Tuned Mass Dampers for Earthquake Vibrations of High-rise Buildings using Bee Colony Optimization Technique

A. Farshidianfar*
Professor

S. Soheili†
PhD Candidate

This paper investigates the application of Artificial Bee Colony (ABC) method for the optimization of Tuned Mass Dampers (TMDs) employed for high-rise structures including Soil Structure Interaction (SSI). The model is a 40-story building, and Newmark method is utilized for the structure response to Bam earthquake data. The objective is to decrease both maximum displacement and acceleration. It is shown that ABC method can be effectively applied to design the optimum TMD for tall buildings. It is also indicated that this model is more accurate than fixed based models. The effects of mass, damping coefficient and spring stiffness are also studied. This study leads the researchers to the better understanding and designing of TMDs for the mitigation of earthquake oscillations.

Keyword: Tuned Mass Damper, Soil-Structure Interaction, Bee Colony Optimization

1 Introduction

In the last decades, high-rise buildings are widely developed and constructed in most countries. These structures are generally flexible, possess low damping properties and are usually subjected to the earthquake vibrations. Therefore, the study of tall buildings vibration mitigation and various absorbers has attracted the interest of many researchers. Moreover, the soil characteristics and the interaction between soil and structure greatly influence the structural responses.

A tuned mass damper (TMD) is a kind of vibration absorber consisting mass, spring and viscous damper attached to the vibrating system to mitigate oscillations. It passively dissipates energy through the interaction of inertial force produced by mass movement and damping effects induced by damper.

As Ormondroyd and Den Hartog [1] mentioned, the application of TMD was firstly proposed in 1909. Since then, many theoretical and experimental researches have been performed to study the TMD's mechanism of vibration mitigation and its application for the structures. The TMDs are usually installed on the top floor, and several researches have been conducted to study their effectiveness for earthquake [2] and wind [3,4] excitations.
Gupta et al. [5] investigated the effects of several TMDs with elastic-plastic properties on the response of single degree of freedom structures subjected to Kern County earthquake (1952).

* Corresponding Author, Professor, Mechanical Engineering Department, Ferdowsi University of Mashhad, Mashhad, Iran, farshid@um.ac.ir
† PhD Candidate, Mechanical Engineering Department, Ferdowsi University of Mashhad, Mashhad, Iran. soheili78@yahoo.com

To investigate the effect of TMDs on the fundamental mode response, Kaynia et al. [6] studied the optimum reduction of structures response subjected to 48 earthquake spectra. They figured out that the TMDs are less effective in decreasing the response of structures than previously thought. Sladek and Klingner [7] investigated best parameters of a TMD placed on top floor of a 25-story building, based on minimization of response to sinusoidal loading.

An optimization method is employed by Wirsching and Campbell [8] to calculate the TMD parameters for 1-, 5- and 10-story buildings. According to their study, TMDs are effective devices in reducing response. Ohno et al. [9] presented the optimized TMD parameters based on the minimization of mean square acceleration response to earthquake excitations. Several studies on the application of TMD and its best values are performed by other researchers such as Villaverde et al. [10]. Later, Sadek et al. [11] presented some formulations for computing the optimal parameters of TMD device based on the equal damping of the first two modes of system.

Considering soil effects, the structure response differs from the fixed base model. The oscillation energy is actually transferred to the foundation through the soil. Therefore, the soil and structure influence each other, which is called the soil-structure interaction (SSI). Various investigations are performed to study the SSI effects. For example, frequency domain analysis was performed by Xu and Kwok [12] to obtain the wind induced vibrations of soil-structure-damper system. Moreover, the frequency independent expressions are proposed by wolf [13] to determine the swaying and rocking dashpots, and the related springs of a rigid circular foundation. Recently, Liu et al. [14] developed a mathematical model for time domain analysis of wind induced oscillations of a tall building with TMD considering soil effects.

Although numerous works are performed concerning SSI effects, few investigations are carried out on the time response of high-rise buildings due to earthquake excitations. In fact, the earthquake time response of tall buildings has usually been calculated employing fixed base models. These analyzes cannot reasonably predict the structural responses. Moreover, the optimal parameters of TMD are extremely related to the soil type. Therefore, the time domain analysis of structures consisting SSI effects is an advantageous process for the better understanding of earthquake oscillations and TMD devices. Furthermore, few works have considered and employed heuristic algorithms, while the heuristic techniques such as Artificial Bee Colony (ABC) method, can be effectively employed for the optimized design of TMDs.

In this paper, a mathematical model is developed for calculating the earthquake response of a high-rise building with TMD. The model is employed to obtain the time response of 40-story building using TMD. The artificial bee colony (ABC) method is applied on the model to obtain the best TMD parameters. The parameters are calculated with and without soil structure interaction (SSI) effects. The effects of different parameters such as mass, damping coefficient, spring stiffness, natural frequency and damping ratio are also investigated.

2 Modeling of Tall Buildings

Figure (1) shows the N-story structure with a TMD and SSI effects. Mass and moment of inertia for each floor are indicated as M_i and I_i , and those of foundation are shown as M_0 and I_0 , respectively. The stiffness and damping between floors are assumed as K_i and C_i , respectively. M_{TMD} , K_{TMD} and C_{TMD} are the related parameters for TMD. Damping of the swaying and rocking dashpots are represented as C_s and C_r , and the stiffness of corresponding springs are indicated as K_s and K_r , respectively. Time histories of displacement and rotation of foundation are respectively defined as X_0 and θ_0, and displacement of each story is shown as X_i. The height of each floor is also assumed as Z_i.

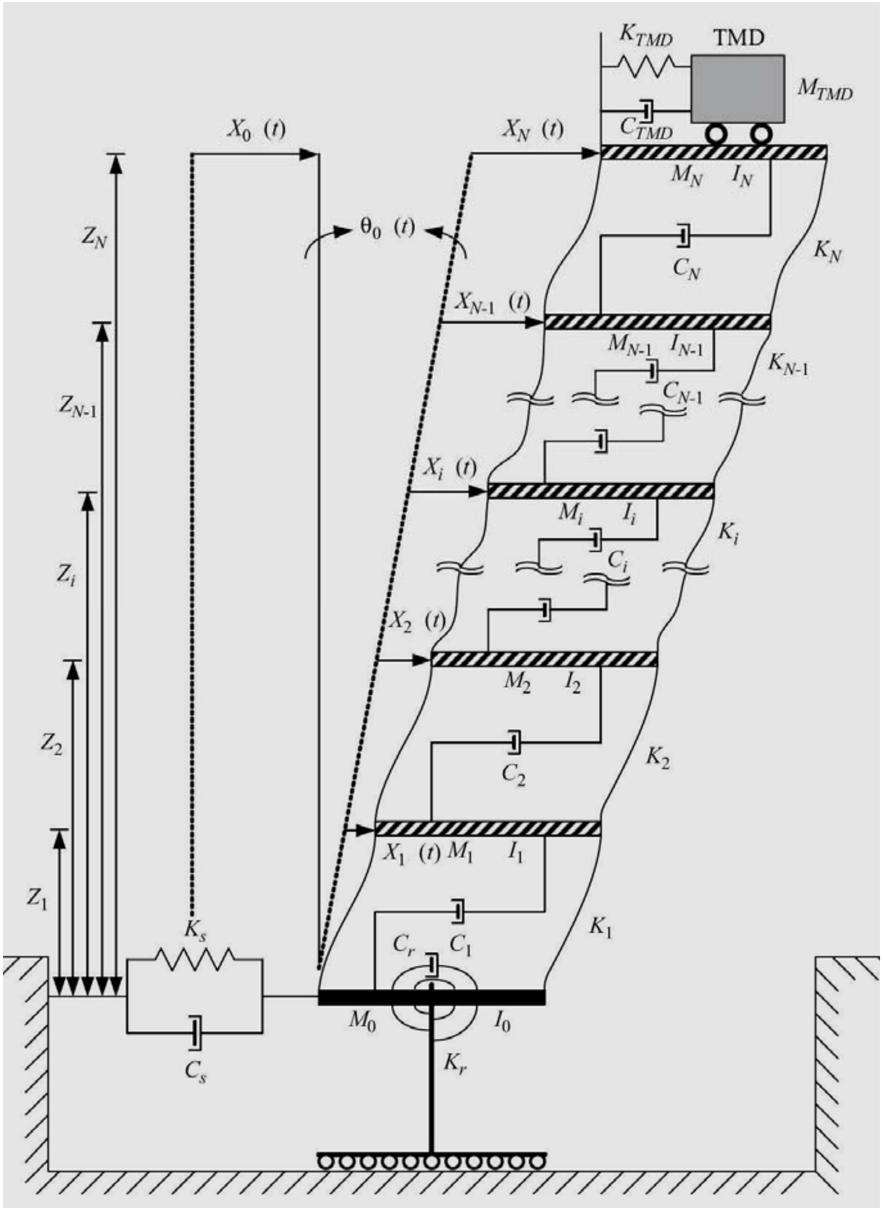

Figure 1 Shear building configuration

Using Lagrange's equation, the equation of motion for a building shown in Figure (1) can be represented as follows [15]:

$$[m]\{\ddot{x}(t)\}+[c]\{\dot{x}(t)\}+[k]\{x(t)\}=-[m^*]\{1\}\ddot{u}_g \tag{1}$$

Where $[m]$, $[c]$ and $[k]$ denote mass, damping and stiffness of the oscillating system. $[m^*]$ indicates acceleration mass matrix for earthquake and $\ddot{u}_g$ is the earthquake acceleration. Considering SSI effects, the N-story structure is N+3 degree-of-freedom oscillatory system. For such building, the mass, damping and stiffness matrices are obtained by employing Lagrange's equation in the following form [14, 15]:

$$[m] = \begin{bmatrix} [M]_{N\times N} & \{0\}_{N\times 1} & [M]_{N\times 1} & [MZ]_{N\times 1} \\ & M_{TMD} & M_{TMD} & M_{TMD}Z_N \\ & & M_0 + \sum_{j=1}^{N} M_j + M_{TMD} & \sum_{j=1}^{N} M_j Z_j + M_{TMD}Z_N \\ symmetry & & & I_0 + \sum_{j=1}^{N}(I_j + M_j Z_j^2) + M_{TMD}Z_N^2 \end{bmatrix} \tag{2}$$

$$[k] = \begin{bmatrix} [K]_{N\times N} & \{K_{TMD}\}_{N\times 1} & \{0\}_{N\times 1} & \{0\}_{N\times 1} \\ & K_{TMD} & 0 & 0 \\ & & K_s & 0 \\ symmetry & & & K_r \end{bmatrix} \tag{3}$$

$$[c] = \begin{bmatrix} [C]_{N\times N} & \{C_{TMD}\}_{N\times 1} & \{0\}_{N\times 1} & \{0\}_{N\times 1} \\ & C_{TMD} & 0 & 0 \\ & & C_s & 0 \\ symmetry & & & C_r \end{bmatrix} \tag{4}$$

$$[m^*] = \begin{bmatrix} [M]_{N\times N} & \{0\}_{N\times 1} & \{0\}_{N\times 1} & \{0\}_{N\times 1} \\ 0 & M_{TMD} & 0 & 0 \\ 0 & 0 & M_0 + \sum_{j=1}^{N} M_j + M_{TMD} & 0 \\ 0 & 0 & \sum_{j=1}^{N} M_j Z_j + M_{TMD}Z_N & 0 \end{bmatrix} \tag{5}$$

Ignoring the SSI effects, rows and columns N+2 and N+3 are neglected, and the mentioned matrices are reduced to (N+1)×(N+1) dimensional matrices.

According to Rayleigh proportional damping, the damping matrix of N-story structure can be represented as follows:

$$[c]_{N\times N} = A_0[m]_{N\times N} + A_1[k]_{N\times N} \tag{6}$$

in which A_0 and A_1 are Rayleigh damping coefficients.

The displacement vector $\{x(t)\}$ including both displacement and rotation of floors and foundation as well as TMD motion can be represented as follows:

$$\{x(t)\} = \{X_1(t) \quad X_2(t) \quad \ldots \quad X_N(t) \quad X_{TMD}(t) \quad X_0(t) \quad \theta_0(t)\}^T \tag{7}$$

The parameters C_s , C_r , K_s and K_r can be obtained from soil properties (i.e. poisson's ratio v_s , density ρ_s , shear wave velocity V_s and shear modulus G_s) and radius of foundation R_0 [14].

In this paper, Bam earthquake acceleration spectrum is applied to the structure, and time response of TMD and building are calculated based on Newmark integration method [16].

3 Artificial Bee Colony (ABC) Method

Natural behavior of bees and their collective activities in their hives has been fascinating researchers for centuries. Several algorithms have been proposed and developed based on the foraging behavior of bees. Regarding combinatorial optimization, the works of Tereshko [17] are leading. He and his colleagues modeled robots as bees having limited intelligence individually, but their cooperative behavior makes real robotic tasks possible. For optimization in continuous domains, Yang developed a method called Virtual Bee Algorithm (VBA) which was applied to optimize benchmark functions with maximum dimension of two [18]. Artificial Bee Colony (ABC) algorithm, the method employed in this paper, was presented by Karaboga in 2005 to optimize numeric benchmark functions [19]. It was then extended by Karaboga and Basturk and showed to outperform other recognized heuristic methods such as GA [20] as well as DE, PSO and EA [21].

Similar to other nature-based algorithms, ABC models honey bees but not necessarily precisely. In this model, the honey bees are categorized as employed, onlooker and scout. An employed bee is a forager associated with a certain food source which she is currently exploiting. She memorizes the quality of the food source and then after returning to the hive, shares it with other bees waiting there via a peculiar communication called waggle dance. An onlooker bee is an unemployed bee at the hive which tries to find a new food source using the information provided by employed bees. A scout, ignoring the other's information, searches around the hive randomly. In nature, the employment of unemployed bees happens in a nearly similar way. In addition, when the quality of a food source is below a certain level, it will be abandoned to make the bees explore for new food sources.

In ABC, the solution candidates are modeled as food sources and their corresponding objective functions as the quality (nectar amount) of the food source. For the first step, the artificial employed bees are randomly scattered in the search domain producing *SN* initial solutions. Here, *SN* represents the number of employed or onlooker bees which are considered equal until the end of algorithm. It is notable that any of these solutions x_i (i=1, 2…, *SN*) is a D-dimensional vector representing *D* design variables constructing the objective function. After this initialization, the main loop of the algorithm described hereafter is repeated for a predetermined number of cycles or until a termination criterion is satisfied.

Firstly, all employed bees attempt to find new solutions in the neighbor of the solution (food source) they memorized at the previous cycle. If the quality (the amount of objective function) is higher at this new solution, then she forgets the former and memorizes the new one. In ABC, a particular mechanism is devised for this purpose; which only allows one of the dimensions of the current solution being subjected to modification:

$$v_{ij} = x_{ij} + \phi_{ij}(x_{ij} - x_{kj}) \tag{8}$$

where $j \in \{1,2,\cdots,D\}$ and $k \in \{1,2,\cdots,SN\}$ are randomly chosen indices, and v_{ij} represents the new solution (new food source position). It should be noted that $k \neq i$. The parameter ϕ is also a random number in the domain [-1, 1].

After that, the onlooker bees should select the solution around which they explore for new food sources. This is performed probabilistically i.e. a mechanism like roulette wheel is employed using the fitness (the related objective function or a similar concept) of all current solutions. With the help of a uniform random number generator, the solutions for further exploration can be easily determined:

$$p_i = \frac{fit_i}{\sum_{n=1}^{SN} fit_n} \tag{9}$$

Noticeably, some onlooker bees might be directed to search around identical solutions. When the solutions are selected, producing new candidate solutions around them is done in the same way that employed bees perform using (8). Additionally, updating food sources is done with the same greedy process by comparing the new solutions produced by onlookers and the corresponding current solutions. It is notable that different approaches have been proposed for assigning fitness to solutions especially when minimization is to be done with an originally maximizing algorithm such as ABC or when negative values of objective function is engaged. Karaboga [22] has utilized a familiar form described below which is adopted in this paper as well:

$$fit_i = \begin{cases} \dfrac{1}{1+f_i} & f_i \geq 0 \\ 1+|f_i| & f_i < 0 \end{cases} \tag{10}$$

Where f_i is the objective function of solution x_i .

If a solution cannot be improved by employed or onlooker bees after certain iterations called *limit*, then the solution is abandoned and the bee becomes a scout. In that case, the scout bee searches randomly for a new solution within the search space. It should be reminded that at each cycle, only one artificial bee is allowed to become scout and perform the search as follows:

$$x_i^j = x_{\min}^j + \varphi(x_{\max}^j - x_{\min}^j) \tag{11}$$

where φ is a random number in domain [0, 1]. Obviously, variables of all dimensions are replaced with new randomly-generated values.

Since the problem is of multi-objective nature trying to minimize both the maximum displacement and acceleration of the building, an overall objective function including both concepts should be employed. Here, as the acceleration results are nearly 10 times greater than displacement, the objective function is defined as follows:

$$f_i = \ddot{u}_{\max} + 10u_{\max} \tag{12}$$

Where $u_{\max}$ and $\ddot{u}_{\max}$ denotes the maximum displacement and acceleration values, respectively.

4 Illustrative example

The methodology outlined previously is employed to calculate the structural response of a 40-story building with TMD. Table (1) shows the structure parameters [14]. The stiffness K_i linearly decreases as Z_i increases. TMD is installed on the top of building for better damping of vibrations.

In this study, three types of ground states, namely soft, medium and dense soil are examined. A structure with a fixed base is also investigated. The soil and foundation properties are presented in Table (2).

Table 1 Structure parameters [14]

No. of stories	40
Story height (Z_i)	4 m
Story mass (M_i)	9.8×10^5 kg
Story moment of inertia (I_i)	1.31×10^8 kgm^2
Story stiffness (K_i)	K_1=2.13×10^9 N/m K_{40}=9.98×10^8 N/m $K_{40}\leq K_i\leq K_1$
Foundation radius (R_0)	20 m
Foundation mass (M_0)	1.96×10^6 kg
Foundation moment of inertia (I_0)	1.96×10^8 kgm^2

Table 2 Parameters of the soil and foundation [14]

Soil Type	Swaying damping C_s (Ns/m)	Rocking damping C_r (Nsm)	Swaying stiffness K_s (N/m)	Rocking stiffness K_r (N/m)
Soft Soil	2.19×10^{8}	2.26×10^{10}	1.91×10^{9}	7.53×10^{11}
Medium Soil	6.90×10^{8}	7.02×10^{10}	1.80×10^{10}	7.02×10^{12}
Dense Soil	1.32×10^{9}	1.15×10^{11}	5.75×10^{10}	1.91×10^{13}

Table (3) represents the first 3 natural and damped frequencies of the structure, with and without SSI effects. The TMD design variables are set in such a way that all the first 3 frequencies of the structure are covered, and damping ratio (ξ) is always less than unity. In this way, the maximum mass ratio is about 6.5% of the first modal mass, i.e. $100\times10^3 \le M_{TMD} \le 2000\times10^3$ (kg), the TMD spring stiffness is set as $0.5\times10^6 \le K_{TMD} \le 60\times10^6$ (N/m) and the TMD damping is tuned to $0.1\times10^3 \le C_{TMD} \le 2000\times10^3$ (Ns/m).

Table 3 Natural and damped frequencies of the structure

ω		ω_1 (rad/s)	ω_2 (rad/s)	ω_3 (rad/s)
Soft Soil	With Damping	-0.02i±1.08	-0.24i±4.45	-0.62i±7.42
	Without Damping	1.09	4.44	7.40
Medium Soil	With Damping	-0.02i±1.54	-0.21i±4.57	-0.58i±7.55
	Without Damping	1.54	4.58	7.58
Dense Soil	With Damping	-0.02i±1.60	-0.21i±4.58	-0.58i±7.57
	Without Damping	1.61	4.59	7.59
Fixed Base	With Damping	-0.03i±1.64	-0.21i±4.59	-0.58i±7.58
	Without Damping	1.65	4.60	7.60

As mentioned before, Bam earthquake data is employed to obtain the optimized mass, damping and stiffness for this TMD device. The objective is to decrease the maximum displacement and acceleration of structure during earthquake oscillation. Therefore, it should be treated as a multi-objective optimization problem.

5 Results and Discussions

The optimized parameters of TMD obtained by ABC are presented in Table (4) for the three soil types. Table (5) shows the values of maximum displacement and acceleration for the three ground states, with and without employing TMD.

Table 4 The optimized TMD parameters

Soil Type	Mass (kg×10^6)	Spring Stiffness (N/m×10^6)	Damping (Ns/m×10^6)	ω_n (rad/s)	ω_d (rad/s)	ξ
Soft Soil	2.000	32.735	0.565	4.046	4.044	0.035
Medium Soil	2.000	31.377	0.0001	3.961	3.961	6.312×10^{-6}
Dense Soil	2.000	30.033	0.0001	3.875	3.875	6.451×10^{-6}
Fixed Base	2.000	28.672	0.0001	3.786	3.786	6.603×10^{-6}

Table 5 Vibration with and without TMD

Soil Type	without TMD		with TMD		%Reduction		%Reduction for Target Function
	$u_{\max}$ (m)	$\ddot{u}_{\max}$ (m/s^2)	$u_{\max}$ (m)	$\ddot{u}_{\max}$ (m/s^2)	$u_{\max}$	$\ddot{u}_{\max}$	
Soft Soil	0.9588	13.2717	0.7530	12.8784	21.46	2.96	10.72
Medium Soil	1.1326	13.3563	1.0285	12.7977	9.19	4.18	6.48
Dense Soil	1.1236	13.1253	1.0231	12.8548	8.94	2.06	5.24
Fixed Base	1.1155	13.1202	1.0217	12.8884	8.60	1.72	4.88

The results show that there is a close relationship between soil and optimized parameters of TMD. According to Table (4), the structure constructed on the soil with greater stiffness and damping needs a TMD with smaller spring stiffness and therefore lower natural and damped frequencies. Considering Table (4), the soil with higher stiffness and damping possesses higher natural and damped frequencies, therefore; it can be deduced that the structure with higher frequency (constructed on the dense soil) requires a TMD with lower frequency. Furthermore, the study of damping ratio reveals that the structure on the dense soil (with greater frequency) needs TMD with smaller damping ratio.

Table (5) shows that the maximum feasible reduction for the building displacement is much greater than its acceleration. It means that the TMD is more effective for the reduction of displacement than acceleration. Furthermore, it can be seen that the soil type brings important effects on the structure vibrations. Generally, the soil with higher stiffness reduces the maximum displacement and acceleration (except for the soft soil), and decreases the maximum possible reduction. It implies that the TMDs are less effective for dense soils. Comparing fixed base model with other three models indicates that ignoring the soil characteristics would result in the underestimation of TMD's frequency and damping ratio. It also leads to the underestimation of the maximum displacement, acceleration and possible reduction.

Tables (4) and (5) reveal that the displacement, acceleration and optimum TMD characteristics for the fixed base structure conform closely to those in which the foundation is on the dense soil. These data suggest that SSI can be neglected when the soil is stiff. Moreover, the optimum mass is obtained as the highest mass quantity in the search domain; which implies that the TMDs with greater mass are more effective in controlling structural responses under earthquake oscillations. These results coincide with other analytical researches; such as reference [14].

Figure (2) shows Bam earthquake acceleration spectrum, which was about 6.7 Richter and occurred in December 26th, 2003 in Bam, Iran. Figure (3) shows the frequency spectrum of Bam earthquake acceleration. According to this figure, the most effective frequency is ω=3.835 (rad/s), which explains that why the optimized TMD frequencies are obtained as values mentioned in Table (5).

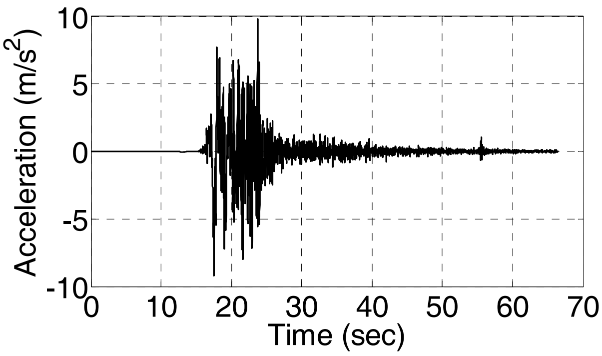

Figure 2 Bam earthquake acceleration spectrum

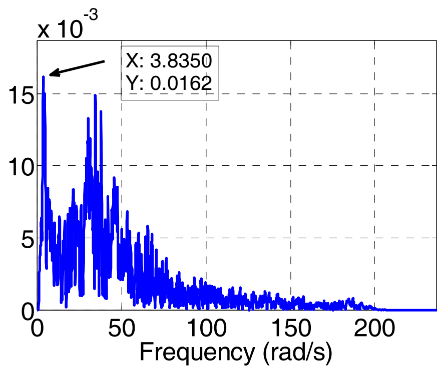

Figure 3 Bam earthquake frequency spectrum

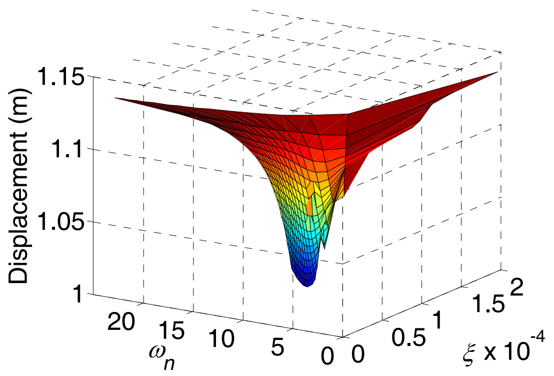

Figure 4 The changes of u_{max} with TMD's ω_n and ξ

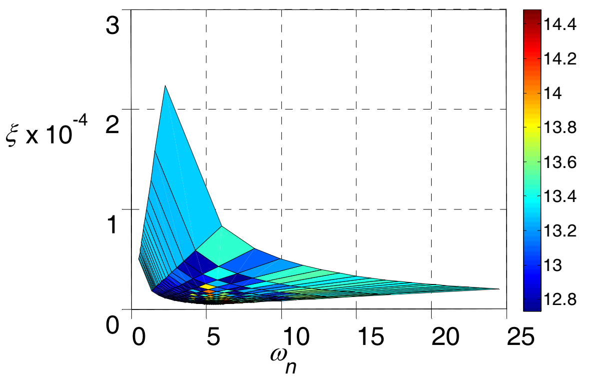

Figure 5 The changes of $\ddot{u}_{\max}$ with TMD's ω_n and ξ

Figures (4) and (5) respectively show the changes of maximum displacement and acceleration with TMD's natural frequency and damping ratio for the medium soil. According to these figures, decreasing the frequency and damping ratio would reduce the displacement and acceleration. In both cases, the best results are obtained when the frequency approaches ω_n=3.8 and the damping ratio is decreased to the least possible quantity.

Figures (6) and (7) represent the effects of TMD's spring stiffness and damping coefficient on the displacement and acceleration, respectively; employing the medium soil and for M=2×10^6 (kg). Figure (6) reveals that the optimum results are obtained when C is decreased and K≈30×10^6 (N/m). Considering Figure (7), it is clear that the acceleration is reduced by decreasing the spring stiffness to K≈10×10^6 (N/m). Obviously, decreasing the damping coefficient may result in the increase of acceleration for K<10×10^6 (N/m) and K>50×10^6 (N/m).

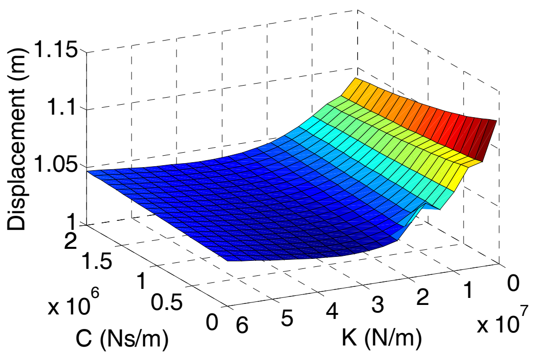

Figure 6 The effects of TMD's C and K on u_{max}

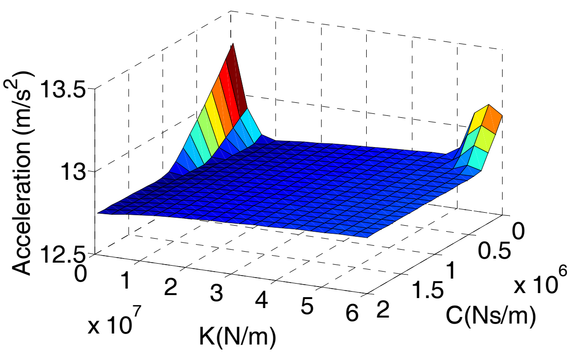

Figure 7 The effects of TMD's C and K on $\ddot{u}_{\max}$

The effects of TMD's spring stiffness and mass on the displacement and acceleration are presented in Figures (8) and (9), respectively; using the medium soil and C=100 (Ns/m). Figure (8) indicates that the minimum displacement yields when the spring stiffness approaches K≈30×10^6 (N/m), as mentioned previously. It is also clear that increasing the TMD's mass decreases the displacement effectively. Considering Figure (9), it is evident that the best results are obtained when K≈15×10^6 (N/m). Obviously, the acceleration is reduced by the enhancement of TMD's mass.

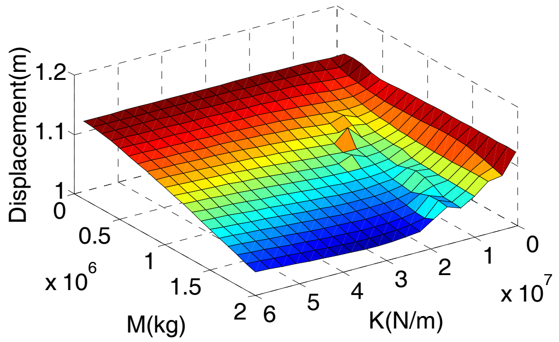

Figure 8 The effects of TMD's M and K on u_{max}

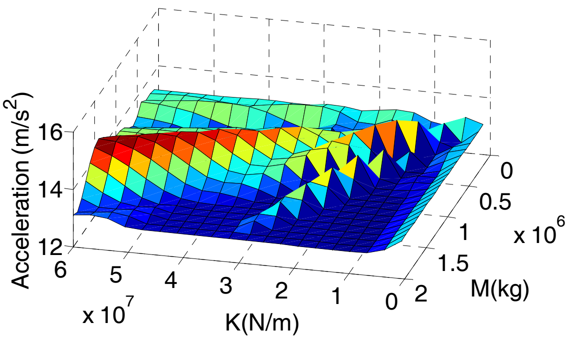

Figure 9 The effects of TMD's M and K on $\ddot{u}_{\max}$

Figures (10) and (11) present the time response of structure with and without TMD for the soft soil, respectively. Comparing these figures, it can be seen that the maximum displacement is reduced due to the TMD device. It is also evident that the displacement patterns of the structure are nearly the same in the mentioned figures, but the TMD displacement pattern somehow differs from the structure, especially in 20-40 seconds. The TMD oscillation amplitude is about 1.5 times greater than the building amplitude of vibration.

The time responses of structure with and without TMD for the medium soil are presented in Figures (12) and (13), respectively. According to these figures, it is clear that the TMD has efficiently decreased the maximum displacement of floors. Comparing these figures, it can be seen that the displacement patterns of the structure are different in two cases, but the TMD pattern more resembles to that of the structure. The TMD amplitude is about 2 times greater than the building amplitude of vibration in this case.

The time responses of structure with and without TMD for the dense soil are shown in Figures (14) and (15), respectively. Considering these figures, the TMD has obviously decreased the maximum displacement of stories. Comparison between these figures reveals that the displacement patterns of the structure are dissimilar, but the structure and TMD patterns are nearly the same in Figure (7). The maximum TMD displacement is about 2 times greater than the maximum building displacement in this case. The difference between Figures (11), (13) and (15) reveals that soil properties greatly affect the structure behavior.

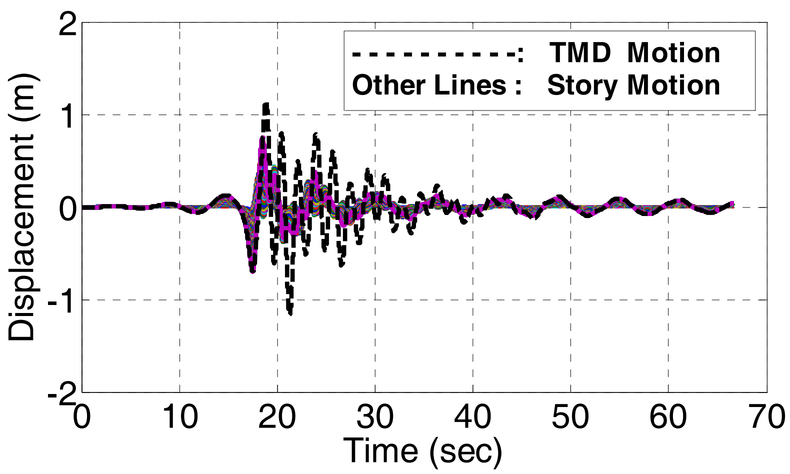

Figure 10 Time response with TMD for soft soil

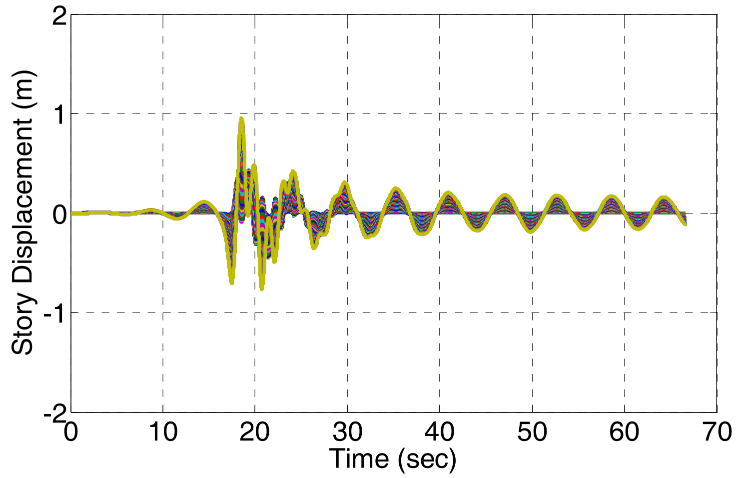

Figure 11 Time response without TMD for soft soil

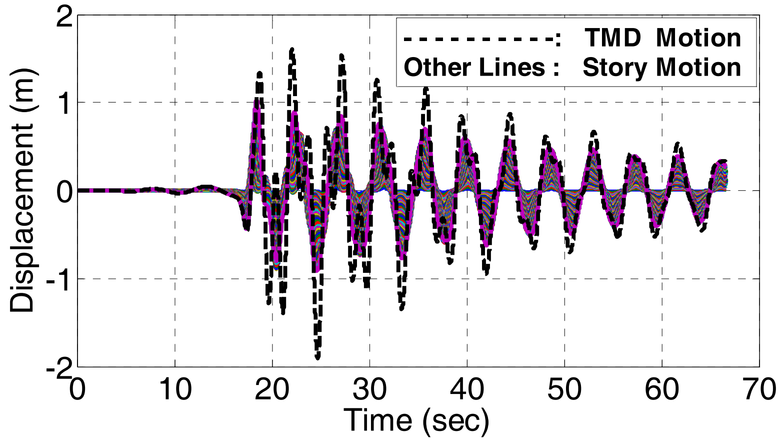

Figure 12 Time response with TMD for medium soil

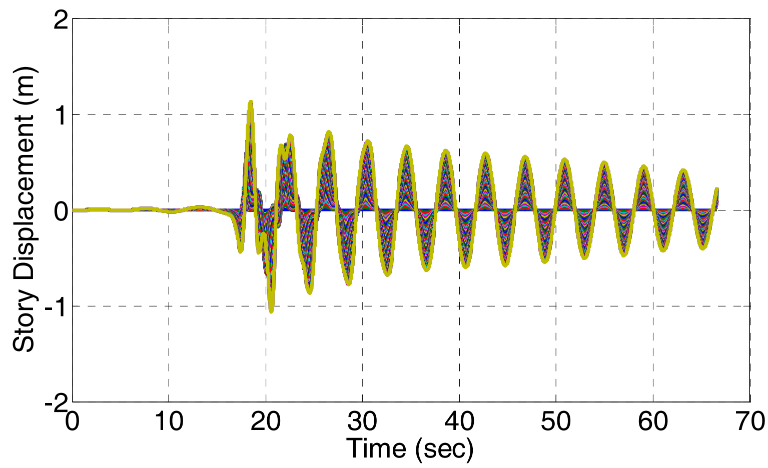

Figure 13 Time response without TMD for medium soil

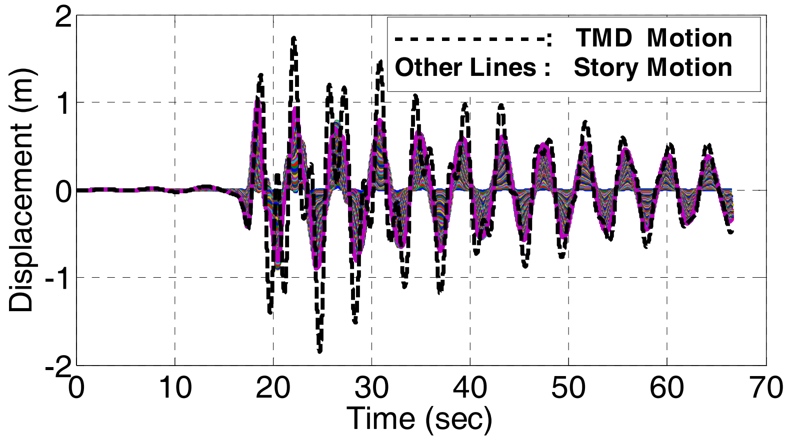

Figure 14 Time response with TMD for dense soil

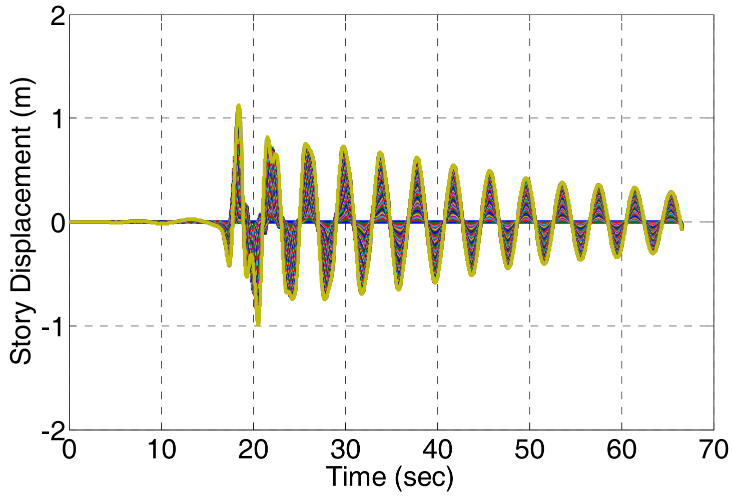

Figure 15 Time response without TMD for dense soil

6 Conclusions

In this paper, a mathematical model is developed to obtain the earthquake response of a high-rise building with TMD, considering SSI effects. The model is based on the time domain analysis. The ant colony optimization technique is utilized to obtain the optimum parameters for TMD. Mass, damping and spring stiffness quantities of TMD are assumed as the design variables; and the objective is to decrease the maximum displacement and acceleration.

The results show that the soil characteristics greatly influence on the favorite TMD parameters. It is indicated that the soil type also severely affects the time response of structures. It is also shown that the TMDs are advantageous devices for earthquake vibration mitigation of high-rise buildings. It is also implied how the artificial bee colony (ABC) method can be employed for the multi-objective design of optimum TMDs; considering soil effects. This study improves the understanding of earthquake oscillations, and helps the designers to achieve the optimized TMD for high-rise buildings.

References

[1] Ormondroyd, J., and Den Hartog, J.P., "The Theory of Dynamic Vibration Absorber", Trans. ASME, Vol. 50, No. 7, pp. 9-22, (1928).

[2] Miyama, T., "Seismic Response of Multi-story Frames Equipped with Energy Absorbing Story on its Top", Proc. 10th World Conf. on Earthquake Engineering, 19-24 July, Madrid, Spain, Vol. 7, pp. 4201-4206, (1992).

[3] Kawaguchi, A., Teramura, A., and Omote, Y., "Time History Response of a Tall Building with a Tuned Mass Damper under Wind Force", Journal of Wind Engineering and Industrial Aerodynamics, Vol. 43, No. 1–3, pp. 1949–1960, (1992).

[4] Tsukagoshi, H., Tamura, Y., Sasaki, A. and Kanai, H., "Response Analyses on Along-wind and Across-wind Vibrations of Tall Buildings in Time Domain", Journal of Wind Engineering and Industrial Aerodynamics, Vol. 46–47, No. 1, pp. 497–506, (1993).

[5] Gupta, Y.P., and Chandrasekaran, A. R., "Absorber System for Earthquake Excitation", Proc. 4th World Conf. on Earthquake Engineering, Santiago, Chile, Vol. II, pp. 139-148, (1969).

[6] Kaynia, A.M., Veneziano, D., and Biggs, J.M., "Seismic Effectiveness of Tuned Mass Dampers", Journal of Structural Engineering, ASCE Div, Vol. 107, No. 8, pp. 1465-1484, (1981).

[7] Sladek, J.R., and Klingner, R.E., "Effect of Tuned Mass Dampers on Seismic Response", Journal of Structural Engineering, ASCE Div, Vol. 109, No. 8, pp. 2004-2009, (1983).

[8] Wirsching, P.H., and Campbell, G.W., "Minimal Structural Response under Random Excitation using Vibration Absorber", Earthquake Engineering & Structural Dynamics, Vol. 2, No. 4, pp. 303-312, (1974).

[9] Ohno, S., Watari, A., and Sano, I., "Optimum Tuning of the Dynamic Damper to Control Response of Structures to Earthquake Ground Motion", Proc. 6th World Conf. on Earthquake Engineering, New Delhi, India, Vol. 3, pp. 157-161, (1977).

[10] Villaverde, R., "Seismic Control of Structures with Damped Resonant Appendages", Proc. 1st World Conf. on Structural Control, 3-5 August, Los Angeles, California, USA, pp. WP4-113-119, (1994).

[11] Sadek, F., Mohraz, B., Taylor, A.W., and Chung, R.M., "A Method of Estimating the Parameters of Tuned Mass Dampers for Seismic Applications", Earthquake Engineering & Structural Dynamics, Vol. 26, No. 6, pp. 617–635, (1997).

[12] Xu, Y.L., and Kwok, K.C.S., "Wind-induced Response of Soil–structure–damper Systems", Journal of Wind Engineering and Industrial Aerodynamics, Vol. 43, No.1–3, pp. 2057–2068, (1992).

[13] Wolf, J.P., "*Foundation Vibration Analysis using Simple Physical Models*", Prentice-Hall, Englewood Cliffs, NJ, (1994).

[14] Liu, M.Y., Chiang, W.L., Hwang, J.H., and Chu, C.R., "Wind-induced Vibration of High-rise Building with Tuned Mass Damper Including Soil–structure Interaction", Journal of Wind Engineering and Industrial Aerodynamics, Vol. 96, No. 6-7, pp. 1092–1102, (2008).

[15] Thomson, W.T., and Dahleh, M.D., "*Theory of Vibration with Applications*", Prentice Hall Inc., 5th Ed., London, (1997).

[16] Newmark, N.M., "A Method of Computation for Structural Dynamics", Journal of Engineering Mechanics, ASCE Div, Vol. 85, No. 3, pp. 67–94, (1959).

[17] Tereshko, V., and Leongarov, A., "Collective Decision-making in Honey Bee Foraging Dynamics", Journal of Computing and Information Systems, Vol. 9, No. 3, pp. 1-7, (2005).

[18] Yang, X. S., "Engineering Optimization via Nature-based Virtual Bee Algorithm", Lecture Notes in Computer Science, Vol. 3562, pp. 317-323, (2005).

[19] Karaboga, D., "An Idea Based on Honey Bee Swarm for Numerical Optimization", Technical Report, Erciyes University, Turkey, (2005).

[20] Basturk, B., and Karaboga, D., "An Artificial Bee Colony (ABC) Algorithm for Numeric Function Optimization", IEEE Symp. Swarm Intelligence, Indianapolis, IN, USA, (2006).

[21] Basturk, B., and and Karaboga, D., "On the Performance of Artificial Bee Colony (ABC) Algorithm", Applied Soft Computing, Vol. 8, No. 1, pp. 687-697, (2008).

Nomenclature

A_0	Rayleigh damping coefficient
A_1	Rayleigh damping coefficient
C_i	story damping
C_r	rocking damping
C_s	swaying damping
C_{TMD}	TMD damping
f_i	the objective function
fit_i	fitness to solutions (for minimization or negative values of objective function)
G_s	soil shear modulus
I_0	foundation moment of inertia
I_i	story moment of inertia
K_i	story stiffness
K_r	rocking stiffness
K_s	swaying stiffness
K_{TMD}	TMD spring stiffness
M_0	foundation mass
M_i	story mass
M_{TMD}	TMD mass
p_i	the probability value for the solutions x_i
R_0	radius of foundation
$u_{\max}$	maximum displacement
$\ddot{u}_{\max}$	maximum acceleration
v_{ij}	new solution (new food source position)
V_s	soil shear wave velocity
X_0	displacement of foundation
x_i	a solution
X_i	displacement of each story
Z_i	height of each floor

Greek Symbols

ξ	damping coefficient
ϕ	a random number in [0, 1]
ρ_s	soil density
θ_0	rotation of foundation
ν_s	soil poisson's ratio
ω_d	damped frequency
ω_n	natural frequency

چکیده

این مقاله به بررسی روش کلونی زنبورها در بهینه‌سازی میراگرهای جرمی تنظیم شده برای ساختمانهای بلند با درنظر گرفتن برهم‌کنش متقابل خاک و سازه می‌پردازد. مدل بصورت ساختمان ۴۰ طبقه درنظر گرفته شده و از روش نیومارک جهت محاسبه پاسخ ساختمان در برابر زلزله بم استفاده شده است. هدف، کاهش هر دو مقدار جابجایی و شتاب ماکزیمم می‌باشد. نشان داده شده است که روش کلونی زنبورها بطور مؤثری می-تواند در طراحی میراگر جرمی بهینه برای ساختمانهای بلند بکار گرفته شود. همینطور نشان داده شده است که مدل ارائه شده از مدل با پایه ثابت دقیقتر است. اثرات جرم، ضریب میرایی و ثابت فنریت نیز مورد مطالعه قرار گرفته است. این بررسی برای محققان در درک و طراحی بهتر میراگرهای جرمی برای ارتعاشات زلزله راهگشا می‌باشد.