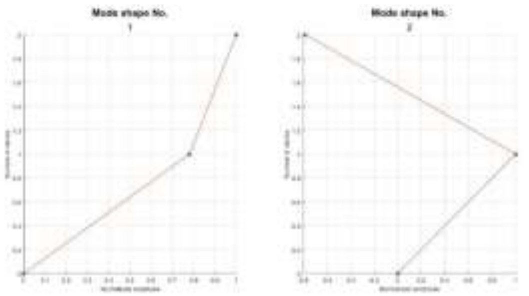
Fig. 2 Mode shapes for case 1. (a) Without TMD (b) MTMD (c) DTMD

Table 8. Mode shape values case 1. a

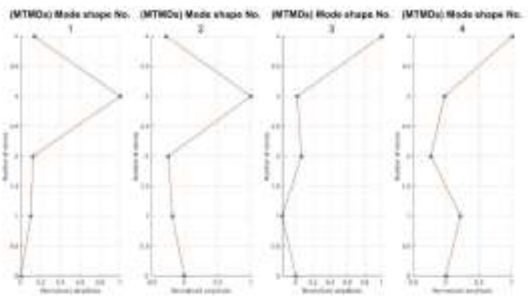
Mode 1	Mode 2	Mode 3	Mode 4
0.0872	-0.1514	-0.1678	0.2449
0.1310	-0.2624	0.0425	-0.2078
1	1	0.0301	-0.0336
0.1512	-0.3153	1	1

Table 9. Mode shape values case 1. b

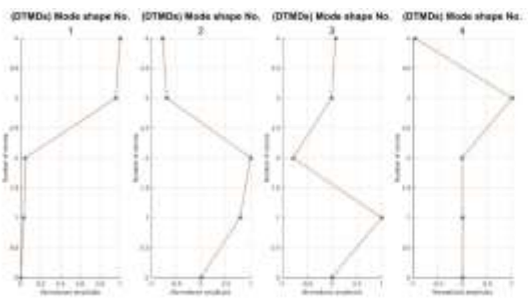
Mode 1	Mode 2	Mode 3	Mode 4
0.0277	0.6259	1	0.0016
0.0511	1	-0.6227	-0.0048
0.9334	-0.6408	-0.0094	1
1	-0.7716	0.0904	-0.9293



(a) Without TMD



(b) MTMD



(c) DTMD

Fig. 3 Mode shapes for case 2. (a) Without TMD (b) MTMD (c) DTMD

Table 10. mode shape values case 2. a

Mode 1	Mode 2	Mode 3	Mode 4
0.1007	-0.1811	-0.1585	0.2203
0.1241	-0.2408	0.0665	-0.2260
1	1	0.0181	-0.0187
0.1358	-0.2717	1	1

Table 11. mode shape values case 2. b

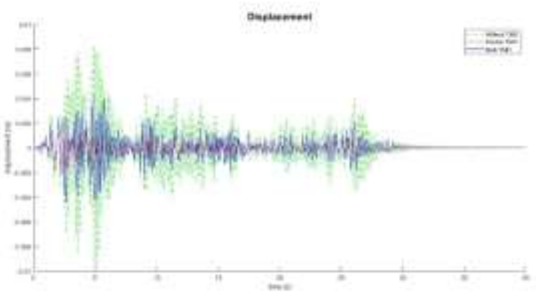
Mode 1	Mode 2	Mode 3	Mode 4
0.0325	0.7871	1	0.0012
0.0458	1	-0.7845	-0.0034
0.9552	-0.6878	-0.0078	1
1	-0.7737	0.0754	-0.9529

Table 12. Comparison between displacements and accelerations of the top story for case 1

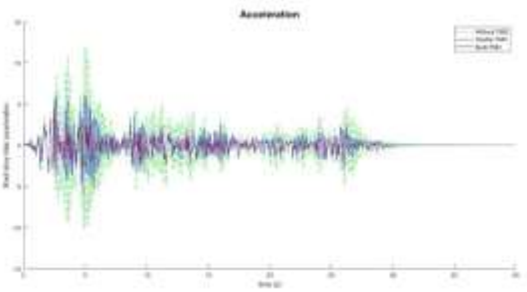
Without TMD		Case 1. a With Multiple TMD		Case 1. b With Double TMD	
Max displacement (m)	0.0096	Max displacement (m)	0.0045	Max displacement (m)	0.0020
Max acceleration (m/s^2)	11.9639	Max acceleration (m/s^2)	6.1634	Max acceleration (m/s^2)	4.8716

Table 13. Comparison between displacements and accelerations of the top story for case 2

Without TMD		Case 2. a With Multiple TMD		Case 2. b With Double TMD	
Max displacement (m)	0.0038	Max displacement (m)	0.0025	Max displacement (m)	0.0012
Max acceleration (m/s^2)	8.4017	Max acceleration (m/s^2)	6.2051	Max acceleration (m/s^2)	5.0391

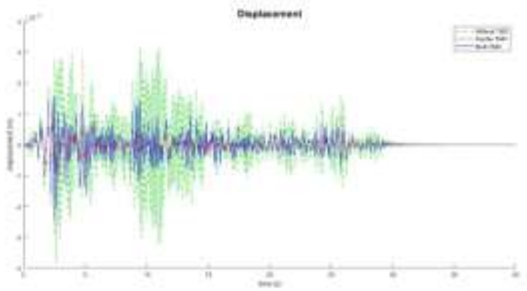


(a) Displacement

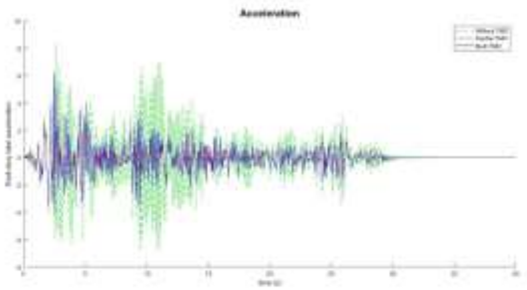


(b) Acceleration

Fig. 4 Responses of the structure for case 1. (a) Displacement. (b) Acceleration.



(a) Displacement



(b) Acceleration

Fig. 5 Responses of the structure for case 2. (a) Displacement. (b) Acceleration.

4 Conclusion

In conclusion, the effectiveness of a multiple TMD system and a Double TMD system as passive vibration control systems when applied to a soft story building subjected to El-Centro seismic excitation, considered as a 4DOF system, was investigated and compared. The parameters of the MTMDs and DTMDs, as well as mode shapes and responses, were thoroughly examined, leading to the following conclusions:

1. The utilization of a double-tuned mass damper (DTMD) at the top of a structure demonstrates superior effectiveness in reducing peak responses, including acceleration and displacement, as compared to the deployment of multiple-tuned mass dampers (TMDs) distributed across the structure's stories. The DTMD achieves a displacement reduction of 125% and an acceleration reduction of 26.51% for structures without soft stories. In the case of structures with soft stories, the results indicate a displacement reduction of 108.33% and an acceleration reduction of 23.14%. This underscores the enhanced performance and applicability of the DTMD system, thereby offering valuable insights into optimizing vibration control strategies in structural engineering.
2. Regarding the frequency aspect, it is evident that employing a double-tuned mass damper (DTMD) leads to higher frequency values when compared to the use of multiple TMDs for both cases.
3. The periods associated with the double TMD model are consistently shorter than those of the multiple TMD model for both cases.
4. It has been ascertained that the parameters governing the tuned mass dampers (TMDs) exhibit uniform characteristics across both the multiple TMD and double TMD configurations. Notably, these parameters reveal a marked increase in values in the context of soft story structures, irrespective of whether we examine the multiple-tuned mass dampers (MTMD) or double-tuned mass dampers (DTMD).

In summary, the primary objective in soft story buildings, where lower stories are more flexible and vulnerable to lateral motion during seismic events, is to enhance lateral stability and mitigate the risk of structural damage or collapse. In this context, a double-tuned mass damper (DTMD) system can prove more effective, as it offers supplementary damping to the primary structure, reducing lateral vibration amplitudes. While multiple-tuned mass damper (MTMD) systems can effectively control vibrations, they may not provide the same level of damping to the primary structure, particularly in soft story buildings characterized by significant flexibility discrepancies between stories. In addition, because the Den Hartog method is used for calculation, the effectiveness of the DTMD is somewhat reduced. To find more suitable DTMD parameters, optimization methods such as Harmony

Search (HS), Teaching-Learning-Based Optimization (TLBO), and Enhanced Teaching-Learning-Based Optimization (ETLBO) can be employed in future work.

References:

[1] Hatipoğlu, Y.S., Düzgün, O.K., Investigation Of The Effectiveness Of Viscous Dampers Connected To Adjacent Buildings On Dynamic Behavior Under Soil-Structure Interaction Effects, *Sigma Journal of Engineering and Natural Sciences Sigma Mühendislik ve Fen Bilimleri Dergisi*, 11 (1), 2020, 51-72.

[2] Rahimi, F., Aghayari, R., Samali, B., Application of Tuned Mass Dampers for Structural Vibration Control, *Civil Engineering Journal*, 6(8). 2020, 2476-3055.

[3] Guevara-Perez, L.T., " Soft Story " and " Weak Story " in Earthquake Resistant Design: A Multidisciplinary Approach. *Semantic Scholar*, 2012.

[4] Hejazi1.F., Jilani. S., Noorzaei. J., Chieng1. C. Y., Jaafar. M. S., ve Abang Ali, A. A., Effect of Soft Story on Structural Response of High Rise Buildings, *IOP Conference Series: Materials Science and Engineering, Conference on Advanced Materials and Nanotechnology,* 2011, (CAMAN 2009) 3–5 November 2009, Putra World Trade Center (PWTC) Kuala Lumpur, Malaysia, DOI 10.1088/1757-899X/17/1/012034.

[5] Koo, J.H., Shukla, A., ve Ahmadian, M., Dynamic Performance Analysis of Non-Linear Tuned Vibration Absorbers. *Communications in Nonlinear Science and Numerical Simulation*,13(9), 2008, 1929-1937.

[6] Soong, T.T., ve Spencer Jr B.F., Supplemental energy dissipation: state-of-the-art and state-of-the-practice, *Engineering Structures*, 24, 2002, 243–259.

[7] Spencer. B. F.; Sain. M. K.; Controlling buildings: a new frontier in feedback. *IEEE Control Systems Magazine*, 17(6), 1997, 19-35.

[8] Spencer. B. F.; Soong. T. T.; Supplemental energy dissipation: state-of-the-art and state-of-the-practice. *Engineering Structures*, 24(2002), 2002, 243–259.

[9] Housner, G.W., Bergman, L.A., Caughey, T.K., Chassiakos A.G., Claus, R.O., Masri, S.F., Skelton, R.E., Soong, T.T., Spencer, B.F., ve Yao, J.T.P., Structural control: present and future, *Journal of engineering mechanics*, 123 (9), 1997, 897-971.

[10] Chunxiang. Li.; Optimum multiple tuned mass dampers for structures under the ground acceleration based on DDMF and ADMF. *Earthquake engineering and structural dynamics*, 31(4), 2001, 897–919.

[11] Suresh. L.; Mini. K.M.; Effect of Multiple Tuned Mass Dampers for Vibration Control in High-Rise Buildings. *Practice Periodical on Structural Design and Construction*, 24(4), 2019.

[12] Patil. S.; Javheri. S. B.; Konapure. C. G.; Effectiveness of Multiple Tuned Mass Dampers. *International Journal of Engineering and Innovative Technology (IJEIT),* 6(1), 2012, 78-83.

[13] Cao, H. Q., & Tran, N. A., Multi-objective optimal design of double tuned mass dampers for structural vibration control. *Archive of Applied Mechanics,* 93(5), 2023, 2129–2144.

[14] Li, C., & Zhu, B., Estimating double tuned mass dampers for structures underground acceleration using a novel optimum criterion. *Journal of Sound and Vibration*, 298(1–2), 2006, 280–297.

[15] Farid. B. J. M.; and Abubakar, M.; Generalized Den Hartog tuned mass damper system for control of vibrations in structures. *WIT Transactions on the Built Environment,* 2009, 185-193.

[16] Argenziano. M.; Faiella. D.; Carotenuto. A. R.; Mele. E.; Fraldi. M.; Generalization of the Den Hartog model and rule-of-thumb formulas for optimal tuned mass dampers. *Journal of Sound and Vibration,* (538), 2022, ISSN 0022-460X.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.