13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2325

SEISMIC EFFECTIVENESS OF TUNED MASS DAMPER (TMD) FOR DIFFERENT GROUND MOTION PARAMETERS

Dr. Mohan M. Murudi[1]
Mr. Sharadchandra M. Mane[2]

ABSTRACT

Tuned Mass Damper (TMD) has been found to be most effective for controlling the structural responses for harmonic and wind excitations. In the present paper, the effectiveness of TMD in controlling the seismic response of structures and the influence of various ground motion parameters on the seismic effectiveness of TMD have been investigated. The structure considered is an idealized single-degree-of-freedom (SDOF) structure characterized by its natural period of vibration and damping ratio. Various structures subjected to different actual recorded earthquake ground motions and artificially generated ground motions are considered. It is observed that TMD is effective in controlling earthquake response of lightly damped structures, both for actual recorded and artificially generated earthquake ground motions. The effectiveness of TMD for a given structure depends on the frequency content, bandwidth and duration of strong motion, however the seismic effectiveness of TMD is not affected by the intensity of ground motion.

INTRODUCTION

Structural vibrations are caused due to dynamic excitations. Traditional methods of design for strength alone do not necessarily ensure that the structure will respond dynamically in such a way that the comfort and safety of the occupants is maintained, thus losing their relevance and are becoming economically non-viable. Many researchers have made efforts to find some alternate method to control the structural response to manageable levels for economical design for earthquake. One such controlling method, which is being currently investigated, is the use of Tuned Mass Damper (TMD).

TMD is a viscous spring-mass unit, when attached to a vibrating main structure, provides a frequency dependant hystersis that increases the damping in the structure. The efficiency of TMD for controlling structural response is sensitive to its parameters i.e. mass, frequency, and damping ratio. TMD acts as a secondary vibrating system when connected to primary vibrating system. When TMD is tuned to frequency close to natural frequency of structure, vibration of structure makes TMD to vibrate in resonance, dissipating maximum vibration energy through damping in damper and also due to relative movement of damper with respect to the structure. The main advantages of TMD are, they are inherently stable and guaranteed to work even during major earthquakes. In addition TMD is attractive as it dissipates a substantial amount of vibration energy of main structure without requiring any connection to ground. Many TMDs have been successfully implemented worldwide for wind response control in buildings, chimneys and towers (Akita, Japan et al. 1994).

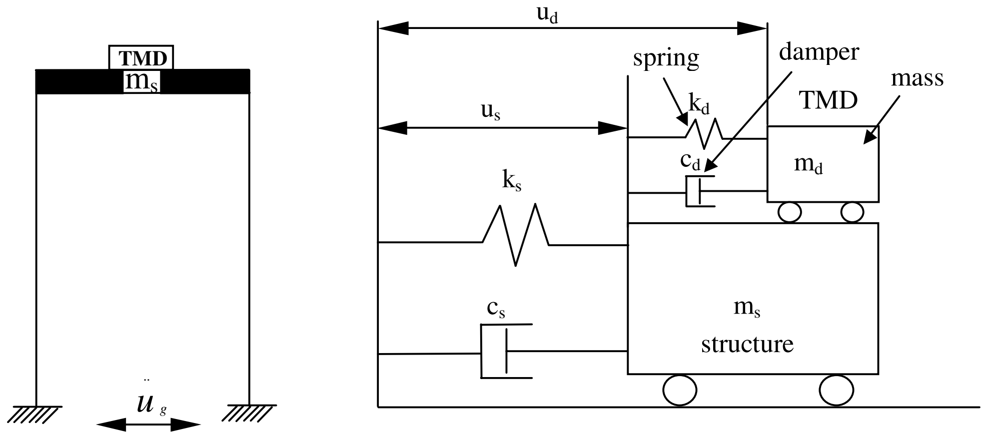
This paper mainly focuses on effect of ground motion parameters namely intensity of ground motion, central frequency, bandwidth of ground motion, duration of strong motion on the effectiveness of TMD and its optimum parameters. For this purpose various ground motions having different ground motion parameters have been considered. The TMD is modeled as a mass with spring and damper, attached to SDOF structure, and thus the combined system together acts as two degrees of freedom system.

1.Professor, Department of Structural Engineering, Bhartiya Vidya Bhavan's Saradar Patel College of Engineering, Munshi Nagar, Andheri (West), Mumbai, India- 400 058.

2Lecturer, Department of Civil Engineering, Mahatma Gandhi Mission's College of Engineering and Technology, At Jun. of NH_4 and Sion Panvel Expressway, Kamothe, Navi Mumbai-410209

GOVERNING EQUATION OF MOTION

TMD- structure interaction model is a single degree of freedom (SDOF) structure with TMD attached to it as shown in fig. 1b. Thus the combined system is a two-degree of freedom system as shown in fig. 1b.



(a) Structure with TMD **(b) TMD-structure interaction model**

Fig. 1. Schematic layout of TMD and TMD-structure interaction model

The equation of motion for combined system is therefore written as

$$m\ddot{u} + c\dot{u} + ku = -m \underset{\approx}{l}\, \ddot{u}_g \qquad (1)$$

Where m, c and k are mass, damping and stiffness matrices of the whole system, respectively. $\underset{\approx}{l}$ is the influence vector and is taken as unit vector for the present case. The structure damping coefficient is given by $c_s=2\varphi_s \varpi_s m_s$ in which φ_s is the structural damping ratio and ϖ_s is the structural frequency. For harmonic base excitation $\ddot{u}_g = \ddot{u}_{g0} \sin \omega_e t$, where ϖ_e is the excitation frequency and $\ddot{u}_{go}$ is the ground motion amplitude, and for earthquake ground motion, $\ddot{u}_g = a_g(t)$ where $a_g(t)$ is the ground acceleration. The above equation is solved using central difference method. The time steps are chosen so as to ensure numerical stability.

OPTIMUM TMD PARAMETERS

The parameters of TMD are :

- Frequency ratio ($f= \omega_d/\omega_s$):

It is defined as the ratio of natural frequency of TMD to natural frequency of the structure.

- And damper damping ratio ($\xi_d= c_d /(2.\omega_d.m_d)$

Where,
m_d=mass of damper,
c_d= damper damping coefficient,
ω_d=Natural frequency of damper,
ω_s=Natural frequency of structure.

TMD parameters are found using minimax optimization technique proposed by Tsai and Lin.

MINIMAX TECHNIQUE:

This technique to determine the optimum values of f and ξ_d for the specified ξ_s and μ is an iterative numerical search. For a fixed value of f, the maximum amplitudes for different values of ξ_d are found. Then the minimum values are selected from the maximum amplitudes of response, which is the minimax amplitude for that value of f. Then the above procedure is repeated for different values of f to find the minimax value of each f. Finally, the smallest minimizes are selected and corresponding f and ξ_d are the optimum parameters of the system having specified mass ratio and structural damping.

INFLUENCE OF GROUND MOTION PARAMETERS:

A set of twenty artificial accelerograms is generated using the software PSEQGN, from the time-modulated Kanai-Tajimi spectrum by defining particular values of its frequency parameters ω_g and damping parameter ξ_g. The filter parameters and shaping function time parameters for these sets of ground motions are given in table 2. Total eight sets of artificial accelerograms have been generated in order to study effect of ground motion parameters on the effectiveness of TMD and its parameters.

Effect of Central Frequency of Ground Motion:

The central frequencies considered are $\varphi_g = 1.5\pi$, 2.0π and 3.0π rad/sec. It can be observed from table 3, the TMD is more effective for the structures whose frequency is in the close vicinity of the central frequency of the ground motion. Around the central frequency of ground motion, the TMD effectiveness increases as the central frequency of ground motion increases. TMD is even more effective significantly for higher damping ratio of 5 percent, when the structure frequency is close to the central frequency of the ground motion. It is to be noted that TMD is most effective for high frequency ground motion. Figure 2 shows mean pseudo-acceleration response spectra for ground motions with different central frequencies for two percent structural damping.

Effect of Frequency Bandwidth of Ground Motion:

Three sets of ground motion having different bandwidth parameters were generated, keeping other parameters constant (The central frequency being taken as 2π.). The different bandwidth parameters considered are ξ_g=0.2 (narrow banded), ξ_g =0.4 (medium banded) and ξ_g =0.6 (broad banded). From table 4, it can be seen that for broad-banded motions, the TMD is effective over a broad spectrum of structural frequencies, whereas for narrow-banded ground motion the TMD is effective only if the structural frequency is in the vicinity of the ground motion central frequency. The reason for the above behavior can be traced to the fact that the narrow-banded ground motion tends towards a harmonic ground motion, for which the TMD is only effective if the structure, TMD and the excitation frequencies are very close to each other. However it should be noted that for structures with natural frequencies in the vicinity of the ground motion central frequency, the effectiveness of the TMD increases as the bandwidth of the ground motion decreases. Figure 3 shows mean pseudo-acceleration response spectra for ground motions with different frequency bandwidth for two percent structural damping.

Effect of Duration of Stationary Intensity of Ground Motion:

Two different sets of ground motions with different values of duration of stationary intensities (t_{sd}) are considered keeping other parameters constant (The central frequency being taken as 2π.). One set is having t_{sd}=11 sec while the other set is having t_{sd}= 4 sec. From the results shown in table 5, it can be seen that for relatively short period structures, the duration of stationary intensity of ground motion does not have significant effect on the performance of TMD. However, for relatively long period structures, the effectiveness of TMD is more for the ground having longer duration of strong motion. This may be because, in case of ground motion with short duration of strong motion, the short period structures get a chance to vibrate for at least a few cycles within the strong motion duration, while for longer period structures, the 4-second strong motion duration is like a pulse-type motion. When structure vibrates in resonance with ground motion, it can be seen that the percentage reduction in different responses is same for both the types of ground motions i.e. effectiveness of TMD doesn't get affected. Figure 4 shows mean pseudo-acceleration response spectra for ground motions with different duration of strong motion for two percent structural damping.

Effect of Intensity of Various Ground Motion:

To study the effect of intensity of ground motions, three different sets of ground motions with varying intensities were generated, keeping other parameters constant (The central frequency being taken as 2π). The peak ground accelerations considered for these motions are 0.35g, 0.5g and 1.0g. On observing table 6, it is very clear that the value of intensity of ground motion doesn't affect the effectiveness of TMD. It can also be seen that, for a particular structure, the percentage reduction in structural response remains same irrespective of intensity of ground motion. This may be because the reason that for all these sets of ground motions, the value of central frequency is kept constant. Figure 5 shows mean pseudo-acceleration response spectra for ground motions with different intensities for two percent structural damping.

TABLE 2. Filter parameters and shaping function time parameters for various sets of artificially generated ground motions

Set No.	ω_g (rad/s)	ξ_g	ti (s)	t_{sd} (s)	t_d (s)	PGA
I	2π	0.4	2	11	30	0.35
II	1.5π	0.4	2	11	30	0.35
III	3π	0.4	2	11	30	0.35
IV	2π	0.2	2	11	30	0.35
V	2π	0.6	2	11	30	0.35
VI	2π	0.4	2	4	30	0.35
VII	2π	0.4	2	11	30	0.5
VIII	2π	0.4	2	11	30	1.0

TABLE 3. Effectiveness of TMD for different central frequencies of ground motions

Structural Properties		Central frequency of ground motion		
Tn (s)	φ_s (%)	ω_g=1.5π	ω_g=2.0π	ω_g=3.0π
		% Reduction in a_{max}	% Reduction in a_{max}	% Reduction in a_{max}
0.67	2	22.77	24.10	29.61
	5	15.13	18.17	25.07
1.00	2	23.14	25.88	26.41
	5	17.41	22.02	22.96
1.50	2	25.83	23.98	23.55
	5	24.40	21.27	21.03

TABLE 4. Effectiveness of TMD for different bandwidth of ground motion

Structural Properties		Bandwidth of ground motion		
Tn (s)	φ_s (%)	φ_g=0.2	φ_g=0.4	φ_g=0.6
		% Reduction in a_{max}	% Reduction in a_{max}	% Reduction in a_{max}
0.50	2	15.12	21.66	24.49
	5	8.30	13.91	17.70
1.00	2	31.10	25.88	27.84
	5	26.66	22.02	23.80
2.00	2	16.90	18.74	18.05
	5	14.50	17.40	16.43

TABLE 5. Effectiveness of TMD for different duration of stationary ground motion

Structural Properties		Duration of stationary ground motion	
Tn (s)	φ_s (%)	t_{sd} = 11sec	t_{sd} = 4 sec
		% Reduction in a_{max}	% Reduction in a_{max}
0.50	2	21.66	18.91
	5	13.91	11.86
1.00	2	25.88	25.76
	5	22.02	24.88
2.00	2	18.74	13.32
	5	17.40	13.28

TABLE 6. Effectiveness of TMD for different peak ground acceleration

Structural Properties		Peak Ground Acceleration		
Tn (s)	φ_s (%)	PGA=0.35g	PGA=0.5g	PGA=1.0g
		% Reduction in a_{max}	% Reduction in a_{max}	% Reduction in a_{max}
0.50	2	21.66	21.78	22.25
	5	13.91	14.16	14.51
1.00	2	25.88	27.20	26.88
	5	22.02	23.23	22.90
2.00	2	18.74	17.64	17.69
	5	17.40	16.12	15.87

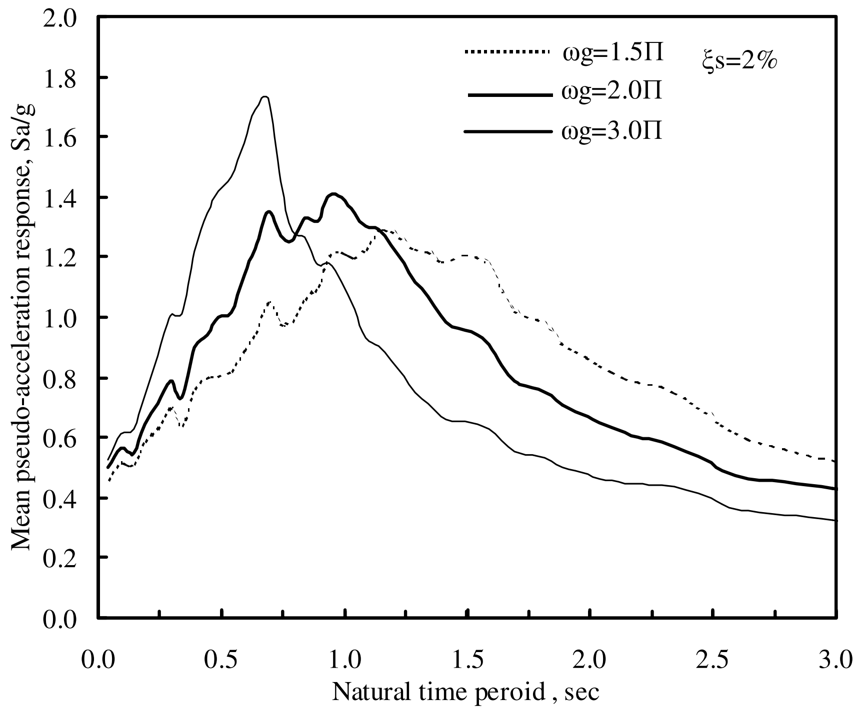


Fig.2 Mean pseudo-acceleration response spectra for ground motions with different central frequencies

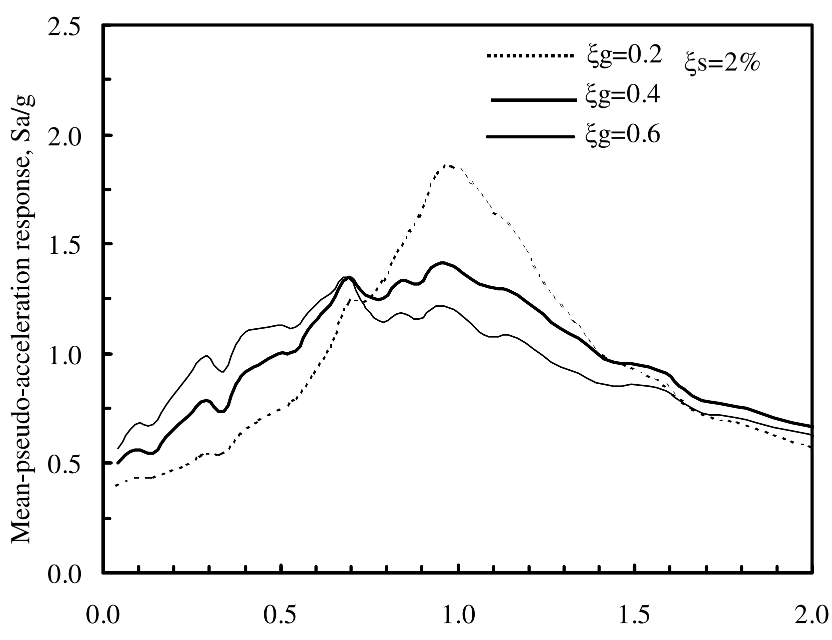


Fig. 3 Mean pseudo-acceleration response spectra for ground motions with different frequency bandwidth

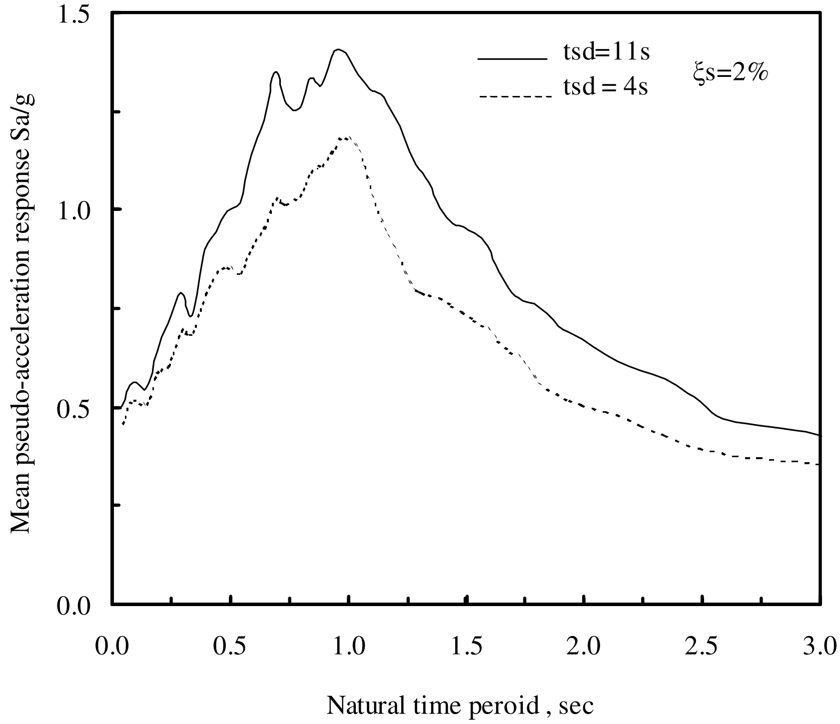


Fig. 4 Mean pseudo-acceleration response spectra for ground motions with different duration of strong motion

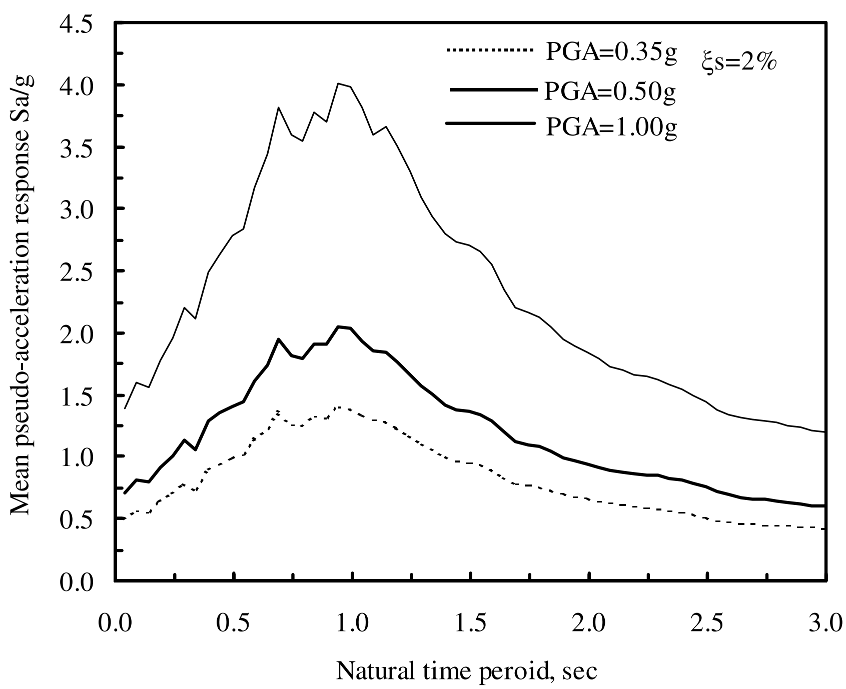


Fig. 5 Mean pseudo-acceleration response spectra for ground motions with different intensities

MAJOR CONCLUSIONS:

- TMD is effective for controlling structural response to harmonic base excitation.
- TMD is most effective for lightly damped structure, and its effectiveness decreases as with increase in structural damping.
- TMD is more effective for long duration earthquake ground motions.
- TMD is most effective when the structural frequency is close to the central frequency of ground motion.
- TMD is reasonably effective for broad banded motions across the spectrum of structural frequencies. However, TMD is also effective for narrow banded motions, if the structure and ground motion frequencies are close to each other.
- Effectiveness and optimum parameters of TMD does not get affected with increasing peak ground acceleration values, keeping all other parameters constant.

REFERENCES:

1) Amir M. Kaynia, Daniele Veneziano and John M. Biggs(1981)," Seismic effectiveness of Tuned Mass Dampers", Journal of the Structural Division, Vol.107, pp1466-1483
2) John R. Sladek and Richard E. Klinger(1982),"Effect of Tuned Mass Dampers on Seismic Response", Journal of the Structural Division, Vol.109, pp 2004-2009.
3) Fahim Sadek, Bijan Mohraz, Andrew W. Taylor and Riley M. Chang (1997)," A Method of Estimating the Parameters of Tuned Mass Dampers for Seismic Applications", Journal of Earthquake Engineering and Structural Dynamics, Vol.26, pp 617- 635.
4) Rahul Rana and T. T. Soong(1998)," Parametric Study and Simplified Design of Tuned Mass Dampers", Journal of Earthquake Engineering and Structural Dynamics, Vol.20, pp 193-201.
5) Hsiang-Chuan Tsai and Guan-Cheng Lin(1993)," Optimum Tuned Mass Damper for Minimizing Steady State Response of Support-Excited and Damped System", Journal of Earthquake Engineering and Structural Dynamics, Vol. 22, pp 957-973, year 1993.
6) Robet J. McNamara(1997)," Tuned Mass Dampers for Buildings", Journal of the Structural Division, Vol.103, pp 1785-1797.
7) Anil K. Chopra(1995)," Dynamics of Structures-Theory and Applications to Earthquake Engineering", Prentice Hall of India Private Ltd.