On the Performance of 2 passive TMDs in Reducing the Seismic Response of 3-D Structural Models Considering the Soil-Structure Interaction

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ABSTRACT :

The application of passive or active Tuned Mass Dampers (TMD) in reducing the seismic or wind induced response of structures has been extensively explored in the literature. On the other hand, the effect of Soil-Structure Interaction (SSI) for the structures located on soft soil, on their dynamic parameters such as natural frequencies, damping ratios and modal shapes can be prominent. This paper investigates the effect of SSI on the performance of a couple of Tuned Mass Dampers (TMD) in reducing the seismic response of the structures situated on soft soil. A number of 3-D steel moment resisting frames with different eccentricities in orthogonal directions are considered. Two TMDs are implemented at the roof level in the orthogonal directions. These models are assumed to be located on a square rigid concrete mat footing, and the underlying soil is considered as a homogeneous half-space. Also, a Cone model has been used for mathematical modeling of the infinite soil medium. The shear wave velocity of the soil is varied from 150m/s to very large velocities to represent different soil types. These models are subjected to a number of bi-directional (horizontal) earthquake excitations according to the site soil type. Using the optimal location of these TMDs in plan from a previous study, their performance in controlling the seismic response of the structural models is studied considering the SSI. The criterion for investigating the performance of TMD in this study is the amount of the reduction in the maximum real story drift. The real story drift is calculated by vector summation of story drift in two orthogonal directions at any time instant. As the result shows, excluding the SSI effect could overestimate the TMD's performance.

KEYWORDS: Tuned Mass Damper (TMD), Soil-Structure Interaction, 3-D Structural Models

1. INTRODUCTION

The application of passive or active Tuned Mass Dampers (TMD) in reducing the seismic or wind induced response of structures has been extensively explored in the literature [1,2]. In majority of these studies, 2-D shear type structural models have been considered with different number of stories, thus neglecting their torsional response. On the other hand, in most of the cases, it is intuitively assumed that the structural models are located on solid ground without any need to consider the support's flexibility. However, in practice, many structures are built on flexible soils, causing considerable interaction between the soil and the superstructure. As Wolf [3,4], and Luco and Wong [5] have indicated, soil-structure interaction could have significant effect on the dynamic characteristics of structures such as frequencies, damping ratios, and mode shapes as well as the seismic input to the system due to the scattering effect of rigid foundation.
On the other hand, the performance of active structural control systems or passive control devices takes place mainly by changing the structure's dynamic characteristics [6]. Therefore, the rational design of a control system that depend on the dynamic properties of the structures, are in turn affected by the soil-structure interaction. As a result, failing to observe the SSI effects on the dynamic characteristics of structures might lead to non-optimal performance of any control system used for their seismic response mitigation.
Xu and Kwok [7] investigated the wind-induced motion of a 76-story RC building and a 370m tall tower,

mounted with TMD, taking into account the effect of soil type under the footing. They concluded that when soil is very soft, TMDs cannot effectively reduce the response of the soil-structure system; and when the soil is moderately stiff, the dampers should be tuned into the fundamental frequency of the soil-structure system instead of the fixed-base structure in order to optimize the TMD's performance. Samali et al. [8] have obtained similar results on the TMD's seismic performance for soil-structure systems. Wu et al. [9] studied the eismic performance of TMD for structures with shallow foundations. They performed numerical investigations for a 45m tall TMD–structural system built on soils with various shear wave velocities and concluded that the TMD effectiveness would decrease rapidly as the soil medium becomes softer. This is due to the fact that the damping of the entire soil–structure system increases for softer soil.

Gao et al. [10] showed that the TMD is an effective vibration control device. He modeled the soil as an elastic half-space without material damping. This assumption may be acceptable for wind loading problems, but becomes questionable for seismic applications. Wang and Lin [11] studied the applicability of Multiple Tuned Mass Dampers (MTMD) on the vibration control of torsionally coupled buildings under base excitations, considering the SSI effect. They used a single-story building subjected to a uni-directional horizontal ground acceleration. It was concluded that reducing the relative stiffness of the soil to the structure would in general amplify both SSI and MTMD detuning effect, especially for the highly torsionally coupled buildings. Enlarging the frequency spacing of the optimal MTMD, would reduce the detuning effect of the passive control system.

The objective of this paper is to investigate the effect of soil-structure interaction on the performance of a couple of TMD's placed at the roof level, in reducing the seismic response of structures. A number of 3-D steel moment resisting frames with a square rigid concrete mat footing are considered. The eccentricities are varied in both orthogonal directions from 0 to 15%. Two TMDs are implemented at the roof level in the orthogonal directions. Using the optimal location of these TMDs in plan from a previous study (Fig. 2), their performance in reducing the seismic response of the structural models is studied considering the SSI. These structural models are subjected to a number of bi-directional seismic inputs in accordance with the site soil type.

2. SYSTEM MODEL

A number of multistory shear buildings consisting of rigid floors, supported on deformable columns shown in Fig. 1-a, are considered. The plan and the related mass and stiffness centers of the floors are shown in Fig. 1-b. However, without any loss of generality it is assumed that the mass and stiffness centers of all floor diaphragms lie on separate vertical axes respectively. Furthermore, each floor has three degrees-of-freedom: two displacements in the x- and y-directions and a rotation θ about the vertical axis. These buildings are supposed to be seismically controlled using TMDs.

2.1. Fixed-base Structure-TMD Systems

When supported on very stiff soil mass, the structure and TMD system can be considered to be a fixed base. The equations of motion of such a building excited by bi-directional seismic inputs in the horizontal plane can be written as

$$\mathbf{M}_s\ddot{\mathbf{D}}_s + \mathbf{C}_s\dot{\mathbf{D}}_s + \mathbf{K}_s\mathbf{D}_s = -\mathbf{r}_g\ddot{\mathbf{g}} \tag{2.1}$$

where M_s, C_s; and K_s, are the mass, damping and stiffness matrices of the system respectively. D_s is the relative displacement vector consisting of the relative translations and rotations of each floor $D_{si} = \{x_i; y_i; \theta_i\}^T$. r_g is the influence vector and $\ddot{\mathbf{g}}^T = \{\ddot{x}_g, \ddot{y}_g\}$ is the vector of the ground acceleration components in x- and y-directions. Assuming classical damping, the damping matrix is defined in terms of the modal damping ratios considered for the first two modes.

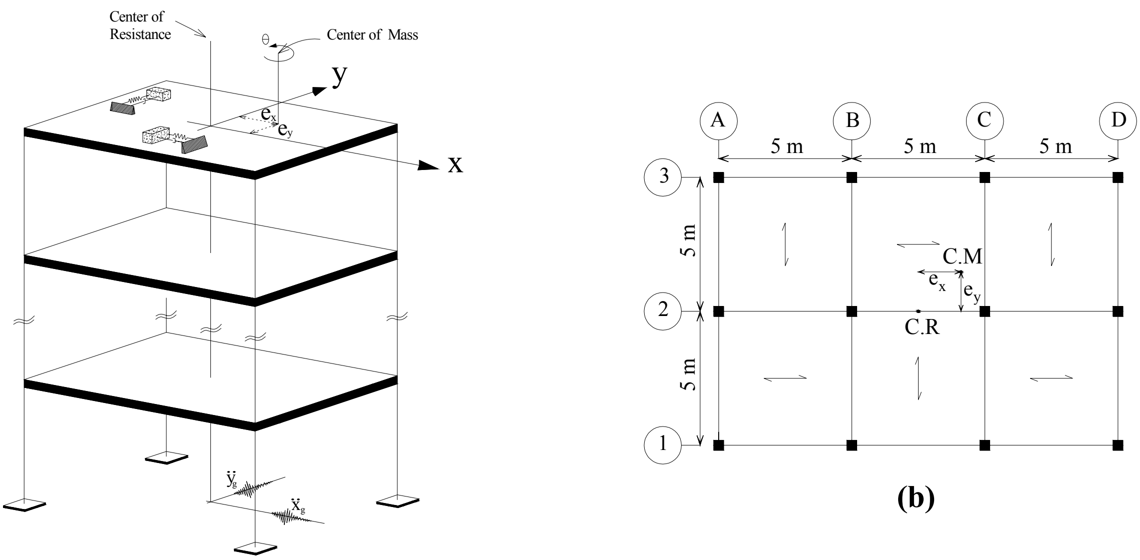
Two tuned mass dampers are installed at the roof level in the orthogonal directions. The mass, stiffness and damping parameters of these TMDs are denoted by: (m_x; m_y), (c_x; c_y), and (k_x; k_y). For determining the optimal location of the orthogonal TMD's(that was already done by the authors), three positions were considered for

TMDs in every direction (Fig. 2). A numerical search was performed to find the best combination of TMD's positions. Finally it was concluded that the optimal configuration of TMD's for buildings without eccentricities is B2 (two TMDs in the center of resistance) and for the torsionally coupled building is C3. The combined equations of motion of the structure-TMD system can be written as :

$$\begin{bmatrix} \mathbf{M}_s & \mathbf{0} \\ \mathbf{0} & \mathbf{M}_d \end{bmatrix} \begin{Bmatrix} \ddot{\mathbf{D}}_s \\ \ddot{\mathbf{d}} \end{Bmatrix} + \begin{bmatrix} \mathbf{C}_s + \mathbf{\Gamma}_1 \mathbf{C}_d \mathbf{\Gamma}_1^T & \mathbf{\Gamma}_1 \mathbf{C}_d \\ \mathbf{C}_d \mathbf{\Gamma}_1^T & \mathbf{C}_d \end{bmatrix} \begin{Bmatrix} \dot{\mathbf{D}}_s \\ \dot{\mathbf{d}} \end{Bmatrix} + \begin{bmatrix} \mathbf{K}_s + \mathbf{\Gamma}_1 \mathbf{K}_d \mathbf{\Gamma}_1^T & \mathbf{\Gamma}_1 \mathbf{K}_d \\ \mathbf{K}_d \mathbf{\Gamma}_1^T & \mathbf{K}_d \end{bmatrix} \begin{Bmatrix} \mathbf{D}_s \\ \mathbf{d} \end{Bmatrix}$$

$$= \begin{bmatrix} \mathbf{r}_g \\ \mathbf{r}_d \end{bmatrix}_{(3n+2)\times 2} \begin{Bmatrix} \ddot{x}_g \\ \ddot{y}_g \end{Bmatrix} \tag{2.2}$$

Where matrices M_d=diag(m_{x1}; m_{y1}), K_d =diag(k_{x1}; k_{y1}), and C_d =diag(c_{x1};c_{y1}), are the mass, stiffness and damping matrices of the damper system respectively; d_T ={x_{d1}; y_{d1}} is a vector consisting of the relative translation of the dampers measured with respect to the center of resistance of the roof floor. The influence coefficient matrix associated with TMDs is represented by r_d. In Eqn. 2.2. $\mathbf{\Gamma}_1$ is the location matrix, defining the location of the dampers.



(a) (b)

Figure 1. a) A schematic view of the structural models with the mounted tuned mass dampers, b)The plan of the structural models.

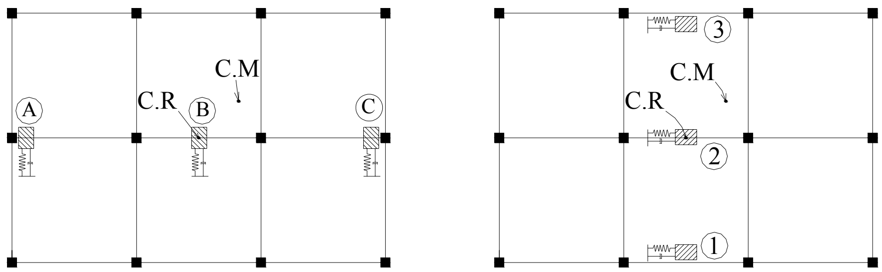


Figure 2. The positions of the TMD in the orthogonal directions.

2.2. Flexible-base Structure-TMD Systems

In this study, the structural models are assumed to be located on a square rigid concrete mat footing. Also, the underlying soil that was considered as a homogeneous half-space, is replaced by a simplified 5DOFs system based on the concept of Voigt viscoelastic Cone models (Fig. 3). The Cone models, based on one-dimensional wave propagation theory, can be used for modeling the underlying soil with sufficient accuracy [12]. Four degrees of freedoms are introduced in this model for the foundation, i.e., sway and rocking motions, as well as the torsional degree of freedom. It is notable that the soil's exact stiffness and damping coefficients are frequency-dependent. But previous studies on soil-structure interaction under earthquake loading have shown that for homogenous soil, the inertial interaction between soil and structure with shallow foundations can be modeled by a set of frequency-independent springs and dashpots [13].

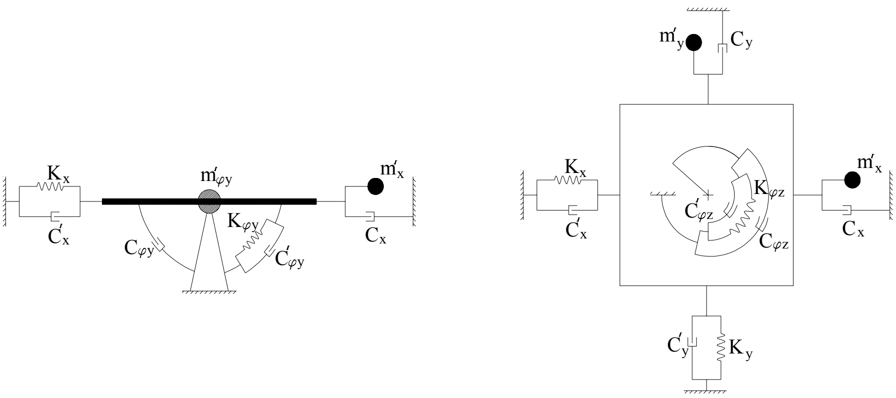


Figure 3. Soil model

The soil related parameters introduced in Fig. 3 are defined as the followings:

$$K = \frac{\rho V^2 A_f}{z_0} \qquad C = \rho V A_f \qquad C' = 2\frac{\zeta_0}{\omega_0}K \qquad m' = \frac{\zeta_0}{\omega_0}C \tag{2.3a}$$

$$K_\varphi = \frac{3\rho V^2 I_f}{z_0} \qquad C_\varphi = \rho V I_f \qquad C'_\varphi = 2\frac{\zeta_0}{\omega_0}K_\varphi \qquad m'_\varphi = \frac{\zeta_0}{\omega_0}C_\varphi \tag{2.3b}$$

where V is the shear wave velocity for sway and torsional motions and the dilatational wave velocity for rocking motions. ρ is the specific mass of soil and z_0 is a parameter that depends on soil's property [12]. Also A_f and I_f are the foundation's area and the area moment of inertia about the axes of rotation respectively. $C', m', C'_\varphi, m'_\varphi$ are augmenting elements for considering the material damping of soil. In these elements, ζ_0, ω_0 is the soil's damping ratio and fundamental frequency of the soil-structure system respectively. The motion equation of the soil-structure-TMD system can be written as:

$$\begin{bmatrix} \mathbf{M} & \mathbf{0} \\ \mathbf{0} & \mathbf{M}_\mathrm{F} \end{bmatrix}\begin{Bmatrix} \ddot{\mathbf{D}} \\ \ddot{\mathbf{D}}_\mathrm{F} \end{Bmatrix} + \begin{bmatrix} \mathbf{C} & -\mathbf{\Gamma C} \\ -\mathbf{C\Gamma}^\mathrm{T} & \mathbf{\Gamma C\Gamma}^\mathrm{T} + \mathbf{C}_\mathrm{F} \end{bmatrix}\begin{Bmatrix} \dot{\mathbf{D}} \\ \dot{\mathbf{D}}_\mathrm{F} \end{Bmatrix} + \begin{bmatrix} \mathbf{K} & -\mathbf{\Gamma K} \\ -\mathbf{K\Gamma}^\mathrm{T} & \mathbf{\Gamma K\Gamma}^\mathrm{T} + \mathbf{K}_\mathrm{F} \end{bmatrix}\begin{Bmatrix} \mathbf{D} \\ \mathbf{D}_\mathrm{F} \end{Bmatrix} = \begin{bmatrix} \mathbf{r} \\ \mathbf{r}_\mathrm{F} \end{bmatrix}\begin{bmatrix} \ddot{\mathbf{d}}_\mathrm{g} \\ \ddot{\boldsymbol{\theta}}_\mathrm{g} \end{bmatrix} \tag{2.4}$$

in which M, C and K correspond to the structural properties referred to in Eq. 2.1. or the structure-TMD properties in Eq. 2.2; D is the corresponding displacement vector relative to the free field ground motion; D_F is the displacement vector of the rigid footing relative to the free field ground motion; M_F is the mass matrix of the rigid footing, and $\mathbf{\Gamma}$ is a transformation matrix which defines the transformation from the free field motion to that of the superstructure. Also, the matrices $\ddot{\mathbf{d}}_\mathrm{g}$ and $\ddot{\boldsymbol{\theta}}_\mathrm{g}$ are the translational and rocking components of the free field acceleration respectively. $\ddot{\boldsymbol{\theta}}_g$ is assumed to be zero in this study. One should observe that, while the structure alone can be considered as a classically damped system, the combined system of the structure and soil medium usually is not. Therefore, the direct integration method should be used instead of modal analysis for calculation of the structural responses.

3. NUMERICAL ANALYSIS

Numerical analyses were carried out using three 3-D structural models with 4, 8 and 15 number of stories, with each story 3m high. The eccentricities in the orthogonal direction were varied up to 15 percent of the models' dimensions. The structural models have been assumed to be classically damped with 2% damping ratios for the first two modes. Two TMDs are implemented at the roof level in the orthogonal directions. The mass ratio μ (ratio of the TMD's mass to the effective modal mass of the system's fundamental mode) and the frequency ratio γ (ratio of the TMD's frequency to the frequency of fundamental mode) of the TMDs are assumed to be 0.02 and 0.98 respectively. Also, the damping of the TMDs, i.e., ζ_{TMD}, is considered to be 0.10. For the three structural models, the characteristics of the system's fundamental mode in each direction and the corresponding TMD's characteristics are provided in Table 1.

Table 1: The modal characteristics of the structural systems and the corresponding TMD's

Model	Dir.	M_n^* (kg)	ω_n (rad/sec)	m_{TMD} (kg)	ω_{TMD} (rad/sec)	K_{TMD} (kgf/m)	C_{TMD} (kgf.sec/m)
4 Story	X	336355	7.02	672.71	6.88	31844.43	925.68
	Y	33971	7.58	679.42	7.43	37497.92	1009.49
8 Story	X	65665	4.19	1313.3	4.11	22190.41	1079.7
	Y	65920	4.48	1318.4	4.39	25398	1157.32
15 Story	X	121021	2.74	2420.4	2.69	17507.5	1301.93
	Y	120210	2.92	2404.2	2.86	19643.4	1374.4

The 10m × 15m rectangular mat footing is assumed to be rigid. Seven shear wave velocities are considered for the underlying soil, ranging from 100 m/s to very large velocities. The other parameters of soil are: $\upsilon = .33$, $\rho = 2000\ kg/m^3$, $\zeta_0 = .05$. These models are subjected to a number of bi-directional earthquake excitations. The selected earthquake records include El-Centro(1940), Tabas(1978), Sanfernando(1971), Imperial Valley(1979), Westmorland(1981), Coalinga(1983), Morgan Hill(1984), Loma Prieta(1989), Cape Mendocino(1992) and Loma Prieta(1992). These earthquake excitations have been recorded on different soil types and are used appropriately depending on the site soil condition. Finally, the real inter-story drift is considered as a measure to compare the performance of TMD's in reducing the seismic response of the structural models. The real inter-story drift is calculated using the vector summation of story drifts in two orthogonal directions at the end of each time step.

Figs. 4-6, show the real story drifts of the uncontrolled and controlled structure with two soil types. These figures are for the regular structures(No eccentricity). As it is shown, the tuned mass dampers are effective in suppressing the response of a soil-structure system with V_s=300 m/s, while demonstrating a poor performance for the structures located on soft soil with V_s=100. The same conclusion can be made from Figs. 7-9, where the response reduction of different structures on different soil types is presented. These figures also indicate that for soils with V_s > 400 m/s, the soil-structure interaction does not have any effect on the performance of the TMDs.

In other words, for soil types with V_s > 400 m/s, the considered structures behave like a fixed base system.
The performance of the TMD for different structural models and for various amount of eccentricities is shown in Fig. 10. As it was mentioned before, the maximum reduction in the story drift is considered as a measure to evaluate the TMD's performance. The results indicate that for taller buildings and stronger soil-structure interaction, the TMD's become less effective. Fig. 10 also indicates that the tuned mass dampers are much less effective for torsionally coupled buildings.

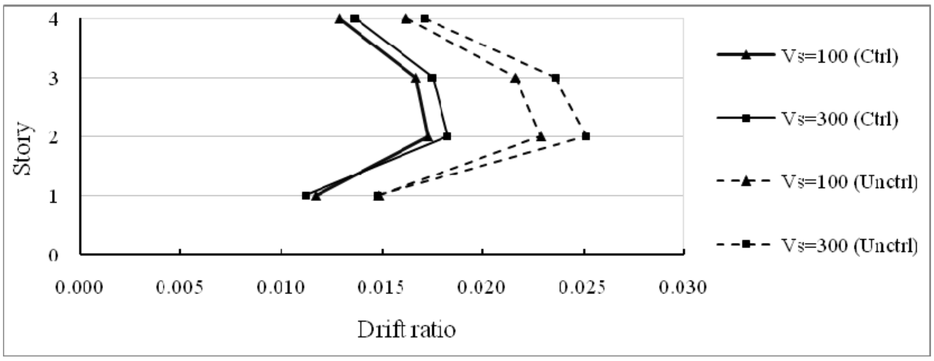


Figure 4. Real story drift for 4story building with Ecc. 0%

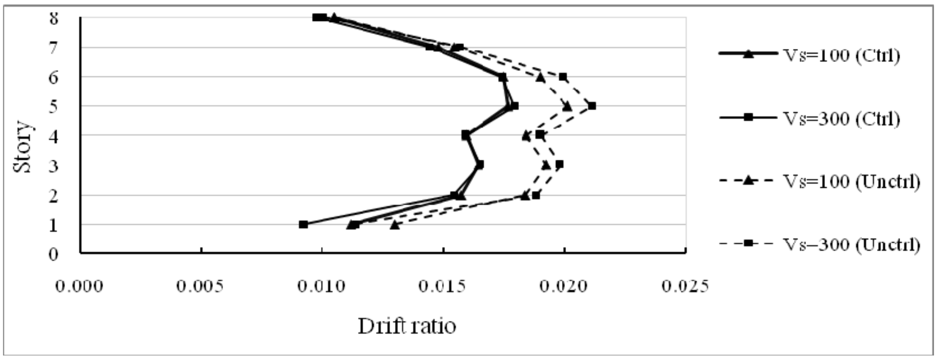


Figure 5. Real story drift for 8story building with Ecc. 0%

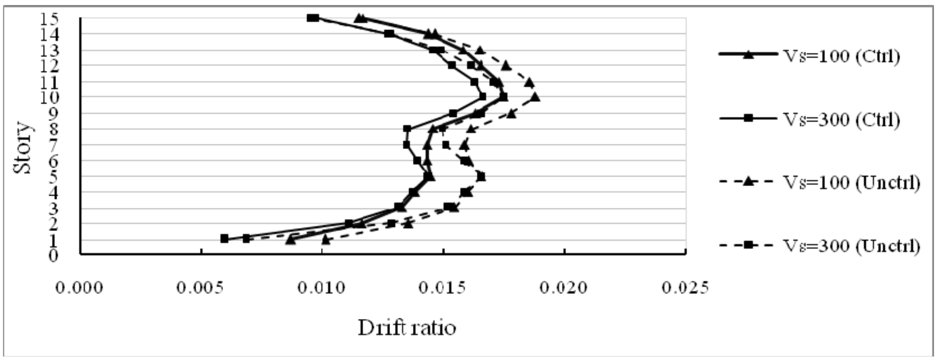


Figure 6. Real story drift for 15story building with Ecc. 0%

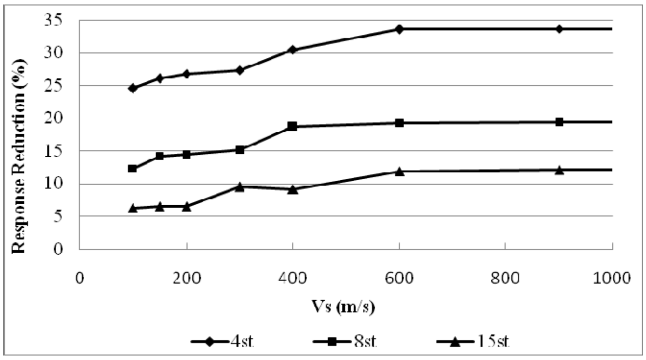


Figure 7. Response reduction for Ecc. 0% and different soil type

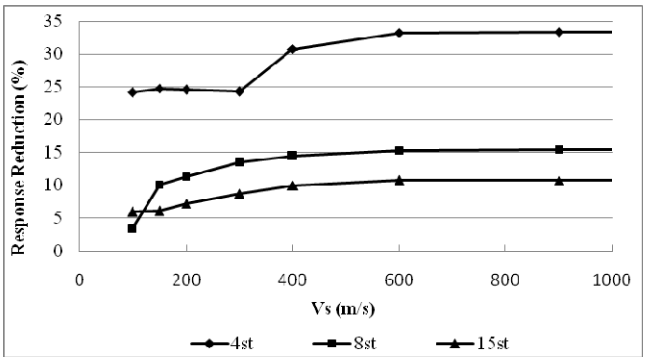


Figure 8. Response reduction for Ecc. 10% and different soil type

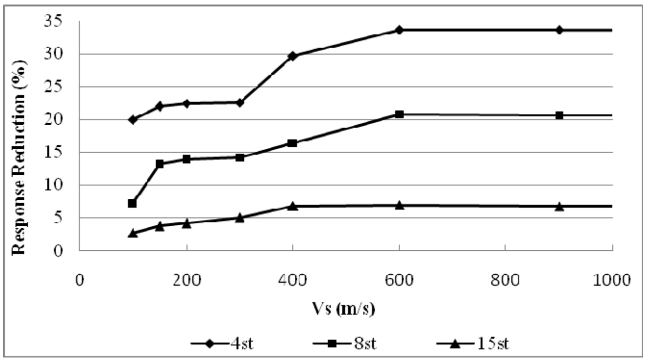


Figure 9. Response reduction for Ecc. 15% and different soil type

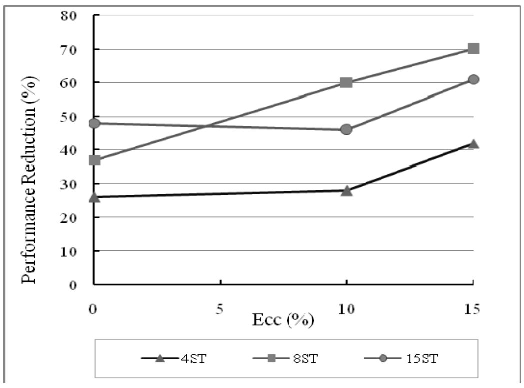


Figure 10. Performance reduction of TMDs for V_s=100 m/s

4. CONCLUSIONS

Strong soil-structure interaction can greatly modify the dynamic characteristics of the structure, which in turn affects the performance of a double TMD system mounted on the top of the structure. The TMD's effectiveness rapidly decreases as the soil medium gets softer. That is caused by the considerable contribution of the soil-structure interaction to the damping of the system that include the soil nonlinear behavior, radiation effect and also decreasing the effective modal mass of the fundamental mode of the system. For taller and more eccentric buildings, the TMD's performance becomes less. Also, in order to reasonably evaluate the feasibility of using tuned mass damper to control the maximum structural responses, soil-structure interaction must be taken into account; otherwise the TMD's performance could be overestimated. In general, TMD is not a feasible choice for vibration control of the structures that are supported on shallow spread footings and underlying soft soil.

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