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Seismic Response Mitigation Of Structure Using Base Isolation System Along With Tuned Mass Damper

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Abstract
The performance of linear base isolation system along with tuned mass damper to mitigate seismic response of structures is investigated in this paper. The stochastic dynamic response quantities with linear base isolation (BI) system, linear BI system along with tuned mass damper (TMD), and without dampers are obtained in random vibration framework using state space formulation to study the possible improvement of performance of combined system (BI and TMD system) compare to that of possible to achieve with BI system. The earthquake excitation is modelled considering a stationary random process. The parametric study is conducted to observe the influence of several parameters like, damping ratio of structures, intensity of earthquake load, mass ratio, and damping ratio of base isolator, on the effectiveness of combined system in comparison with BI system. A numerical study demonstrates that combined system is more effective to mitigating the seismic response of the primary structure compare with only BI system.

Keywords: *Linear Base Isolation, Tuned Mass Damper, MDOF system, stochastic earthquake load.*

1. Introduction

Civil Engineering structures, such as buildings, bridges, and towers, may vibrate severely or even collapse while subjected to strong earthquake excitations. To prevent the structure from such damage, passive energy dissipation systems have emerged as special devices incorporated within the structure to absorb a portion of the input seismic energy. As a result, the energy dissipation demand on primary structural members is significantly reduced, along with the potential for structural damage. Amongst all the passive vibration devices, base isolator and tuned mass dampers are being mostly utilized for reducing structural vibrations for years. Tuned mass dampers, in their simplest form, consist of an auxiliary mass-spring-dashpot system anchored or attached to the main structure, usually on the top of the structure. Base isolation is a well established application of the passive control approach. A building mounted on a material with low lateral stiffness, such as rubber, achieves a flexible base. During the earthquake, the flexible base is able to filter out high frequencies from the ground motion and to prevent the building from being damaged or collapsing.

Several studies have been performed in the past years regarding the application and effectiveness of base isolators and tuned mass dampers in mitigating seismic response of framed structures. A survey of the numerical simulation of base isolation systems for the vibration control of buildings and their equipment, primarily against earthquakes show that the seismic response of buildings using any of the existing base isolation systems is considerably improved compared to a conventional fix base design (Barbat *et al.* 1997). The nonlinear dynamic response of HDRB and Hybrid HDRB-Friction Sliders Base Isolation Systems can be used as a suitable combination in series and in parallel devices, which can help to optimize the seismic response and to control the higher modes amplification by minimizing the nonlinearities of Hybrid isolation systems (Braga *et al.* 1999). The use of TMD combined with BI always involves a reduction of the overall system response even in presense of non-linear behaviour of isolators (Bruno *et al.* 1999). A parametric study of linearly and non linearly passivly damped seismic isolation systems for buildings depicts the increasing trend of damping in the isolation system with increase in story drift ratios and floor accelerations for low stiffness isolation systems (Cenk *et al.* 2003). The results of the various base isolation schemes implemented by Chakraborty (2012) showed that the structure with fixed base is subjected to huge peak inter-storey drift outside the allowable range that needed to be checked. The Combined Effect of Seismic Base Isolation and Viscoelastic Dampers results in drastic reduction of time history values of the fixed-base case in column bending moments (up to 64%), while the displacements get increased (Erkal *et al.* 2011). The Hu spectral model, a modified Kanai-Tajimi spectral model can be used for analysis of the stationary stochastic process of earthquake ground motion which is consistent well with actual earthquake induced ground motion (Honjing *et al.* 2008) . The stochastic response of building frames isolated by lead-rubber bearings (LRB) is analysed using time dependent equivalent linearization technique (Jangid 2007). Using a particular configuration, multiple TMDs can reduce the drift responses of many degrees of freedom at the cost of a slight increase in a few floors (Janak 2005). The study on the seismic performance of isolated RC building in terms of reduction in responses under four realistic unidirectional earthquakes has proposed two seismic controls, that is, LRB control and NZ control to mitigate the responses of ten storied RC building isolated by elastomeric base isolator without and with lead core during excitation due to various earthquakes (Jadhao 2013). Nonlinear dynamic steady state analysis of a structure with a friction-based seismic base isolation system with the aid of periodic solution solvers provide a valuable insight in the nonlinear dynamic behaviour of the base-isolated structure (Suy *et al.* 2007). These studies have provided a considerable insight into the dynamic response characteristics of the structure using base isolation and tuned mass damping. The objectives of the present study are: (i) to obtain the RMS displacement of the structure with BI, (ii) to evaluate the RMS displacement of the structure with combined effect of BI and TMD system. A numerical study demonstrates that combined system is more effective to mitigating the seismic response of the primary structure compare with only BI system.

2. Theoretical formulations:

2.1 The dynamic equation of motion of structure and linear BI System

The equation of motion of a multiple degree of freedom (MDOF) system attached with base isolator system can be expressed as,

$$M\ddot{X}+C\dot{X}+KX=-Mr\ddot{x}_g \quad (1)$$

Where, M,C and K represents mass, damping and stiffness matrix of base isolated structure and

$$M=\text{diag}\left[m_b,\ m_1,\ m_2,\ m_3,\ m_4,\ m_5\right],$$

,

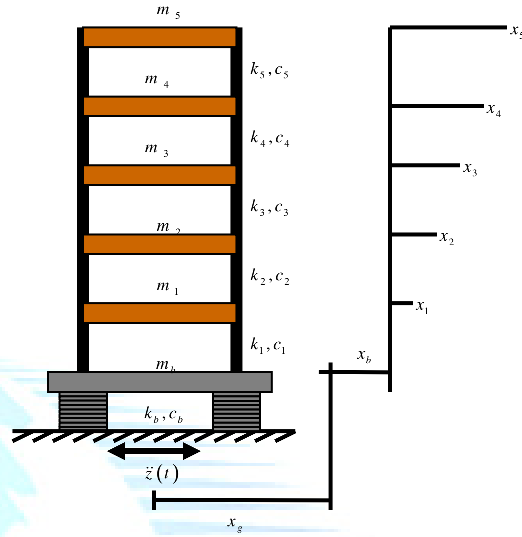

Fig.1 Base isolated structure

$$K=\begin{bmatrix}(k_b+k_1) & -k_1 & 0 & 0 & 0 & 0\\ -k_1 & (k_1+k_2) & -k_2 & 0 & 0 & 0\\ 0 & -k_2 & (k_2+k_3) & -k_3 & 0 & 0\\ 0 & 0 & -k_3 & (k_3+k_4) & -k_4 & 0\\ 0 & 0 & 0 & -k_4 & (k_4+k_5) & -k_5\\ 0 & 0 & 0 & 0 & -k_5 & k_5\end{bmatrix}$$

$$C=\begin{bmatrix}(c_b+c_1) & -c_1 & 0 & 0 & 0 & 0\\ -c_1 & (c_1+c_2) & -c_2 & 0 & 0 & 0\\ 0 & -c_2 & (c_2+c_3) & -c_3 & 0 & 0\\ 0 & 0 & -c_3 & (c_3+c_4) & -c_4 & 0\\ 0 & 0 & 0 & -c_4 & (c_4+c_5) & -c_5\\ 0 & 0 & 0 & 0 & -c_5 & c_5\end{bmatrix}, \quad (2)$$

Where
$$k_b=\omega_b^2 m_b$$
$$c_b=2m_b\xi_b\omega_b$$
$$c_i=2m_i\xi_s\omega_s \ \text{ for i=1 to 5}$$

and

Introducing the state space vector,

$$\mathbf{Y}_s=(x_b,x_1,x_2,x_3,x_4,x_5,\dot{x}_b,\dot{x}_1,\dot{x}_2,\dot{x}_3,x_4,\dot{x}_5)^T \quad (3)$$

The equilibrium equations of motion can be expressed as,

$$\dot{\mathbf{Y}}_s=\mathbf{A_s}\mathbf{Y}_s+\tilde{\mathbf{r}}\,\ddot{z}_b \ \text{ where, } \mathbf{A}_s=\begin{bmatrix}0 & \mathbf{I}\\ \mathbf{H}_k & \mathbf{H}_c\end{bmatrix}_{12\times12} \quad (4)$$

Where, $\mathbf{H_k}=\mathbf{M^{-1}K}$, $\mathbf{H_c}=\mathbf{M^{-1}C}$

In which $\tilde{\mathbf{r}}=\left[0,\mathbf{I}\right]^T$ with **I** and 0 is the (n+1)x(n+1) unit and null matrices, respectively.

2.2 Evaluation of Response Covariance

The structure with linear base isolation system as shown in Fig.1 is subjected to stochastic load due to the random seismic acceleration that excites the primary structure at base. A widely adopted stationary model of $\ddot{z}_b(t)$ is obtained by filtering a white noise process acting at the bed rock through a linear filter which represents the surface ground. This is the well-known Kanai– Tajimi stochastic process [Tajimi 1960] which is able to characterize the input frequency content for a wide range of practical situations. The process of excitation at the base can be described as:

$$\ddot{x}_f(t) + 2\xi_f \omega_f \dot{x}_f + \omega_f^2 x_f = -\omega(t) \quad \text{and} \quad \ddot{z}_b(t) = \ddot{x}_f(t) + \omega(t) = 2\xi_f \omega_f \dot{x}_f + \omega_f^2 x_f \tag{5}$$

Where, $\omega(t)$ is a stationary Gaussian zero mean white noise process, representing the excitation at the bed rock, ω_f is the base filter frequency and ξ_f is the filter or ground damping. Defining the global state space vector is defined as: $\mathbf{Y}_s = (x_b, x_1, x_2, x_3, \ldots x_5, x_f, \dot{x}_b, \dot{x}_1, \dot{x}_2, \dot{x}_3, \ldots \dot{x}_5, \dot{x}_f)^T$, Eqn. (4) and (5) leads to an algebraic matrix equation of order six i.e. the so called Lyapunov equation (Lutes and Sarkani 1997):

$$\mathbf{AR} + \mathbf{RA}^T + \mathbf{B} = 0 \tag{6}$$

The details of the state space matrix **A** and **B** in Eqn. (6) are as below:

$$[\mathbf{A}] = \begin{bmatrix} 0 & \mathbf{I} \\ \bar{\mathbf{H}}_\mathbf{k} & \bar{\mathbf{H}}_\mathbf{c} \end{bmatrix}_{14\times14} \tag{7}$$

Where,

$$\bar{\mathbf{H}}_\mathbf{k} = \begin{bmatrix} & & & & \vdots & \omega_f^2 \\ & -\mathbf{M}^{-1}\mathbf{K} & & & \vdots & \omega_f^2 \\ & & & & \vdots & . \\ & & & & \vdots & \omega_f^2 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & \ldots & 0 & \vdots & -\omega_f^2 \end{bmatrix}$$

$$\bar{\mathbf{H}}_\mathbf{c} = \begin{bmatrix} & & & & \vdots & 2\xi_f\omega_f \\ & -\mathbf{M}^{-1}\mathbf{C} & & & \vdots & 2\xi_f\omega_f \\ & & & & \vdots & . \\ & & & & \vdots & 2\xi_f\omega_f \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & 0 & \vdots & -2\xi_f\omega_f \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} 0 & \cdots & \cdots & \cdots & \cdots & 0 \\ \vdots & \cdots & \cdots & \cdots & \cdots & \vdots \\ \vdots & \cdots & \cdots & \cdots & \cdots & \vdots \\ \vdots & \cdots & \cdots & \cdots & \cdots & \vdots \\ \vdots & \cdots & \cdots & \cdots & \cdots & \vdots \\ 0 & \cdots & \cdots & \cdots & \cdots & 2\pi S_o \end{bmatrix}_{14\times14} \tag{8}$$

The space state covariance matrix **R** is obtained as the solution of the Lyapunov equation. The state space covariance matrix is represented by the sub-matrices $R_{zz}, R_{z\dot{z}}, R_{\dot{z}z}$ and $R_{\dot{z}\dot{z}}$. The root mean square (RMS) displacement and the primary system can be then obtained as:

$$\sigma_{xb} = \sqrt{R_{zz}(1,1)} \quad \text{and} \quad \sigma_i = \sqrt{R_{zz}(i,i)}, \text{ where i=2 to n} \tag{9}$$

2.3 Base Isolated Structure with TMD

A five storied base isolated structure along with tuned mass damper as shown in Fig.2.

Introducing the state space vector for a linear base isolated primary structure along with TMD system.

$$\mathbf{Y}_s = (x_b, x_1, x_2, x_3, ...x_5, x_t, \dot{x}_b, \dot{x}_1, \dot{x}_2, \dot{x}_3, ...\dot{x}_5, \dot{x}_t)^T \quad (10)$$

$\dot{\mathbf{Y}}_c = \mathbf{A}_c \mathbf{Y}_c + \hat{\mathbf{r}}\, \ddot{z}_b$ where,

$$\mathbf{A}_c = \begin{bmatrix} 0 & \mathrm{I} \\ \hat{\mathbf{H}}_k & \hat{\mathbf{H}}_c \end{bmatrix}_{14\times 14} \quad (11)$$

Similarly, the space state covariance matrix can be obtained using previous Lyapunov Eqn (6). The root mean square (RMS) displacement of base isolator, tuned mass damper and the primary structure can be obtained as:

$$\sigma_{x_b} = \sqrt{R_{zz}(1,1)},$$

$$\sigma_t = \sqrt{R_{zz}(6,6)}, \quad (12)$$

$$\sigma_{xi} = \sqrt{R_{zz}(i,i)}, \text{ where i=2 to 5}$$

3. Numerical Study

A five storied building using BI system along with TMD as shown in Fig 1 subjected to stochastic earthquake load is undertaken to study the effectiveness of combined system (BI and TMD). The mass and stiffness values are: $m_1 = 2.83\times10^5$ kg, $m_2=m_3=m_4=m_5=2.76\times10^5$ kg, $k_1=3.31\times10^8$ N/m, $k_2=k_3=k_4=1.06\times10^9$ N/m $k_5 = 6.79\times10^8$ N/m, $m_s = \sum_{i=1}^{5} m_i$, $\omega_t = \sqrt{\frac{k_t}{m_t}}$, Unless mentioned otherwise, the following nominal values are assumed for the present numerical study: $m_b = 0.6 m_s$,

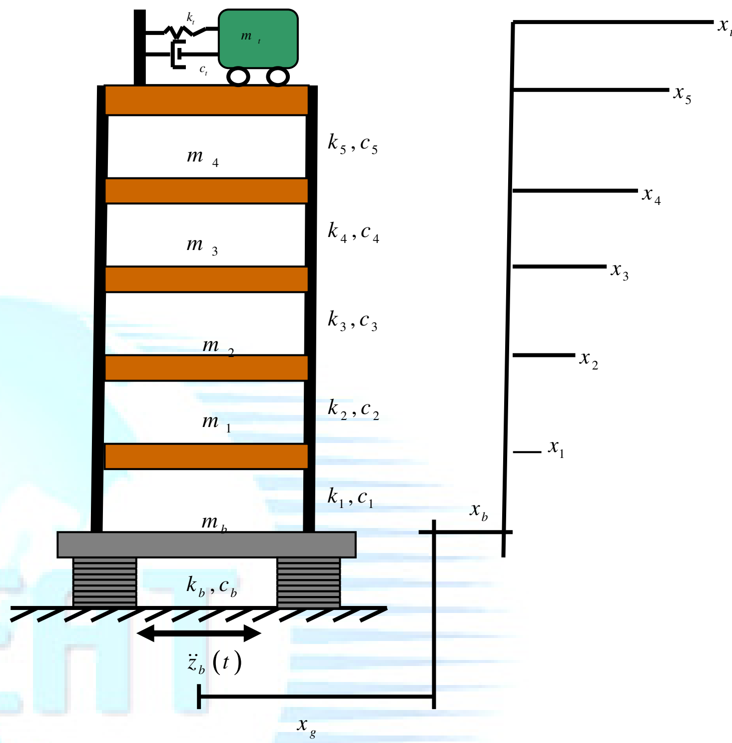

Fig.2 Base isolated structure with TMD

$m_t = 0.2 m_s$, damping ratio of the structure, $\xi_s = 3\%$, $S_0 = 100\text{cm}^2/\text{sec}^3$. The mean value of the filter frequency (ω_f) and damping (ξ_f) are taken as 7π rad/sec and 0.6, respectively. The base solated structure and base isolated structure along with TMD, both are tuned based on fundamental frequency of primary structure.

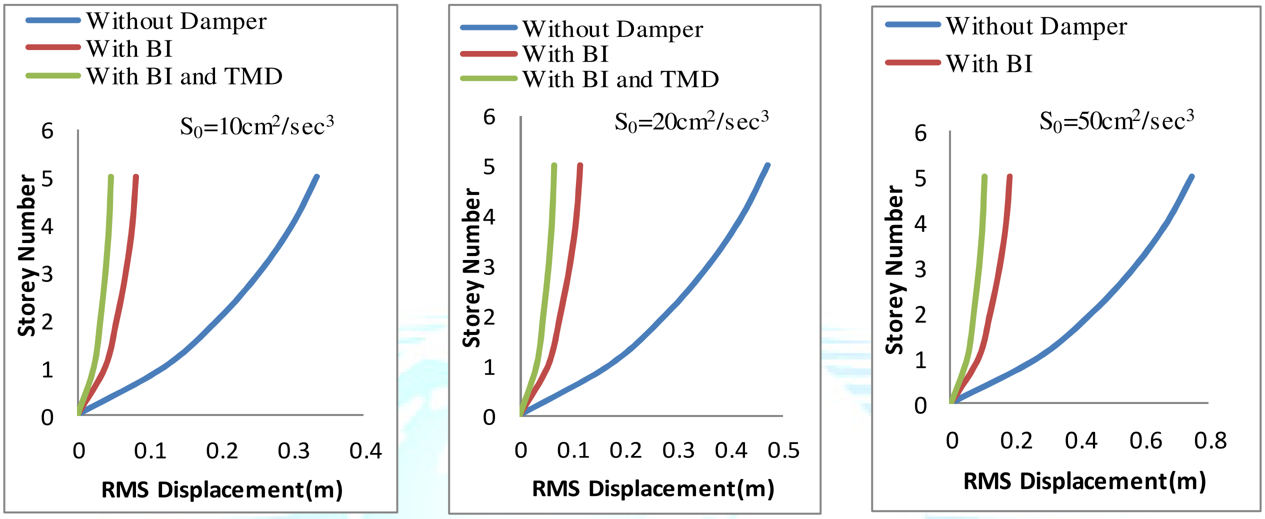

Fig.3 Variation of RMS Displacement of structure with number of stories for different earthquake load, $S_0\left(cm^2/sec^3\right)$ and damping ratio of structure $\xi_s = 1\%$

The variations of RMS displacement of structure with different number of storeys are shown in Fig.3 for different earthquake load and 1% damping of structure. It is observed that the RMS displacement decreases at the different storey level using linear BI system with compared to the structure without BI system. Further, it is also observed that the reduction of RMS displacement is more using combined system,i.e, BI system along with TMD for different earthquake load and 1% damping ratio of structure.

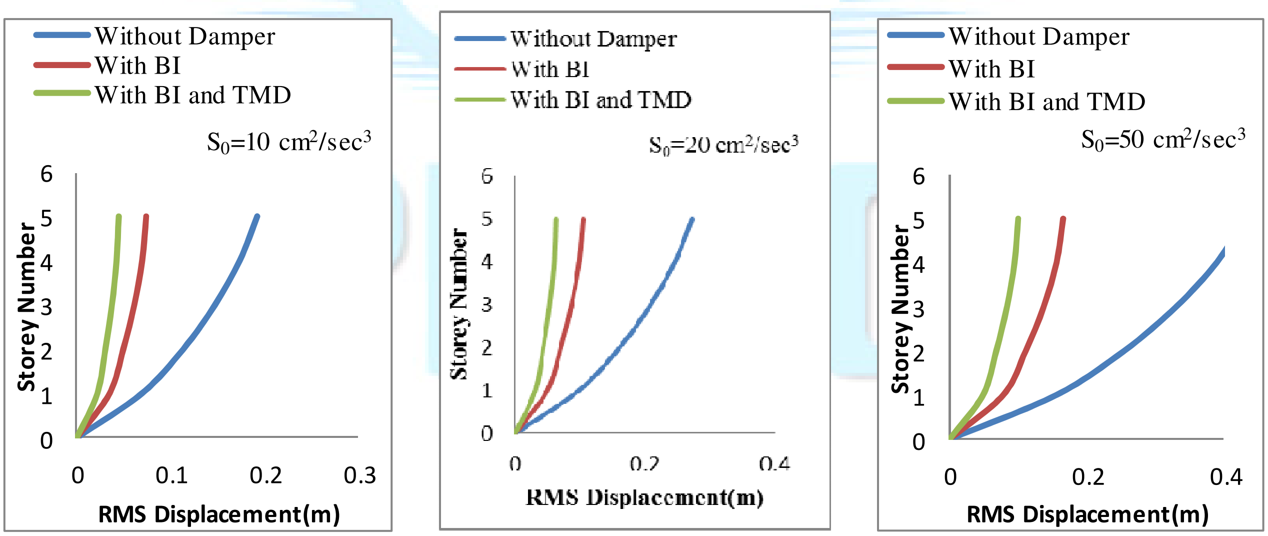

Fig.4 Variation of RMS Displacement of structure with number of story for different earthquake load, $S_0\left(cm^2/sec^3\right)$ and damping ratio of structure $\xi_s = 3\%$

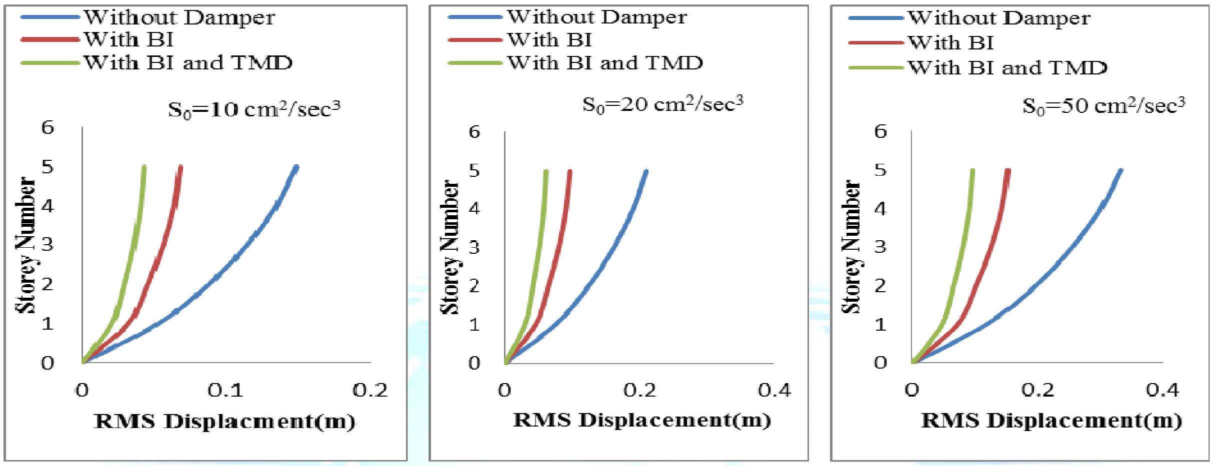

Fig.5 Variation of RMS Displacement of structure with number of storeys for 5% damping ratio of structure and different values of S_0 (cm^2/sec^3)

The variations of RMS displacement of structure with different number of storeys are shown in Fig.4 and 5 for different earthquake load and 3% damping of structure. From these figures, it is seen that the RMS displacement reduction is more at the different storey level using BI system along with TMD with compared to the structure with BI system for 3% and 5% damping ratio of structure considering different earthquake load.

The variation of top floor RMS displacement with different intensity of earthquake load for 1%, 3% and 5% damping ratio of structure is shown in Fig.6. It is seen that the RMS displacement increases with increasing values of earthquake load. It is also observed that RMS displacement decreases with increasing value of damping ratio of structure, ξ_s.

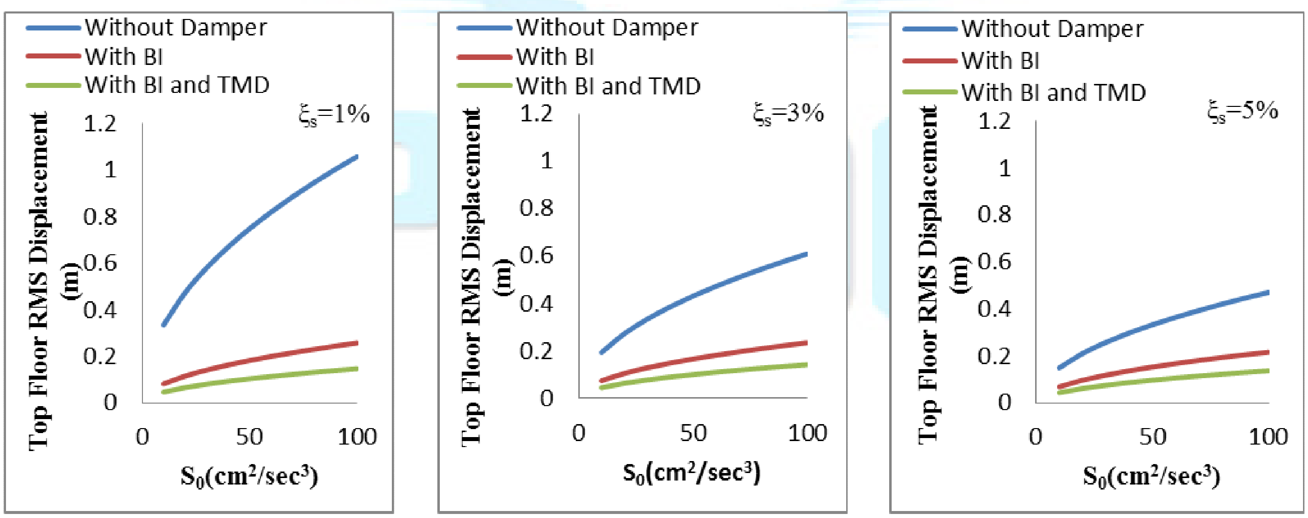

Fig.6 Variation of RMS Displacement of top floor of primary structure with earthquake load for different damping ratio of structure, ξ_s

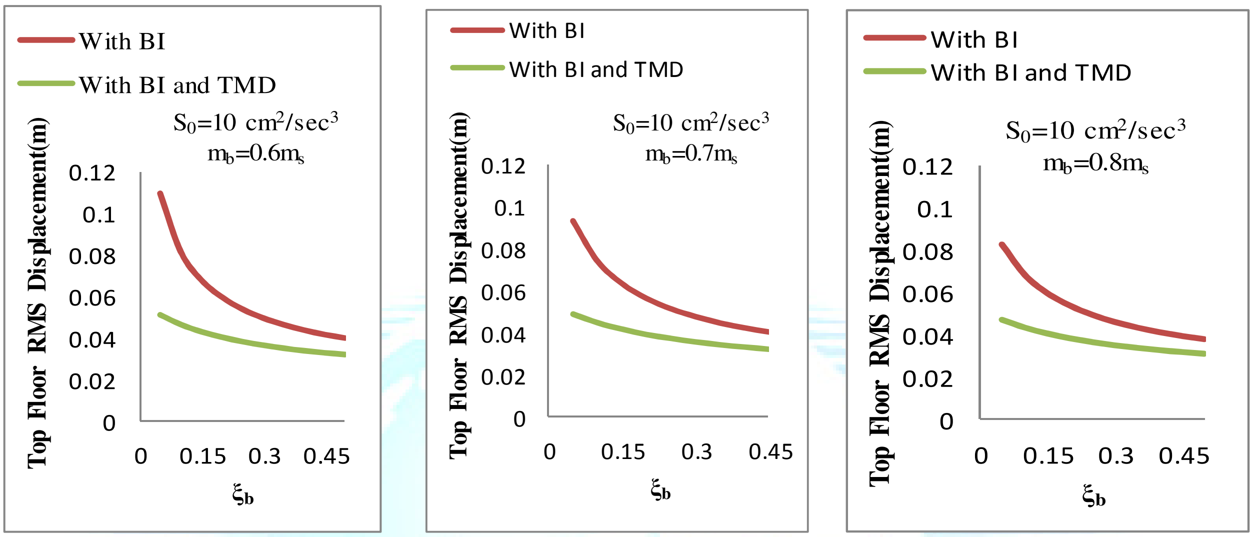

Fig.7 Variation of RMS displacement of top floor with damping ratio of base isolator , ξ_b for different mass ratio of base isolator and 1% damping ratio of structure, ξ_s and earthquake load, $S_0 = 10 cm^2 / sec^3$

The variations of RMS displacement of top floor for different damping ratio of the base isolator, ξ_b for 1%, 3% and 5% damping ratio of structure, ξ_s are shown in Figs.7, 8 and 9 considering three different mass ratios of base isolator. From these Figs. it is observed that RMS displacement decreases with increase in the damping ratio of base isolator. It is also observed that further RMS displacement reduces for base isolated structure along with TMD. RMS displacement decreases with increasing mass ratio of base isolator for all damping ratio of structures.

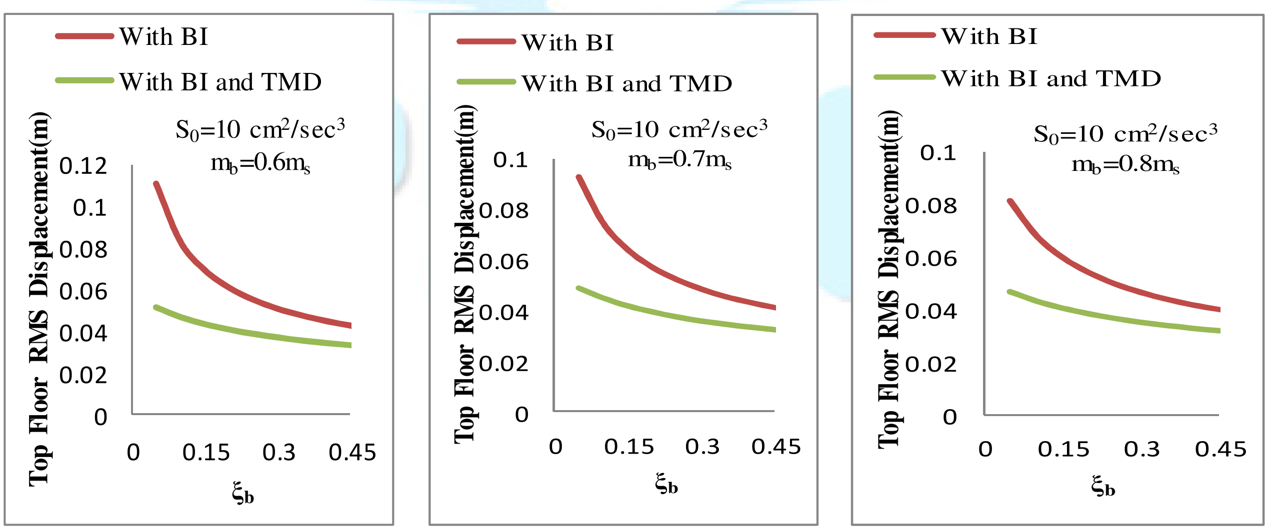

Fig.8 Variation of RMS displacement of top floor with damping ratio of base isolator, ξ_b for different mass ratio of base isolator and 3% damping ratio of structure, ξ_s and earthquake load , $S_0 = 10 cm^2 / sec^3$

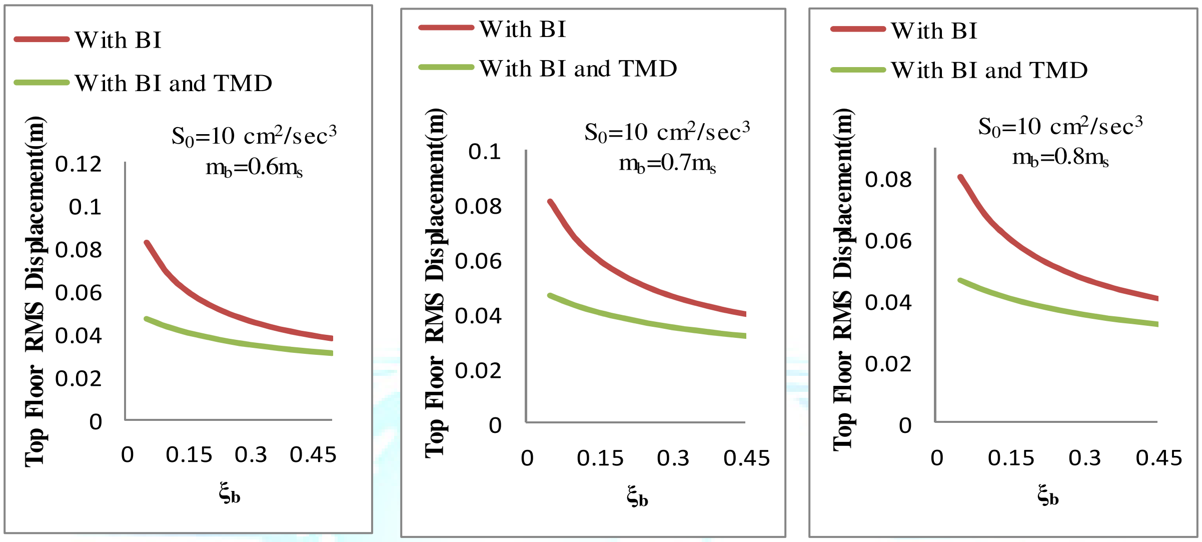

Fig.9 Variation of RMS displacement of top floor with damping ratio of base isolator, ξ_b for different mass ratio of base isolator and 5% damping ratio of structure, ξ_s and earthquake load , $S_0 = 10 cm^2/sec^3$

The variations of percentage reduction in RMS displacement with damping ratio of structure for different earthquake load are shown in Fig.10. The percentage reduction of RMS displacement increases with smaller value of damping ratio of structure for base isolated structure and as well as base isolated structure along with TMD. The percentage reduction is more for combined system compared to BI system.

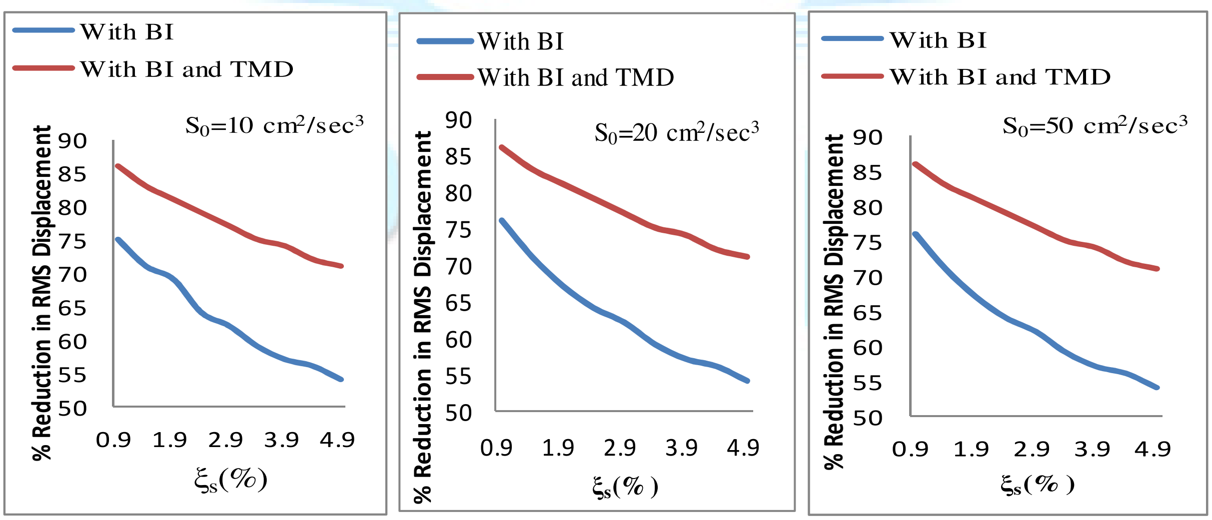

Fig.10 Variation of percentage reduction in RMS displacement with damping ratio of structure for different earthquake load

5. Conclusions

The performance of base isolated structure along with tuned mass damper is investigated in the present study. The parametric study is conducted to observe the influence of several parameters like, damping ratio of structures, intensity of earthquake load, mass ratio, and damping ratio of base isolator, on the effectiveness of combined system in comparison with BI system. It is observed that RMS displacement reduces for base isolated and base isolated along with tuned mass damper with increasing values of damping ratio of structure. But, RMS displacement increases with power spectral density function of white noise increases for all damping ratio of structure. It is observed that the reduction of RMS displacement is more for base isolated structure along with tuned mass damper with compare to base isolated structure. It is also seen that RMS displacement decreases with increases the damping ratio of base isolator for all mass ratio of base isolator. But, percentage reduction in RMS displacement is more for smaller damping ratio of structure for different earthquake load.

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