*16th World Conference on Earthquake, 16WCEE 2017*

*Santiago Chile, January 9th to 13th 2017*

*Paper N° 0020*

*Registration Code: S-T1464750342*

# DISTRIBUTED MULTIPLE TUNED MASS DAMPERS FOR SEISMIC RESPONSE CONTROL OF CHIMNEY WITH FLEXIBLE FOUNDATION

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## *Abstract*

Multi-mode seismic response control of chimneys on flexible foundation is studied. The multi-mode control is achieved using distributed multiple tuned mass dampers (d-MTMDs). A reinforced concrete (RC) chimney is considered as an assemblage of beam elements, each assumed to have constant diameter over the element length, and soil-structure interaction (SSI) is duly accounted for. The soil is idealized in single strata beneath the foundation, which consist of annular raft foundation having the internal and external diameter 15 m and 40 m, respectively and having depth of 2.5 m. The raft and the surrounding soil are modeled considering frequency independent constants for the springs and dashpots. The time domain seismic analysis based on Newmark's method of average acceleration is employed for the non-classically damped system. The performance of the d-MTMDs is compared with the case of single tuned mass damper (STMD), d-MTMDs controlling the fundamental modal responses (d-MTMDs-1), and arbitrarily installed distributed MTMDs (ad-MTMDs). In addition, parametric studies are conducted for varying mass and damping ratios in the STMD, d-MTMDs-1, ad-MTMDs, and d-MTMDs. The displacement and acceleration response at the top of the chimney under different earthquake ground motions are computed to study the effectiveness in the STMD, d-MTMDs-1, ad-MTMDs, and d-MTMDs cases. It is concluded that the d-MTMDs are more effective than the STMD, d-MTMDs-1, and ad-MTMDs, while considering equal total mass of the TMD(s). Furthermore, the soil type greatly affects the design parameters of the STMD/ d-MTMDs-1/ ad-MTMDs/ d-MTMDs, and seismic response of the chimney with flexible foundation.

*Keywords: Chimney; Distributed multiple tuned mass dampers (d-MTMDs); Soil-structure interaction (SSI)*

## 1. Introduction

Industries commonly use reinforced concrete (RC) chimneys with varied geometries for releasing flue gases. Earthquake forces have caused damages or collapse of several chimneys, as observed during Kocaeli earthquake in 1999 and Chile earthquake in 2010. The design of chimneys is a well-known procedure for structural engineers. If the chimney is to be founded in medium to soft soil, the mathematical modeling is required to account for the soil flexibility. Typically at such sites, the chimney is supported on very deep foundation if the rock is too deep, or it is supported on a combination of mat foundation and deep foundation, where part of the site is reinforced using piles, or it is supported on rock-socketed piles or drilled shafts. The effects of soil-structure interaction (SSI) have been ignored in some earlier studies [1-4]; whereas, the effects of the SSI on the dynamic behavior of the structures were included in some other studies [5-7]. It is generally concluded that for structures founded on soft to medium soils, the effects of the SSI are quite pronounced, hence cannot be ignored, especially for tall and slender structure like chimneys.

Tuned mass damper (TMD) is a classical passive vibration control device, which consists of a mass, spring, and a viscous damper attached to a vibrating main system in order to attenuate any undesirable vibrations induced therein. Several researchers [8-10] had employed the TMD in structures and reported fairly improved vibration response control in the parent structures. However, single TMD (STMD) is reported to be less effective due to possible miss-tuning; therefore, the researchers proposed using multiple TMDs (MTMDs) [11-13]. However, the issue of placing huge mass on top of the structure was still a problem. The recent appealing solution to counter this issue is to distribute the MTMDs along the height of the structures (d-MTMDs) [14]. The d-MTMDs are used for vibration control of different types of structures under varied loading conditions [15-17]. However, study on the earthquake response control of chimney wherein placement and tuning of the d-MTMDs are made in accordance with the modal properties of the chimney duly accounting for the SSI is yet to be reported.

The objective of the present study is to investigate the effective placement and tuning of the d-MTMDs based on the mode shapes and frequencies of the fixed-base (rigid foundation) uncontrolled chimney (no control, NC). In this approach, the TMDs are placed where the mode shape amplitude of the chimney is the largest or larger in the particular mode and the TMD(s) is (are) tuned to the corresponding modal frequency. Thus, the d-MTMDs are placed to suppress the responses in the first few selected modes of the chimney. Herein, the chimney is considered with flexible foundation, i.e. the SSI is considered, and its vibration response is mitigated by installing the d-MTMDs. In order to show the effectiveness of the d-MTMDs placed according to the mode shapes, assessment is made with the seismic response obtained using: (i) single tuned mass damper controlling only the fundamental modal response (STMD); (ii) d-MTMDs controlling the fundamental modal response (d-MTMDs-1); and d-MTMDs placed arbitrarily (ad-MTMDs). Further, a detailed parametric study is conducted to identify the parameters which affect the response control under the real earthquakes.

## 2. Modeling of Tall RC Chimney with SSI

The RC chimney is modeled as an assemblage of beam elements with sway degrees of freedom considered to be the dynamic degrees of freedom, and the effects of the SSI are taken into consideration by including soil flexibility in the mathematical modeling (Fig. 1). The theoretical development is based on the assumption that the cross-sectional dimension within the element remains the same. Additional assumptions made for the numerical formulation are: (i) the RC chimney is considered to remain within the elastic limit under earthquake excitation; and (ii) the system is subjected to a single horizontal (uni-directional) component of the earthquake ground motion. Fig. 1(a-f) shows the $N$ degree of freedom (DOF) model of the chimney with $n$ DOF of the TMDs installed on it, and two DOF corresponding to the SSI effect. Mass ($M_i$) at each node and area moment of inertia ($I_i$) of the beam elements of the chimney are shown in Fig. 1(c). Moreover, the mass and mass moment of inertia of the foundation are designated as $M_0$ and $I_0$, respectively. The stiffness and damping for the beam elements are assumed as $K_i$ and $C_i$, respectively. The mass, stiffness, and damping of the TMDs are respectively shown as $m_i$, $k_i$, and $c_i$. Stiffness of the swaying and rocking springs of the soil medium are represented as $K_s$

and $K_r$, and the corresponding damping in the dashpots are indicated as $C_s$ and $C_r$, respectively. The governing equation of motion for the non-classically damped system under consideration can be expressed as,

$$[M_s]\{\ddot{x}_s\}+[C_s]\{\dot{x}_s\}+[K_s]\{x_s\}=-[M_*]\{r\}\ddot{x}_g \tag{1}$$

where $[M_s]$, $[C_s]$, and $[K_s]$ are the mass, damping, and stiffness matrices of the chimney, respectively of order $(N+n+2)\times(N+n+2)$ installed with the TMDs and the SSI duly considered. Further, the unknown relative nodal displacements are denoted as: $\{x_s\}=\{X_1, X_2,\cdots, X_{N\text{-}1}, X_N, x_1,\cdots, x_n, \theta_0, X_0\}^T$; whereas, $\{\dot{x}_s\}$ and $\{\ddot{x}_s\}$ are velocity and acceleration vectors, respectively. The inertial mass matrix under the action of earthquake is $[M_*]$, the earthquake ground acceleration is denoted by $\ddot{x}_g$, and $\{r\}$ denotes the vector of influence coefficients.

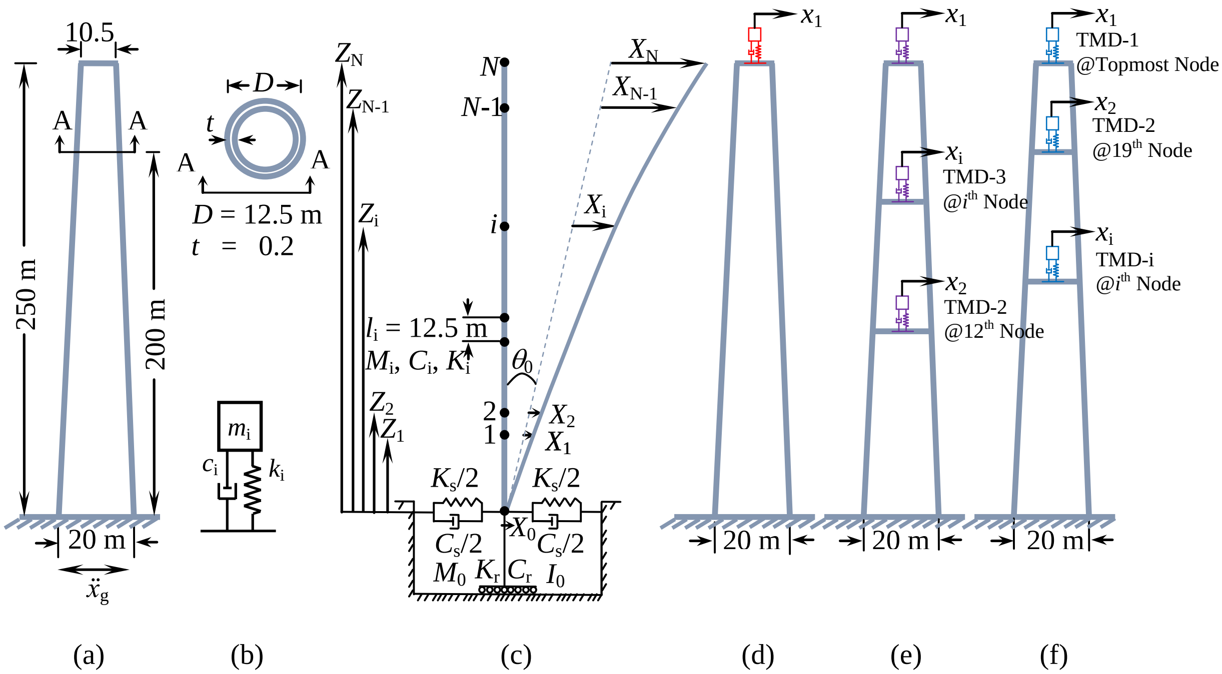


Fig. 1 - Details of the RC chimney (a) with no-control, i.e. uncontrolled (NC), (b) section A-A and schematic diagram of TMD, (c) lumped mass idealization for the chimney including the SSI and installed with: (d) STMD, (e) ad-MTMDs, and (f) d-MTMDs.

The Chilean and other national codes recommend that 90% or above of the modal mass has to be taken into consideration in the dynamic analysis; therefore, for the present study authors have decided that the controlled mode should have modal mass greater than or equal 90%. The first three modal responses of the chimney are controlled by installation of the STMD, d-MTMDs, ad-MTMDs, and d-MTMDs. The mass participation factor is determined to be 0.615 for the first mode, 0.190 for the second mode, and 0.100 for the third mode. Thus, it is decided to have more number of TMDs to control the first modal response as compared to the number of TMDs employed for the second and third modal response control. The modal frequencies and mode shapes of the chimney are shown in Fig. 2 without installation of any TMD; in addition, the figure shows locations of the 9d-MTMDs to be installed along the height of the RC chimney. In this study, the total number of TMDs are: $n$ = 9, out of which 5d-MTMDs are installed for the first modal response control, 3d-MTMDs are installed for the second modal response control, and single TMD is installed for the third modal response control. The performance of the 9d-MTMDs is compared with those of the STMD, 9d-MTMDs-1, and 9ad-MTMDs. The mass matrix for the chimney is $[M_N]_{N\times N}$ and the mass matrix of the TMDs is $[m_n]_{n\times n}$. Further, $M_t=\sum_{i=1}^{i=N} M_i$ is the total mass of the chimney and $m_t=\sum_{i=1}^{i=n} m_i$ is the total mass of the TMDs. The TMDs are modeled by assuming that the mass is equally divided such that, $m_i = m_t / n$. If $Z_i$ ($i$ = 1 to $N$) is the height of the $N^{th}$ node of the chimney and $Z_i$ ($i$ = 1 to $n$) shows the height of the $n^{th}$ TMD installed [Fig. 1(c)] then the mass matrix is of order ($N$+$n$+2)×($N$+$n$+2) such as,

$$[M_s]=\begin{bmatrix} [M_N]_{N\times N} & [0]_{N\times n} & [M_N]_{N\times 1} & [M_N Z_N]_{N\times 1} \\ & [m_n]_{n\times n} & [m_n]_{n\times 1} & [m_n Z_n]_{n\times 1} \\ & & M_0+M_t+m_t & \sum_i^N M_i Z_i + \sum_i^n m_i Z_i \\ \text{Symmetry} & & & I_0+\sum_{i=1}^N I_i + M_i Z_i^2 + \sum_i^n m_i Z_i^2 \end{bmatrix} \tag{2}$$

Natural frequencies of the d-MTMDs-1, ad-MTMDs, and d-MTMDs are uniformly distributed around their average frequencies. The natural frequency of each TMD ($\omega_i$) is expressed by,

$$\omega_i=\omega_T\left[1+\left(i-\frac{n+1}{2}\right)\frac{\beta}{n-1}\right] \quad \text{for} \quad i=1\,\text{to}\,n \tag{3}$$

$$\omega_T=\sum_i^n\frac{\omega_i}{n} \tag{4}$$

$$\beta=\frac{\omega_n-\omega_1}{\omega_T} \tag{5}$$

where $\omega_T$ is the average frequency of all the d-MTMDs-1/ ad-MTMD/ d-MTMDs and $\beta$ is the non-dimensional frequency bandwidth of the d-MTMDs/ ad-MTMDs/ d-MTMDs systems. The stiffness ($k_i$) is used for adjusting the frequency of each TMD unit such that,

$$k_i=m_i\,\omega_i^2 \quad \text{for} \quad i=1\,\text{to}\,n \tag{6}$$

The damping ($c_1=c_2=\dots c_n$) of the TMDs is kept the same and the damping ratio ($\zeta_i$) of the TMDs is,

$$\zeta_i=\frac{c_i}{2m_i\omega_i} \quad \text{for} \quad i=1\,\text{to}\,n \tag{7}$$

Tuning frequency ratio ($f$) of the STMD/ d-MTMDs-1/ ad-MTMDs/ d-MTMDs system is expressed as,

$$f=\frac{\omega_T}{\Omega_N} \tag{8}$$

where $\Omega_N$ is the natural frequency of the RC chimney. The same procedure as described in Equations 3 through 8 is used for calculating the parameters of the MTMDs, wherein their average tuning frequencies are tuned with the second and third modal frequencies of the RC chimney. The STMD is placed at the topmost node of the RC chimney and tuned to its fundamental frequency. The Eigen vectors of the natural frequencies of the fixed-base uncontrolled chimney are evaluated and used to facilitate the placement of the d-MTMDs. In this procedure, the d-MTMDs controlling only fundamental modal response are attached. Subsequently, the d-MTMDs controlling the second modal response are attached, and finally the last single TMD controlling the third modal response is attached. It should be mentioned clearly that there is only one TMD placed at a node. The subsequent TMDs are placed as per the criteria of the amplitude of the largest to larger in the particular mode.

## 3. Numerical Study

In this study, properties of the RC chimney are taken from the model investigated by Datta and Jain [4]. The chimney is having 250 m height and subjected to single lateral component of earthquake ground motion. The chimney is divided in to 20 beam elements and the length ($l_i$) of each beam element is 12.5 m. The chimney is having 20 degrees of freedom and only the first three modal responses are controlled because 90% of the seismic mass is participating in the first three modes. The outer diameters ($D$), from the base to the top of the chimney are: 20 m, 19.5 m, 19 m, 18.5 m, 18 m, 17.5 m, 17 m, 16.5 m, 16 m, 15.5 m, 15 m, 14.5 m, 14 m, 13.5 m, 13 m, 12.5 m, 12 m, 11.5 m, 11 m, and 10.5 m, respectively. The corresponding thicknesses ($t$) are: 0.85 m, 0.6 m, 0.55 m, 0.5 m, 0.45 m, 0.4 m, 0.35 m, 0.3 m, 0.25 m, 0.24 m, 0.23 m, 0.22 m, 0.21 m, 0.2 m, 0.2 m, 0.2 m, 0.2 m, 0.2 m, 0.2 m, and 0.2 m, respectively. It is assumed that the modulus of elasticity ($E_c$) of the concrete is $2.5 \times 10^{10}$ N/m$^2$ and the density ($\rho_c$) of the concrete is considered as 2,400 kg/m$^3$. Rayleigh's approach is used to evaluate the damping matrix, because the damping matrix is not explicitly known. In this method, the damping ratio ($\zeta_s = 5\%$) in all modes of vibration is considered. The STMD is installed on top of the chimney as shown in Fig. 1(d). The arbitrarily distributed multiple tuned mass dampers (ad-MTMDs) installed along the height of the chimney are indicated in Fig. 1(e). It is to be noted that in the ad-MTMDs, the placement of the TMDs along the height of the chimney did not follow any criteria. Further, the chimney installed with the distributed multiple tuned mass dampers as per the modal properties of the chimney (d-MTMDs) is shown in Fig. 1(f). The placement of the d-MTMDs-1 is exactly same as that of the case d-MTMDs, multi-mode control; they control the fundamental modal response. The mass participation factors ($\Gamma_i$) for the first, second, and third vibration modes are about 0.615, 0.190, and 0.100, respectively. The first three natural frequencies of the fixed-base uncontrolled chimney are: $\Omega_1$ = 2.088 rad/sec, $\Omega_2$ = 7.933 rad/sec, and $\Omega_3$ = 18.800 rad/sec, which are the average tuning frequencies ($\omega_{T1}$, $\omega_{T2}$, and $\omega_{T3}$) for the 5d-MTMD-1, 3d-MTMD-2, and d-MTMD-3, respectively controlling first, second, and third modal responses. The number of the TMDs is chosen from the mass participation factor; therefore, $n$ = 9 is considered such that around 56%, 33%, and 11% mass of the TMDs are used respectively for controlling the fundamental, second, and third modal responses. The placement (location) of the nine TMDs (9d-MTMDs) in the d-MTMDs scheme is shown in Fig. 2. Note that only one TMD is placed at the same node while the placement of the TMDs is in accordance with the largest or larger amplitude of the mode shape, which would facilitate easier installation of the TMDs.

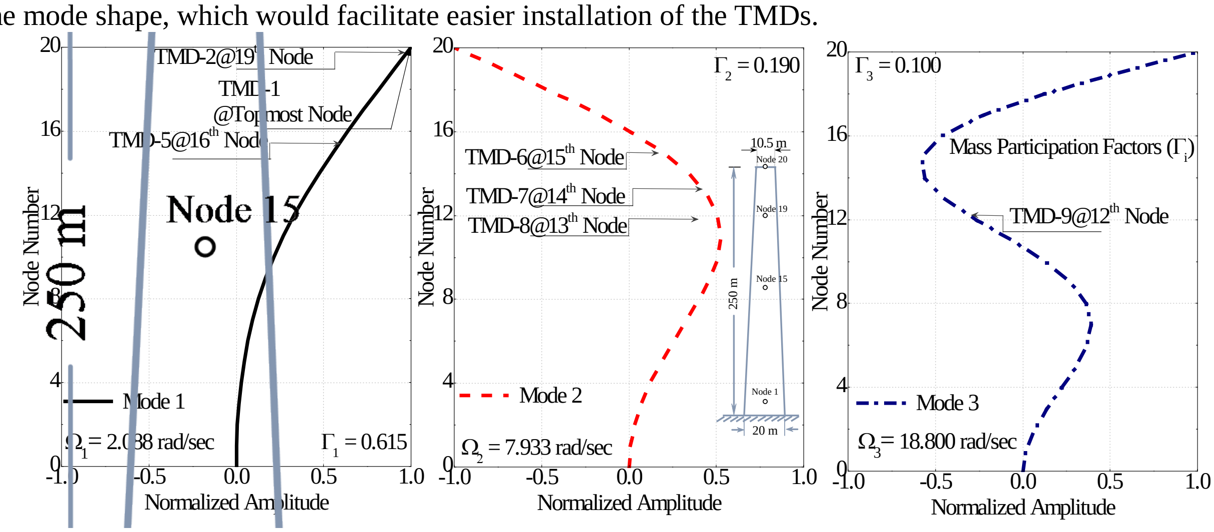


Fig. 2 - Mode shapes and frequencies of the uncontrolled RC chimney (NC).

The soil is idealized in single strata beneath the foundation, which consist of annular raft foundation having the internal and external diameter 15 m and 40 m, respectively and having depth of 2.5 m. The raft and the surrounding soil are modeled considering springs and corresponding dashpots as shown in Fig. 1(c) with frequency independent parameters. The effect of considering different soil type is investigated, such that, the shear wave velocity ($V_s$) of 1200 m/sec, 600 m/sec, 300 m/sec, and 150 m/sec are considered for rock, dense soil, medium soil, and soft soil, respectively. Seismic response of the RC chimney is investigated under two real earthquake ground motions and shown in Fig. 3 through Fig. 9, obtained for the soil properties considered: elastic modulus ($E_s$), density ($\gamma_s$), and Poisson's ratio ($\nu_s$). Two historical earthquakes, Llolleo at station LLO in Chile and Nahanni at 6097 Site 1 in Canada are taken as input excitations to evaluate the seismic performance of the chimney with the proposed vibration control strategies. The peak ground acceleration (PGA) for the Llolleo, 1985 and Nahanni, 1985 earthquake ground excitations are 0.712$g$ and 1.096$g$, respectively; where $g$ denotes gravitational acceleration. To show the effectiveness of the control strategy, the effectiveness criteria for displacement ($R_1$), and acceleration ($R_2$) are defined as follows,

$$R_1 = \left[1 - \frac{x_{20}}{X_{20}}\right] \times 100 \tag{9}$$

$$R_2 = \left[1 - \frac{\ddot{x}_{20}}{\ddot{X}_{20}}\right] \times 100 \tag{10}$$

where $x_{20}$ and $\ddot{x}_{20}$ respectively are the controlled peak displacement and peak acceleration at the topmost node (node number 20) of the chimney. Further, $X_{20}$ and $\ddot{X}_{20}$ respectively are the uncontrolled peak displacement and peak acceleration at the topmost node of the chimney.

3.1 Effectiveness of TMD(s)

The comparison between the performances of the four TMD schemes in seismic response control is studied. These schemes are used to control the response of the fixed-base chimney and the chimney including the SSI effect. Fig. 3 and Fig. 4 show the comparison between the time histories of the displacement and acceleration at the topmost node of the chimney respectively under the Llolleo, 1985 and Nahanni, 1985 earthquake ground motions. Time step of 0.005 sec is taken for solving the equations of motion for both the Llolleo, 1985 and Nahanni, 1985 earthquake ground motions. In addition, the figures show the peak displacement relative to ground and peak absolute acceleration at top of the chimney for the uncontrolled and controlled cases using different configurations of the TMDs.

The uncontrolled peak displacement response of the RC chimney with fixed-base, dense soil, medium soil, and soft soil respectively are: 0.630 m, 0.633 m, 0.640 m, and 0.660 m under the Llolleo, 1985 earthquake ground motion. The peak displacement response for the different uncontrolled cases are: 0.555 m, 0.553 m, 0.553 m, and 0.512 m under the Nahanni, 1985 earthquake ground motion. The peak acceleration response for the cases of fixed-base, dense soil, medium soil, and soft soil respectively are: 2.847$g$, 2.699$g$, 2.452$g$, and 2.389$g$ under the Llolleo, 1985 earthquake ground motion and are: 2.964$g$, 2.900$g$, 2.732$g$, and 2.629$g$ under the Nahanni, 1985 earthquake ground motion. It is observed that there are around 5% to 10% variations in the peak displacement response under the considered different soil types. Also, it is seen that there are 10% to 20% variations in the peak acceleration response. It is observed that the TMDs are effective in controlling the displacement response of the chimney in all the configurations considered herein except the STMD case. The response of the uncontrolled RC chimney with different soil types are amplified by installing the STMD. Further, from the time history plots for the top floor displacement it is observed that the post-peak response reduces substantially when the MTMDs are installed as compared to the NC and STMD cases. It is also seen that the acceleration at top of the chimney is reduced by installing TMD(s) in different schemes. The 9d-MTMDs generally observed to provide maximum reduction in top node acceleration of the chimney as compared to the STMD, 9d-MTMDs-1, and 9ad-MTMDs. Hence, it is concluded that the d-MTMDs controlling multi-modal response are more reliable in effectively reducing the displacement response and the acceleration response.

3.2 Effect of TMD mass ratio ($\mu$) and damping ratio ($\zeta_d$)

The effect of the change in mass ratio ($\mu$), i.e. ratio between masses of the units of the TMD to the mass of the chimney, of the STMD, 9d-MTMDs-1, 9ad-MTMDs and 9d-MTMDs is studied under different earthquakes. The mass ratio ($\mu$) is varied from 0.5% to 2% with an increment of 0.5%. Also, the TMD damping ratio ($\zeta_d$) is varied from 1% to 20% with an increment of 1%. Two reduction criteria for the peak displacement ($R_1$) and peak acceleration ($R_2$) of the chimney are used for comparison. The variations of these two reduction criteria with different mass and damping ratios are shown in Fig. 5 for the case where the chimney is fixed at base and installed with different TMD(s) schemes. It is seen from the figure that the nature of variations in the reduction of the responses is uniform for different excitations in case of the MTMD schemes; however, it varies drastically for the STMD scheme. Further, it is seen that in case of the STMD, by increasing the mass ratio there is significant reduction in the seismic performance of the STMD, which is due to miss-tuning effect in the STMD. It is seen that for the case of STMD, optimum damping exists which could range between 5% to 8%. The improved response reduction is observed by installing different MTMD schemes. The increased mass ratio improved the seismic performance of the MTMD schemes. Also, it is observed that optimum damping ratio exists for the MTMD schemes, which is reduced as compared to the STMD scheme. Further, it is also seen that maximum response reduction is achieved with installation of the 9d-MTMDs as compared to the STMD, 9d-MTMDs-1, and 9ad-MTMDs. It is concluded that by increasing the mass ratio of the MTMDs the response reduction is improved, as it is not the same for the STMD scheme.

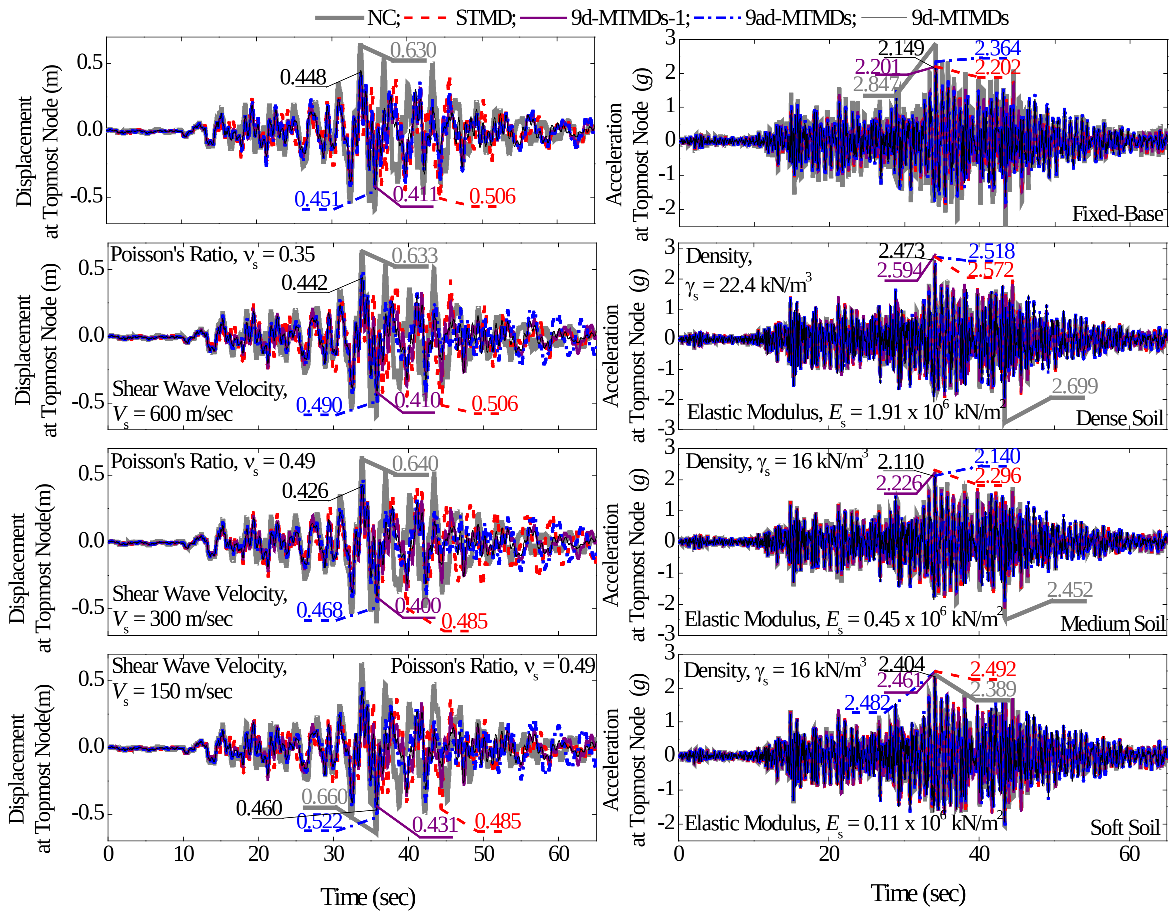


Fig. 3 - Time variation of displacement and acceleration at topmost node of the RC chimney under the Llolleo, 1985 earthquake; TMDs with mass ratio ($\mu$) of 2% and damping ratio ($\zeta_d$) of 5%.

Fig. 6 through Fig. 9 show the variations in $R_1$ and $R_2$ for different damping ratios ($\zeta_d$) and mass ratios ($\mu$) of the STMD, 9d-MTMDs-1, 9ad-MTMDs, and 9d-MTMDs installed on the chimney including SSI under the Llolleo, 1985, and Nahanni, 1985 earthquake ground motions. Four different types of soil are considered in order to compare the performance of the different TMD schemes. It is observed that the softer soil properties greatly decrease the performance of the STMD. However, in the MTMD schemes it is seen that they are robust as compared to the STMD scheme. It is seen that increase in the damping ratios ($\zeta_d$) may not improve the seismic performance under the different schemes with varied soil properties considered, which is attributed to the availability of the soil damping introduced in the models. It is noted that the optimum damping does exist for the fixed-base RC chimney installed with the TMDs. However, damping ratio ($\zeta_d$) may not improve the performance under the different schemes with varied soil properties considered. The performance of the MTMD schemes improved as the mass ratio increases, which is not the same for the STMD scheme. Maximum displacement response control is achieved by installing the d-MTMDs-1 and d-MTMDs. It is around 35% to 40% and 15% to

20% reduction in the displacement response, respectively under the Llolleo, 1985 and Nahanni, 1985 earthquake ground motions.

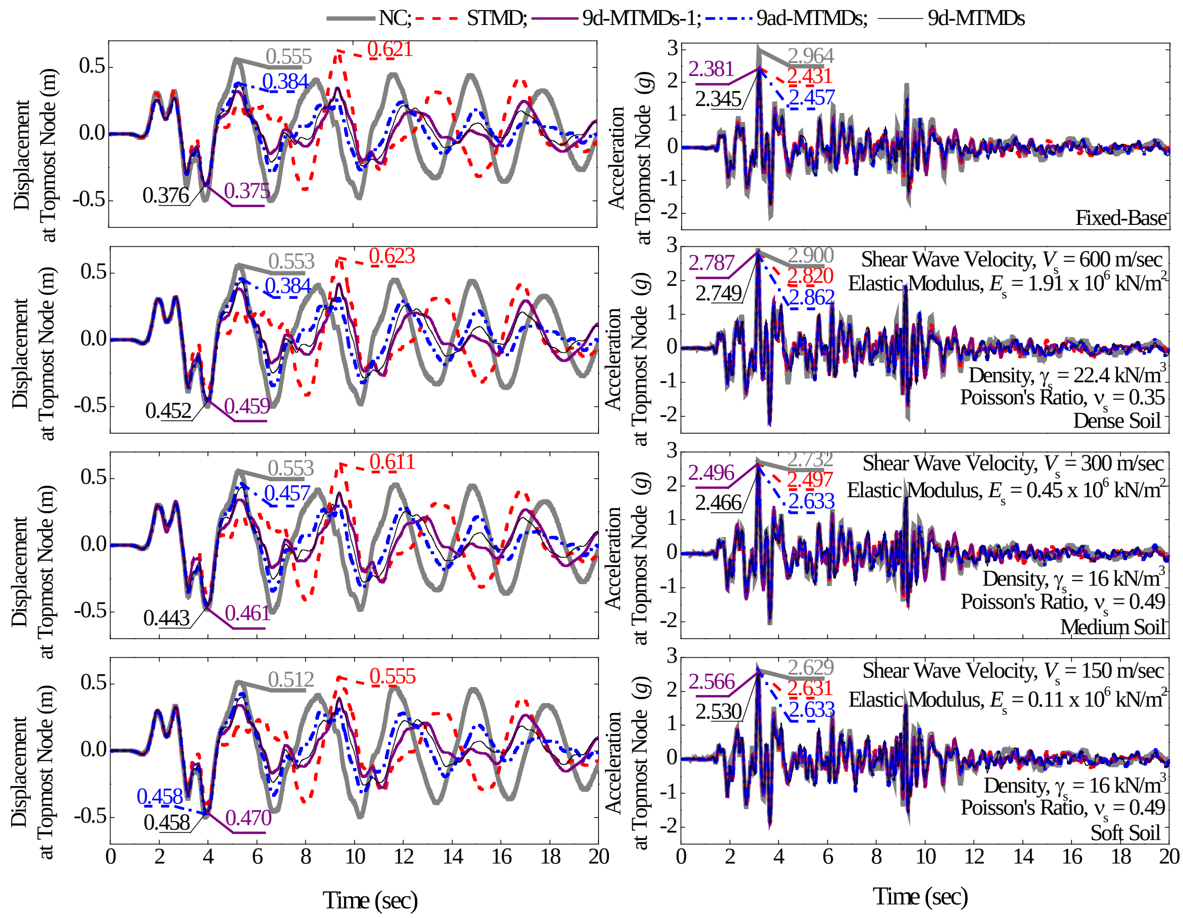


Fig. 4 - Time variation of displacement and acceleration at topmost node of the RC chimney under the Nahanni, 1985 earthquake; TMDs with mass ratio (μ) of 2% and damping ratio ($\zeta_d$) of 5%.

The d-MTMDs placed arbitrarily (ad-MTMDs) shows less effectiveness as compared to the d-MTMDs-1, and d-MTMDs cases. However, it is still exhibiting improved performance in the displacement response reduction as compared the STMD. It is seen in Fig. 8 and Fig. 9 that multi-modal response control schemes are quite effective in acceleration response control as well. Generally, the best acceleration response reduction is achieved for the RC chimney installed with the 9d-MTMDs. Increasing the mass ratio increases the control capacity of the different TMD schemes. It is seen that the chimney installed with the STMD and 9d-MTMDs-1 schemes the acceleration response increased as compared to the uncontrolled chimney. It is also seen that the performance of the 9d-MTMDs is quite same under different soil types considered herein, which confirms that the control scheme is robust. Therefore, it is concluded that increase in the mass ratio (μ) of the TMDs leads to the improvement in the seismic response reduction for most of the schemes studied herein (d-MTMDs-1, ad-MTMDs, and d-MTMDs). In addition, the soil type greatly affects the design parameters of the STMD/ d-MTMDs-1/ ad-MTMDs/ d-MTMDs schemes and seismic responses of the chimney with flexible foundation. Further, the d-MTMDs are more robust as compared to the STMD, d-MTMDs-1, and ad-MTMDs.

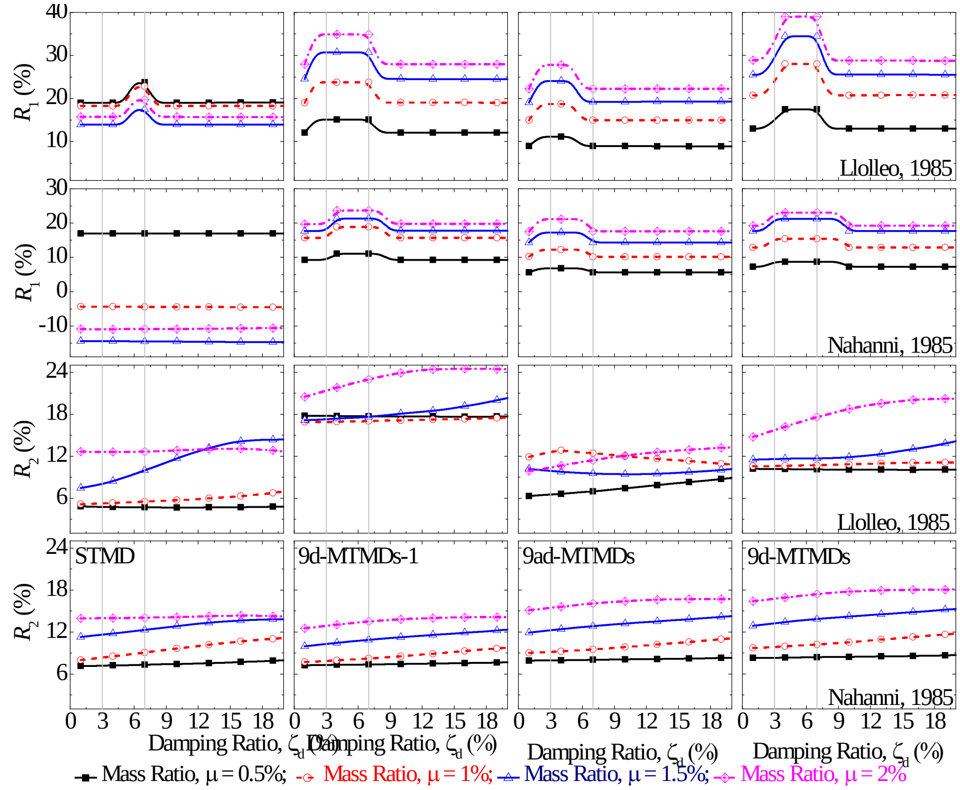


Fig. 5 - Response variations with changing damping ratios ($\zeta_d$) and mass ratios (μ) of the STMD, 9d-MTMDs-1, 9ad-MTMDs, and d-MTMDs installed on chimney with fixed-base under different earthquakes.

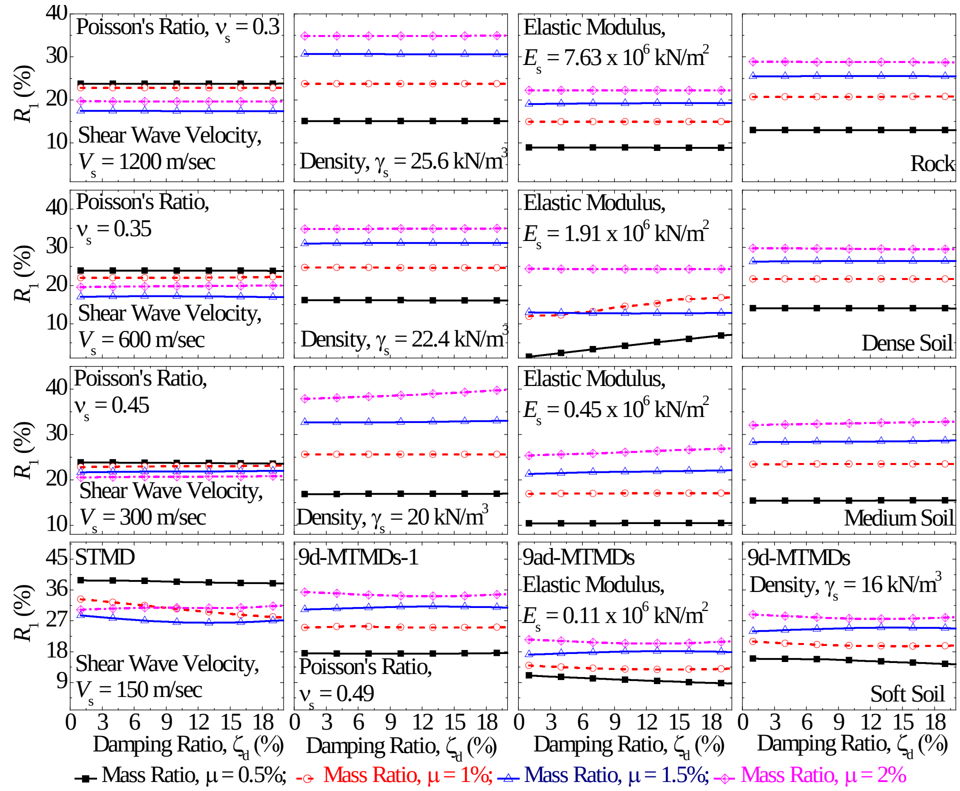


Fig. 6 - Response variations with changing damping ratios ($\zeta_d$) and mass ratios (μ) of the STMD, 9d-MTMDs-1, 9ad-MTMDs, and d-MTMDs installed on the chimney including SSI under the Llolleo, 1985 earthquake.

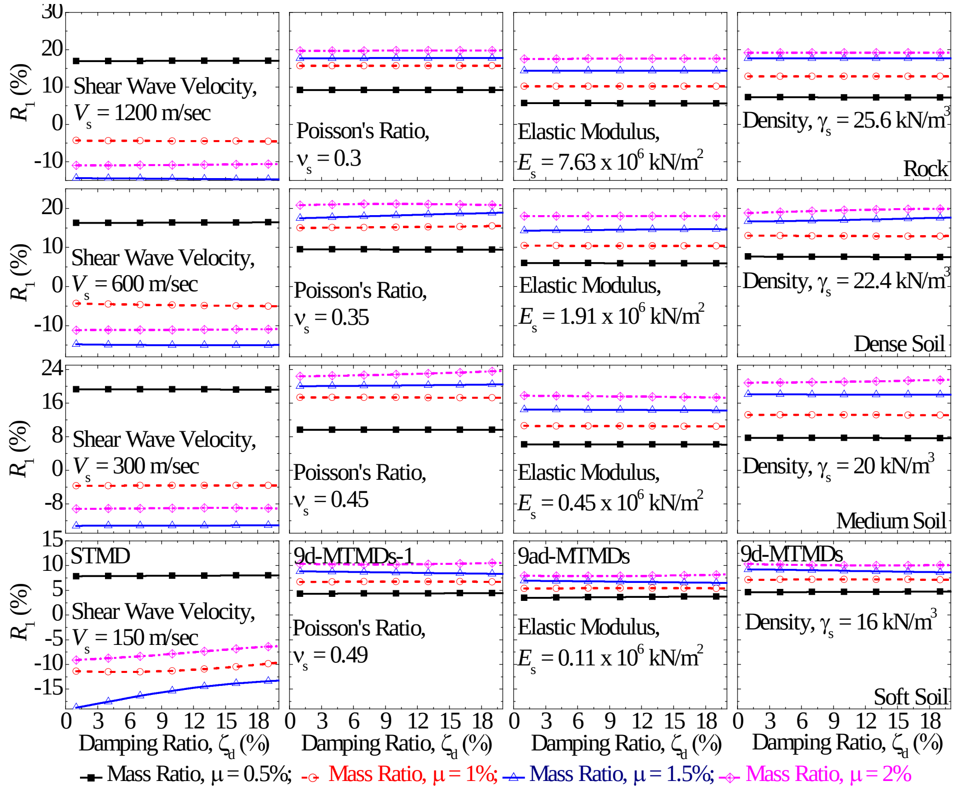


Fig. 7 - Response variations with changing damping ratios ($\zeta_d$) and mass ratios ($\mu$) of the STMD, 9d-MTMDs-1, 9ad-MTMDs, and d-MTMDs installed on the chimney including SSI under the Nahanni, 1985 earthquake.

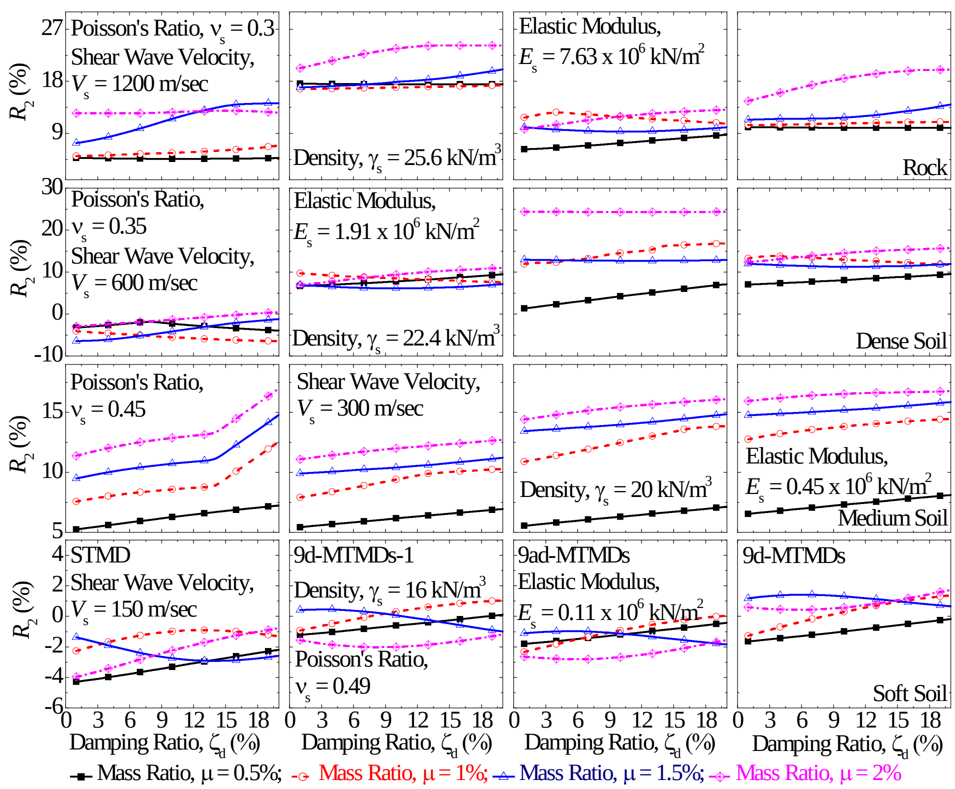


Fig. 8 - Response variations with changing damping ratios ($\zeta_d$) and mass ratios ($\mu$) of the STMD, 9d-MTMDs-1, 9ad-MTMDs, and d-MTMDs installed on the chimney including SSI under the Llolleo, 1985 earthquake.

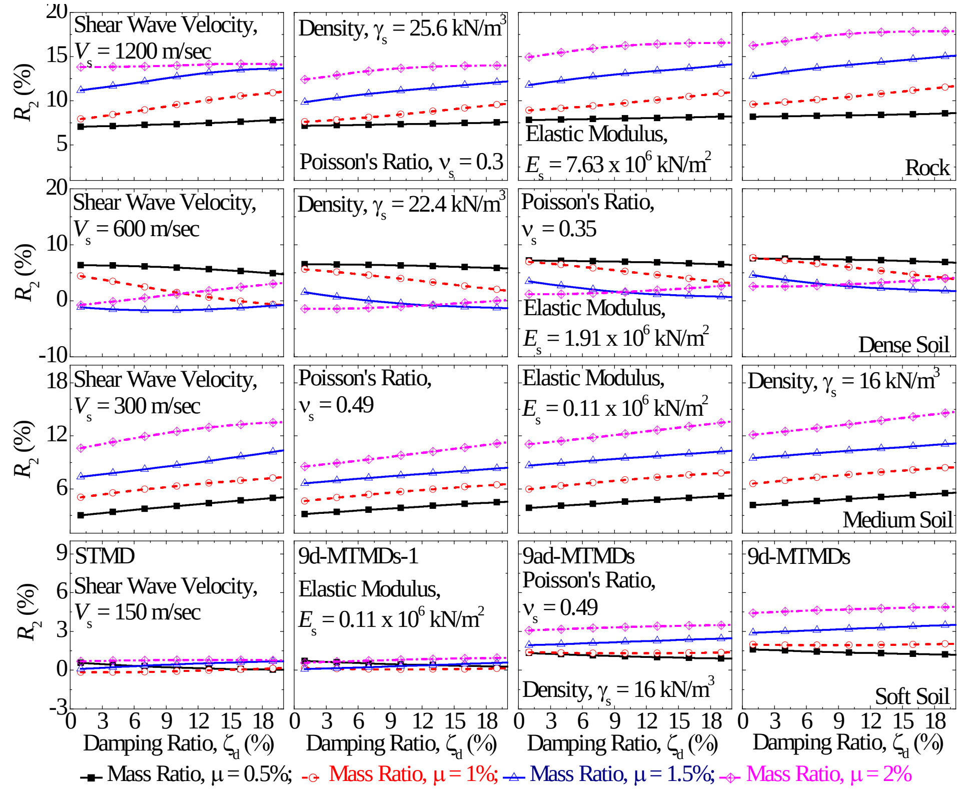


Fig. 9 - Response variations with changing damping ratios ($\zeta_d$) and mass ratios ($\mu$) of the STMD, 9d-MTMDs-1, 9ad-MTMDs, and d-MTMDs installed on the chimney including SSI under the Nahanni, 1985 earthquake.

## 4. Conclusions

Multi-mode response control of the chimneys including soil-structure interaction (SSI) under earthquake ground motions is presented. Distributed multiple tuned mass dampers (d-MTMDs) are installed for multi-mode control of the RC chimney including the SSI. Comparison of the seismic response is made for the chimney installed with the single tuned mass damper (STMD), distributed multiple tuned mass dampers all controlling the fundamental modal response (d-MTMDs-1), arbitrarily distributed tuned mass dampers (ad-MTMDs), and distributed tuned mass dampers (d-MTMDs) under different real earthquake ground motions. The following conclusions are drawn from the results of the numerical study presented here:

1. The d-MTMDs controlling multi-modal seismic response are more reliable in effectively reducing the displacement and acceleration response.
2. The optimum damping exists for the fixed-base RC chimney installed with the TMDs. However, damping ratios ($\zeta_d$) may not improve the control performance of the different schemes under varied soil properties considered herein.
3. The increase in the mass ratio ($\mu$) of the TMDs leads to the improvement in the seismic response reduction for most of the TMD(s) schemes studied herein (i.e. d-MTMDs-1, ad-MTMDs, and d-MTMDs).
4. The soil type greatly affects the design parameters of the STMD/ d-MTMDs-1/ ad-MTMDs/ d-MTMDs schemes and seismic response of the chimney with flexible foundation, and the d-MTMDs are more robust as compared to the STMD, d-MTMDs-1, and ad-MTMDs.

## 5. Acknowledgements

The Afghanistan Association on Earthquake Engineering (AAEE) partially approved the travel expenses to Mr. Said Elias for attending this conference, which is greatly appreciated.

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