Lateral Response Reduction of Tall Buildings Using Portal Frame as TMD

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Lateral Response Reduction of Tall Buildings Using Portal Frame as TMD

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Abstract Majority of construction industries are aiming to go for taller and lighter buildings which may result in flexible and slender structures. Hence serviceability and safety become a critical issue during the occurrence of heavy winds and high magnitude earthquakes. Therefore, considerable techniques are adopted to minimize the vibrations caused by these natural responses of the structures. One of the techniques used prominently for tall structures is Tuned Mass Damper (TMD). TMD's have been very effective in controlling structural vibrations. This study proposes a detailed analysis of a 2D frame structure with a TMD system placed at different levels of the structure in order to evaluate the behaviour of structure for given earthquake ground motions. The results obtained indicate installation of simple frames can decrease the response of the structure during an earthquake and location of TMD is also discussed in detail.

Keywords TMD- tuned mass damper · Damping · And vibration control

1 Introduction

A growing population and advancement in technology have led to the evolution of new construction techniques which focuses on alternatives to reduce the damage caused to the structure due to heavy winds and seismic loads. Size and density of the cities influence the height of the building hence taller structures are majorly adopted

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by many of the construction industries. However, taller structures are sensitive to wind and seismic excitations. These excitations can cause large displacements in the structures such that they fail to satisfy the serviceability criteria. Therefore, to reduce these structural responses in tall structures different types of damping systems are used. Dampers act as shock absorbers. Base isolation is ideal for short structures which tend to undergo shear failures during an earthquake. The most commonly used base isolation units used in the construction are laminated rubber bearing. These bearings are made of alternative layers of vulcanized rubber and steel [1]. But this phenomenon doesn't give effective results for high rise buildings. The concept of tuned mass damper (TMD) was evolved and first suggested by Frahm in 1909 to enervate unenviable vibrations in ships. The device predominantly consists of a mass (m), spring (k) and damping devices (c). The device is mounted on the structure to avert the failure of building [2]. The working principle of TMD is when building begins to oscillate, it sets the TMD into motion by means of spring, when building sways to the right side, and consequently the TMD sways to left side in order to narrow down the excitation of structure.

A TMD is naturally tuned to the first natural frequency of the structure. The energy dissipation effectiveness of a TMD depends on (a) The accuracy of its tuning, (b) Mass of damper compared to modal mass of its target mode and (c) Extent of internal damping built-in TMD [3]. The main advantage of incorporating TMD in tall structures is they don't need any external power sources for their operation, unlike other dampers. TMD's are easy to maintain and also respond small excitations. Few other dampers used in structures for the controlling of the wind and seismic excitations are Tuned Liquid Column Dampers (TLCD), Pendulum modelled TMD, Viscous dampers, etc.[4]. TLCD was proposed by sakai [5] to test the vibrations induced by wind and seismic excitations in the structure. The efficiency of TLCD depends on tuning the frequency of TLCD with respect to the frequency of structures.

The viscous damper for structures is similar to the shock absorber on an automobile but operates at a much higher force level [6]. It is constructed of stainless steel. Pendulum Tuned Mass Dampers (PTMDs) are substituted with a translational spring and damper system with a pendulum, it comprises of a mass sustained by a cable which pivots about a point. They are often designed as a simple pendulum [7]. Even slight angular oscillations make the PTMD act similar to a translational. It is preferred over the translational TMD system because of the absence of any type of bearings. PTMDs are economical, adaptable and easy to maintain. PTMD is implemented in Taipei 101 tower in Taipei and Crystal Tower in Osaka [8].

2 Existing TMD's

2.1 One Wall Center, Sheraton Vancouver, Canada

One Wall Centre is a skyscraper hotel opened in Vancouver's downtown. The building is of 157.8 m height above the ground level and extends up to 4 floors below the ground level [9]. As the building is tall and slender wind tunnel tests signified that storm winds approaching in the vicinal of the building would sway the structure. Therefore, a conventional technique is followed to minimize the displacements without changing the mass and stiffness of the structures; the structure is connected to a damper which functions as a shock absorber.

Two water tanks each with 16 m long × 4.5 m wide × 8 m tall and each tank designed with a capacity of 50,000-imperial-gallon are installed as a pendulum modelled Tuned Water Damper in the building. The frequency of the splash of the water in the tanks counteracts the frequency of the swaying of the building. Therefore, when the building proceeds to sway under wind loading, the water moves to and fro transmits its momentum to the structure and restrains the effects of wind vibration.

2.2 Taipei 101 Tower, Taipei

The Taipei 101 is an iconic super-tall structure. The structure used high-performance steel and concrete in its construction. Besides five basement levels, It also comprises of 101 floors above ground. Outrigger trusses were installed at eight-floor intervals, which joins the columns in the building's core to those on the exterior. These components made Taipei 101 one of the most stable buildings. It is located just above 201.16 m from a major fault line, as a result, it is viable to earthquakes, and even stormy winds are common in this area of the Asia-Pacific. Therefore, to attain stability and lessen the impact of violent motion engineers had to design a gigantic TMD that could withstand gale winds up to 216 km/h and the strongest earthquakes.

It's basically an enormous weighted ball of 728 tons steel pendulum that serves as a TMD, which is placed on hydraulic cylinders and counteracts the building's movement. The TMD system is suspended from the 92nd to 87th floor with the design of the simple pendulum. And this pendulum oscillates to counterbalance movements triggered in the building by strong gale. The dimensions of the sphere are 5.48 m in diameter, comprising 41 circular steel plates of varying diameters, each 0.125 m thick, welded together to form a 5.5 m diameter sphere. Two additional TMD's, each weighing 6 tones, are installed at the tip of the spire which halts the damage to structure due to strong wind loads [10].

2.3 Chiba Port Tower, Japan

Chiba Port Tower (125 m high) is a high-rise steel structure incorporated with steel-framed reinforced concrete construction. A two-mass model TMD is installed at the top of the tower to reduce the wind vibrations on the structure. The damper system consists of a mass of 15 tones, two frames overlapped at right angles, these frames can slide in X and Y direction with the help of roller bearings. These frames consist of coil springs and damping devices. The damping devices have a rotator in high viscosity liquid and produce a damping force by shearing the liquid.

The TMD is designed by setting the damper weight to 100th of the first mode of effective weight [11]. Thereby the TMD reduces the earthquake vibrations by 30% and wind vibrations by 10% effectively.

2.4 Chiba Port Tower, Japan

The Shanghai Center Tower (SHC) is a high-rise building with an elevation of 631.85 m. The design company stated that a building of this tall could be malleable to more than 1.524 m of sway during the typhoon conditions. In order to counterbalance its vibrations during wind storms, a new eddy-current TMD was stationed on the 125th floor.

Special protective appliances were blended to prevent excessively large amplitude motion of the TMD under extreme wind or earthquake scenarios. The damper is a 1000-ton weight is suspended with the aid of steel cables. TMD is incorporated with two systems (hydraulic rams, and a ‘tuneable’ self-generated magnetic field) which prevent the weight from moving too fast. The iron weight hangs above 10 m $\times$ 10 m copper plate, which is studded with 125 powerful magnets. As the iron swings over the magnets, it initiates electrical current in the copper plate, which is enough to limit the motion of the mass. The merit is in its simplicity, there’s no necessity of power source, and is a completely a self-regulating system [12].

3 Numerical Formulation

The present paper is centred on an MDOF structural system interconnected with single TMD on top, an overture has been evolved to detect the optimum parameters of TMD placed in a multi-storied building for minimum top deflection caused by lateral excitation. Over the last few decades, considerable numbers of buildings were incorporated with TMD’s all over the world.

3.1 Dynamic Analysis

The first step for performing a dynamic analysis is to set up the equations of motions and most basic is Newton's second law of motion which states that "the rate of change of momentum of a mass equals the force acting on it" [13] . Figure 1 shows steps involved in derivation of dynamic equation of motion with and without damper.

$$\mathrm{d}/\mathrm{d}t\, m(\mathrm{d}u/\mathrm{d}t) = F(t) \tag{1}$$

If one affixes a spring and a damper to the mass, by postulating that the spring complies with Hooke's law and the damping is of viscous type (the damping force is proportional to the velocity of the mass), the equilibrium is formulated by summing up the terms of spring and damping-induced forces.

$$M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = P(t) \tag{2}$$

where the dot over the symbol represents differentiation with respect to time t. M, C, K represents the mass, damping, and stiffness of the structure respectively.

Undamped Free vibration: During the initial excitation, when $P(t)$ and damping are zero the response is termed as free vibration.

From Eq. (1),

$$m\ddot{u}(t) + ku(t) = 0 \tag{3}$$

Linear, homogeneous second-order differential equation

$$\ddot{u} + \frac{k}{m}u = 0 \tag{4}$$

For notational convenience, let's assume

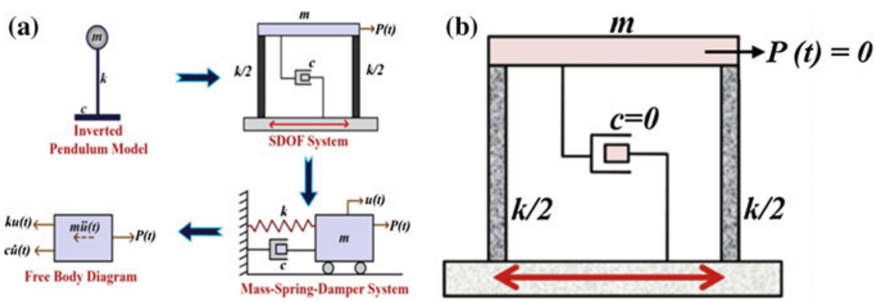

Fig. 1 **a** Equation of single degree of freedom system, **b** Undamped free vibration system

$$\frac{k}{m} = \omega^2 \text{ (Hence } \omega^2 \text{ is positive number)}. \tag{5}$$

$$\frac{\mathrm{d}^2 u}{\mathrm{d}t^2} = -\omega^2 u \tag{6}$$

This is the differential equation for SHM. The sinusoidal solution for displacement of spring can be given by

$$x = A * \cos(\omega t) \tag{7}$$

where A is the amplitude of the motion and ω is the angular frequency.

$$\omega^2 = \frac{k}{m} => \omega = \sqrt{\frac{k}{m}} \tag{8}$$

3.2 Optimization Theory for TMD

Many studies have been carried out in the past to understand and determine the optimal parameters for a TMD under different kinds of excitations, to predict the vibrational behaviour of the main structures and assess the efficiency of the TMD contributions in terms of attenuating vibrations in the main structure. Outcome of few studies has clearly mentioned that usage of elastic body can be supplanted by an equivalent SDOF system for reduction of amplitudes during natural disasters. Provided that the frequencies of the elastic body are well distinguished and the damper response is majorly contributed by the fundamental mode.

In the damping of the main system, it is recommended that constrained damping of the main system has a very small effect on the TMD's optimal parameters. In real systems with light damping, if this frequency condition is satisfied, it is plausible to apply the optimal parameters of the TMD for the undamped equivalent system to lessen the dynamic response of the system.

Single Degree of Freedom System.
The equations of motion for an undamped SDOF system with TMD

$$M\_m\ddot{u} + K\_mu + c\_a\dot{u} + k\_au - c\_a\dot{u}\_a - k\_au\_a = p(t) \tag{9}$$

$$m_a\ddot{u}_a + c_a\dot{u}_a + k_a u_a - c_a\dot{u} - k_a u = 0 \tag{10}$$

where M, K, U represents mass, stiffness, and displacement, respectively, whereas m and a refers to the parameters of structure and TMD, respectively.

If harmonic forces act on the system, then $p(t) = pe^{i\omega t}$. Therefore, the displacement of the main system can be reduced if the vibration of system is with its natural

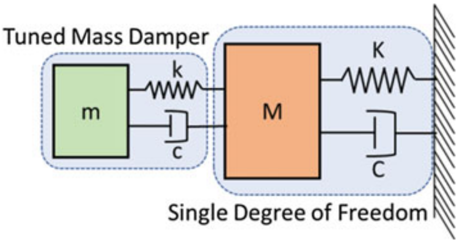

Fig. 2 Schematic diagram of SDOF with TMD

frequency, schematic diagram of SDOF with tuned mass damper is shown in Fig. 2.

$$u = \frac{\left(k_a - m_a\omega^2 + i\omega c_a\right)pe^{i\omega t}}{\left(K_m + k_a - M_m\omega^2 + i\omega c_a\right)\left(k_a - m_a\omega^2 + i\omega c_a\right) - (k_a + i\omega c_a)^2} \tag{11}$$

Velocity of the system is

$$\dot{u} = \frac{\left(k_a - m_a\omega^2 + i\omega c_a\right)i\omega pe^{i\omega t}}{\left(K_m + k_a - M_m\omega^2 + i\omega c_a\right)\left(k_a - m_a\omega^2 + i\omega c_a\right) - (k_a + i\omega c_a)^2} \tag{12}$$

Acceleration of the system is

$$\ddot{u} = \frac{-\omega^2\left(k_a - m_a\omega^2 + i\omega c_a\right)pe^{i\omega t}}{\left(K_m + k_a - M_m\omega^2 + i\omega c_a\right)\left(k_a - m_a\omega^2 + i\omega c_a\right) - (k_a + i\omega c_a)^2} \tag{13}$$

Mass ratio:

$$\mu = m_a/M_m \tag{14}$$

Tuning ratio:

$$f = \omega_a/\omega_m \tag{15}$$

$$\omega_a^2 = \frac{k_a}{m_a} \tag{16}$$

$$\omega_m^2 = K_m/M_m \tag{17}$$

Forced frequency ratio:

$$r = \omega_a/\omega_m \tag{18}$$

Absorber damping ratio:

$$\gamma_a = c_a/2m_a\omega_a \tag{19}$$

$P(t) =$ Force vector

$$m_a Z_{jr} \ddot{u}_a + c_a Z_{jr} \dot{u}_a + k_a Z_{jr} u_a - c_a Z_{jr} \dot{U}_j - k_a Z_{jr} U_j = 0 \tag{20}$$

Z is the matrix of orthogonal characteristics modes of the system and Z_r is the vector of the r^{th}

Mode,

$$Z_r = \left(Z_{1r}, Z_{2r}, \ldots, Z_{jr}, \ldots, Z_{nr}\right)^T \tag{21}$$

4 Numerical Modelling

Initially, a two-Dimensional 15 storey structure is modelled using ETABS as shown in Fig. 4. Respective dimensions for the structure are assigned based on Table 1. Modal analysis has been carried out. The time period of the structure is found to be 1.141 cycles/sec. Using trial and error basis, a single portal frame is analysed to get same frequency of the structure. This portal frame is mounted on the top of 15th storey and time history analysis is carried out. Same procedure is followed with TMD on different floors of the structure. For the next trial, the dimensions of the portal frame are changed to 5 m (beam) × 2 m (column) and made sure that its frequency matches with 15 storey structure. Portal frame is mounted on various floors of the structure and checked for the minimum response. Similarly, same procedure is carried (for both the portal frames) by placing the portal frame in inverted position.

Table 1 Geometry and material property of 2D framed structure

Property	Dimension
Structure Column dimension	450 mm × 300 mm
Structure Beam dimensions	300 mm × 300 mm
Column dimensions of TMD	161 mm × 161 mm
Beam dimensions of TMD	1324 mm × 1324 mm
Grade of Concrete	M 25
Rebar’s	HYSD 415
Height of storey	3 m

5 Case Study

5.1 System Model

The 15 storey structure consisting of rigid floors and beams which are supported by deformable columns is modeled with uniform bay with 3 m. All the numerical models presented in this study are developed using commercially available ETABS software. And natural period of 15 storey structure 1.141 s.

The joints at the base of the structure are restrained to rotation and translation in both x and y directions. The designed TMD is tuned to the same natural frequency of the building and installed on the building.

Case 1. Erected TMD system of height 2 m installed on top of slab. In this study, a TMD of column and beam length of 2 m specified in Table 1 is placed at 15th, 14th and 13th storey of building as shown in the Fig. 3a.

Case 2. Inverted TMD system of height 2 m: In this case the TMD is placed in an inverted position and analysis is carried. The same TMD dimensions mentioned in the Table 1 are considered.

Case 3. Erected TMD system of height 5 m installed on top of slab: In this case, the column length of the TMD is increased to 5 m and the dimensions of the column and beam of TMD remain same as mentioned in Table 1.

Case 4. Inverted TMD system of height 5 m: In this case, we have placed the TMD inverted at 13th, 14th and 15th storey as shown in fig i, ii and iii, respectively. The dimensions of TMD are unchanged.

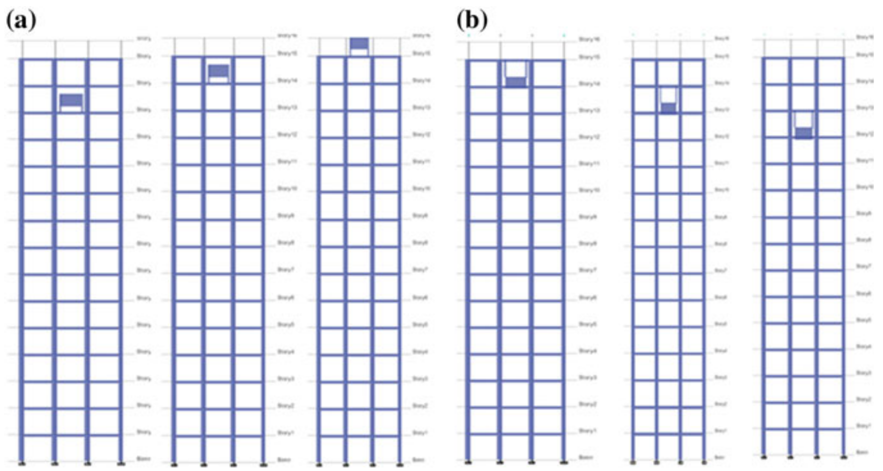

Fig. 3 **a** Installation of TMD on 13 th, 14th, 15th floor, **b** Installation of inverted TMD on 15th, 14th, 13th floor

6 Results

A parametric study for installation of TMD at three different heights is carried to understand the response of the structure.

6.1 Model Analysis

Structural displacement response is compared with and without TMD and for the same plots have been plotted in Fig. 4. It is observed that the response of the structure having the TMD decays faster than that of without TMD. It is observed that when the TMD is placed over the 14th storey, the structural response to the applied ground motion is less when compared to the responses of the building with TMD installed at 12th or 13th storey of the structure.

6.2 Dynamic Analysis

To analyse the 2D frame EL CENTRO (Centro 1940 North–South Component, Peknold Version) earthquake ground motion with a scale factor of 10 with equal time interval of 0.02 s. Figure 5 shows the comparisional time history for various scenarios. Maximum seismic response reduction is found when TMD of height 5 m is erected of 14th storey of the structure. Comparably from the analysis and results obtained, erected portal frame TMD is more effective than inverted portal frame TMD model.

7 Conclusion

This study indicates using a portal frame as TMD can be very effective in controlling vibrations of structure due to seismic or high wind loads and few major observations of this research work are give as follows:

i. Portal frame in the structure is more effective TMD than on the top.
ii. Inverted TMD's are observed to be more efficient in reducing the lateral vibration.
iii. Location of the TMD has greatly affected the vibration behavior of the structure.

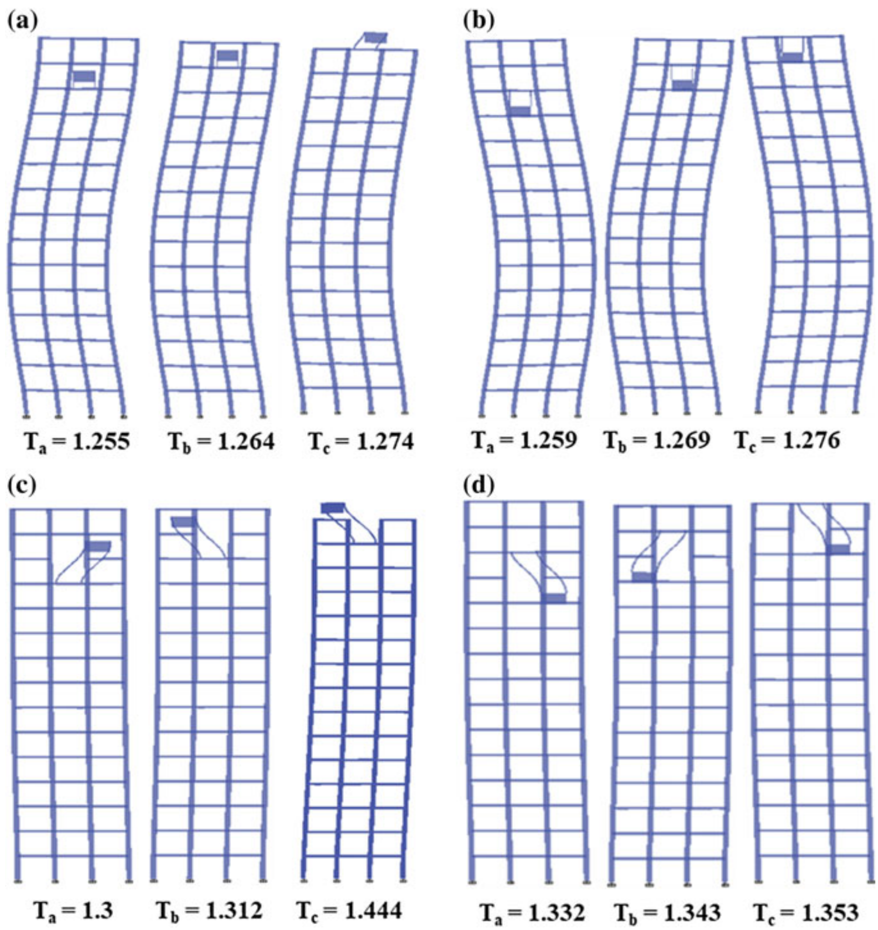

Fig. 4 Mode shapes of the structure with TMD of **a** column length 2 m placed at 13th, 14th, 15th, **b** column length 2 m placed inverted at 13th, 14th, 15th, **c** column length 5 m placed at 12th, 13th, 14th and **d** column length 5 m placed inverted at 15th, 14th, 13th

References

1. Tsai, H.-C. (1994). The effect of tuned-mass dampers on the seismic response of base-isolated structures. *International Journal of Solids and Structures, 32*(8–9), 1195–1210.
2. Tuan Alex, Y., & Shang, G. Q. (2014). Vibration control in a 101-storey building using a Tuned Mass Damper. *Applied Science and Engineering, 17*(2), 141–156.
3. Tuned Mass Dampers, http://www.deicon.com/air-suspended-tuned-mass-damper/. Accessed 9 Sepetember 2018.
4. Tuned Mass Dampers, https://www.slideshare.net/subhajitbiswas102/tuned-mass-damper.
5. Tuned Liquid Column Dampers, Natural Hazards, University of Notre Dame.
6. Samuele, I., Jamieson, R., & Rob, S. (2008). Viscous dampers in high rise buildings. *14th World Conference on Earthquake Engineering*.

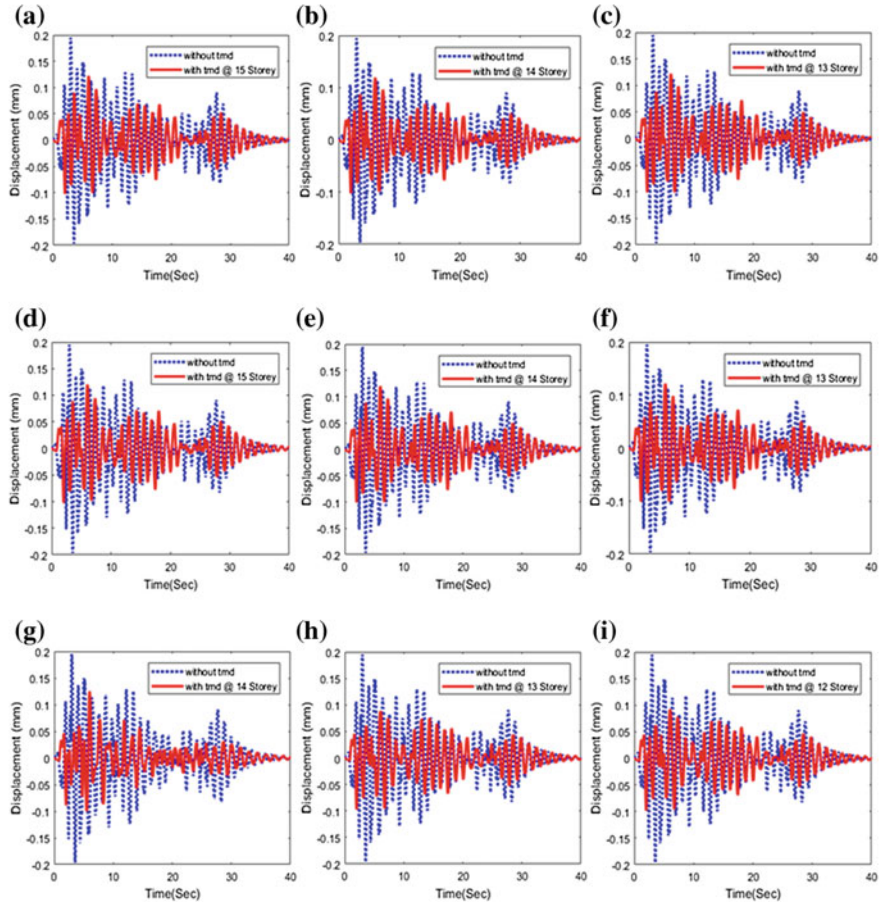

Fig. 5 Displacement of structure with **a** 2 m TMD at 15th storey, **b** 2 m TMD at 14th storey, **c** 2 m TMD at 13th storey, **d** 2 m inverted TMD at 15th storey, **e** 2 m inverted TMD at 14th storey, **f** 2 m inverted TMD at 13th storey, **g** 5 m TMD at 14th storey, **h** 5 m TMD at 13th storey, **i** 5 m TMD at 12th storey, **j** 5 m inverted TMD at 14th storey, **k** 5 m inverted TMD at 15th storey and **l** 5 m inverted TMD at 13th storey

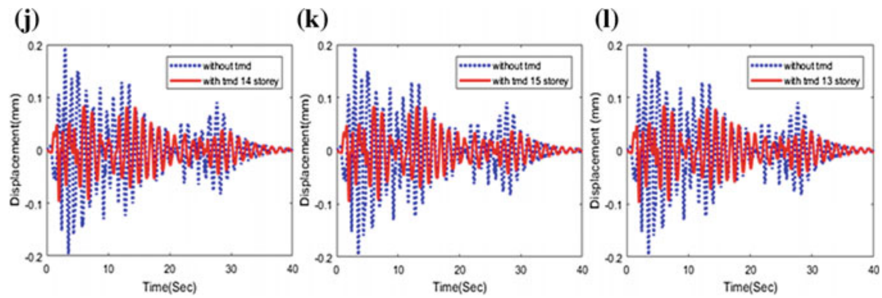

Fig. 5 (continued)

7. Richard, L. (2011). *Design, construction and testing of an adaptive pendulum tuned mass damper*. University of Waterloo.
8. https://en.wikipedia.org/wiki/Tuned_mass_damper.
9. Robert, S. (2001). One Wall Centre, Vancouver. Canadian Consulting Engineer magazine.
10. Eric, L. (2015). Taipei 101's mass damper. Popular mechanics.
11. Harruyuki, K., & Takafumi, F. (1988). Design and analysis of a tower structure with a Tuned Mass Damper. *Ninth World Conference on Earthquake Engineering*.
12. Chris, M. (2015). How a 121 storey building uses a giant magnet to prevent swaying, Gizmodo.
13. Chopra, A. K. (2017). *Dynamics of structures: Theory and applications to earthquake engineering* (5th ed.). Englewood Cliffs, NJ: Prentice Hall.