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EFFECTIVENESS OF MULTIPLE TUNED LIQUID DAMPERS IN SEISMIC RESPONSE MITIGATION OF ISOLATED BUILDING

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Abstract

This article presents the effectiveness of multiple tuned liquid dampers (MTLDs) for seismic response mitigation of a reinforced concrete (RC) base isolated (BI) building. The performance of MTLDs is compared with the tuned mass dampers (TMDs) and with a swimming pool designed as a tuned liquid dampers (TLDs). The three schemes are installed at the top of the BI building. Equations of motion for the BI building controlled by these three schemes are solved by numerical approach. The BI buildings with and without TMD and TLD schemes are subjected to earthquake ground motions. Top floor acceleration and bearing displacement are determined for the BI building with and without TMD and TLD schemes while subjected to earthquake ground excitations. It is noticed that that vibration mitigation of BI building is achieved by installing TMD and TLDs schemes as the frequency amplitudes of the acceleration magnitudes have significantly reduced. To be noted that the MTLDs is more effective as compared to the TMD and is similar to a TLD to mitigate the seismic response of BI building. The TLD schemes observed to have a much lower value for frequency tuning ratio as compared to the TMD scheme which is close to 1.

Keywords: Base isolated building; Tuned mass damper; Tuned liquid damper; Multiple tuned liquid damper

1. Introduction

1.1 Base Isolation system

The first patent to the base isolation of civil structures was presented by Kelly [1]. Earlier the layer of soft mud was used as a cushion to absorbs the shocks of earthquake as acted as base isolation [2]. Later, some example of use of rubber as base isolation are applied in Skopje, Macedonia [3]. However, the rubber block was bulge in sideway due to weight of structure.

The base isolation method is a technique developed to prevent or minimize damage to the building during the earthquake. The main use of isolation system is to decrease the acceleration, base reactions and member forces in the structure. The isolation can be done by use of various technique like rubber bearing, friction bearing, ball bearing, springs system and other means. The base isolator bearings were developed in New Zealand by Robinson during 1970 (see Figure 1). The most suitable condition for base isolation is to be used for low to medium rise building rested on the hard soil underneath.

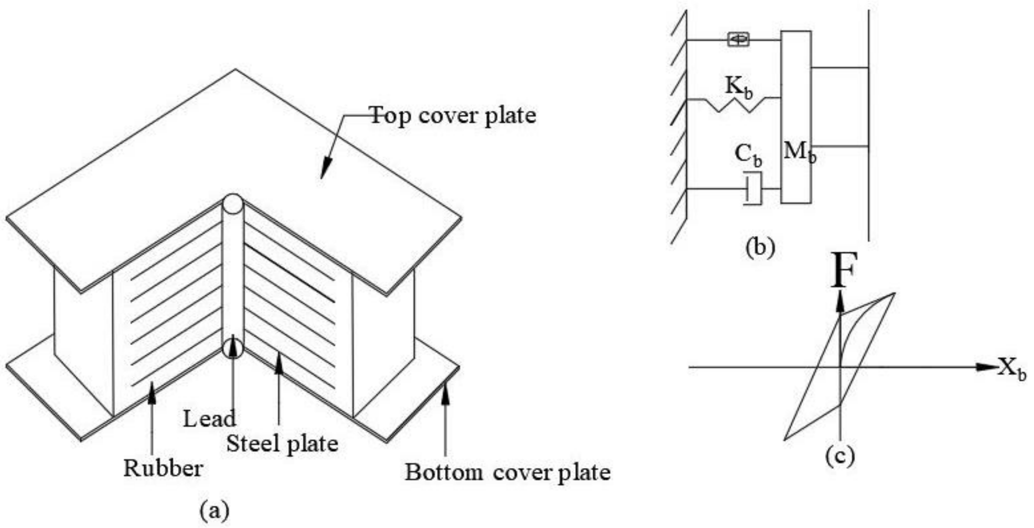


Fig 1. NZ bearing system (a)Section and element (b)Analytical model (c)Force deformation

1.2 Tuned mass damper

Tuned mass dampers (TMDs) are (attached to the upper node of a structure) passive dampers to control the response and prevent the discomfort to the occupant. It is primarily used to control the vibration of the structure. It is well understood that TMDs impact the vibratory characteristics only in the range of their own frequency i.e. they can suppress only a specific mode and the tuning is very important for their efficiency [4]. TMDs are suitable only when the structure responds significantly in one mode. These dampers occupy large space at the top of the building. Therefore, instead of single TMD, multiple small TMD's along the height of structure can be installed. These TMD's can also take care of the response of the structure due to higher mode. If the one damper is not working properly then remaining will control the response of the structure.

Tuan and Shang [5] performed an analysis to find out the effects of a TMD on the structural dynamic response of Taipei 101Tower. A detailed dynamic analysis is conducted to evaluate the behavior of the Structure-TMD system, and the TMD was found effective in reducing the wind induced vibration. Stanikzai et al. [6] had performed the seismic analysis of the base isolated building using single TMD, multiple TMDs under real earthquake excitations. The five, ten and fifteen story building was taken for the study with single TMD at the top of the building, multiple TMDs at the top and bottom of the building. The building was isolated using LRB, NZ, FPS and R-FBI isolation. The installation of MTMD at the top is effective to reduce the top floor acceleration as compare to the installing the STMD. The performance of the MTMD is more effective in case high rise buildings.

1.3 Tuned liquid damper

Tuned liquid dampers (TLDs) have been used in anti-rolling tanks for stabilizing marine vessels during the period of 1950s. In the late 1970s TLD has started to be used in the field of civil engineering. Bauer [7] is the first to propose the damping device consisting of a liquid. Fuji [8] have found that reduction in the vibration of Nagaski Airport Tower and Yokohama Marine Tower (height 101m) by half upon installation of the Tuned sloshing damper. Sun [9] developed an analytical model for TLD, based on shallow water wave theory. Wakahara et al. [10] carried out the theoretical and experimental studies to design an optimum TLD and verified the TLD with actual application to the Shin Yokohama Prince Hotel in Yokohama. The interaction model considered by them was based on the boundary element method. Koh [11] have done numerical studies to investigate the effect of use of number of liquid damper tuned to the different vibration frequencies of multi degree of freedom structure. The results show it is effective to use dampers tuned to several vibration modes of the structure. Numerically, they concluded that, effectiveness of the dampers is dependent on the frequency content of the earthquake spectrum and the placement of the dampers. Yu et al. [12] proposed a solid mass damper model which they referred as non-linear-stiffness-damping (NSD) model, for the TLD with non-linear stiffness and damping. They calibrated that the non-linear characteristics of the NSD model from shaking table experiment. It is an expansion of TMD. Tait [13] had developed an equivalent linear mechanical model that account for the energy dissipated by the damping screens. An equivalent linear damping ratio expression were developed for both sinusoidal and random excitation. The equivalent linearized damping ratio was found to depend on the response amplitude of the TLD, water depth, tank length, damping screen location and damping screen loss coefficient. Experimental tests were conducted on a scaled model structure-TLD system subjected to the both sinusoidal and random excitation to validate the proposed model. He proposed the TLD design theory with the damping screen.

Tait et al. [14] had conducted a series of experimental test on model scale structure-TLD systems to evaluate the performance of the TLD. The unidirectional and bidirectional tuned liquid dampers were used on the structure and excitation by the random earthquake motion. They developed the performance chart for TLD which provide a method of investigating the influence of various parameter on the efficiency and robustness of a TLD. These charts are useful for initial design of Tuned liquid damper when the precise frequency of the structure is not known. Love and Tait [15] developed an equivalent mechanical model for a structure-MTLD system. MTLD system consist of one (traditional TLD), two or three tanks were used to reduce the resonant response of a single degree of freedom structure. They claimed that it was the first-time non-linear energy dissipation associated with damping screen and non-linear coupling amongst the sloshing mode has been considered for MTLD systems. It was found superior than traditional TLD and found that is more robust to change to the structural natural frequency than the traditional TLD.

1.4 Hybrid System

In recent year, several building and bridge in the seismic region have been equipped with the base isolation system. However, there is large movement of the structure at the base level of the structure. The hybrid base isolation system is one of the solutions of a such problem. Different type of damper was used along with base isolation of the structure to improve the performance during the earthquake and wind induced vibration. Love et al. [16] had investigated TLD as a cost-effective method to reduce the wind induced vibration of the base isolated structure. They found that it was effective and inexpensive method to control wind induced vibration of a two-story base isolated structures. They recommend further work should be done to determine the performance of a hybrid tuned liquid damper-base isolation system which is subjected to the seismic excitation. Shoaei [17] investigated a hybrid structural control system using TLDs and lead rubber bearing (LRB) systems for mitigating earthquake induced vibration. It also accounts the uncertainties associated with the steel shear building. Based on the analysis result, they found that the base displacement can be reduced 23% by average, however, the maximum reduction can go beyond 30%. Matteo et al. [18] used three different type of dampers (TMD, Tuned Liquid Column Damper and New TMD) to mitigate the seismic response of a base-isolated structure. They examine and compare the seismic induced vibration control of base isolated structure equipped with the TMD, TLCD, New TMD and found that new TMD is most effective in controlling the response of the base isolated structures.

2. Mathematical Model

Figure 2 shows the mathematical model for the cases where base-isolated (BI) building is installed by a TLD, TMD or MTLDs.

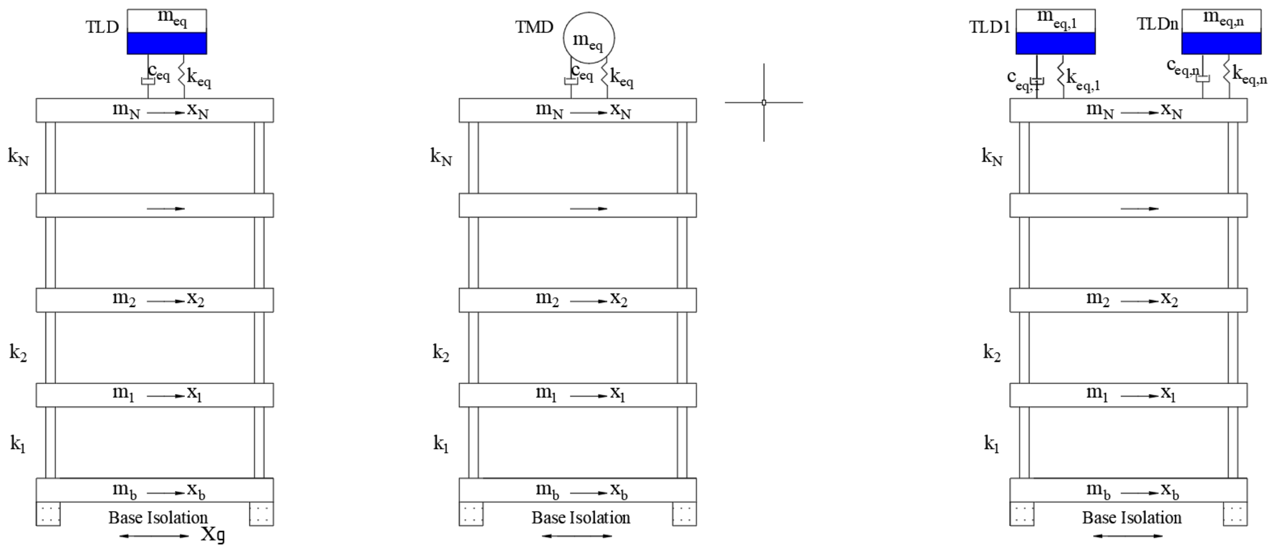


Fig 2.Base isolated building with TLD, TMD and MTLD

The governing equation of motion is

$$[M]\{\ddot{x}(t)\} + [C]\{\dot{x}(t)\} + [K]\{x(t)\} = -[M]\{r\}\ddot{x_g}(t) \quad (1)$$

where [*M*], [*C*] and [*K*] are the mass, damping, stiffness matrix of the building. The total mass of the system is given by

$$M = m_b + \sum_{i=0}^{n} m_i \quad (2)$$

m_b is the mass of the base isolator and m_i is the mass of structure on i[th] floor, x(t), $\dot{x}(t)$and $\ddot{x}$(t) are the unknown relative (isolator, floor, TMD,TLD) displacement, velocity and acceleration vectors, and $\ddot{x_g}$(t) is the earthquake ground acceleration vector. *r* is the vector of influence coefficient.

3.Numerical Study

The time history analysis of the five-story base-isolated building equipped with the TMD, TLD and MTLD is performed. Earthquake ground motion data used to study the performance of the BI building with and without TLD, TMD and MTLD is given in Table 1. The differential equation of motion was solved by using Newmark’s integration method. The time period of the fixed base building was 0.5 second. Properties of the BI system is given in Table 2. Table 3 provides the superstructure properties.

Table 1. Ground motion data

SN	Earthquake	Event	Recording Station	Event	Component	PGA (g)	Duration (s)	Time Step (s)
1	Mexico City	Sept 19,1995	Station 1	Sept 19,1995	180	0.168	180.12	0.02
2	Campano Lucano	Nov 23, 1980	Brienza	Nov 23, 1980	NS	0.222	30.15	0.01
3	Mammoth Lakes	May 25,1980	Convict Creek	May 25,1980	180	0.392	65	0.02

Table 2. NZ system data

SN	Description	
1	Isolation time period (T_b)	2 sec
2	Damping ratio of isolation system (zii)	0.05
3	Weight of the base of the building (m_b)	200 KN
4	Yield displacement of the isolator (q)	5 cm
5	Force (Fo)	0.075 of total weight

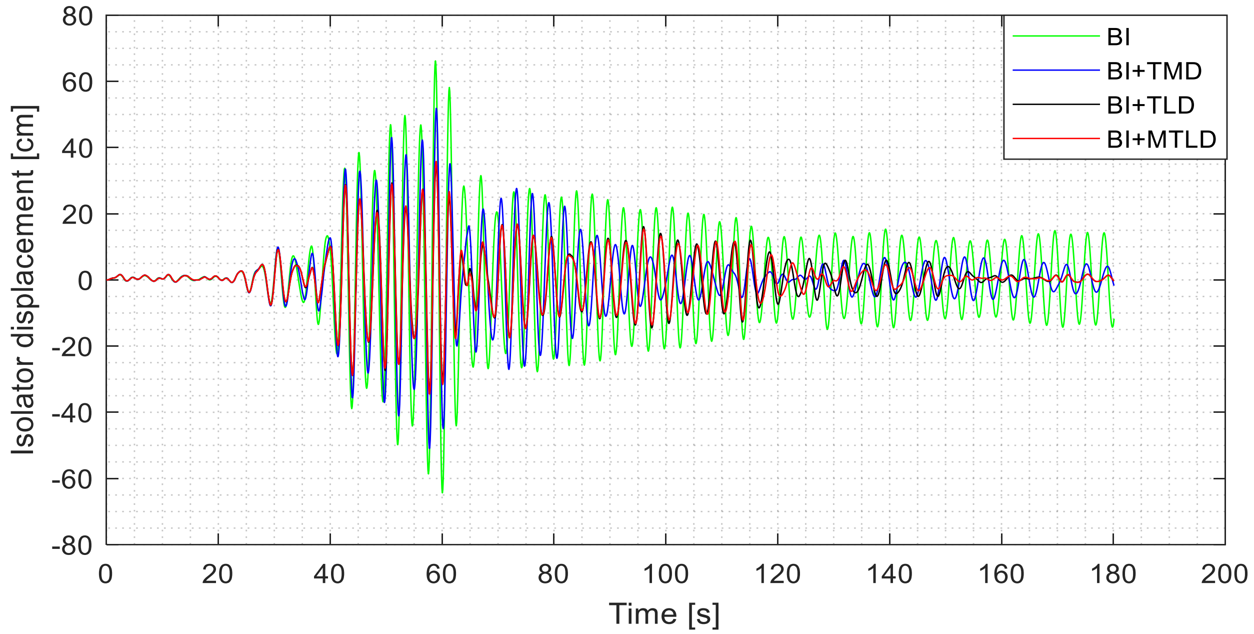
Table 3. Superstructure Data

SN	Description	
1	Number of story	5
2	Superstructure damping ratio	0.02
3	Weight of each floor of the building	200 KN
4	Stiffness of each floor	39700

Table 4. Tuned Liquid Damper parameter

SN	Desxription	TLD	TLD1	TLD 2	TLD3
1	Fluid density (ro) in kg/m^3	1000	1000	1000	1000
2	Length of the tank (TLD_L) m	4.25	3	3	3
3	Height/Depth of the fluid in the tank (TLD_H) m	1.8	0.53	0.67	0.82
4	Width of the tank (TLD_B) m	1.84	1.78	1.78	1.78
5	Screen number	1	1	1	1

Table 4 provides the dimension of the single TLD and multiple TLDs. The dimension of the multiple TLDs is provided in such a way that the total mass of the MTLDs system is equal to the mass of TLD. The tuning frequency of the each MTLD tanks are slightly higher, one is equal and one is slightly less than tuning frequency of the STLD. Figures 3 through 7 are the time history and furrier amplitude (FAS) of the base displacement and top floor acceleration of the base isolated(BI) building, BI with TMD, BI with TLD and BI with MTLD.



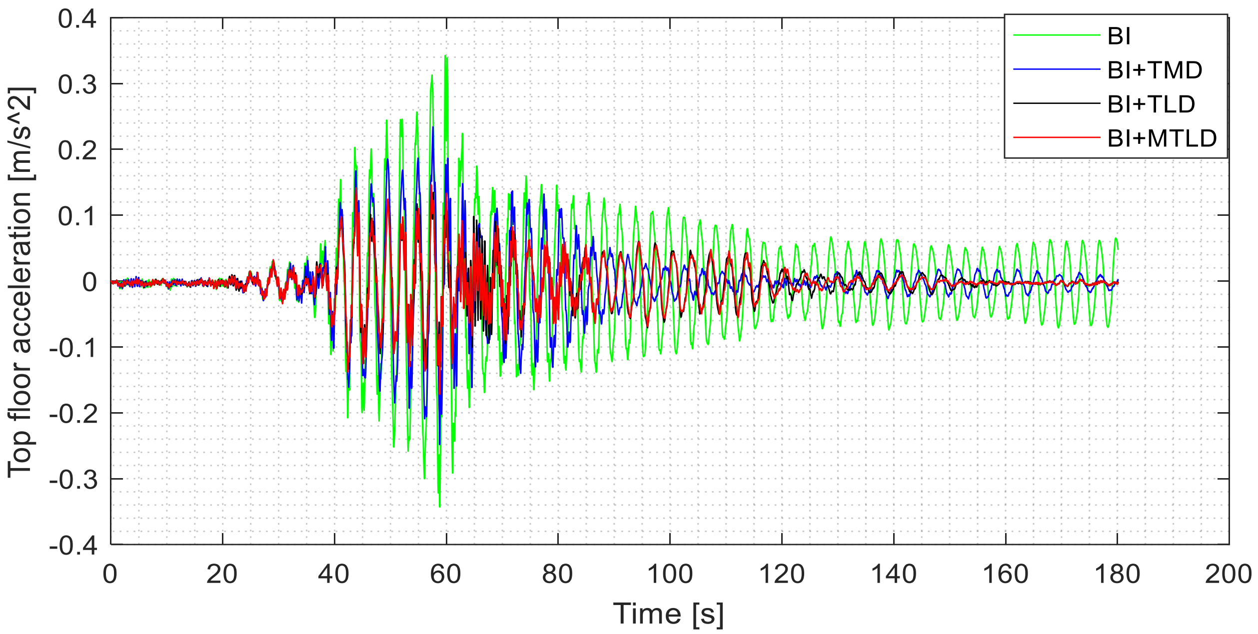


Fig. 3 Time history of the Isolator displacement and top floor acceleration equipped with BI, BI+ under the Mexico city Earthquake

It is observed that the BI building has relatively low acceleration at the top of building, but very large bearing displacement. The TLDs effectively reduce this large displacement demand. The peak bearing displacement of BI, BI + TMD, BI + TLD, and d-MTLDs are, respectively, are given in Table 5. It is observed that the TMD could reduce the displacement by about 25%, whereas, TLD and MTLDs could reduce displacement by up to 50%. It is also evident that this reduction in bearing displacement is not at the cost of amplified acceleration. Maximum acceleration reduction of 37%, 57% and 56% is respectively achieved for TMD, TLD and MTLD. Both TLD schemes are quite the same, however, it is interesting to check their performance while considering the uncertainties in ground motions and as well in structure parameters. However, this is not the focus of this study and requires a detailed investigation in future.

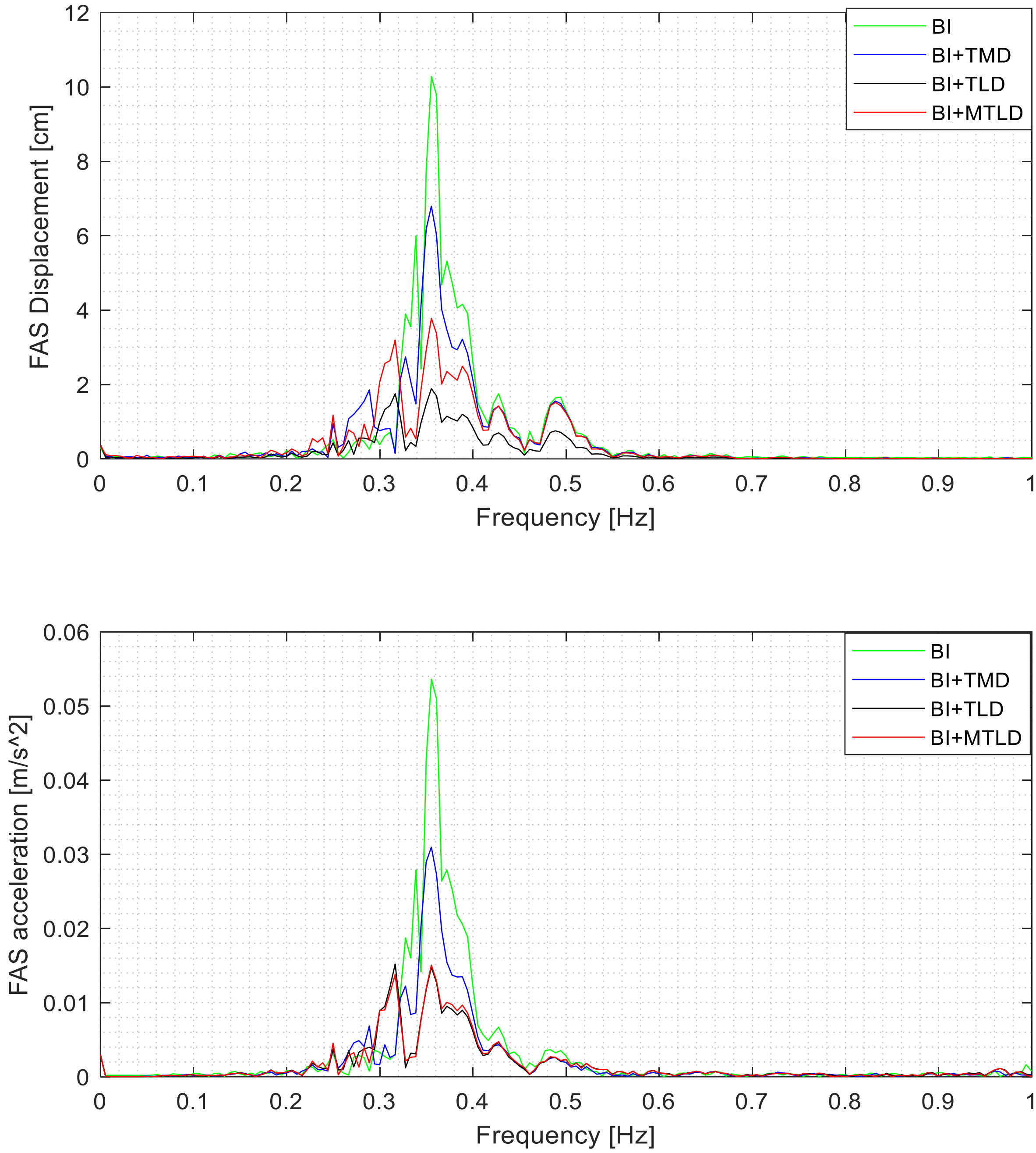


Fig. 4 FAS of the Isolator displacement and top floor acceleration equipped with BI, BI+ under the Mexico city Earthquake

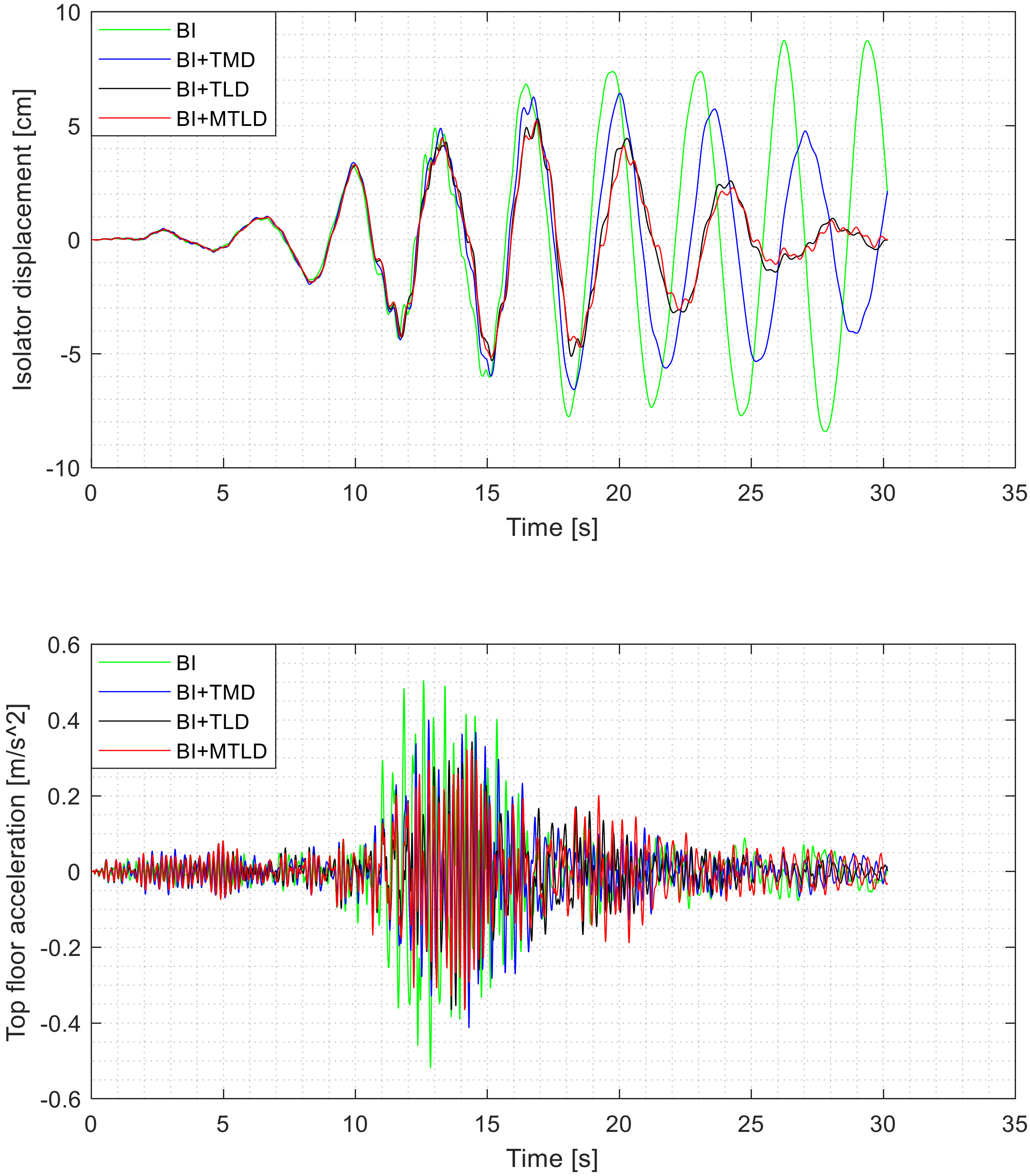
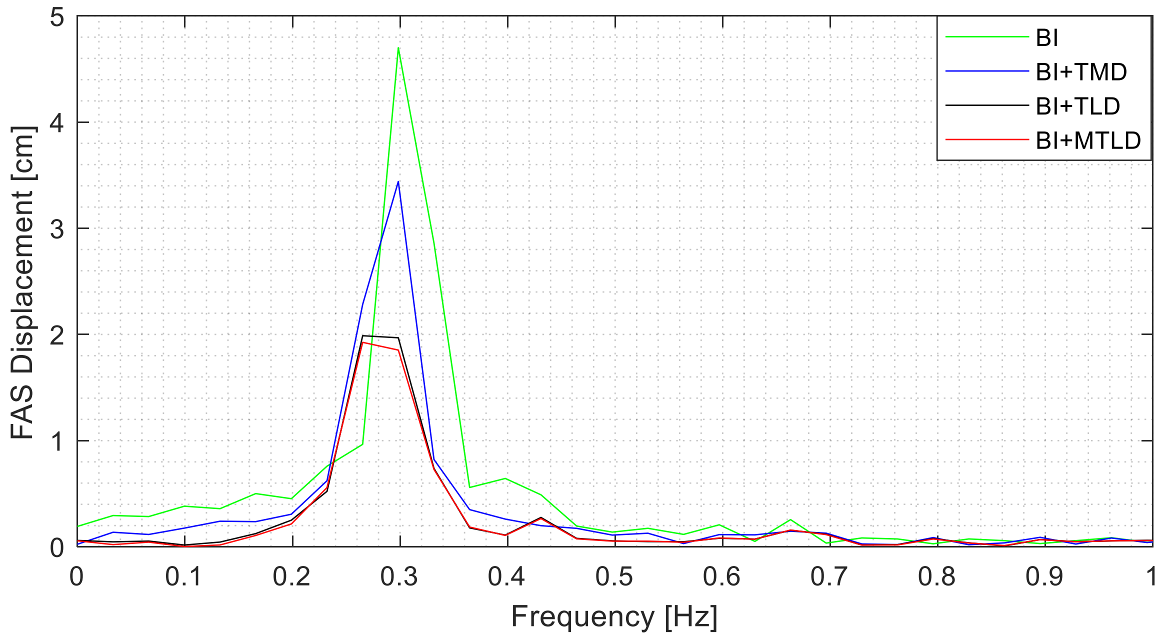


Fig. 5 Time history of the Isolator displacement and top floor acceleration equiped with BI, BI+ under the Campano Lucano Earthquake



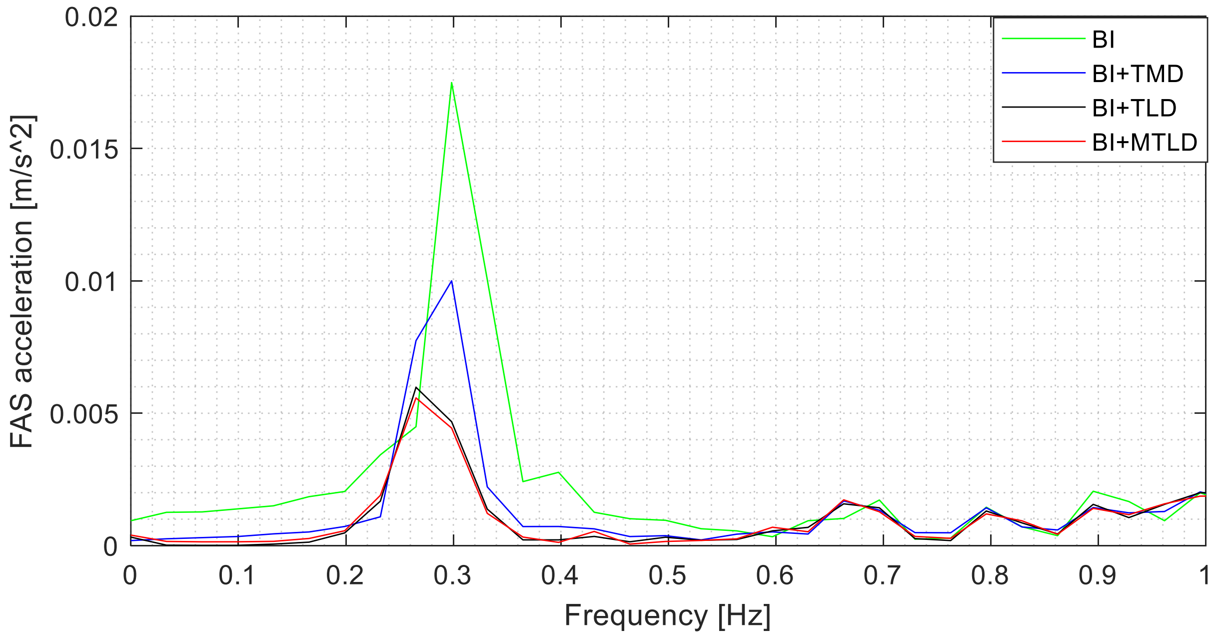
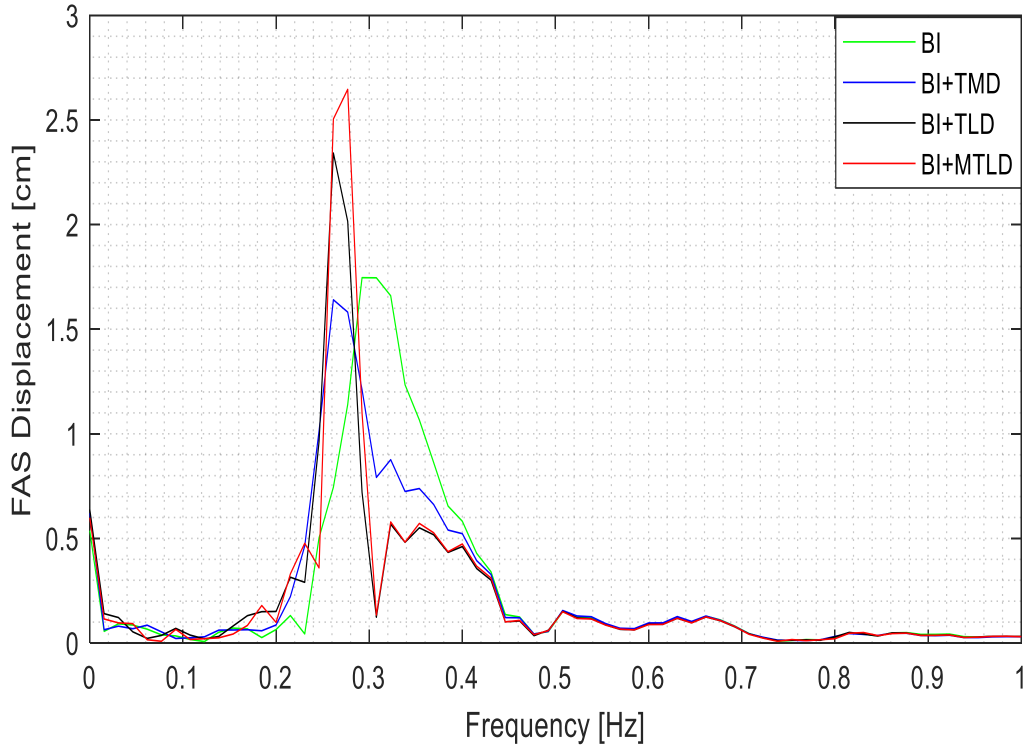


Fig. 6 FAS of the Isolator displacement and top floor acceleration equipped with BI, BI+ under the Campano Lucano Earthquake



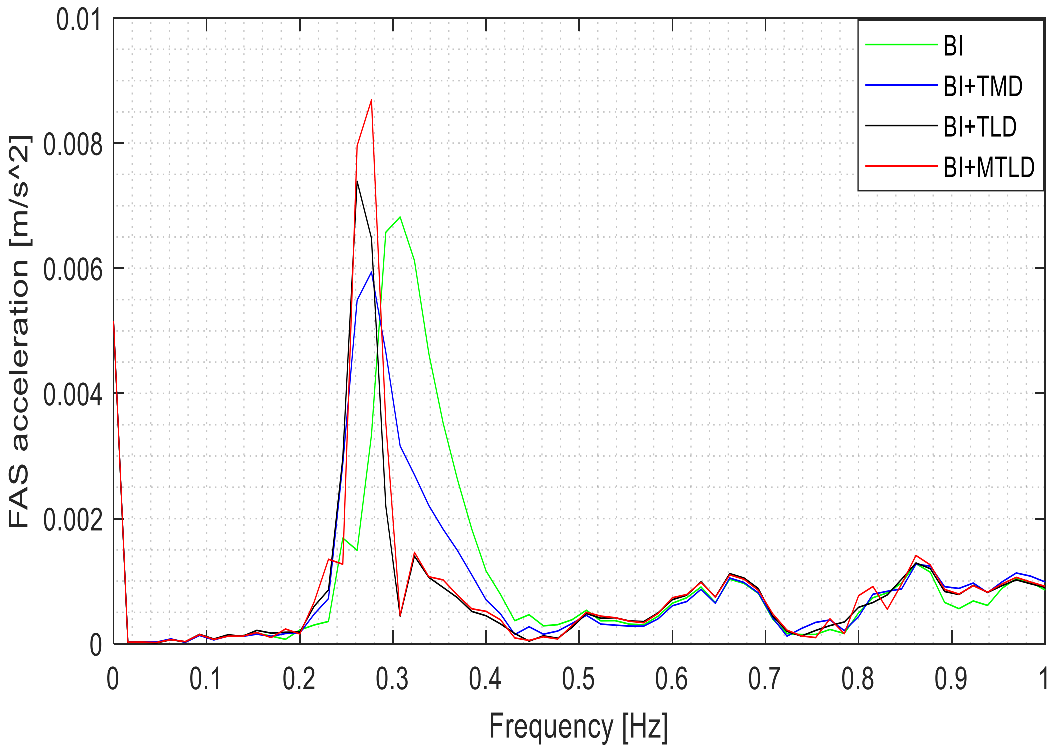


Fig. 7 FAS of the Isolator displacement and top floor acceleration equipped with BI, BI+ under the Mammoth Lakes Earthquake.

Table 5. Peak displacement and acceleration response

SN	Earthquake	Peak Displacement				Peak Acceleration			
		BI (cm)	BI+TMD (cm)	BI+TMD (cm)	BI+MTLD (cm)	BI (m/s/s)	BI+TMD (m/s/s)	BI+TLD (m/s/s)	BI+MTLD (m/s/s)
1	Mexico City	66.2	51.86 (22%)	34.67 (48%)	35.85 (46%)	0.343	0.248 (28%)	0.156 (55%)	0.172 (50%)
2	Campano Lucano	8.75	6.56 (25%)	5.31 (40%)	5.21 (41%)	0.52	0.412 (21%)	0.364 (30%)	0.364 (30%)
3	Mammoth Lakes	10.7	8.98 (16%)	6.96 (35%)	7.156 (33%)	1.09	0.685 (37%)	0.474 (57%)	0.476 (56%)

4. Conclusion

Seismic response mitigation of base-isolated (BI) building installed with a tuned mass damper (TMD), tuned liquid damper (TLD), and multiple TLD (MTLD) are investigated. Numerical analysis of two BI buildings equipped with TMDs is performed using analytical models of 5 10-storey building. Results were analyzed to investigate effectiveness of different TMD schemes in reducing displacement and acceleration demand of the BI structure.

TMD schemes are can be used to control bearing displacement of BI buildings subjected to earthquake ground excitations without compromising the control in acceleration response achieved by BI.

TLD and MTLD are significantly better than a TMD in controlling the bearing displacement of the BI building. The effectiveness of TLD and MTLD are much superior than STMD for mitigating top floor acceleration. The study recommends a detailed investigation for consideration of uncertainties in earthquake ground motions and as well in parameters of the building.

4. Acknowledgements

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5. Copyrights

6. References

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