Performance comparison of location of optimum TMD on seismic structures

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Abstract: - The parameters of mechanical components of tuned mass dampers (TMDs) need to optimally tuned for an effective vibration reduction of seismic structures. Generally, metaheuristic algorithms are employed for this optimization problem. In the present study, location of a TMD on a seismic structure is investigated. The case structure is a 15-story building and the lowest story has a low stiffness to represent a base isolation level. The optimum TMD parameters are found for the placement of TMD on the top and base isolation level. The performance of TMD is best when it is on the top, but the optimum damping ratio value is small for a TMD positioned on the base isolation floor. The optimum TMDs are effective to reduce base isolation floor displacement and structural accelerations.

Key-Words: Tuned Mass Dampers, Structural Control, Optimization, Metaheuristic algorithms, Flower Pollination Algorithms.

1 Introduction

The vibrations of civil structures can be reduced by using control systems. These control systems may be passive, active, semi-active or hybrid. Generally, passive systems are less effective in vibration control, but it is more feasible comparing to active control systems which need the generation of a control force by using an external source like linear actuators.

The key factor in a passive control system is the fine tuning. Otherwise, the passive control system may not be effective or it also may be harmful to the structure. Due to this reason, optimization is essential in the design of passive control systems for seismic structures. The optimized values are generally properties of the mechanical components of the system and the main objective is to reduce a critical response of the structure.

Tuned mass dampers and base isolation systems are the examples of passive control systems used in seismic structures. Especially, base isolation systems are effective in reduction of structural accelerations, but the displacement of base isolation level must be kept in a feasible limit to prevent rupture of the rubber isolator systems or to provide a feasible seismic gap around the structure. Nigdeli et al. [1] proposed an optimization methodology to find the optimum period and damping of base isolation systems. A music inspired metaheuristic algorithm called harmony search (HS) [2] was employed in that study. Then, Bekdaş et al. [3] employed Bat algorithm developed by Yang [4] for the same problem.

Tuned mass dampers (TMDs) can be used on all types of mechanical systems including civil structures. The main idea is to tune the frequency (or period) of mass damper close to the first natural frequency (or period) of the structure. In

documented methods, several formulations are proposed for optimum ratio of frequencies (f_{opt}) of TMD ($\omega_{d,opt}$) and superstructure (ω_s) was proposed with the optimum damping ratio ($\xi_{d,opt}$). Some of the formulations are presented in Table 1. In these formulations, μ is the ratio of mass of TMD (m_d) and structure (m). The damping coefficient of TMD is shown with $c_{d,opt}$ and ξ is the superstructure damping.
The formulations presented in Table 1 are for single degree of freedom (SDOF) superstructures. These formulations can be used for multiple degree of freedom system by considering a single vibration mode only. For a more general optimum tuning by considering multiple modes and effect of earthquake excitations, metaheuristic algorithms can be employed [5-22].
In the present study, the position factor of TMD was investigated by positioning TMD on the first and top story of the structure. The case structure is a base isolated building with a soft first story (base isolation level). The optimum TMD parameters are found by using Flower Pollination Algorithm (FPA) developed by Yang [26] and the optimization objective is to reduce the maximum inter story drifts which occur at the base isolation level.

TABLE I. THE FREQUENCY AND DAMPING RATIO EXPRESSIONS OF THE TMD OPTIMIZATION

Method	$f_{opt}=\frac{w_{d,opt}}{w_s}$	$\xi_{d,opt}=\frac{c_{d,opt}}{2m_d w_{d,opt}}$
Den Hartog [23]	$\frac{1}{1+\mu}$	$\sqrt{\frac{3\mu}{8(1+\mu)}}$
Warburton [24]	$\frac{\sqrt{1-(\mu/2)}}{1+\mu}$	$\sqrt{\frac{\mu(1-\mu/4)}{4(1+\mu)(1-\mu/2)}}$
Sadek *et al.* [25]	$\frac{1}{1+\mu}\left[1-\xi\sqrt{\frac{\mu}{1+\mu}}\right]$	$\frac{\xi}{1+\mu}+\sqrt{\frac{\mu}{1+\mu}}$
Leung & Zhang [11]	$\frac{\sqrt{1-(\mu/2)}}{1+\mu}+(-4.9453+20.2319\sqrt{\mu}-37.9419\mu)\sqrt{\mu}\xi+(-4.8287+25.0000\sqrt{\mu})\sqrt{\mu}\xi^2$	$\sqrt{\frac{\mu(1-\mu/4)}{4(1+\mu)(1-\mu/2)}}-5.3024\xi^2\mu$

2 Methodology

In this section, the equations of motion of shear buildings with TMD on the top (Figure 1) and on the first story (Figure 2) are given. The equation of a N-story shear building can be written as Eq. (1) in matrix form.

$$M\ddot{x}(t)+C\dot{x}(t)+Kx(t)=-M\{1\}\ddot{x}_g(t) \tag{1}$$

If the TMD is on the top or on the first story (base isolation floor), the mass matrix (M) can be written as follows:

$$M=\mathrm{diag}[m_1\, m_2 \,........... m_N\;\; m_d] \tag{2}$$

$\ddot{x}(t)$, $\dot{x}(t)$ and x(t) represent the acceleration, velocity and displacement vectors with respect to ground and the displacement vector as shown below.

$$x(t)=\mathrm{diag}[x_1\, x_2 \,........... x_N\;\; x_d]^T \tag{3}$$

The stiffness (K) and damping (C) matrices for TMD at the top is as follows:

$$K=\begin{bmatrix} (k_1+k_2) & -k_2 & & & & \\ -k_2 & (k_2+k_3) & -k_3 & & & \\ & . & . & & & \\ & . & . & . & & \\ & & . & . & . & \\ & & & -k_N & (k_N+k_d) & -k_d \\ & & & & -k_d & k_d \end{bmatrix} \tag{4}$$

$$C=\begin{bmatrix} (c_1+c_2) & -c_2 & & & & & \\ -c_2 & (c_2+c_3) & -c_3 & & & & \\ & . & . & & & & \\ & . & . & . & & & \\ & & . & . & . & & \\ & & & & -c_N & (c_N+c_d) & -c_d \\ & & & & & -c_d & c_d \end{bmatrix} \quad (5)$$

If the TMD is on the first story, the K and C matrices are written as Eqs. (6) and (7), respectively.

$$K=\begin{bmatrix} (k_1+k_2+k_d) & -k_2 & & & & & -k_d \\ -k_2 & (k_2+k_3) & -k_3 & & & & \\ & . & . & & & & \\ & . & . & . & & & \\ & & . & . & . & & \\ & & & & -k_N & (k_N) & 0 \\ -k_d & . & . & . & . & 0 & k_d \end{bmatrix} \quad (6)$$

$$C=\begin{bmatrix} (c_1+c_2+c_d) & -c_2 & & & & & -c_d \\ -c_2 & (c_2+c_3) & -c_3 & & & & \\ & . & . & & & & \\ & . & . & . & & & \\ & & . & . & . & & \\ & & & & -c_N & c_N & 0 \\ -c_d & . & . & . & . & 0 & c_d \end{bmatrix} \quad (7)$$

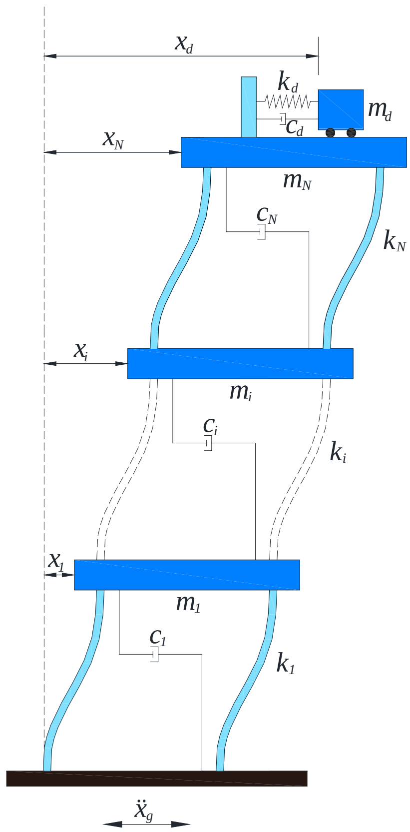

Figure 1 Model of N-story shear building including a TMD on the top.

m, k and c values are the mass, stiffness and damping coefficient values of a story and lower indices represent the story number or the TMD with d. The period (T_d) and damping ratio (ξ_d) of TMD can be found as follows:

$$T_d = 2\pi\sqrt{\frac{m_d}{k_d}} \quad (8)$$

$$\xi_d = 2c_d m_d\sqrt{\frac{k_d}{m_d}} \quad (9)$$

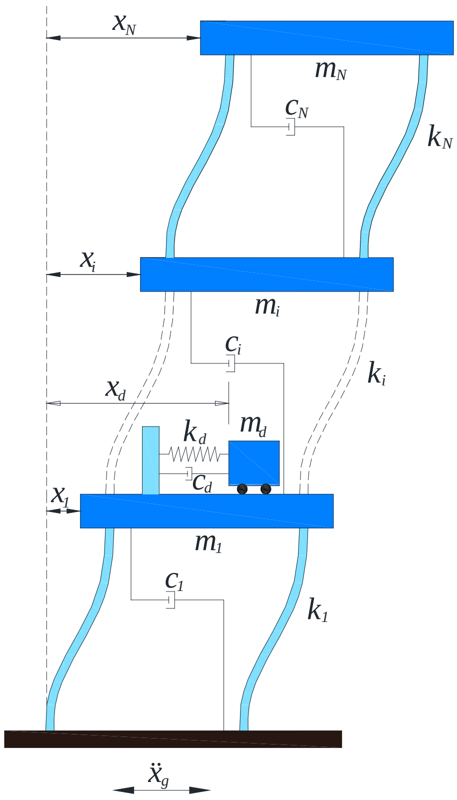

Figure 2 Model of N-story shear building including a TMD on the first story.

The optimization objective (f(x)) is to minimize the maximum inter-story drifts as formulated as Eq. (10) by considering a normalized TMD stroke constraint shown as Eq. (11). st-max is the allowed value for the normalized stroke. The maximum drift of the base isolated structure is always at the first story.

$$f(x) = \max[x_1] \quad (10)$$

$$\frac{\max[|x_d - x_N|]_{\text{with TMD}}}{\max[|x_N|]_{\text{without TMD}}} \le st\_max \quad (11)$$

The mass of the structure is taken as constant. T_d and ξ_d are the design variables searched for a set of earthquake records (Table II) by using Flower Pollination Algorithm (FPA).

In nature, flowers reproduce by pollination in two ways. In the first way, pollens can be transferred by pollinators such as insects, birds, bats or other animals (cross-pollination). In the second way, some flower types have ability for self-pollination. According to the following four rules, FPA is developed [26].

1.The pollinators obey the rules of a Lévy distribution in cross-pollination and it is the global pollination process.

2.Self-pollination is local pollination process and it occurs from pollen of the same flower species.

3.Flower constancy is used as a reproduction strategy. İt is the similarity of two flowers involved in pollination.

4.A probability is used to choose the pollination type. It is called the switch probability.

In the optimization methodology, design constants (structural properties, external excitations and ranges of design variables) are initially defined. Then, the super-structure (the building without TMD) is analyzed. Then, the results will be used to compare the effectiveness of the TMD. Then, the initial solutions for design variables such as period and damping ratio of TMD are randomly generated and the dynamic analyses are done for all set of variables as many as population number. Then, the iterative optimization process starts.

TABLE II. FEMA FAR-FAULT RECORDS [27]

Earthquake No.	Earthquake Name	Recording Station	Year	Magnitude	FN Component	FP Component
1	Northridge	Beverly Hills - Mulhol	1994	6,7	NORTHR/MUL009	NORTHR/MUL279
2	Northridge	Canyon Country-WLC	1994	6,7	NORTHR/LOS000	NORTHR/LOS270
3	Duzce, Turkey	Bolu	1999	7,1	DUZCE/BOL000	DUZCE/BOL090
4	Hector Mine	Hector	1999	7,1	HECTOR/HEC000	HECTOR/HEC090
5	Imperial Valley	Delta	1979	6,5	IMPVALL/H-DLT262	IMPVALL/H-DLT352
6	Imperial Valley	El Centro Array #11	1979	6,5	IMPVALL/H-E11140	IMPVALL/H-E11230
7	Kobe, Japan	Nishi-Akashi	1995	6,9	KOBE/NIS000	KOBE/NIS090
8	Kobe, Japan	Shin-Osaka	1995	6,9	KOBE/SHI000	KOBE/SHI090
9	Kocaeli, Turkey	Duzce	1999	7,5	KOCAELI/DZC180	KOCAELI/DZC270
10	Kocaeli, Turkey	Arcelik	1999	7,5	KOCAELI/ARC000	KOCAELI/ARC090
11	Landers	Yermo Fire Station	1992	7,3	LANDERS/YER270	LANDERS/YER360
12	Landers	Coolwater	1992	7,3	LANDERS/CLW-LN	LANDERS/CLW-TR
13	Loma Prieta	Capitola	1989	6,9	LOMAP/CAP000	LOMAP/CAP090
14	Loma Prieta	Gilroy Array #3	1989	6,9	LOMAP/G03000	LOMAP/G03090
15	Manjil, Iran	Abbar	1990	7.4	MANJIL/ABBAR--L	MANJIL/ABBAR--T
16	Superstition Hills	El Centro Imp. Co.	1987	6.5	SUPERST/B-ICC000	SUPERST/B-ICC090
17	Superstition Hills	Poe Road (temp)	1987	6.5	SUPERST/B-POE270	SUPERST/B-POE360
18	Cape Mendocino	Rio Dell Overpass	1992	7.0	CAPEMEND/RIO270	CAPEMEND/RIO360
19	Chi-Chi, Taiwan	CHY101	1999	7.6	CHICHI/CHY101-E	CHICHI/CHY101-N
20	Chi-Chi, Taiwan	TCU045	1999	7.6	CHICHI/TCU045-E	CHICHI/TCU045-N
21	San Fernando	LA Hollywood Stor	1971	6.6	SFERN/PEL090	SFERN/PEL180
22	Friuli, Italy	Tolmezzo	1976	6.5	FRIULI/A-TMZ000	FRIULI/A-TMZ270

In the global pollination, the solution of the next step (x_i^{t+1}) is found by using the values of the previous step (step t) defined as x_i^t (Eq. (12)).

$$x_i^{t+1}= x_i^t+L(x_i^t-g_*) \quad (12)$$

In Eq. (12), i represents the *i*-th pollen, g_* is the current best solution and L is a Lévy distribution.

Local pollination is formulized with random walks as seen in Eq. (13).

$$x_i^{t+1}= x_i^t+\in(x_j^t- x_k^t) \quad (13)$$

In local pollination, x_j^t and x_k^t are solution of different plants. ∈ is a linear distribution randomized between 0 and 1. The iteration continue until the objective function is minimized.

3 Numerical Example

The properties of the structure model are given as Table III. The maximum drift and acceleration of the structure under FEMA far-field earthquake records as given in Tables IV and V, respectively. The maximum responses occur for the fault parallel component of 19th station. The maximum displacement of the first story is 1.271 m and the maximum acceleration is 6.7262 m/s^2.

TABLE III. PROPERTIES OF STRUCTURE [28]

Story	Mass	Stiffness	Damping Coefficient
1	$4.500x10^5$	$1.805x10^7$	$2.617x10^4$
2-15	$3.456\ x10^5$	$3.404\ x10^8$	$2.937x10^5$

TABLE IV. THE MAXIMUM DRIFT OF STRUCTURE

EQ/i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1,FN	0.190	0.008	0.010	0.012	0.014	0.015	0.017	0.017	0.017	0.017	0.015	0.013	0.010	0.007	0.004
1,FP	0.160	0.007	0.008	0.009	0.010	0.011	0.012	0.012	0.012	0.011	0.010	0.009	0.007	0.005	0.002
2,FN	0.171	0.009	0.009	0.008	0.008	0.008	0.008	0.008	0.007	0.006	0.005	0.004	0.004	0.003	0.001
2,FP	0.189	0.009	0.009	0.010	0.010	0.010	0.009	0.009	0.009	0.008	0.007	0.006	0.005	0.003	0.002
3,FN	0.350	0.016	0.016	0.017	0.016	0.016	0.016	0.016	0.015	0.013	0.012	0.011	0.009	0.006	0.003
3,FP	0.202	0.010	0.010	0.010	0.010	0.011	0.013	0.013	0.014	0.013	0.012	0.010	0.008	0.005	0.003
4,FN	0.163	0.008	0.008	0.008	0.008	0.008	0.008	0.007	0.007	0.006	0.006	0.005	0.004	0.002	0.001
4,FP	0.212	0.011	0.011	0.010	0.010	0.009	0.008	0.008	0.007	0.007	0.006	0.006	0.005	0.004	0.002
5,FN	0.468	0.022	0.020	0.019	0.018	0.017	0.016	0.015	0.013	0.012	0.010	0.009	0.007	0.005	0.002
5,FP	0.241	0.012	0.013	0.014	0.014	0.014	0.014	0.013	0.013	0.011	0.010	0.008	0.006	0.004	0.002
6,FN	0.306	0.015	0.014	0.013	0.013	0.012	0.011	0.011	0.010	0.009	0.008	0.007	0.005	0.004	0.002
6,FP	0.235	0.011	0.011	0.010	0.010	0.010	0.009	0.008	0.007	0.006	0.005	0.005	0.004	0.003	0.001
7,FN	0.145	0.007	0.009	0.010	0.011	0.011	0.011	0.010	0.009	0.009	0.009	0.009	0.007	0.005	0.003
7,FP	0.162	0.008	0.008	0.008	0.008	0.008	0.008	0.007	0.007	0.007	0.007	0.006	0.005	0.004	0.002
8,FN	0.180	0.009	0.008	0.008	0.008	0.008	0.008	0.008	0.007	0.007	0.007	0.006	0.004	0.003	0.002
8,FP	0.139	0.007	0.006	0.007	0.007	0.007	0.007	0.006	0.006	0.005	0.004	0.004	0.003	0.002	0.001
9,FN	1.174	0.058	0.055	0.051	0.048	0.044	0.040	0.036	0.032	0.027	0.023	0.018	0.014	0.009	0.005
9,FP	0.417	0.020	0.020	0.019	0.019	0.018	0.017	0.016	0.015	0.013	0.011	0.009	0.007	0.005	0.003
10,FN	0.111	0.005	0.005	0.005	0.005	0.005	0.004	0.004	0.004	0.003	0.003	0.002	0.002	0.001	0.001
10,FP	0.332	0.016	0.015	0.015	0.014	0.013	0.012	0.011	0.010	0.009	0.007	0.006	0.005	0.003	0.002
11,FN	0.343	0.017	0.016	0.016	0.015	0.014	0.014	0.013	0.011	0.010	0.009	0.007	0.006	0.004	0.002
11,FP	0.278	0.013	0.012	0.012	0.013	0.012	0.012	0.011	0.010	0.009	0.008	0.007	0.005	0.004	0.002
12,FN	0.139	0.006	0.007	0.007	0.007	0.007	0.007	0.007	0.006	0.006	0.006	0.005	0.004	0.003	0.001
12,FP	0.107	0.005	0.005	0.005	0.006	0.005	0.005	0.004	0.004	0.005	0.005	0.004	0.004	0.003	0.001
13,FN	0.076	0.004	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.004	0.003	0.002
13,FP	0.124	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.005	0.005	0.004	0.003	0.002	0.001
14,FN	0.200	0.010	0.009	0.009	0.009	0.009	0.008	0.008	0.008	0.007	0.007	0.006	0.005	0.004	0.002
14,FP	0.229	0.011	0.011	0.011	0.011	0.010	0.010	0.009	0.008	0.007	0.006	0.006	0.005	0.003	0.002
15,FN	0.334	0.016	0.015	0.014	0.013	0.013	0.012	0.011	0.010	0.009	0.008	0.006	0.005	0.004	0.002
15,FP	0.395	0.019	0.018	0.017	0.017	0.016	0.014	0.013	0.012	0.011	0.010	0.008	0.007	0.005	0.002
16,FN	0.543	0.027	0.025	0.024	0.023	0.021	0.020	0.018	0.016	0.014	0.012	0.009	0.007	0.005	0.002
16,FP	0.339	0.017	0.016	0.015	0.014	0.013	0.012	0.011	0.010	0.009	0.007	0.006	0.005	0.003	0.002
17,FN	0.278	0.014	0.014	0.014	0.013	0.013	0.012	0.011	0.010	0.010	0.009	0.008	0.006	0.005	0.002
17,FP	0.264	0.014	0.013	0.013	0.013	0.012	0.011	0.011	0.010	0.009	0.008	0.006	0.005	0.003	0.002
18,FN	0.127	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.005	0.005	0.004	0.003	0.002	0.001
18,FP	0.098	0.006	0.006	0.006	0.006	0.006	0.006	0.005	0.005	0.005	0.005	0.005	0.004	0.003	0.002
19,FN	1.154	0.057	0.054	0.051	0.049	0.046	0.043	0.039	0.035	0.031	0.027	0.022	0.017	0.011	0.006
19,FP	1.271	0.060	0.057	0.056	0.054	0.052	0.049	0.046	0.042	0.037	0.032	0.027	0.020	0.014	0.007
20,FN	0.162	0.009	0.008	0.008	0.008	0.008	0.007	0.006	0.005	0.005	0.005	0.005	0.004	0.003	0.001
20,FP	0.148	0.007	0.007	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.007	0.006	0.005	0.004	0.002
21,FN	0.420	0.020	0.019	0.019	0.018	0.016	0.015	0.014	0.013	0.012	0.010	0.008	0.006	0.004	0.002
21,FP	0.171	0.008	0.007	0.007	0.007	0.007	0.006	0.006	0.006	0.005	0.004	0.004	0.003	0.002	0.001
22,FN	0.084	0.004	0.004	0.004	0.005	0.005	0.004	0.004	0.004	0.004	0.004	0.003	0.003	0.002	0.001
22,FP	0.098	0.005	0.005	0.005	0.005	0.004	0.004	0.004	0.004	0.004	0.004	0.003	0.003	0.002	0.001

TABLE V. THE MAXIMUM ACCELERATION OF STRUCTURE

EQ/i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1,FN	3.395	3.322	3.085	2.835	2.505	2.029	1.395	0.898	0.995	1.522	2.074	2.650	3.133	3.460	3.620
1,FP	2.395	2.331	2.206	1.961	1.769	1.601	1.414	1.442	1.226	1.179	1.468	1.793	2.096	2.334	2.447
2,FN	1.376	1.299	1.050	0.935	1.021	1.145	1.112	1.094	1.179	1.196	1.283	1.188	1.033	1.228	1.396
2,FP	1.506	1.488	1.384	1.272	1.130	1.009	0.898	1.034	0.975	1.041	1.139	1.338	1.487	1.585	1.658
3,FN	2.717	2.567	2.433	2.654	2.705	2.548	2.174	1.743	1.860	2.053	2.303	2.316	2.587	3.068	3.324
3,FP	2.440	2.443	2.415	2.173	1.725	1.303	1.161	0.922	1.148	1.281	1.830	2.263	2.501	2.570	2.654
4,FN	1.011	0.994	0.923	0.863	0.808	0.720	0.673	0.612	0.664	0.796	0.907	1.014	1.125	1.207	1.253
4,FP	1.629	1.563	1.366	1.094	1.159	1.296	1.373	1.389	1.407	1.282	1.081	1.038	1.373	1.664	1.825
5,FN	1.885	1.919	1.904	1.856	1.864	1.868	1.829	1.744	1.669	1.750	1.866	1.943	2.085	2.199	2.259
5,FP	2.072	2.041	1.905	1.725	1.553	1.418	1.305	1.118	1.183	1.441	1.673	1.865	2.003	2.113	2.205
6,FN	1.632	1.561	1.426	1.379	1.380	1.333	1.259	1.262	1.293	1.297	1.342	1.425	1.613	1.758	1.839
6,FP	1.350	1.260	1.101	1.100	1.160	1.201	1.228	1.217	1.369	1.311	1.124	1.093	1.179	1.390	1.466
7,FN	2.724	2.439	2.067	1.520	1.502	1.720	1.996	1.949	1.765	1.586	1.449	1.433	1.970	2.507	2.839
7,FP	2.041	1.842	1.474	1.056	0.952	1.049	1.165	1.223	1.198	1.075	0.959	1.021	1.390	1.787	2.038
8,FN	1.540	1.579	1.529	1.386	1.163	0.907	0.846	0.849	0.839	0.878	0.953	1.138	1.350	1.489	1.577
8,FP	0.885	0.863	0.847	0.841	0.821	0.800	0.730	0.722	0.760	0.832	0.864	0.851	0.901	0.971	1.006
9,FN	3.422	3.574	3.704	3.815	3.906	3.980	4.056	4.162	4.272	4.365	4.441	4.498	4.536	4.557	4.575
9,FP	1.979	2.013	1.997	1.940	1.856	1.762	1.660	1.536	1.626	1.802	1.946	2.127	2.303	2.427	2.491
10,FN	0.491	0.503	0.503	0.480	0.476	0.473	0.495	0.489	0.514	0.516	0.557	0.559	0.568	0.610	0.643
10,FP	1.168	1.202	1.227	1.250	1.256	1.250	1.232	1.202	1.195	1.263	1.325	1.385	1.444	1.497	1.526
11,FN	1.710	1.643	1.551	1.518	1.526	1.516	1.472	1.390	1.382	1.523	1.615	1.660	1.765	1.883	1.949
11,FP	1.560	1.565	1.579	1.556	1.488	1.368	1.218	1.064	1.087	1.278	1.453	1.581	1.651	1.735	1.814
12,FN	1.349	1.285	1.162	1.104	1.102	1.005	0.874	0.759	0.770	0.841	0.952	1.000	1.142	1.281	1.458
12,FP	1.334	1.168	0.916	0.780	0.815	0.829	0.878	0.871	0.781	0.773	0.766	0.708	0.972	1.267	1.436
13,FN	1.131	1.090	1.002	1.011	1.110	1.116	1.005	0.744	0.648	0.761	0.850	0.905	1.136	1.420	1.624
13,FP	0.889	0.876	0.840	0.778	0.870	0.887	0.852	0.768	0.849	0.927	0.906	0.876	0.986	1.038	1.063
14,FN	1.634	1.480	1.242	1.104	1.073	1.138	1.129	1.133	1.073	1.181	1.181	1.137	1.396	1.659	1.815
14,FP	1.446	1.292	1.147	1.102	1.209	1.236	1.150	1.121	1.132	1.124	1.167	1.213	1.325	1.515	1.632
15,FN	1.495	1.322	1.481	1.494	1.363	1.432	1.484	1.339	1.325	1.425	1.572	1.602	1.539	1.701	1.878
15,FP	1.923	1.830	1.873	1.830	1.653	1.663	1.599	1.596	1.578	1.715	1.826	1.879	2.010	2.194	2.324
16,FN	1.868	1.938	1.985	2.007	2.008	1.991	1.961	1.924	1.987	2.094	2.187	2.263	2.323	2.364	2.384
16,FP	1.146	1.183	1.207	1.211	1.224	1.303	1.362	1.378	1.344	1.277	1.296	1.388	1.474	1.548	1.589
17,FN	1.945	1.800	1.585	1.358	1.397	1.568	1.700	1.734	1.638	1.521	1.434	1.465	1.840	2.151	2.324
17,FP	1.596	1.510	1.362	1.353	1.444	1.432	1.275	1.172	1.235	1.352	1.425	1.527	1.535	1.592	1.779
18,FN	1.030	0.974	0.950	0.946	0.958	0.784	0.633	0.600	0.565	0.812	0.932	1.020	0.956	1.072	1.172
18,FP	1.474	1.268	0.985	0.862	1.095	1.277	1.256	1.092	1.245	1.205	1.018	0.872	1.083	1.330	1.523
19,FN	4.216	4.343	4.402	4.392	4.389	4.353	4.247	4.213	4.206	4.501	4.809	5.084	5.304	5.456	5.533
19,FP	5.552	5.754	5.881	5.907	5.812	5.590	5.247	4.807	4.721	5.203	5.661	6.092	6.458	6.726	6.869
20,FN	1.213	1.101	0.938	0.717	0.994	1.212	1.309	1.296	1.233	1.064	0.905	0.844	1.089	1.252	1.404
20,FP	1.633	1.553	1.446	1.282	1.160	1.045	0.934	0.776	0.767	0.869	1.056	1.223	1.408	1.652	1.825
21,FN	1.751	1.783	1.771	1.724	1.675	1.695	1.691	1.649	1.675	1.755	1.789	1.890	2.041	2.151	2.208
21,FP	0.854	0.865	0.856	0.843	0.815	0.765	0.700	0.641	0.662	0.676	0.742	0.810	0.884	0.960	1.007
22,FN	0.963	0.898	0.765	0.661	0.849	0.886	0.811	0.741	0.751	0.789	0.720	0.620	0.790	0.926	1.002
22,FP	1.002	0.856	0.631	0.547	0.654	0.803	0.941	0.926	0.884	0.804	0.660	0.636	0.762	1.015	1.150

The mass of TMD is taken as 10% of the total mass of the structure. The stmax is taken as 2. Also, the design variables are searched in the following ranges:

TMD period: Between 0.5 and 1.5 times of the critical period of the super-structure

TMD damping ratio: Between 1% and 30%

The optimum TMD parameters are presented in Table VI. According to the results, the positioning of TMD on the top is more effective in the reduction of the objective function. An increase in the period and the reduction of the damping ratio is seen for the optimum TMD positioned on the base floor.

The critical excitation for the TMD controlled structure are also the same. By using an optimum TMD on the top, it is possible to reduce the base isolation floor displacement to 0.929 m for the critical excitation. This value is also a big one for the rupture protection of base isolators. In that case, additional damping is needed for the base isolation floor. For the TMD on the base floor, the critical displacement reduces to 1 m.

TABLE VI. THE OPTIMUM RESULTS

Story	m_d(kg)	T_d(s)	ξ_d(kg)	max (X_1) (m)
On the top floor	5.2884×10^5	5.3581	0.2433	0.929
On the base floor	5.2884×10^5	5.6855	0.1715	1.00

4 Conclusions

Generally, additional damping is needed for preventing the maximum displacement of base isolation floors. By the increase of the damping, the performance of base isolation on reduction of structural accelerations reduces. In the present study, the optimum TMDs is effective in reduction of displacement of base isolation floor and additional TMD is also effective to reduce maximum accelerations by 15.2% and 17.8% by positioning on the base floor and top, respectively. In the case structure, the base floor displacement reduces up to 26.9%, but it is not enough for rupture protection of base isolator and more additional damping is in need. Also, the stroke of TMD limitation may be enlarged for a better performance, but the allowed stroke capacity (stmax=2) is also a big value. As a conclusion, TMDs are effective to reduce the base displacement of the base isolated structure with an acceleration reduction bonus, but this reduction may not be feasible without additional damping for the base isolation floor.

References:

[1] Nigdeli, S.M., Bekdas, G, Alhan, C., 2013, Optimization of seismic isolation systems via harmony search, Engineering optimization, 46(11):1553-1569.

[2] Geem, Z.W., Kim, J.H., Loganathan, G.V., 2001. A new heuristic optimization algorithm: harmony search. Simulation 76, 60–68.

[3] Yang, X. S. (2010). A new metaheuristic bat-inspired algorithm. Nature inspired cooperative strategies for optimization (NICSO 2010), 65-74.

[4] Bekdaş, G. Davas, SÖ, Nigdeli, SM, Alhan, C., A seismic isolation optimization methodology adopted with bat algorithm, International Conference on Bioinspired Optimization Methods and their Applications (BIOMA 2018), 16-18 May 2018, Paris, France.

[5] Hadi, M.N.S. and Arfiadi, Y. (1998), Optimum design of absorber for MDOF structures, Journal of Structural Engineering-ASCE, 124, 12721280.

[6] Marano, G.C., Greco, R. and Chiaia, B. (2010), A comparison between different optimization criteria for tuned mass dampers design, Journal of Sound and Vibration, 329, 4880-4890.

[7] Singh, M.P., Singh, S. and Moreschi, L.M. (2002), Tuned mass dampers for response control of torsional buildings, Earthquake Engineering and Structural Dynamics, 31, 749769.

[8] Desu, N.B., Deb, S.K., Dutta, A. (2006), Coupled tuned mass dampers for control of coupled vibrations in asymmetric buildings, Struct. Control Hlth., 13, 897-916.

[9] Pourzeynali, S., Lavasani, H.H., Modarayi, A.H. (2007), Active control of high rise building structures using fuzzy logic and genetic algorithms, Eng. Struct., 29, 346-357.

[10] Leung, A.Y.T., Zhang, H., Cheng, C.C. and Lee, Y.Y. (2008), Particle swarm optimization of TMD by non-stationary base excitation during earthquake, Earthquake Engineering and Structural Dynamics, 37, 1223-1246.

[11] Leung, A.Y.T. and Zhang, H. (2009), Particle swarm optimization of tuned mass dampers, Engineering Structures, 31, 715-728.

[12] Steinbuch, R. (2011), Bionic optimisation of the earthquake resistance of high buildings by tuned mass dampers, Journal of Bionic Engineering, 8, 335-344.

[13] Bekdaş, G. and Nigdeli, S.M. (2017), Metaheuristic based optimization of tuned mass dampers under earthquake excitation by considering soil-structure interaction, Soil Dynamics and Earthquake Engineering, 92, 443-461.

[14] Nigdeli, S.M. and Bekdaş, G. (2017), Optimum tuned mass damper design in frequency domain for structures, KSCE Journal of Civil Engineering, 21(3), 912-922.

[15] Zhang, H. Y. and Zhang, L. J. (2017). Tuned mass damper system of high-rise intake towers optimized by improved harmony search algorithm. Engineering Structures, 138, 270-282.

[16] Nigdeli SM, Bekdas G, Aydın A. Metaheuristic based optimization of tuned mass dampers on single degree of freedom structures subjected to near fault vibrations. International Conference on Engineering and Natural Sciences (ICENS 2017), 3-7 May 2017, Budapest, Hungary.

[17] Bekdas G, Nigdeli SM, Aydın A. Optimization of Tuned Mass Damper for Multi-Story Structures by using Impulsive Motions. 2nd International Conference on Civil and Environmental Engineering (ICOCEE 2017), 8-10 May 2017, Cappadocia, Turkey.

[18] Farshidianfar, A., Soheili, S. (2013), Ant colony optimization of tuned mass dampers for earthquake oscillations of high-rise structures

including soilstructure interaction, Soil Dyn. Earthquake Eng., 51, 14-22.

[19] Farshidianfar, A., Soheili, S. (2013), ABC optimization of TMD parameters for tall buildings with soil structure interaction, Interact. Multiscale Mech., 6, 339-356.

[20] Nigdeli SM, Bekdas G, Yang X-S (2017), Optimum Tuning of Mass Dampers by Using a Hybrid Method Using Harmony Search and Flower Pollination Algorithm. In: Harmony Search Algorithm. Advances in Intelligent Systems and Computing, vol 514, Del Ser J. (eds) Springer, pp. 222-231.

[21] Nigdeli SM, Bekdas G (2015), Teaching-Learning-Based Optimization for Estimating Tuned Mass Damper Parameters. 3rd International Conference on Optimization Techniques in Engineering (OTENG '15), 7-9 November 2015, Rome, Italy.

[22] Nigdeli SM, Bekdas G, Yang XS. Optimum Tuning of Mass Dampers for Seismic Structures Using Flower Pollination Algorithm. 7th European Conference of Civil Engineering (ECCIE '16), 17-19 December 2016, Bern, Switzerland.

[23] Den Hartog, J.P. (1947), Mechanical Vibrations, McGraw-Hill, New York

[24] Warburton, G.B. (1982), Optimum absorber parameters for various combination of response and excitation parameters, Earthquake Engineering and Structural Dynamics, 10, 381401.

[25] Sadek, F., Mohraz, B., Taylor, A.W. and Chung, R.M. (1997), A method of estimating the parameters of tuned mass dampers for seismic applications, Earthquake Engineering and Structural Dynamics, 26, 617635.

[26] Xin-She Yang, Flower pollination algorithm for global optimization, in: Unconventional Computation and Natural Computation 2012, Lecture Notes in Computer Science, Vol. 7445, pp. 240-249 (2012).

[27] FEMA, P. 695 (2009) Quantification of seismic performance factors. FEMA P-695 report, the Applied Technology Council for the Federal Emergency Management Agency, Washington, DC

[28] Guclu, R., & Yazici, H. (2008). Vibration control of a structure with ATMD against earthquake using fuzzy logic controllers. Journal of Sound and Vibration, 318(1-2), 36-49.