MULTIPLE TUNED MASS DAMPER IN TALL BUILDINGS

A Thesis submitted to the faculty of

San Francisco State University

In partial fulfillment of

the requirements for

the Degree

Master of Science

In

Engineering: Structural/Earthquake Engineering

by

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May 2019

CERTIFICATION OF APPROVAL

I certify that I have read Multiple Tuned Mass Damper in Tall Buildings by Laura Marji, and that in my opinion this work meets the criteria for approving a thesis submitted in partial fulfillment of the requirement for the degree Master of Science in Structural/Earthquake Engineering at San Francisco State University.

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Tall structures are subject to dynamic excitations from wind and seismic loads. In this study, the efficiency of utilizing MTMDs in a 20 story height building are tested with special attention given to the seismic response due to the distribution of TMDs across a given story and through the elevation. The story displacements, shear force, and acceleration results showed that TMDs can dramatically dissipate energy in structures when they are used in groups with various distribution. The study indicates that, firstly, whatever the amount of total TMD mass increases, the reduction in structural dynamic response also increases. Secondly, the vertical distribution of MTMD is more effective in controlling the performance of structures than horizontal distribution, especially under ground motions with short wavelength. And lastly, the most optimum distribution of TMDs is on the floor plan and through the elevation of the model at the same time in order to have the most controlled behavior.

I certify that the Abstract is a correct representation of the content of this thesis.

_______________________________ MAY 13, 2019

Chair, Thesis Committee Date

PREFACE AND/OR ACKNOWLEDGEMENTS

This basis for my research was stemmed from my passion for developing better methods of earthquake resistance in buildings. As the world moves further into the construction of high rise buildings, earthquakes can cause significant damage to buildings and high fatalities. This presents a greater need to utilize energy dissipation devises that control the behavior of structures minimizing damage. How will we utilize this method? It is my passion to not only find out, but to test the efficiency of methods that make structures earthquake resistant for the safety of the future generations.

In truth, I could not have achieved my current level of success without a strong support group. First, my parents, who supported me with love and understanding. And secondly, my committee members, each of whom has provided patient advice and guidance throughout the research process. Thank you all for your unwavering support.

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1. Introduction

Earthquakes are one of the natural catastrophes that can kill or incapacitate people, cause damage or even complete demolition of buildings, and ultimately decay the useful life of a structure. Structural damage is caused by strong vibrations from ground shaking which are accentuated by situations such as poor soil conditions and sliding in the foundation. Ground shaking is the primary cause of damage to man-made structures, and its occurrence is unpredictable. Therefore achieving earthquake resistant design of structures in seismic regions is very substantial. The best designs of any structure address safety, serviceability, and economy.

This study tests and observes the effectiveness of utilizing multiple tuned mass dampers (MTMDs). This is achieved by quantifying the changes in seismic response due to the distribution of tuned mass dampers (TMDs) across a given story and through the elevation of a 20-story concrete moment resisting frame (MRF).

The motivation for this study originates with a paper titled, "Optimum Design of TMD System for Tall Buildings" [Farghaly, 2012]. In this paper, Farghaly evaluated the performance of 20 different TMD systems with different quantities of devices and distributions. He paid special attention to the observed the change in displacement, shear force and acceleration between the different TMD systems. His main conclusions were TMD can dramatically reduce the response of structures, whatever the amount of dynamic amplitude is increased, the performance of TMDs is much better, and that single TMD distributed through the elevation of the model is better than using only in the top of the model. However, upon review of his study there were a number of limitations to the work and questionable results including the displacements plots showing the maximum displacement at the mid-length rather than at the top floor of the structure and using equal total TMD mass in all 20 scenarios with different distribution and still showing the reduction in displacement, shear force, and acceleration results.

Noting the above gaps in knowledge, this studies objectives were achieved by completing the following tasks:

a) Model a 20 story tall structure (Moment Resisting Frame building).
b) Apply TMDs based on 20 scenarios with varying numbers and distribution of devices to compare against a structure without TMDs and structure equipped with Shear Wall.
c) Conduct dynamic analyses using SAP2000.
d) Generate plots for displacements of each floor, shear forces on four columns of each floor, and the acceleration in X, Y, and Z directions at the base, 1st floor, mid-height, and the top floor for each scenario.

2. Background

Structural vibration control is a rapidly developing area with passive, active, semi-active, and hybrid systems controlling structural performance as shown in Table 1. The design process is based on nonlinear, yielding, or ductile response of the structures undergoing intense winds and earthquakes loads.

Table 1: Types of Control Systems (Elias, 2017)

Control systems			
Passives	Active	Semi-active	Hybrid
Energy dissipation	Adaptive control	Semi-active energy dissipation	Hybrid bracing
Base isolation	Active bracing	Semi-active isolation	Active isolation
Tuned mass dampers	Active mass damping	Semi-active mass damping	Hybrid mass damping

Passive systems are the most common systems to control structural vibrations because they are made of simple mechanical elements that absorb input energy caused by wind and earthquake excitations decreasing structural response and damage. Additionally, these devices do not demand any external power or magnitude observation. Many passive systems have been proposed by researchers, such as the friction control devices, fluid viscous dampers, seismic base isolation, tuned liquid dampers, and tuned mass dampers.

Active systems require a strong power source for functionality since electro-hydraulic actuators are used to supply the control forces. It also demands a large external power source for active wind and earthquake response control, in which it increases structural damping with minor adjustments in stiffness. These systems consist of three elements: sensors, actuators, and a controller with a predetermined control algorithm (control law).

Semi-active systems are passive energy-dissipating and integrate adaptive systems to improve efficiency. These devices collect information about the excitation, structural response, and then modifies the damper performance accordingly. A semi-active damper system is made up of sensors, a control computer, a control actuator, and a passive damping device.

Innovative hybrid control systems are constructed by combining passive to passive, passive to active, and alike control techniques. These systems have features of both hybridized techniques and mitigate the limitations of either technique alone.

Out of all these systems, engineers prefer to choose passive devices due to their simplicity. The passive system, tuned mass dampers, is the focus of this paper and will be discussed in more detail in the following section.

3. Tuned Mass Dampers

3.1 Overview

A tuned mass damper (TMD) is a device installed in structures to decrease the amplitude of mechanical vibrations. Their application restrains structural damage during a seismic activity using an enormous mass. This mass can be placed near the top of a building in three different shapes, TMD can be applied as a pendulum as Figure 2, a water tank as Figure 3, or as a device that consists of heavy mass and surrounded by springs and dashpot as figure 4, and this is the system that I'll be testing in my study.

3.2 Origin

TMD was invented in 1909 by a Frahm who tried to use a mass-spring absorber to control rolling motion in ships, which resulted in reducing the amplitude of the main system to zero for a single frequency (Frahm, 1909). Two other scientists in 1928, Ormondryd and Den Hartog improved the study Frahm started in which they designed a vibration absorber for broadband frequency vibration, Den Hartog (1947, 1956). In addition, they introduced the system of invariant points that became a path for an analytical optimal solution that controls the behavior of a system's motion.

In their book, the theory for TMDs was presented for an undamped main structure. They expressed the equations of motion for a single degree of freedom (SDOF) structure and multi-DOF structure with the TMD mechanism as:

$$[\,M s\,]\,\{\,\ddot{X}s\,\} + [\,Cs\,]\,\{\,\dot{X}s\,\} + [\,Ks\,]\,\{\,Xs\,\} = \{\,F(t)\,\} \tag{1}$$

where $[\,M\ s\,]$, $[\,C\ s\,]$, and $[\,K\ s\,]$ are the mass, damping, and stiffness matrices of the structure; and the base excitation case, $\{\,F\ t\,\} = -[\,M\ s\,]\,\{\,r\}\,\ddot{X}g$ where $\{\,r\,\}$ is the influence coefficients vector and $\ddot{X}g$ is the uni-directional ground excitation.

The natural frequency (fn) of the primary system is the sum of the lower (f1) and higher (f2) frequency as shown in Figure 2. The most considerable variable in designing a damper is the mass ratio (μ) which is calculated in equation 1, as it has been proven that when the ratio increases the efficiency of TMD increases (Al-Hulwah, 2005). However, the value of the mass ratio is usually between 1-10%.

$$\mu = \frac{m_2}{m_1} \tag{2}$$

Other significant variables were developed by Den Hartog (1947), such as tuning frequency ratio (f) and damping ratio (ζd) are given by equation 2 and 3 respectively:

$$f = \frac{w}{\Omega} = \frac{1}{1-\mu} \tag{3}$$

$$\zeta d = \sqrt{\frac{3\mu}{8(1+\mu)}} \tag{4}$$

The design parameters for the TMD under base excitations were similarly developed as follows:

$$f = \frac{w}{\Omega} = \frac{1}{1-\mu}\left(\sqrt{\frac{2-\mu}{2}}\right) \tag{5}$$

$$\zeta d = \sqrt{\frac{3\mu}{8(1+\mu)}}\left(\sqrt{\frac{2-\mu}{2}}\right) \tag{6}$$

TMDs are typically tuned to the natural frequency of the primary mass that it is attached to. TMD systems must be efficient when it is tuned to a particular natural frequency. On the other hand, TMD systems can be inefficient and increase the vibration of a structure, when it is off-tuned which means that it has closely spaced natural frequency (Wbster & Vaicaitis, 1992).

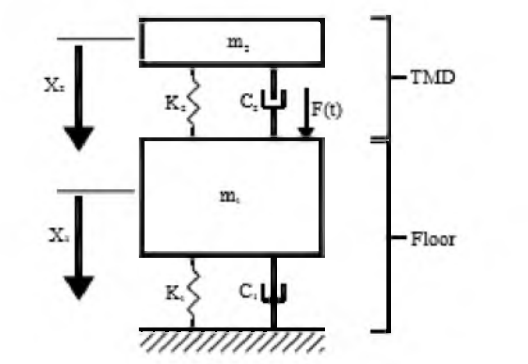


Figure 1. Schematic Representation of a Two DOF System (Farghaly, 2012)

The most optimum location for TMD is at the largest damping ratio ζ, and in the first two modes are maximums. Typically, the first mode controls the response, and it is the location where the damping ratio is at its highest (Villaverde, 1988). A study also showed that TMDs attached to the structures controls the response only in the first two modes and had no effect on the other modes (Sadek, Mohraz, Taylor & Chung, 1997).

3.3 Research and Development

TMDs have evolved over the past century with several key studies advancing their development.

Table 2: TMD Research Development

Year	**Type of development**	**Name of Researcher**
1959	The steady-state behavior of the TMD was showed	Snowdon
1963	The efficiency of the TMD to control the random vibration was discussed	Crandal and Mark
1973	A study has been conducted on optimized active and passive TMDs, and it has been concluded that the optimal systems have showed developed behavior as compared to the conventional systems.	Morison and Karnopp

1979	The TMDs were first utilized to reduce the dynamic response caused by wind on the tall structures.	Crandal and Mark
1983	a method for calculating seismic floor response spectra for classically and non-classically damped structures was suggested	Sharma and Singh
1983	A study has been conducted on the effect of TMDs in seismic response reduction on structures, and interestingly, the result showed that TMD is not efficient in reducing the seismic behavior of tall structures.	Sladek and Klingner
1983	The effectiveness of TMD on wind-induced response of structures was tested	Tanaka and Mak
1987	A single TMD was found not as efficient in decreasing seismic response of structure because earthquake loads are propulsive and extend to the maximum values fast and that earthquake ground motion has a wide spectrum of frequency components which causes big movements in higher modes of a tall structure. Thus, using a single TMD is not efficient in decreasing the total response of the structures. They also observed that when TMD are tuned to a primary mode in a structure, it could increase the behavior of higher modes due to the coupling effect.	Chowdhury and Iwuchukwu
1992	The time history response of a tall structure that utilizes a TMD under wind forces was investigated.	Kawaguchi, Teramura, and Omote
1993	The damped resonant appendages to increase potential damping in structures were first tested and suggested various effective methods for STMD to control the responses of the structures.	Villaverde and Koyama

1994	The first successful study of the passive TMDs in reducing vibration response was conducted	Lin, Hu, Wang, and Hu
1997	The loss of effectiveness of the tuned mass dampers supported on nonlinear systems and reported that as the nonlinearity grows, the effectiveness decreases was studies	Ruiz and Esteva
1999	It was reported that greater the distance between the TMD and mass center of the installed floor, more the vibration reduction achieved.	Lin, Zhang, Sun, He, Lark, and Williams
2000	A numerical method was proposed to design parameters of TMD to absorb forces. He concluded that passive systems, such as TMD are more economical and reliable than the active control systems.	Schmitendorf
2000	The effects of uni-directional damper were investigated and compared its behavior in reducing vibration with the bi-directional and tri-directional damper. The result showed that the bi-directional and tri-directional dampers are independent of the excitation direction; therefore, bi-directional and tri-directional can better control the behavior of structure compared to the single uni-directional dampers	Ankireddi and Yang
2001	TMD was found to be the most simple and cost-effective ways to control the vibration of a beam structure by attaching a single mass to the beam structure by visco-elastic material. It has been reported that the mass ratio, damping ratio, tuning frequency, and number of the TMDs provide maximum critical flutter wind speed of the suspension bridge.	Gurgoze et al
2002	Showed the performance of the TMD in control of the flutter in suspension bridge deck was showed	Pourzeynali and Datta

2003	Showed that the TMD was a useful vibration control device in reducing vertical displacements in the bridge, its absolute accelerations, end rotations, and train accelerations during resonant speeds	Wang, Lin, and Chen
2008	The TMDs were more effective in suppressing structural oscillations for the higher soil stiffness and the soil-structure interaction (SSI) is required to be accounted for accurate predictions with low soil stiffness.	s. Liu, Chiang, Hwang, and Chub
2014	The performance of the TMD installed on the Taipei 101 Tower under wind and remote (long-distance) seismic excitation was investigated. They reported that the TMD is effective in reducing the response in the building under wind loads, but it is not effective in mitigating the remote seismic vibration responses.	Tuan and Shang
2016	Three-dimensional (3D) response reduction of structure using three directions TMD was proposed. The results show that the three directional response of a structure can be reduced using the TMD scheme.	Ohsaki, Tsuda, and Hasegawa

A single TMD is not considered as efficient and strong because it is off-tuned. This is due to the stiffness changes structures experience in yielding due to strong earthquakes. When the structure becomes less stiff, the performance of a single TMD would be inadequate because of the off-tuning of the frequency and low damping ratio. Therefore, multiple tuned mass dampers (MTMDs) have been proposed.

3.4 Multiple Tuned Mass Dampers

With the vast advancement in TMD research, multiple tuned mass dampers (MTMDs) are the latest development. MTMD systems consist of using more than one TMD that can be distributed in various ways vertically and horizontally

Table 3: MTMD Research Development

Year	Type of development	Name of Researcher
1980	Dual tuned mass dampers (2TMD) was first proposed and a study on the optimum design of 2TMD for harmonically forced vibration of the structure was conducted. The results prove that utilizing 2TMD make structures more efficient in resisting earthquakes compared to a single TMD	Iwanami and Seto
1990	Multiple tuned mass dampers (MTMD) with distributed natural frequencies was proposed. Researchers derived a simple formula of equivalent additional damping and an integral form for the impedance.	Igusa and Xu
1991	Based on Igusa and Xu's study, a study of different combinations of the stiffness, mass, damping coefficient and damping ratio on five MTMD models was conducted. The MTMD was shown to be more effective in mitigating the oscillations of structures with respect to a single TMD. These research findings have also confirmed the merit of the MTMD in seismic applications.	Li
1992	MTMD can control the wind-induced response in the tall	Xu and Igusa
1993	Optimum MTMDs system was proved to decrease the steady-state response of the base-excited and damped structures	Tsai and Lin

1993	Investigated MTMD optimum parameters when the dynamic response of a base-excited structure in a specific mode	Tsai and Lin
1999	Inertial dynamic dampers were used for multi-mode control of structures with closed and well-separated frequencies. There wasn't any difference between the vibration of the systems with close frequencies and those with widely separated modal frequencies. However, the effectiveness of the MTMDs in controlling the behavior of structure was not significant. Therefore, researchers focused on optimization of the system with the MTMDs under the dynamic loads.	Carotti and Turci
2000	Studies have shown that the MTMDs are more efficient in restraining the accelerations on lower floors than on the upper floors	Wu and Chen
2004	MTMD system that has many MTMD subsystems was tested, in which each consists one set of TMD units, in which the frequency plus a bandwidth to cover the effect of detuning was observed using an average frequency. This study was conducted on continuous truss bridge that has moving train loads, and showed effective vibration control.	Yau and Yang
2004	A method was proposed to decreasing the vibration of cable-stayed bridges that are used for the passage of high-speed trains, the TMD system consists of many subsystems that each tuned for one resonant frequency	Yau and Yang
2004	TMD was test using various mass ratios and numbers of dampers but same damping ratio. The aim was to minimize the steady-state displacement response of the	Bakre and Jangid

	main undamped system that subjected to a harmonic base excitation.	
2008	Studies have been conducted on the MTMD installation space, such as evaluating non-interconnected (NI) and interconnected (I) MTMD using different parameters. (Non-interconnected (NI) MTMD is when the MTMD masses are attached directly to a vibrating main system, while the interconnected (I) MTMD is when the first mass may be attached to the main system while other masses may be connected to each other.)	Rubia, Suzana, Jose
2008	Studies were conducted on the performance of MTMD when random wind and seismic loads are applied to the structure	Rubia, Suzana, Jose
2012	The use of MTMD with non-linear damping devices to suppress man-induced vibrations on a pedestrian bridge was tested.	Daniel, Lavan, and Levy

3.5 Application

TMDs come in various forms with some examples provided in this section. One application is a TMD pendulum that has a heavy mass supported by a steel cable or connected to the structure's members by viscous dampers. When an earthquake hits, the building will move in the direction of the excitation, while the pendulum will oppose this motion reducing the structure's dynamic response and introducing energy equilibrium. A second application is the creation of a TMD via a water tank which can be placed on the top of the structure. The water acts like a heavyweight performing similarly to a pendulum with the water moving in the opposite direction of seismic excitation. Lastly, a TMD can also present itself as a heavy mass surrounded by spring and dashpot. When an earthquake hits, the TMD makes the structure have counteract resonance and balance in the energy. This systems resist earthquake loads when its heavy masses displace proportional to each other, the whole damper gets stretched and compressed, in a way that mitigates the vibration of structures.

TMDs are used in many high-rise buildings around the world as shown in Table 4, and some of them have resisted recent earthquakes.

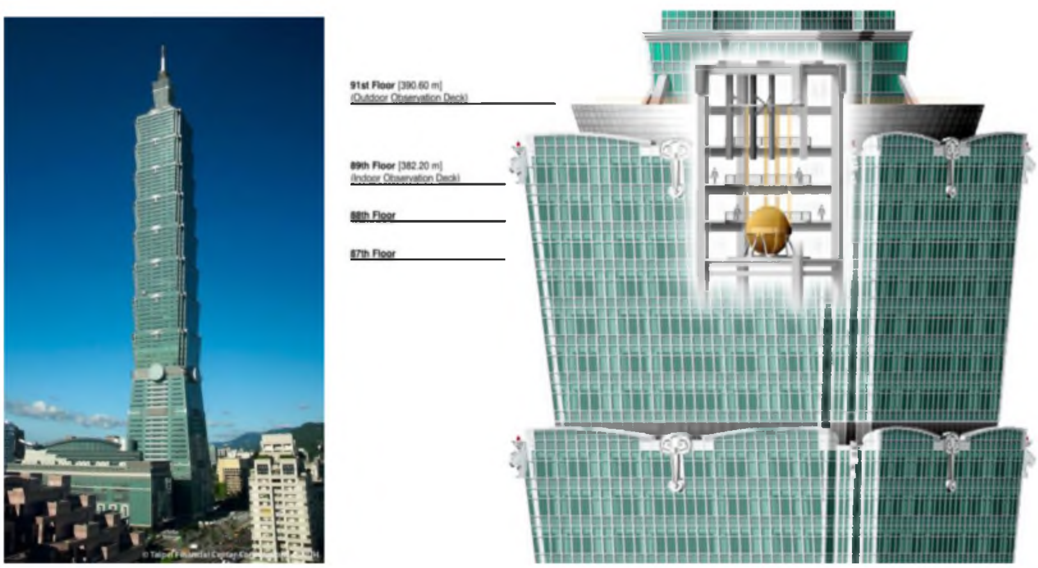


Figure 2: Taipai 101 (Shape 1: Pendulum TMD)

Taipei 101's damper was built at a cost of US$4 million, its weight is 730 tons, it is the world's largest tuned mass damper, and perhaps the only one visible to the public.

Figure 3: One Rincon Hill (Shape 2: Liquid TMD)

One Rincon Hill is the only building on the West Coast to have a “tuned liquid mass damper”, it is located in San Francisco. The tank contains 50,000 gallons of water.

Figure 4: Millennium Bridge (Shape 3: Spring and Dashpot TMD)

Millennium Bridge is located in London, its TMD is composed of a heavy mass surrounded by spring and dashpot, and this type of TMD is the same type that I will be using in my study.

Multiple TMD has not been utilized in any building in the world, its idea was proposed in 1992, and until now many studies are being conducted to approve its effectiveness.

Table 4: Application of tuned mass damper (TMD) (Farghaly, 2012)

Name	City, Country	Height (m)	Year	Frequencies	Mass
C N Tower	Toronto, Canada	773	1973	-	-
John Hancock	Boston, USA	244	1977	0.14 Hz	2x 300 t
City Corp Center	New York, USA	278	1978	0.16 Hz	370 t
Sydney Tower	Sydney, Australia	305	1980	0.10, 0.50 Hz	20 t
Al Khobar Chimney	Saudi Arabia	120	1982	0.44 Hz	7 t
Ruwais Utilities Chimney	Abu Dhabi	-	1982	0.49 Hz	10 t
Deutsche Bundespost Cooling Tower	Nurnberg, Germany	278	1982	0.67 Hz	1.5 t
Yanbu Cement Plant Chimney	Saudi Arabia	81	1984	0.49 Hz	10 t
Hydro-Quebec Wind Generator	Canada	-	1985	0.7–1.2 Hz	18 t
Chiba Port Tower	Chiba, Japan	125	1986	0.43–0.44 Hz	10, 15 t
Pylon, Aratsu Bridge	Japan	-	1989		-
Pylon, Yokohama Bridge	Yokohama, Japan	-	1988		-
Bin Qasim Thermal Power Station	Pakistan	70	1989	0.99 Hz	4.5 t
Tiwest Rutile Plant Chimney	Australia	73	1989	0.92 Hz	0.5 t
Fukuoka Tower	Fukuoka, Japan	151	1989	0.31–0.33 Hz	25, 30t
Higashiyama Sky Tower	Nagoya, Japan	134	1989	0.49-0.55 Hz	20 t
Pylon, Bannaguru Bridge	Japan	-	1990		-
Crystal Tower	Osaka, Japan	157	1990	0.24-0.28 Hz	180, 360 t
Huis Ten Bosch Domtoren	Nagasaki, Japan	-	1990	0.67 Hz	7.8 t
Hibikiryokuchi Sky Tower	Kitakyushu, Japan	135	1991		-
HKW Chimney	Frankfurt, Germany	120	1992	0.86 Hz	10.5 t
BASF Chimney	Antwerp, Belgium	100	1992	0.34 Hz	8.5 t
Siemens Power Station	Killingholme, UK	70	1992	0.88 Hz	7t
Rokko Island P and G	Kobe, Japan	117	1993	0.62 Hz	270 t
Chifley Tower	Sydney, Australia	209	1993		400 t
Al Taweeiah Chimney	Abu Dhabi	70	1993	1.4 Hz	1.35 t
Akita Tower	Akita, Japan	112	1994	0.41 Hz	-
Burj Al-Arab	Dubai	-	1999		-
Millennium Bridge	London, England	-	2001	1.2 Hz	1.0 t
One Wall Centre Tower	Vancouver, Canada	-	2001	-	50,0 0 0 gallon
Spire of Dublin	Dublin, Ireland	-	2003	-	-
Taipei 101	Taiwan	-	2004	-	730 t
One Rincon Hill	California, USA	165	2008	-	50,000 gallon
Air Traffic Control (ATC) Tower	Delhi, India	102	2015	-	50 t

4. Model

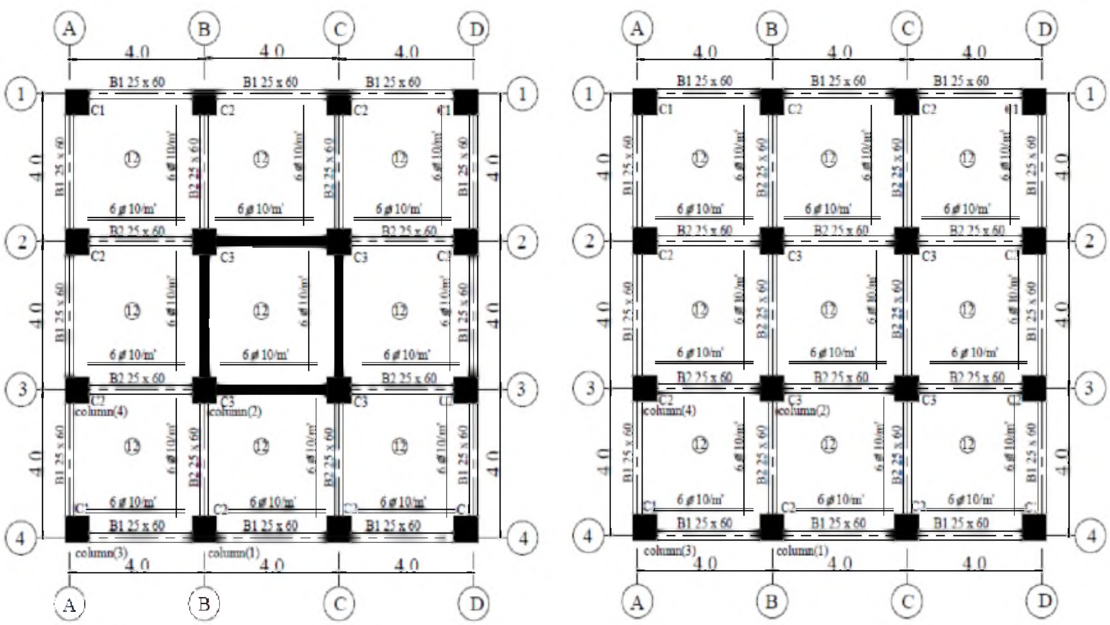
The structural system described in the following sections were modeled in SAP2000. Note the study included a control model (one without TMDs) and the rest had TMDs based on the scenario of interest.

4.1 Structure

For this study, a 20 story concrete MRF building found in Farghaly's literature was used. The concrete and steel stress values are fc=9.81 MPa and fs=196.133 MPa respectively. The definitions of the columns and beams are shown in Table 5 and a typical floor plan is shown in Figure 5. It was assumed that the floors were rigid diaphragms and the frames were rigid. This structure is comparable to Farghaly's except for one additional assumption that the shear wall is 0.35m thick. This thickness was selected based on the article "Concrete Shear Wall Construction" (Nagar, 2002) that states that the maximum concrete core can be 0.5m thick. The dimensions of the columns and beams are shown in Table 5. The height of each floor is 3 meters with the typical floor plan shown in Figure 5.

Table 5. Dimensions of reinforced concrete elements of the MRF building (dimensions in cm) (Farghaly, 2012)

Floor	Dimension				
	Columns			Beams	
	C1	C2	C3	B1	B2
1,2,3	70x70	70x70	70x70	25x60	25x60
4,5,6	65x65	65x65	65x65	25x60	25x60
7,8,9	60x60	60x60	60x60	25x60	25x60
10,11,12	55x55	55x55	55x55	25x60	25x60
13,14,15	50x50	50x50	50x50	25x60	25x60
16,17,18	45x45	45x45	45x45	25x60	25x60
19,20	40x40	40x40	40x40	25x60	25x60



(i) Shear wall model (SW) (ii) Bar MRF

Figure 5. Typical structural plan of each floor of the 20th story building model (Farghaly, 2012)

4.2 TMD

The TMDs were attached to columns so it will control the performance of structure by reducing the values of the displacements and base shear in each floor level in both X and Y directions due to earthquake in direction of EN(X) and SN(Y) as shown in Figure 6:

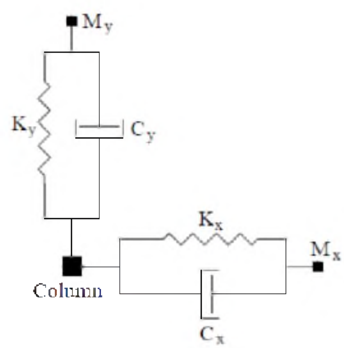
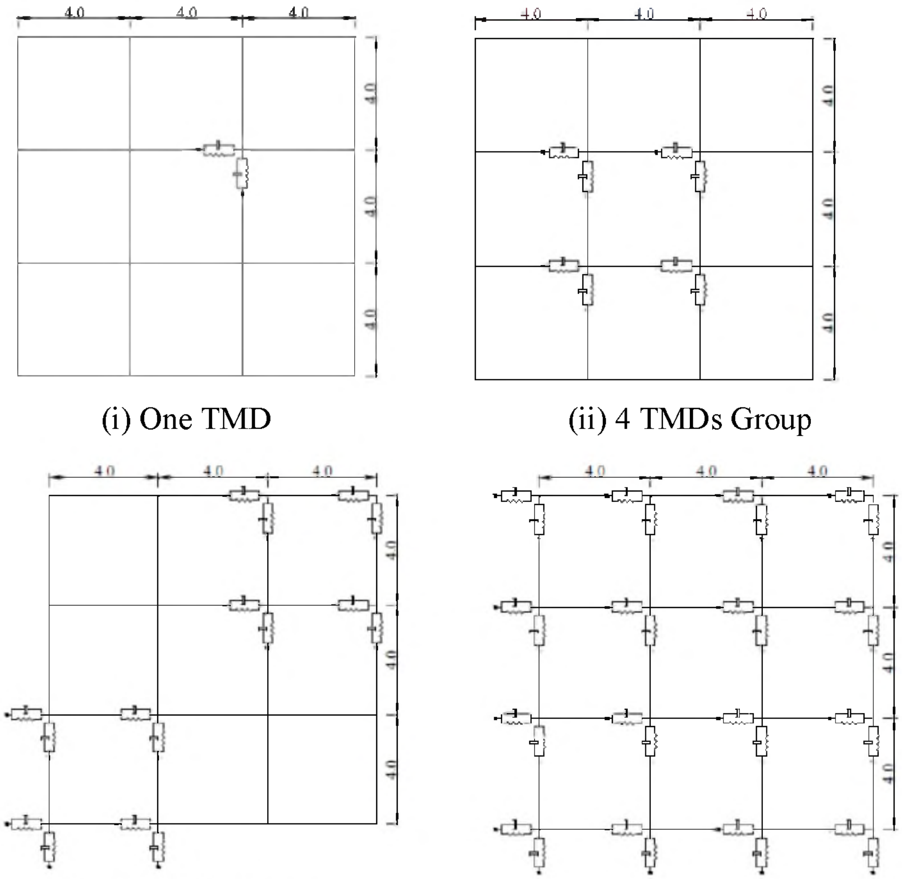


Figure 6. Plan of TMD components in X and Y directions (Farghaly, 2012)

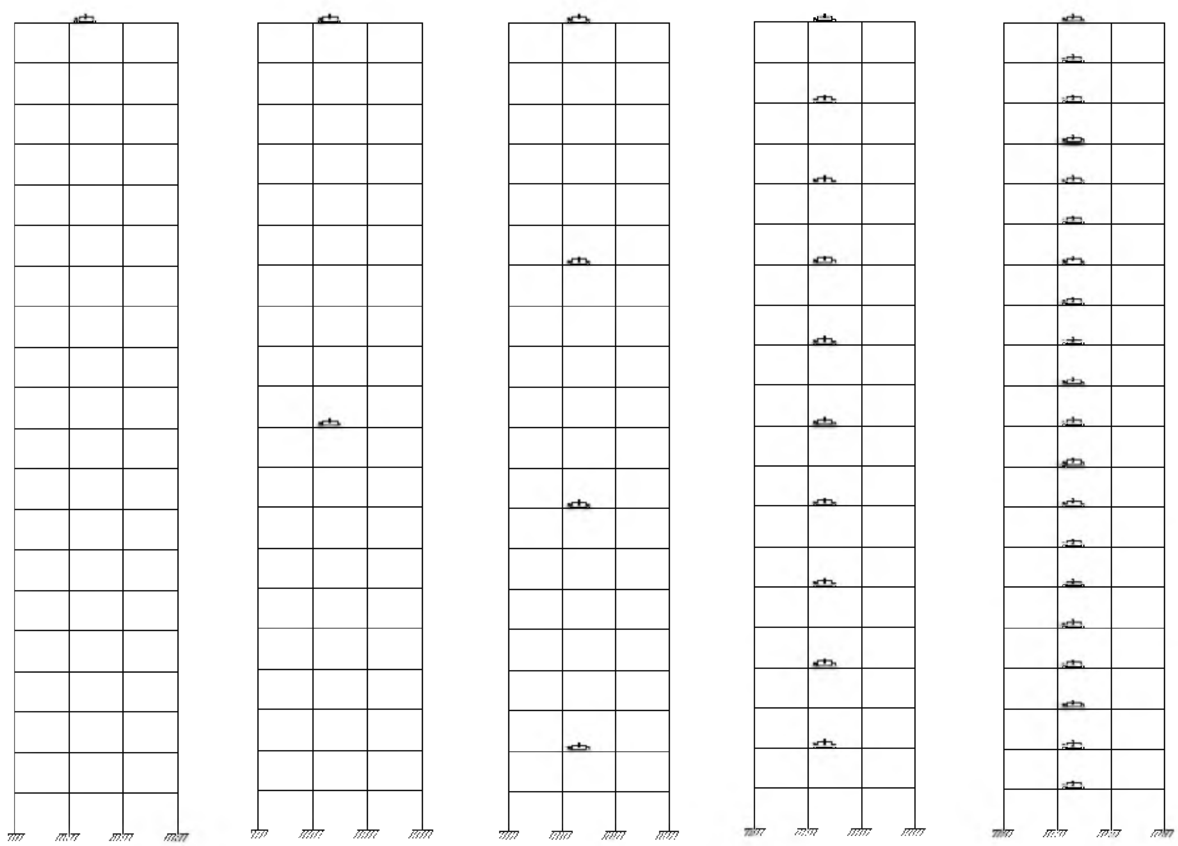
For the MTMD systems, there were 20 different scenarios based on TMD placement; there were four horizontal distributions and five vertical distributions as shown in Figures 7 and 8. The 20 scenarios are named with abbreviations, such as XxX. The first X represents the number of TMD on a floor plan, and the second X represents the number of TMD distributed along the elevation of the model. The scenarios are described in Table 6.



(i) One TMD (ii) 4 TMDs Group

(iii) 8 TMDs Group (iv) 16 TMDs Group

Figure 7. Horizontal arrangement of TMDs on floor plan (Farghaly, 2012)



(i) One TMD (ii) 2 TMDs (iii) 4 TMDs (iv) 10 TMD (v) 20 TMDs

Figure 8. Vertical arrangement of TMDs on model elevation (Farghaly, 2012)

Table 6. TMD Scenarios

Scenario	**Abbreviation**	**TMD Placement**
1	1x1	(1) TMD, one TMD on the 20th floor at the right corner of the core on the floor plan (see Figure 7(i) and 8(i))
2	1x2	(2)TMD, one at the right corner of the core of the 20th and 10th floors (see Figure 7(i) and 8(ii))
3	1x4	(4) TMD, one at the right corner of the core on the 2nd, 8th, 14th and 20th floors (see Figure 7(i) and 8(iii))
4	1x10	(10) TMD, one at the right corner of the core on the 2nd, 4th, 6th, 8th, 10th 12th, 14th, 16th, 18th and 20th floors (see Figure 7(i) and 8(iv))
5	1x20	(20) TMD, one at the right corner of the core on all floors (see Figure 7(i) and 8(v))

6	4x1	(4) TMDs on the (4) core columns of the first floor (see Figure 7(ii) and 8(i))
7	4x2	(8) TMDs on the (4) core columns of the 20^{th} and 10^{th} floors (see Figure 7(ii) and 8(ii))
8	4x4	(16) TMDs on the (4) core columns of the 2^{nd}, 8^{th}, 14^{th} and 20^{th} floors (see Figure 7(ii) and 8(iii))
9	4x10	(40) TMDs on the (4) core columns of the 2^{nd}, 4^{th}, 6^{th}, 8^{th}, 10^{th}, 12^{th}, 14^{th}, 16^{th}, 18^{th} and 20^{th} floors (see Figure 7(ii) and 8(iv))
10	4x20	(80) TMDs on the (4) core columns of all floors (see Figure 7(ii) and 8(v))
11	8x1	(8) TMDs at two corners of the floor plan on the 20^{th} floor (see Figure 7(iii) and 8(i))
12	8x2	(16) TMDs at two corners of the floor plan on the 20^{th} and 10^{th} floors (see Figure 7(iii) and 8(ii))
13	8x4	(24) TMDs at two corners of the floor plan on the 2^{nd}, 8^{th}, 14^{th} and 20^{th} floors (see Figure 7(iii) and 8(iii))
14	8x10	(80) TMDs at two corners of the floor plan on the 2^{nd}, 4^{th}, 6^{th}, 8^{th}, 10^{th}, 12^{th}, 14^{th}, 16^{th}, 18^{th} and 20^{th} floors (see Figure 7(iii) and 8(iv))
15	8x20	(160) TMDs at two corners of the floor plan on all floors (see Figure 7(iii) and 8(v))
16	16x1	(16) TMDs attached to each column on the floor plan on the 20^{th} floor (see Figure 7(iv) and 8(i))
17	16x2	(16) TMDs attached to each column on the floor plan on the 20^{th} and 10^{th} floors (see Figure 7(iv) and 8(ii))
18	16x4	(16) TMDs attached to each column on the floor plan on the 2^{nd}, 8^{th}, 14^{th} and 20^{th} floors (see Figure 7(iv) and 8(iii))
19	16x10	(16) TMDs attached to each column on the floor plan on the 2^{nd}, 4^{th}, 6^{th}, 8^{th}, 10^{th}, 12^{th}, 14^{th}, 16^{th}, 18^{th} and 20^{th} floors (see Figure 7(iv) and 8(iv))
20	16x20	(16) TMDs attached to each column on floor plan on all floors (see Figure 7(iv) and 8(v))

The TMDs were modeled as link elements that represent springs and dashpots. The initial set of TMD properties are provided in Table 7. These properties include spring stiffness k_d, damping coefficient of damper c_d, and relative damping ζ_{opt}.

Table 7. Properties of TMDs used in the testing models in both X, Y directions with equal total mass (Farghaly, 2012)

No. TMDs	Mass (ton)	Weight	Mass Ratio	Frequency Ratio	Damping Ratio	kd	cd	Total Mass (ton)
1	216	2118.96	0.05	0.94	0.22852141	152.789	83.029	216
2	108	1059.48	0.025	0.97	0.16459168	40.597	21.797	216
4	54	529.74	0.0125	0.985	0.11747973	10.467	5.586	216
8	27	264.87	0.006	0.992	0.08345648	2.658	1.414	216
10	21.6	211.896	0.005	0.994	0.07470693	1.706	0.907	216
16	13.5	132.435	0.003	0.996	0.05918555	0.67	0.356	216
20	10.8	105.948	0.002	0.997	0.05296199	0.429	0.228	216
32	6.75	66.2175	0.002	0.998	0.04178818	0.168	0.089	216
40	5.4	52.974	0.001	0.998	0.03731952	0.108	0.057	216
64	3.375	33.10875	0.001	0.9984	0.03484131	0.0594	0.0312	216
80	2.7	26.487	0.001	0.999	0.02592593	0.027	0.014	216
160	1.35	13.2435	0	1	0.02057378	0.007	0.004	216
320	0.68	6.6708	0	1	0.01355815	0.002	0.001	217.6

Using the above properties, however, produced inconsistencies in results. For example, the results shown in Figure 9 illustrate that all the systems provide the same overall displacement within a given range. Logically, this did not make sense given that the expectation should be a clear decrease in displacement with increased numbers of TMDs.

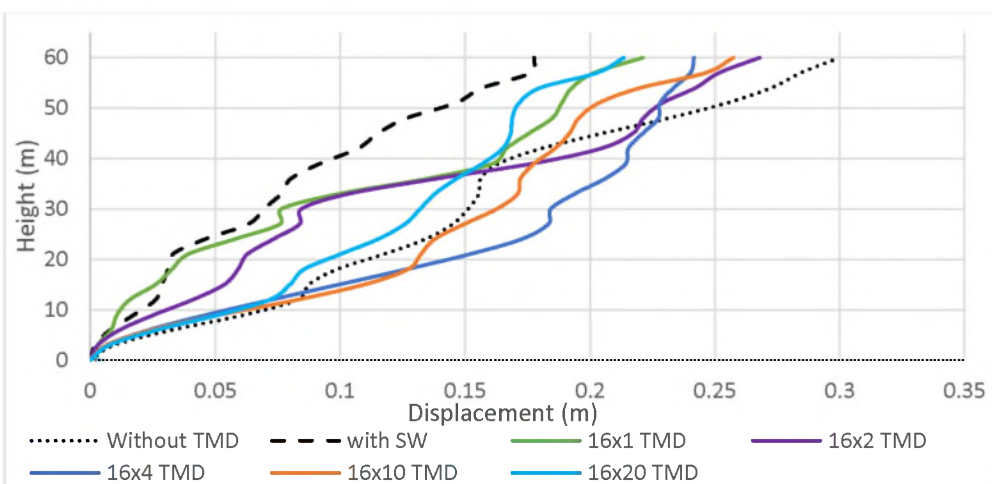


Figure 9: Comparison of displacement of models without TMD, with Shear wall, and scenarios 16-20 with the equal TMD total mass.

After conducting a mass analysis on the TMD systems, it was concluded that the reason the displacement did not show any reduction is that all TMD systems have equal value of total mass. When the quantity of TMDs is multiplied by its mass for each system, we get the same total mass that equals 216 tons. By changing the mass distribution alone, Figure 9 shows this does not create a significant impact.

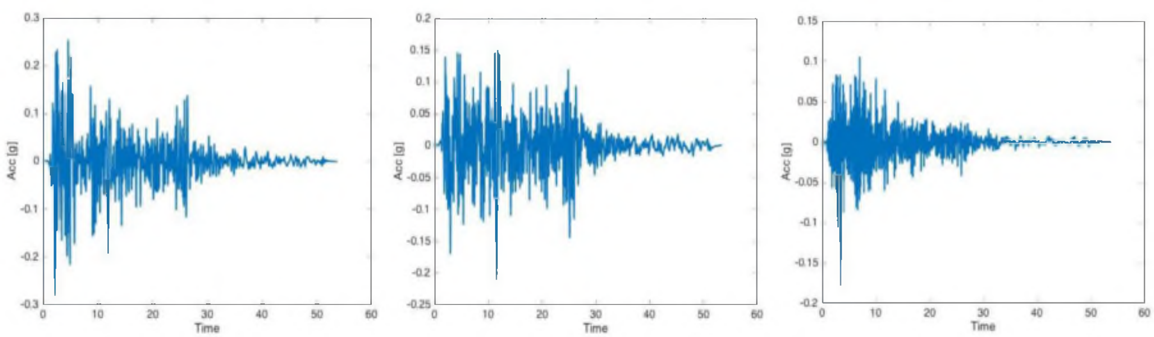
Based on the comparison of results, it was concluded that the Farghaly properties did not accurately reflect the true TMD system used. As a result, this study adjusted this table as shown in Table 8 increasing the amount of mass present for each scenario. This effectively introduces not only a variation of TMD placement but also a redistribution of mass in the structure. This produced more variation in distribution as expected and will be discussed further in the Results section.

Table 8. Properties of TMDs in both X, Y directions with different total mass

No. TMDs	Mass (ton)	Weight	Mass Ratio	Frequency Ratio	Damping Ratio	k	c	Total Mass (ton)
1	216	2118.96	0.05	0.94	0.22852141	152.789	83.029	216
2	216	2118.96	0.05	0.94	0.22852141	152.789	83.029	432
4	216	2118.96	0.05	0.94	0.22852141	152.789	83.029	864
8	216	2118.96	0.05	0.94	0.22852141	152.789	83.029	1728
10	216	2118.96	0.05	0.94	0.22852141	152.789	83.029	2160
16	216	2118.96	0.05	0.94	0.22852141	152.789	83.029	3456
20	216	2118.96	0.05	0.94	0.22852141	152.789	83.029	4320
32	216	2118.96	0.05	0.94	0.22852141	152.789	83.029	6912
40	216	2118.96	0.05	0.94	0.22852141	152.789	83.029	8640
64	216	2118.96	0.05	0.94	0.22852141	152.789	83.029	13824
80	216	2118.96	0.05	0.94	0.22852141	152.789	83.029	17280
160	216	2118.96	0.05	0.94	0.22852141	152.789	83.029	34560
320	216	2118.96	0.05	0.94	0.22852141	152.789	83.029	69120

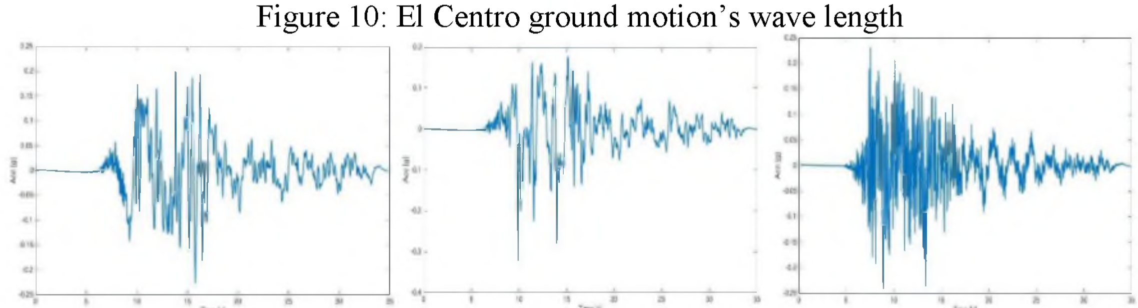
5. Results

Using SAP2000, a linear dynamic analysis was conducted using two different ground motions: 1940 El Centro, Imperial Valley (Figure 10) and 1999 Kocaeli, Turkey (Figure 11). El Centro is along Imperial Valley Fault. It is considered a mild earthquake as its magnitude is 6.95 M_w, its peak ground acceleration is at 2.9 m/s^2, and it has a short period. While Kocaeli is located along North Anatolian Fault, its magnitude is 7.6 M_w, its peak ground acceleration is at 2.3 m/s^2 and it has a long period.



(a) Horizontal 180 (b) Horizontal 270 (c) Vertical

Figure 10: El Centro ground motion's wave length



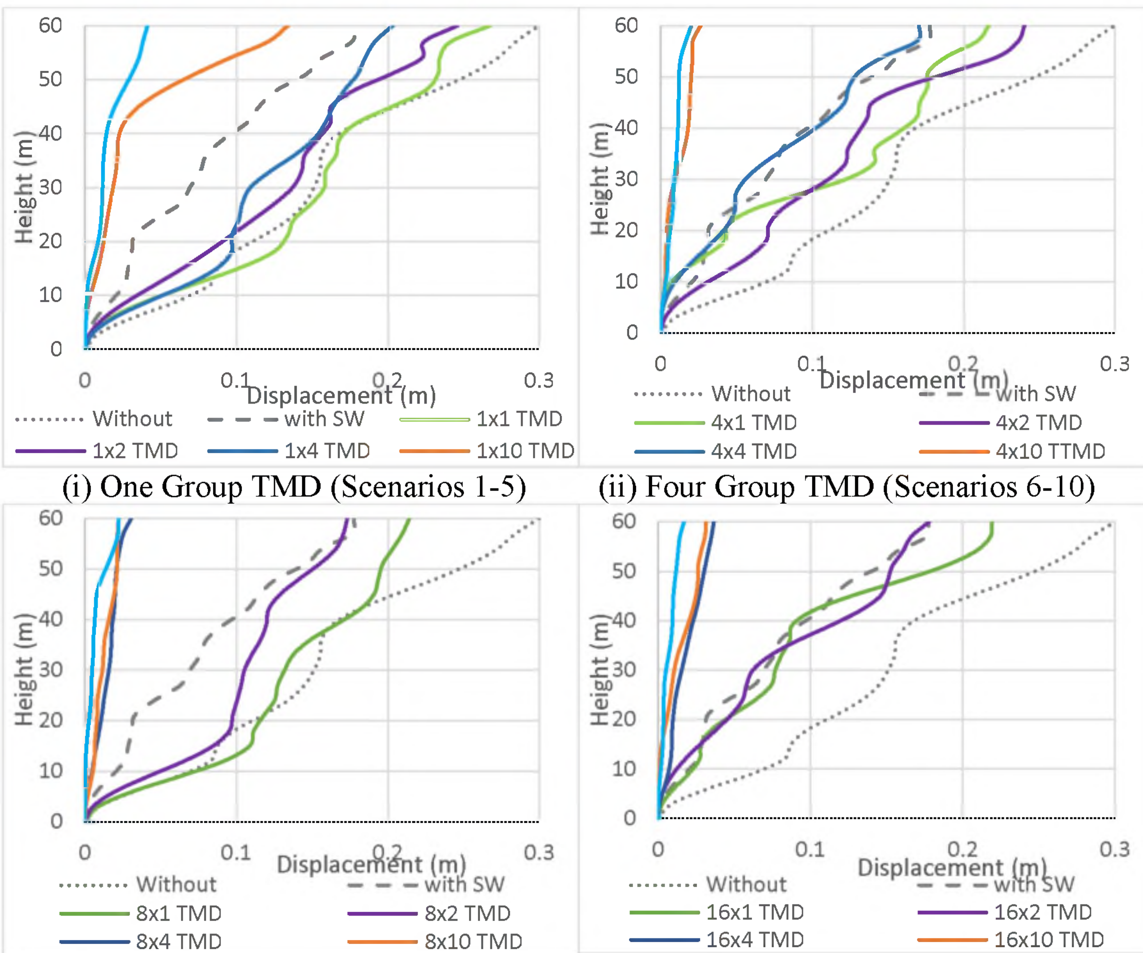
(b) Horizontal 60 (b) Horizontal 150 (c) Vertical

Figure 11: Kocaeli ground motion's wave length

From these analyses, the seismic responses of interested included: story displacements, the shear force for scenarios 1-5 and 16-20, and accelerations of the system without TMD or SW for scenarios 1, 3, 6,10 and 20 in the X direction and scenarios 3, 6, and 20 in the Z direction. The following presents highlights from these results with additional plots presented in the Appendix.

5.1 El Centro

Figure 12 shows the displacements of each system under El Centro. Firstly, structures with TMDs have reduced displacement by 90% at most compared with structures without any TMD. Generally, this reduction is observed to increase as the number of TMDs increases both vertically and horizontally. The highest reductions were observed in Scenario 20 (16x20) with the lowest displacement being 0.2m. The reductions then occur in the following order 8x20, 16x10,4x20, 8x10, 4x10, 16x4, 1x20, 8x4, 8x2, 1x10, SW, 4x4, 16x2, 4x2, 16x1, 1x4, 1x2, 4x1, 8x1 and 1x1 TMDs.



(i) One Group TMD (Scenarios 1-5) (ii) Four Group TMD (Scenarios 6-10)

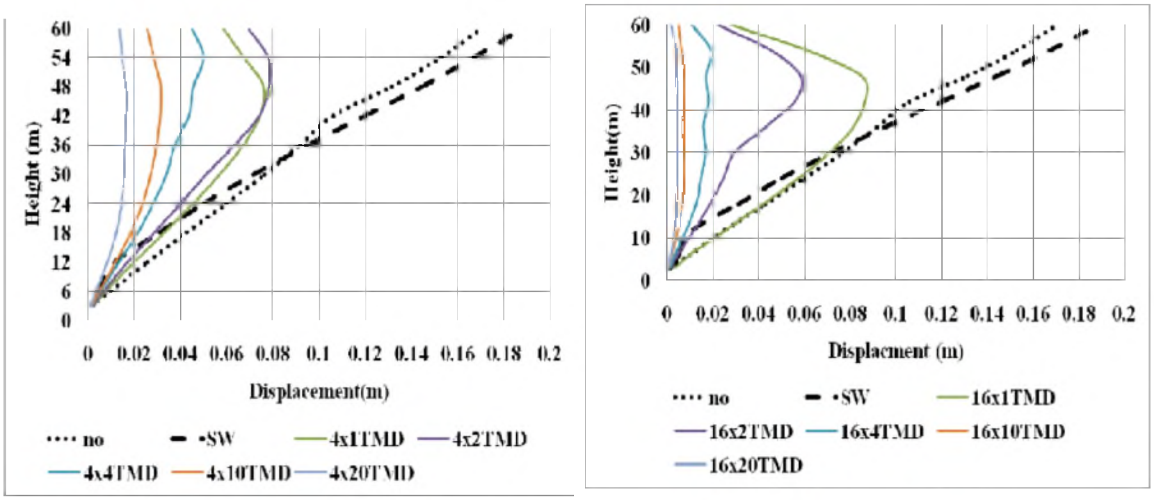
(iii) Eight Group TMD (Scenarios 11-15) (iv) Sixteen Group TMD (Scenarios 16-20)

Figure 12. Comparison of Displacements Across Structural Profile under (El Centro) seismic load with different arrangements of TMDs

Each of the scenarios have varying mass contributions to the structure. As a result, let us compare two systems with the same total TMD mass but with a different distribution. For example, the 1x4 and 4x1 TMD (Scenarios 3 and 6) have equal total mass but two different distributions. In this case, the 1x4 scenario produces lower displacements than the 4x1 scenario by 16%. This can be observed in comparisons including the 4x2 versus 8x1; 16x1 versus 8x2 versus 4x4; and numerous other scenarios. This indicates that vertical distribution of the TMD is more effective in reducing the displacement of structures than horizontal distribution.

However, the most optimum distribution of TMDs is both on the floor plan and through the elevation of the model at the same time to have the most controlled behavior as scenario 20. The reduction of displacement mostly depends on the number of TMDs, then it is observed that vertical TMDs are more effective than horizontal TMDs, in systems with the same amount of TMD total mass.

Figure 13 illustrates the Farghaly's displacements results across structural profile under seismic (El Centro) load with different arrangements of TMDs. It is this paper's standing that the results presented here are more accurate than Farghaly's. His plots show that the maximum displacements are at the mid-height of the model which does not seem reasonable given that Table 5 shows that the dimensions of the reinforced concrete beams are larger at the bottom floors and smaller on the top floors. Therefore, the displacement of floors should increase ascendingly at the top floors, as weaker columns are more affected by earthquake loads.



(i) Four Group TMD (Scenarios 6-10) (ii) Sixteen Group TMD (Scenarios 16-20)

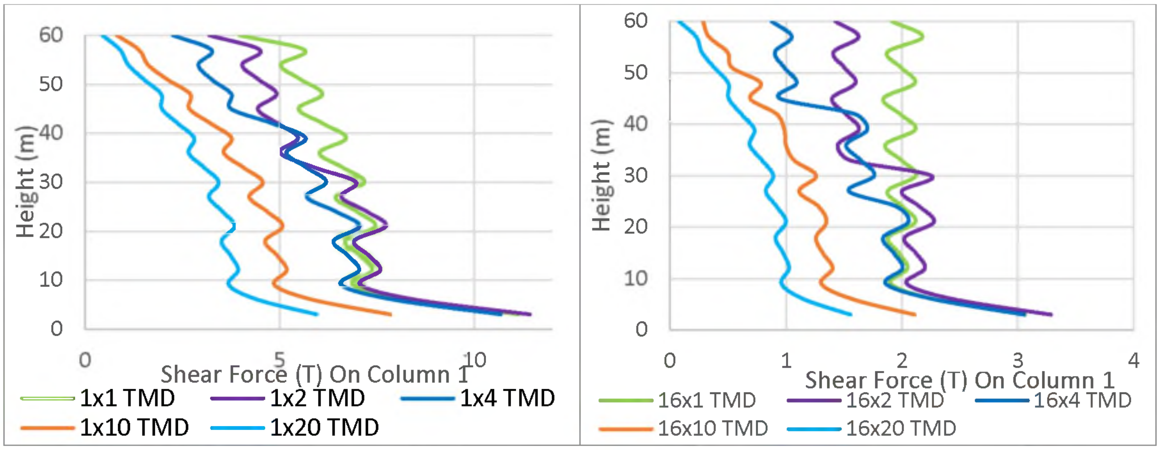
Figure 13. Comparison of Author's Displacements Across Structural Profile under seismic (El Centro) load with different arrangements of TMDs (Farghaly, 2012)

Figure 14 shows the results of shear forces on four chosen columns under (El Centro) earthquake load using the twenty different TMDs arrangements. (Note: The most pertinent plots are displayed in this section with the remaining plots in Appendix A.) Figure 5 illustrates where the four chosen columns are located on the floor plan. By adding more TMD to the system, this effectively reduces shear force in the column thus will control the structure's reaction to earthquake load.

Figure 14(c) shows that Column 3 in the twenty systems has the highest shear force, the reason being is because it is located at the corner of the model as Figure 5 illustrates, and therefore it has to resist the more lateral load. On the other hand, the shear force results of Column 2 have the lowest shear force, because Column 2 is located around the core of the building, thus it resists lower lateral load. However, it still has a high shear force at the base of the structure.

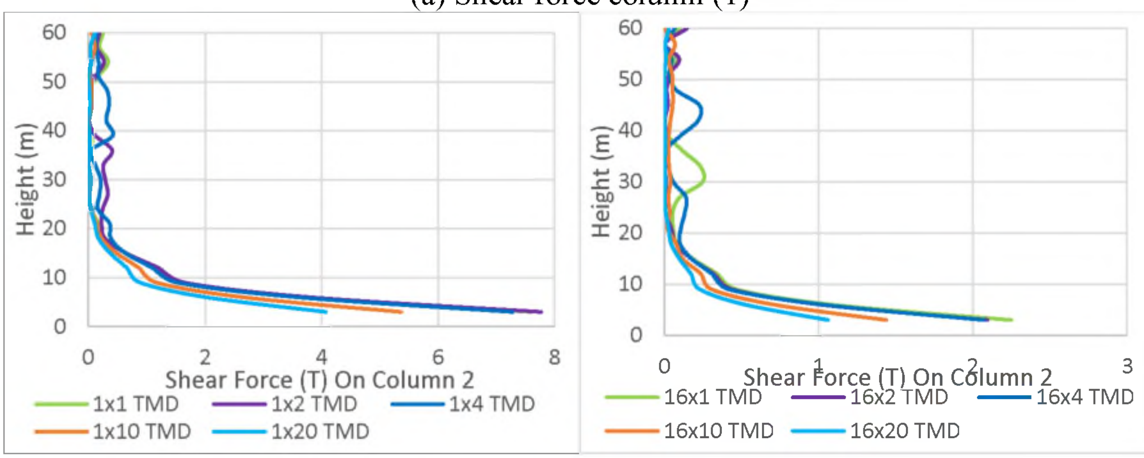
The ratios between shear force at the top of the model of columns (1) without TMD or shear wall is approximately 20 times higher than the system with the most number of TMD (16x20) scenario 20, as figures 14 (e) and (a)iv show. For column (2), 16x20 TMDs decrease base shear to approximately zero, for columns (3), 16x20 TMDs decrease base shear by approximately 20 times, and for columns (4) by 5 times.

Each of the scenarios has varying mass contributions to the structure. As a result, let us compare two systems with the same total TMD mass but with a different distribution. For example, the 1x4 and 4x1 TMD (Scenarios 3 and 6) have equal total mass but two different distribution. In this case, the 1x4 scenario produces lower shear force than 4x1. This can be observed in comparisons including the 4x2 versus 8x1; 16x1 versus 8x2 versus 4x4; and numerous other scenarios. This indicates that vertical distribution of the TMD is more effective in reducing the shear force on structures than horizontal distribution, which is the same as displacement results observation.



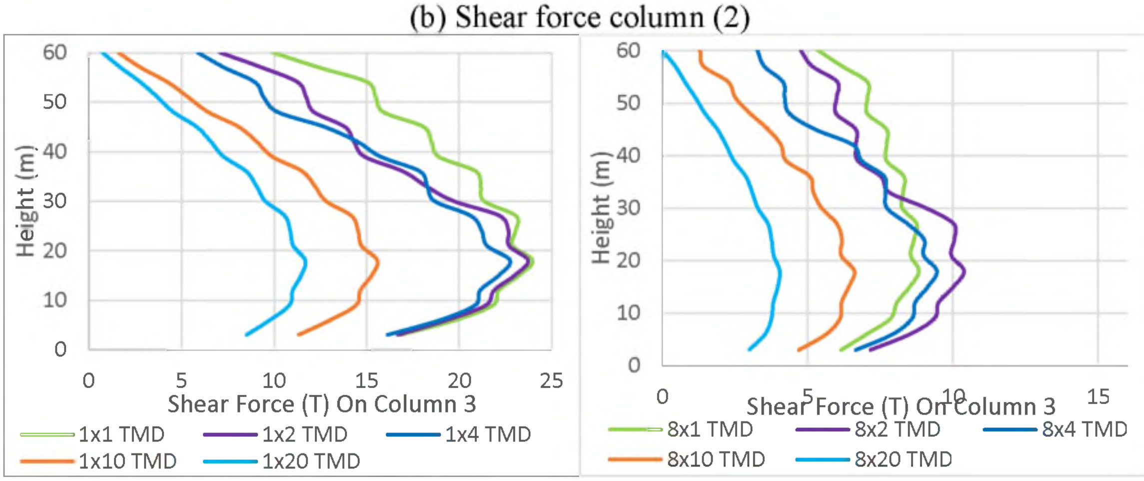
(i) One Group TMD (iv) Sixteen Group TMD

(a) Shear force column (1)



(i) One TMD (iv) Sixteen Group TMD

(b) Shear force column (2)



(i) One TMD (iii) Eight Group TMD

(c) Shear force column (3)

Figure 14. Comparison of Shear Forces of the model under (El Centro) Seismic load with different arrangements of TMDs

Figures 15 through 21 illustrate the period versus acceleration at the base, 1st floor, mid-length and top of the model, when the structure is undamped, equipped with shear wall, single TMD and group of TMDs with different arrangements. The acceleration was recorded in the X, Y and Z directions. (Note: The most pertinent plots are displayed in this section with the remaining plots in Appendix B.)

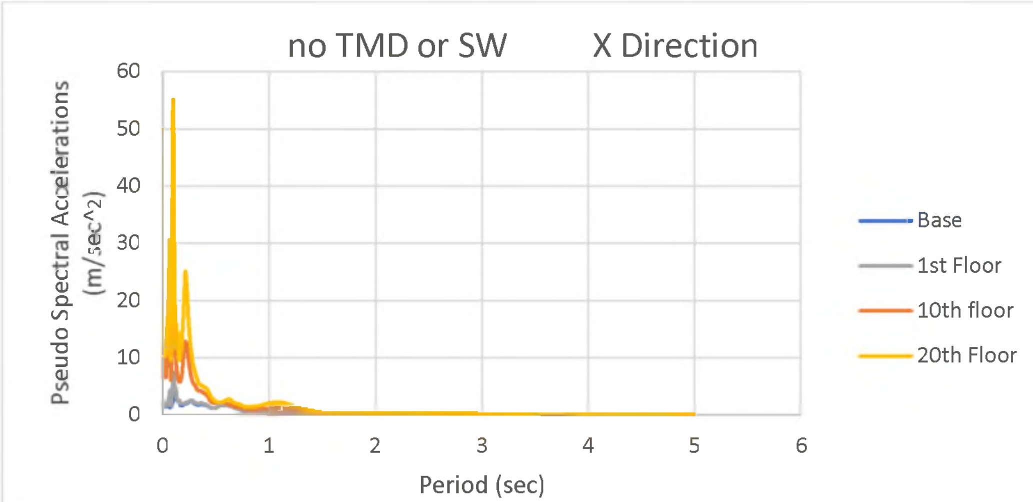
The maximum acceleration was recorded at the top of the undamped system which is nearly equal to 55 m/s^2. The more TMDs added to the system, the more the acceleration at the top of the model decreases. Interestingly, adding TMDs reduces acceleration at the top and mid-length of the model but does not reduce the acceleration at the base. Thus, the acceleration at the top of the mid-lengths that are equipped with many TMDs could become lower than the acceleration at the base of the structure especially for Scenario 20 as Figure 21 illustrates

Using TMDs does reduce the acceleration in the Z or vertical direction, even though the TMD was not designed to have a spring and dashpot in the Z direction as Figure 6 illustrates. However, using TMDs does not make the acceleration at the top floor to be lower than the acceleration at the base in the Z direction; except in scenario 20, when the acceleration at the top floor reached zero, the TMD began to control the behavior of structure in the Z direction by reducing the acceleration of the top floor to be lower than the acceleration at the base. I had the same observation using the second ground motion.

The ratios between the acceleration at the top point of the undamped system is approximately 70 times higher than the system with the most number of TMD (Scenario 20). This indicates that when we increase number of TMDs utilized in the model, the more the reduction of structural vibration, especially those distributed both on floor plan and through the elevation of the model.

Each of the scenarios have varying mass contributions to the structure. As a result, let us compare two systems with the same total TMD mass but with a different distribution. For example, the 1x4 and 4x1 TMD (Scenarios 3 and 6) have equal total mass but two different distributions. In this case, both scenarios have different reactions, in such that the 4x1 scenario accelerates more than 1x4 scenario as Figures 18 and 19.

Based on my acceleration, shear force and displacement results, we can conclude that the systems with TMDs distributed vertically along the elevation of the model, are more effective in controlling the performance of structures than the TMDs systems that are distributed horizontally on the floor plan of the model.



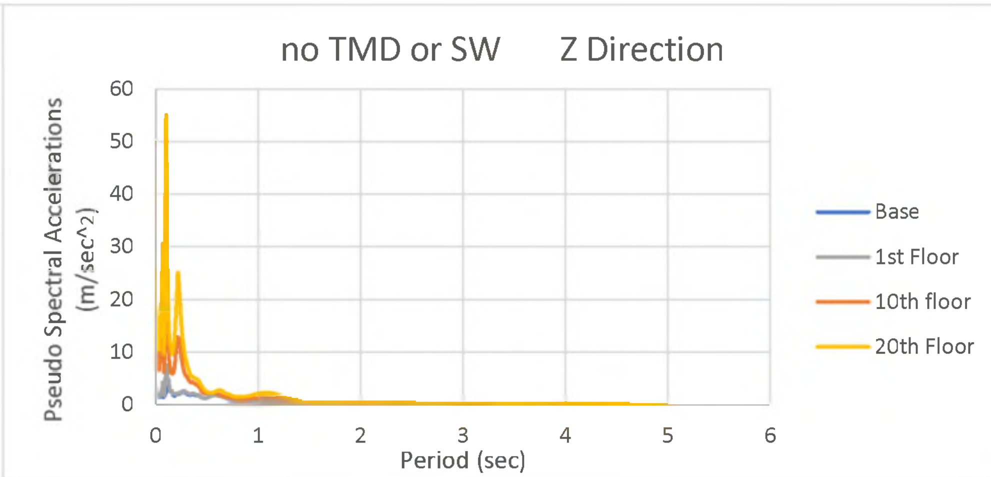


Figure 15. Period vs. Pseudo Acceleration Spectral using No TMD and SW

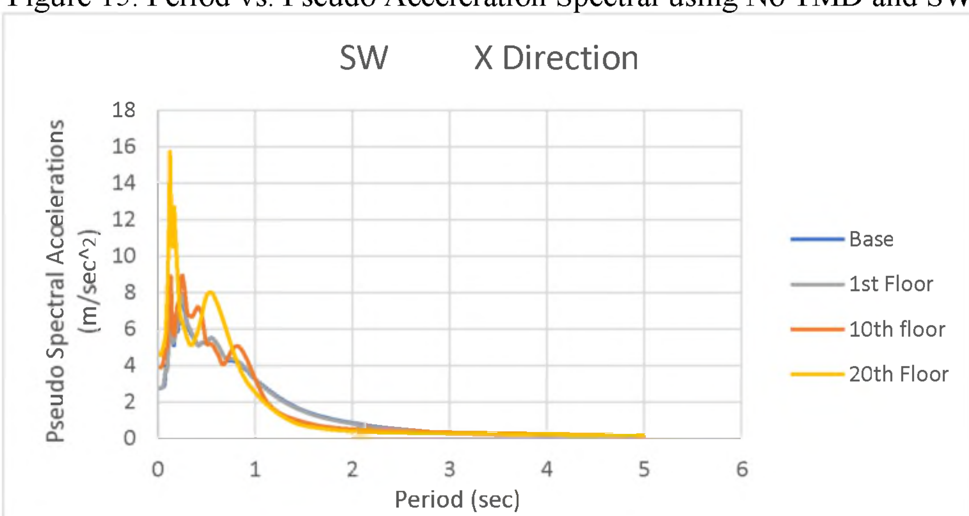


Figure 16. Period vs. Pseudo Acceleration Spectral using Shear Wall

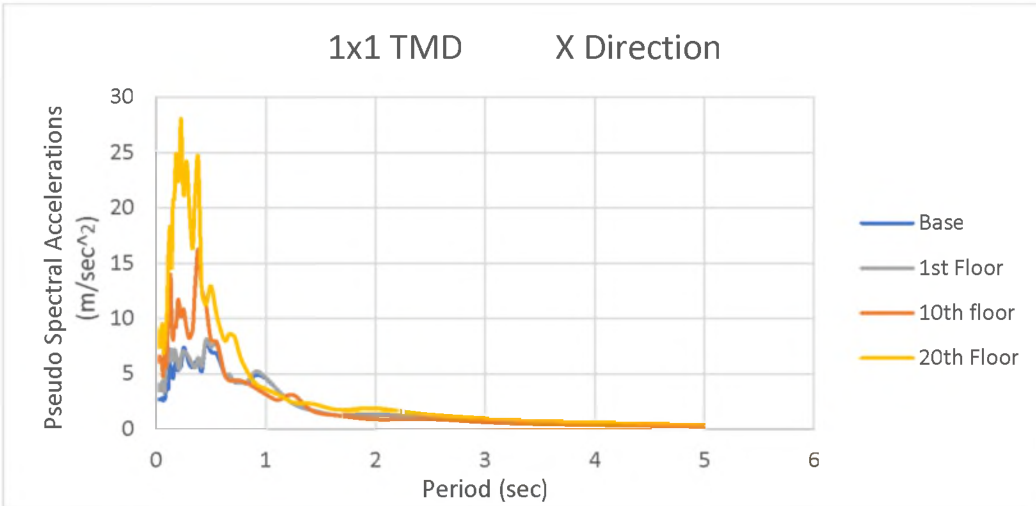


Figure 17. Period vs. Pseudo Acceleration Spectral using 1x1 TMD

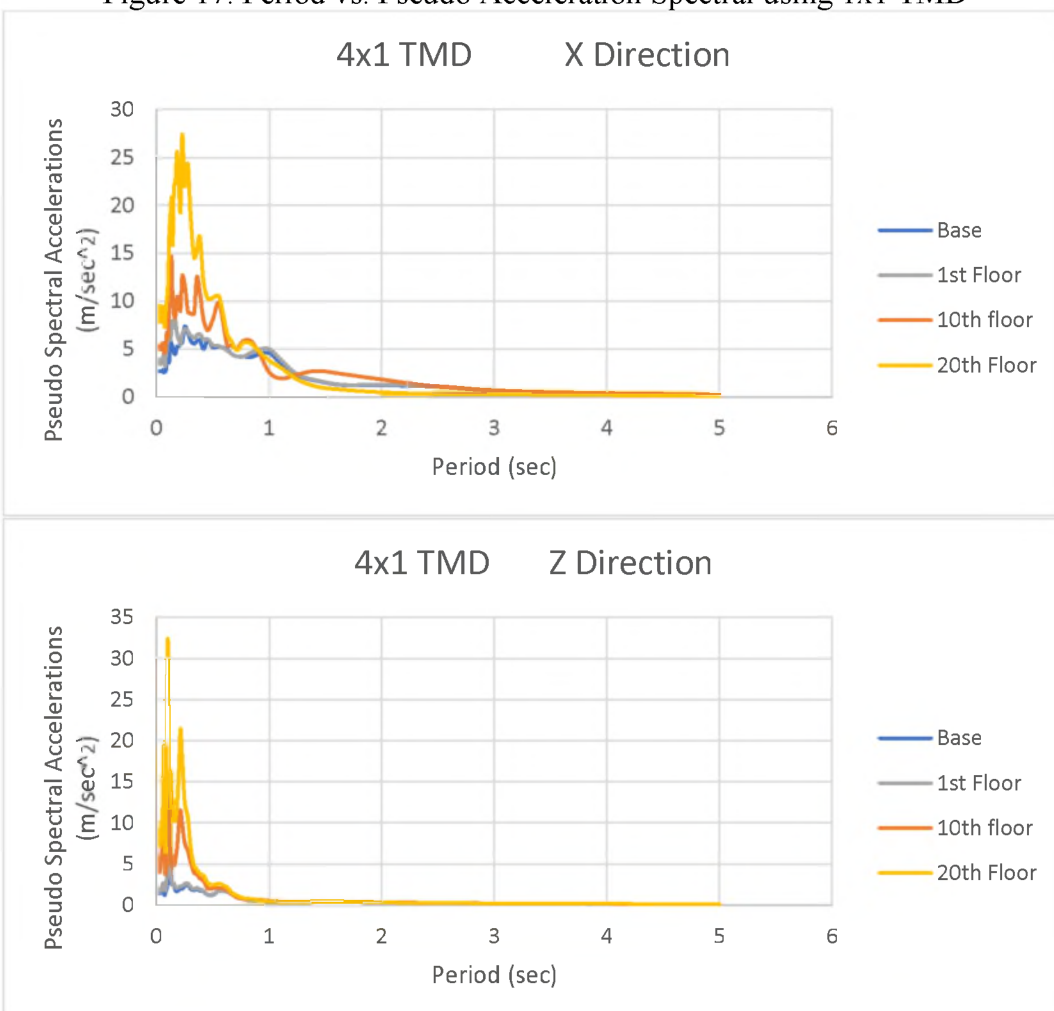


Figure 18. Period vs. Pseudo Acceleration Spectral using 4x1 TMD

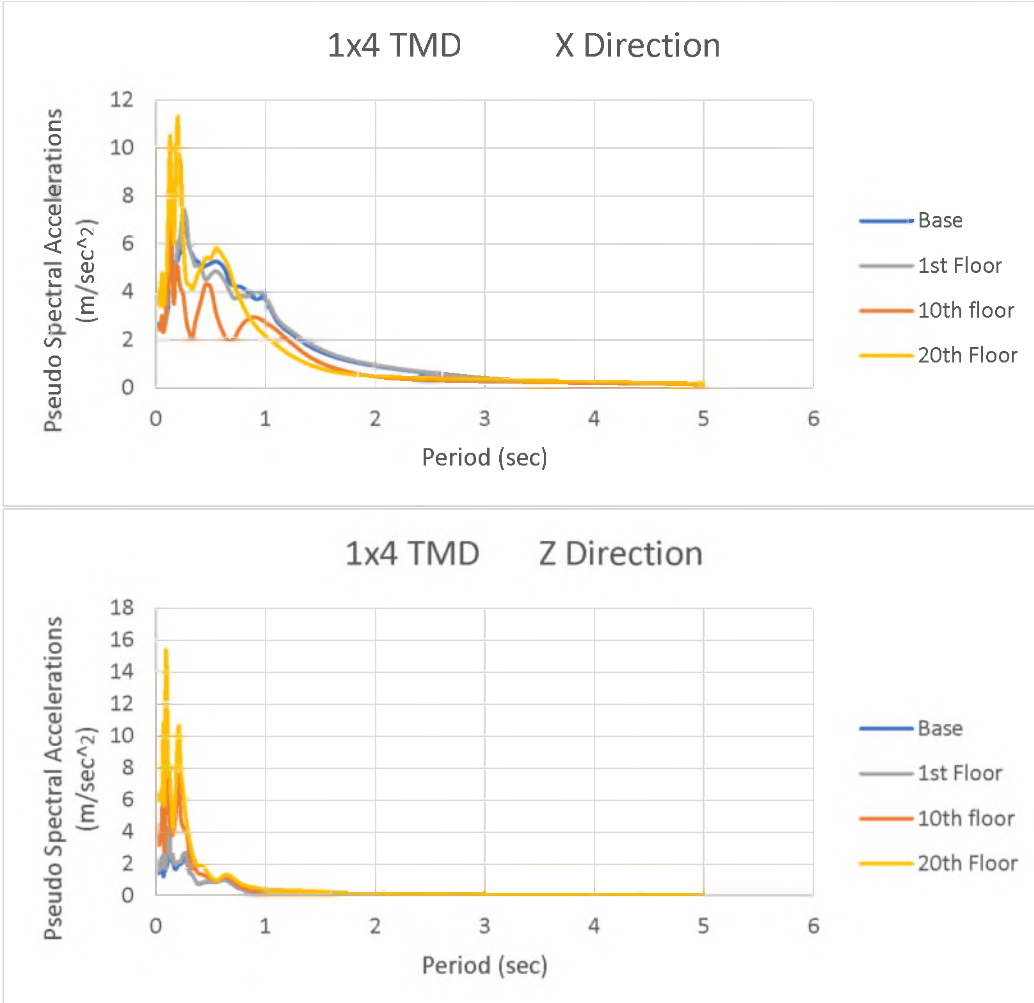


Figure 19. Period vs. Pseudo Acceleration Spectral using 1x4 TMD

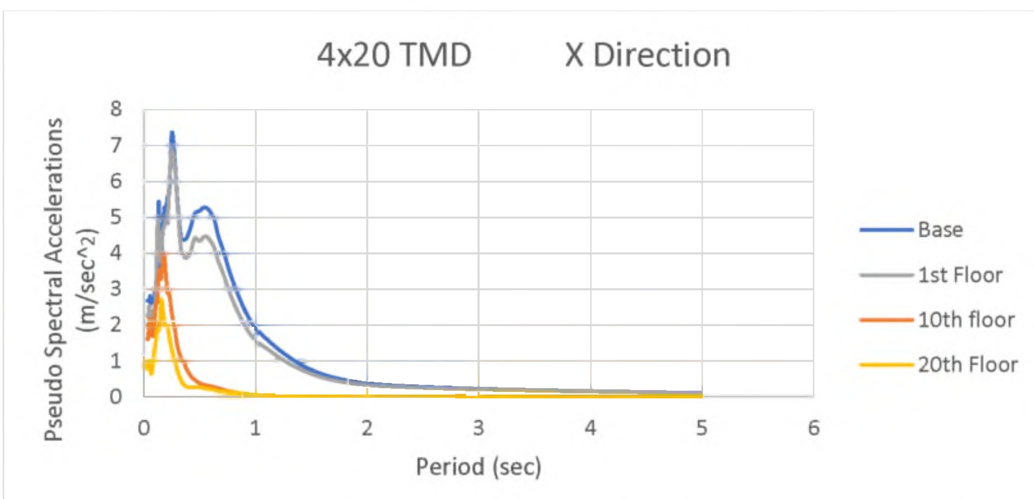


Figure 20. Period vs. Pseudo Acceleration Spectral using 4x20 TND

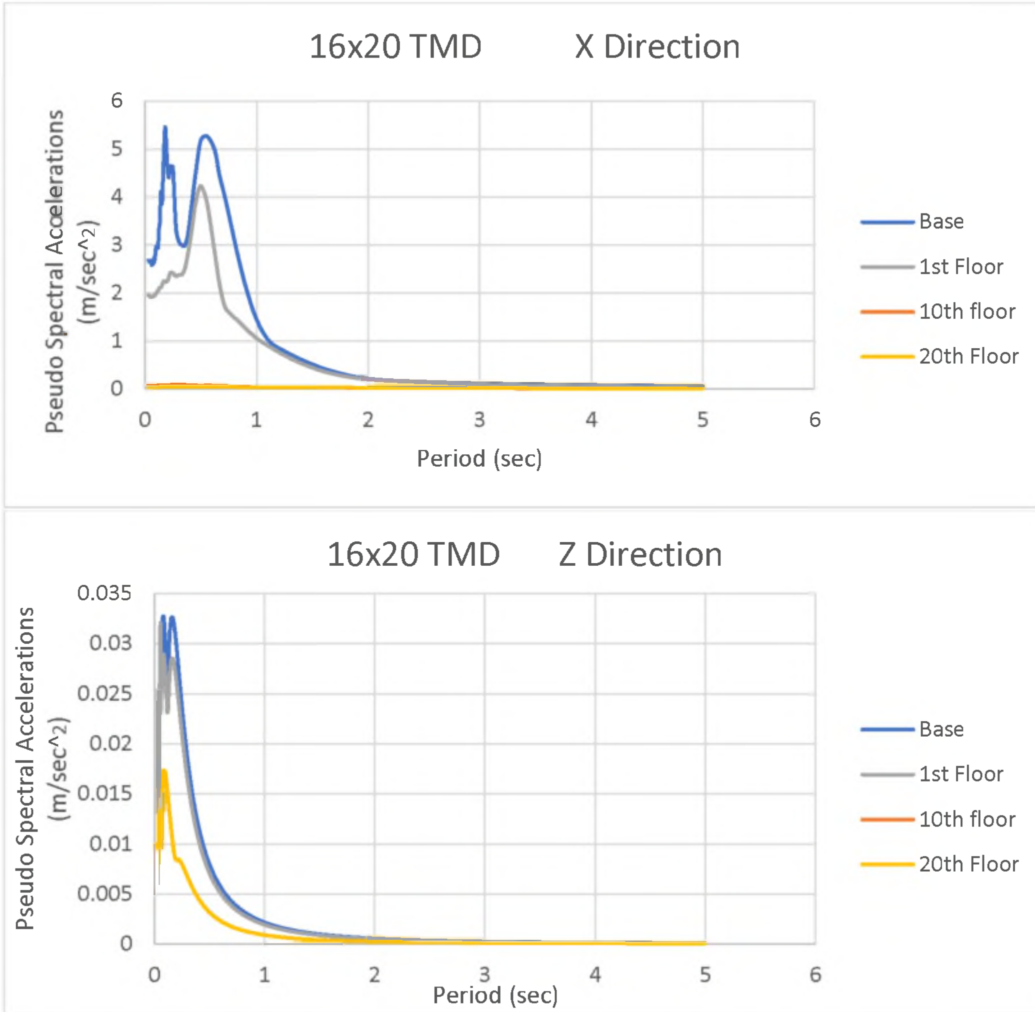


Figure 21. Period vs. Pseudo Acceleration Spectral using 16x20 TMD

5.2 Kocaeli

Figure 22 on page 47 shows the displacements of each system under the Kocaeli earthquake using several distributions of TMDs. First, it can be observed that the systems with more TMDs have higher displacement reduction compared with the systems with few TMDs or the system without any TMD under the second ground motion as well. Utilizing TMD systems turned out to be 5% more effective in reducing displacement under Kocaeli compared with El Centro ground motion, as Figure 12 and 22 illustrate.

It can also be observed that the second ground motion has a slightly lower displacement than the first ground motion for the system with the most number of TMDs (Scenario 6). 16x20 TMD system (Scenario 6) has almost zero displacement, which indicates that utilizing TMD can control the vibration of structures up to 100%, especially those distributed both in floor plan and through the elevation of the model.

Secondly, the system with the shear wall has a very similar reaction as the system without TMD at the top of the model but has lower displacement at the mid-length of the model. On the other hand, the shear wall has a lower displacement value undergo the first ground motion compared to the second ground motion. This indicates that systems equipped with concrete shear wall could have the same effect as the ones equipped with moment resistance frame, but this could change depending on the ground motion.

The high performance of the arrangement group in reducing displacements of floors appears in 16x20 TMDs then 8x20, 4x20,16x10, 16x4, 4x10, 8x4, 16x2, 8x2, 16x1, 4x4, 1x20, 8x1, 1x10, 1x4, 4x1, 4x2, 1x2, 1x1 TMDs. It is interesting that the model has an almost equal displacement on the 17th floor when equipped with 8x2-20 TMDs.

However, the most optimum distribution of TMDs is both on the floor plan and through the elevation of the model at the same time in order to have the most controlled behavior.

The displacement results under kocaeli ground motion are different from El Centro ground motion. TMD systems turned out to be 5% more effective in reducing displacement under Kocaeli ground motion, but the system without any TMD or SW showed the exact displacement under both ground motion. This indicates that TMD systems behave differently to ground motions, in such, that they show more reduction under earthquakes with larger wavelength.

On the other hand, the displacement results under Kocaeli ground motion does not show that vertical distribution of TMD is more effective in reducing the displacement than horizontal distribution, as 1x4 and 4x1 have very similar displacement reactions. This indicates that the fact that vertical distribution is more effective in reducing the behavior of structure than horizontal distribution is only observed when using ground motion that has a short wavelength.

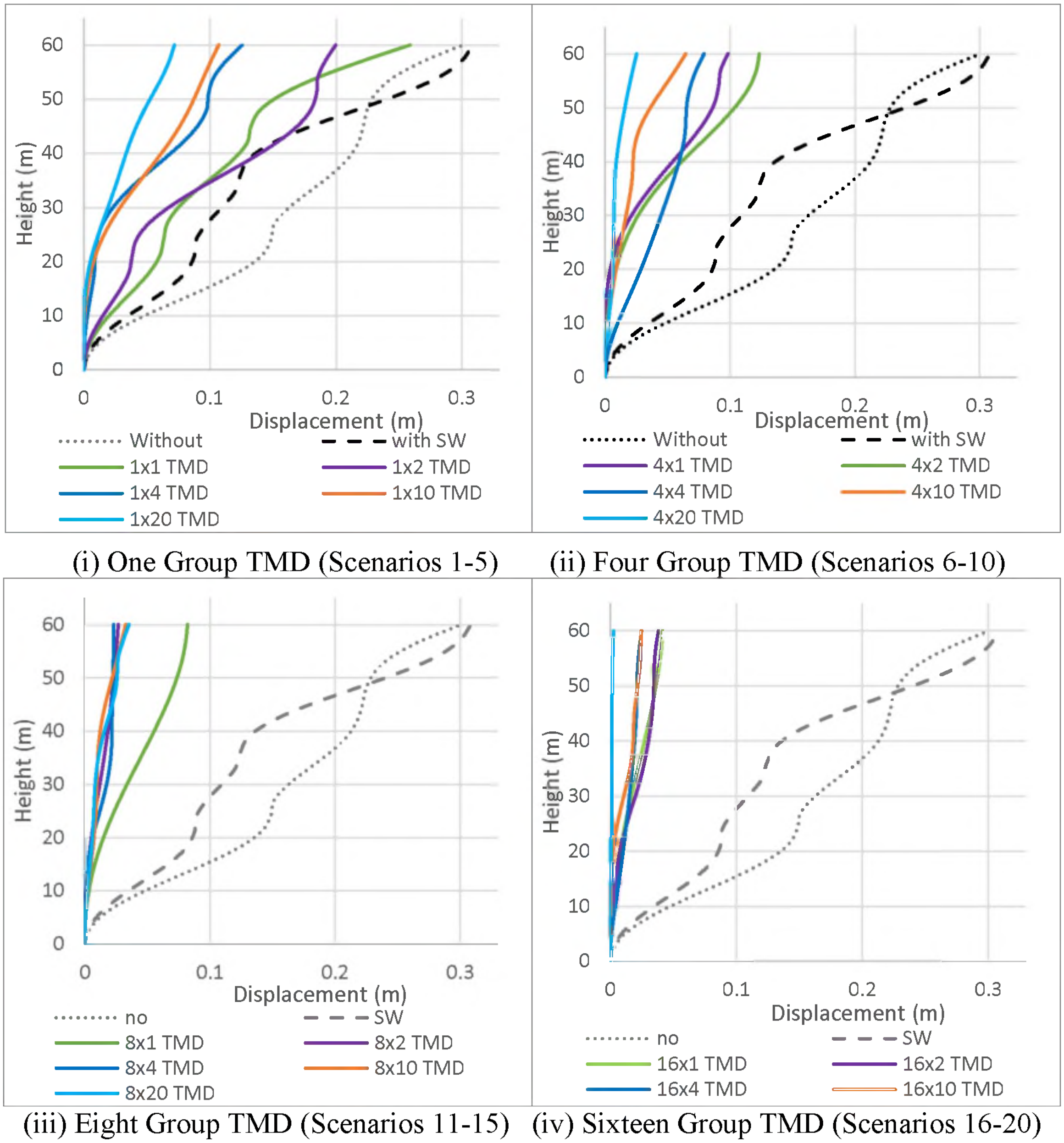


Figure 22. Comparison of Displacements Across Structural Profile under (Kocaeli) seismic load with different arrangements of TMDs

Figure 23 on page 50 shows the results of shear forces on four chosen columns under Kocaeli. Figure 5 illustrates where the four chosen columns are located on the floor plan.

The most pertinent plots are presented here with the additional evidence provided in Appendix C.

It is obvious that adding more TMD to the system will reduce the shear force in each column thus will control the structure's reaction to earthquake load, using the second ground motion as well.

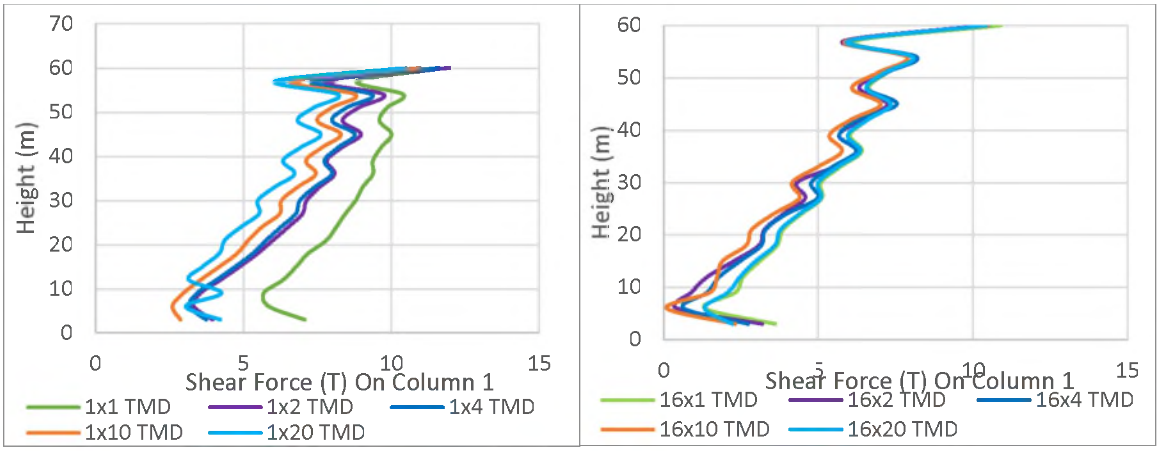
We also observed that in some cases like Figure 23(b)iii column 2 increased the shear force when adding more TMD rather than decreasing it, it happened when a system with the shear force equals zero, adding more TMD would cause the structure to have counter-reaction which increased the shear force. However, if we look at it from the bigger picture, we would notice that the shear force is decreasing, as Figure 23(b)iv illustrates.

The shear force results under Kocaeli Ground motion are in the same range as the shear force results under El Centro ground motion. The most obvious difference in the results is that under ECentro ground motion, the shear force in column 2 did not increased when adding more TMD rather than decreasing it, as we observed under El Centro ground motion. This indicates that TMD does not cause counter-reaction under ground motions with short wavelength as El Centro, while Kocaeli ground motion caused the TMD to make counter-reaction which increased the shear force in column 2 that has close to zero shear force values.

We can observe from Figure 23(c) that Column 3 in the twenty systems has the highest shear force, the reason being is because it is located in the corner of the model as Figure 5 illustrates, and therefore it has to resist more lateral load. On the other hand, Column 2 in the twenty systems has the lowest shear force, because it is located around the core of the building, thus it resists less lateral load, but it still has high shear force at the base of the structure.

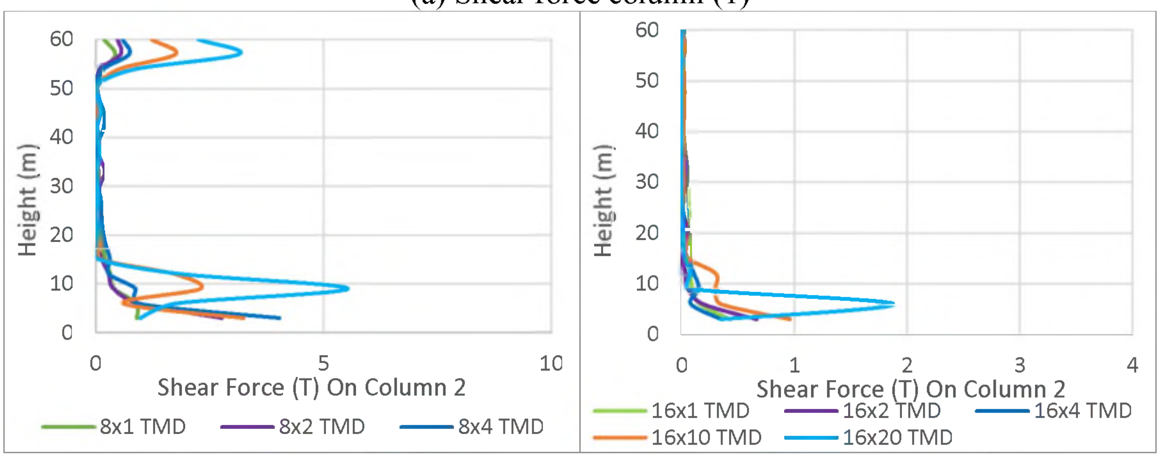
The ratios between the top shear force of columns (1) without TMD or shear wall is approximately 50 times higher than the system with the most number of TMD (16x20) Scenario 6, as Figures 23(e) and 23(a)iv show. For column (2), base shear stayed close to zero at the top of the model, and the application of TMD did not show any improvements because column 2 resists a small amount of lateral load. For columns (3), 16x20 TMDs decrease base shear of by approximately 50 times, and for columns (4) by 5 times.

In addition, the system with concrete shear wall also has higher shear force using the second ground motion than the system without or with TMD, which is the same observation from the author's results in Figure 15.



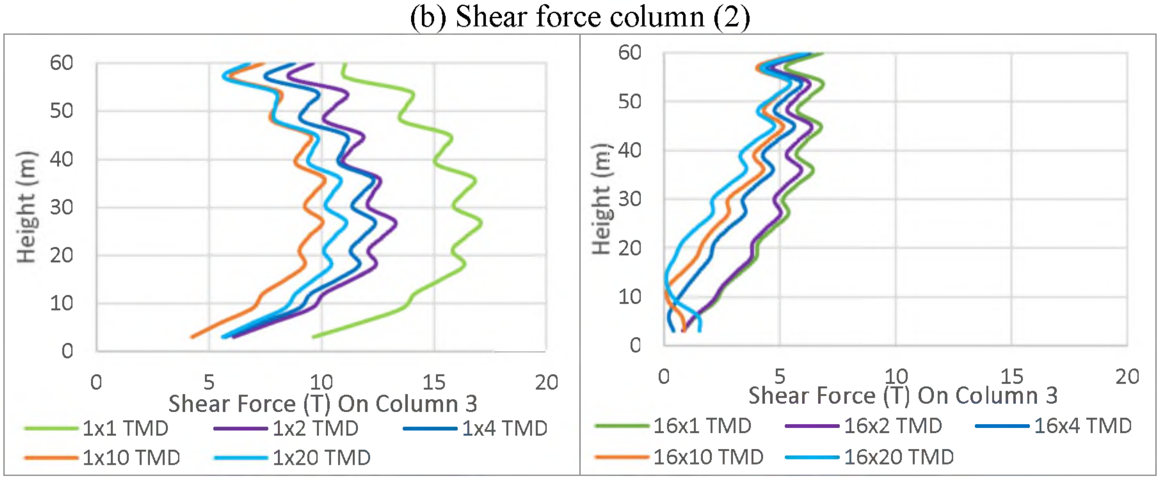
(i) One Group TMD (iv) Sixteen Group TMD

(a) Shear force column (1)



(iii) Eight Group TMD (iv) Sixteen Group TMD

(b) Shear force column (2)



(i) One Group TMD (iv) Sixteen Group TMD

(c) Shear force column (3)

Figure 23. Comparison of shear forces of the model under (Kocaeli) Seismic load with different arrangements of TMDs

Figures 24 through 30 on pages 53 through 57 illustrate the period versus acceleration of the model under (Kocaeli) ground motion excitation at the base, 1^{st} floor, mid-length and top of the model, when the structure is undamped, equipped with shear wall, single TMD and group of TMDs with different arrangements. The acceleration was recorded in the X, Y and Z directions. I pulled the most pertinent plots from the entire results section and put the remaining plots that further back up my argument in Appendix D.

The maximum acceleration was recorded at the top of the undamped systems which is nearly equal to 22.5 m/s^2 as Figure 24 shows. The acceleration of the second ground motion is less than the acceleration of the first ground motion by almost 3 times, the reason being is that Kocaeli ground motion has larger wave length than El Centro ground motion as Figures 10 and 11 illustrate.

Interestingly, adding TMDs reduces acceleration at the top and mid-length of the model but does not reduce the acceleration at the base. Thus, the acceleration at the top of the models that are equipped with many TMDs could become lower than the acceleration at the base of the structure as Figure 29 illustrate, which is the same results we observed using the first ground motion.

On the other hand, the TMD does not reduced the acceleration in the Z direction, which indicates that two directional TMD does not control the behavior of structure in the third direction under ground motions that have a longer period.

The ratios between the acceleration at the top point of the undamped system is approximately 32 times higher than the system with the most number of TMD (Scenario 20). This indicates that when we increase the number of TMDs utilized in the model, the more the reduction of structural vibration, especially those distributed both on floor plan and through the elevation of the model.

Each of the scenarios has varying mass contributions to the structure. As a result, let us compare two systems with the same total TMD mass but with different distributions. For example, 1x4 and 4x1 TMD systems, that have the same TMD total mass but have different distributions, we will observe that both have different reactions, in such that 1x4 has less acceleration than 4x1 at the mid-length of the structure, but higher acceleration than 4x1 at the top of the structure, which is different than the reaction under the first ground motion. Here, we can also conclude that the fact that vertical distribution of TMD is more effective than horizontal distribution of TMD is only observed when running the structure under ground motions with short period as El Centro.

The acceleration results under Kocaeli and El Centro ground motions have some things in common such as the acceleration at the top floor reduces and become lower than the acceleration at the base in X and Y direction. On the other hand, the acceleration reduction is different under the two ground motions, which indicates that two directional TMD have different effect in reducing the acceleration in Z direction under ground motions with different periods.

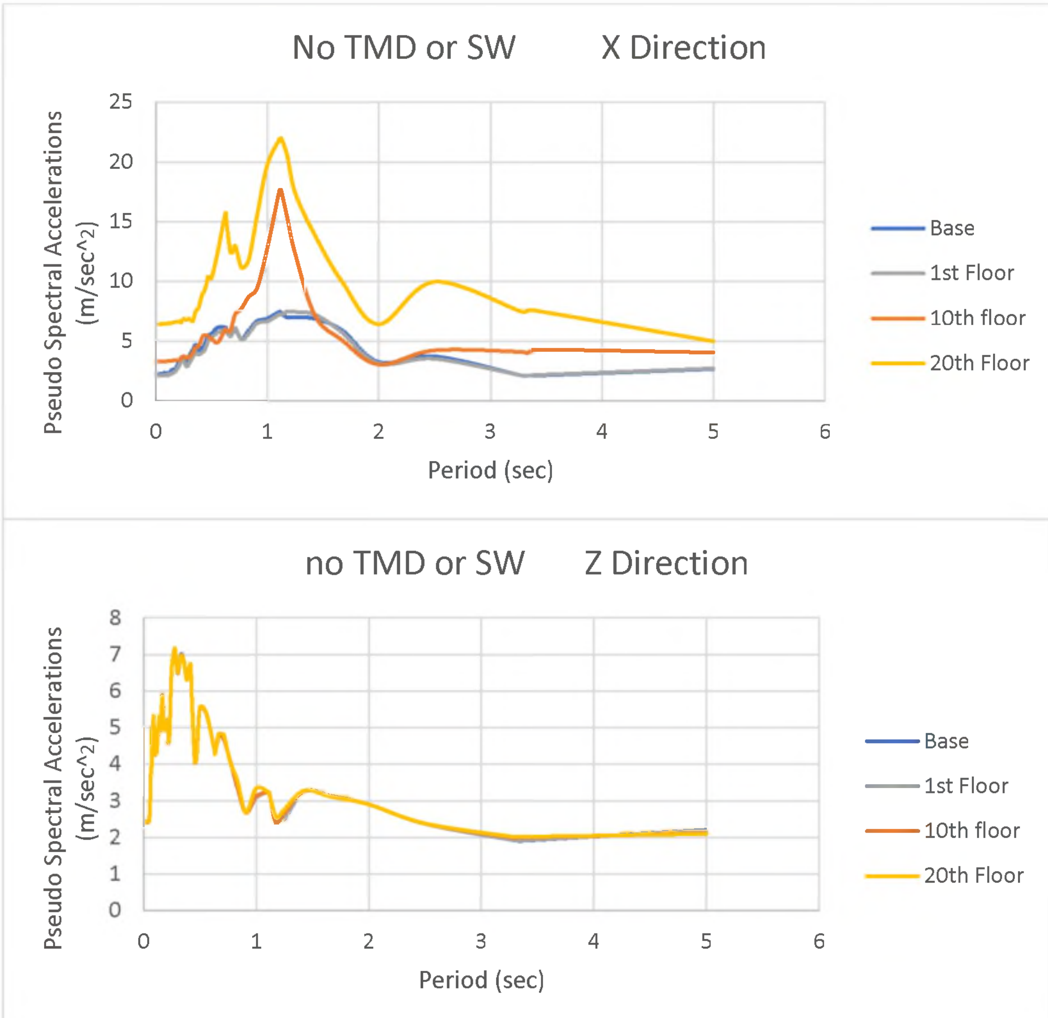


Figure 24. Period vs. Pseudo Acceleration Spectral using no TMD or SW

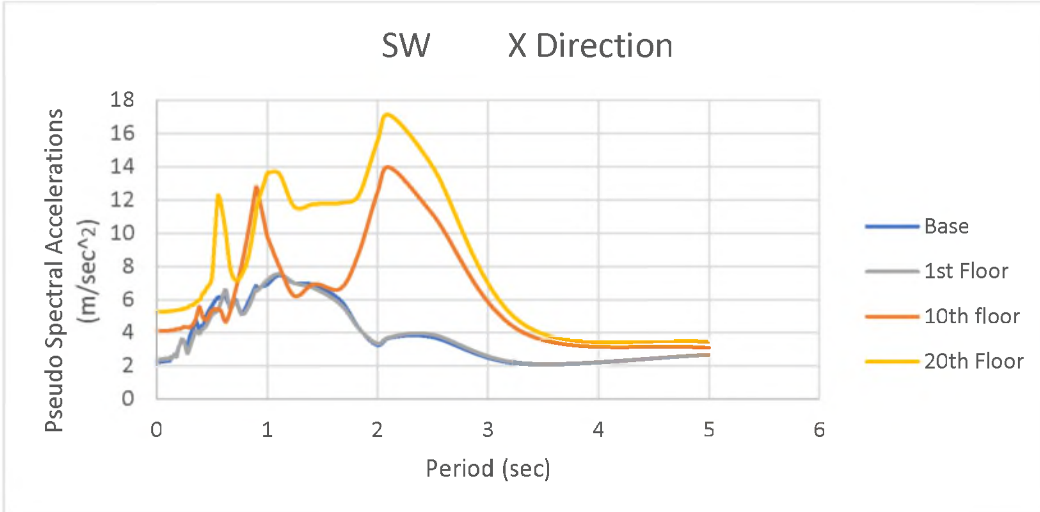


Figure 25. Period vs. Pseudo Acceleration Spectral using Shear Wall

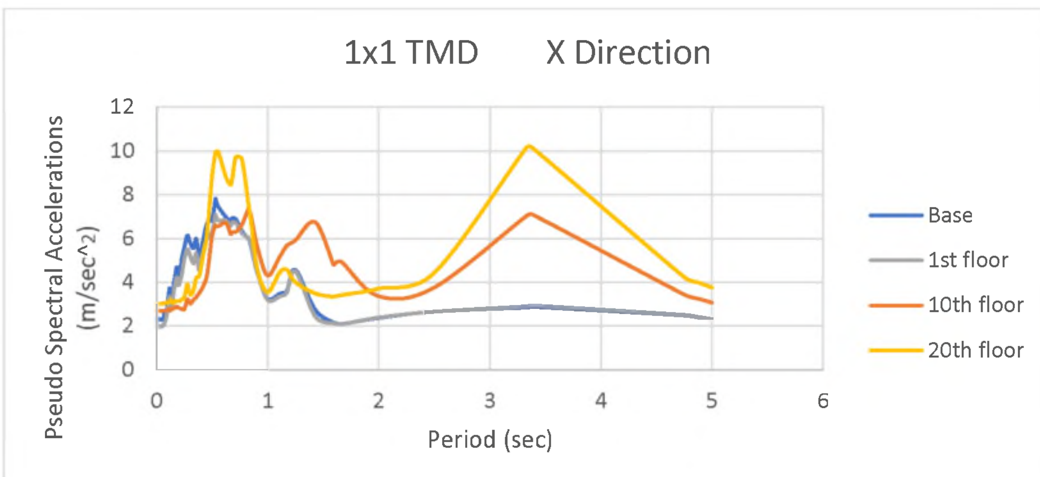
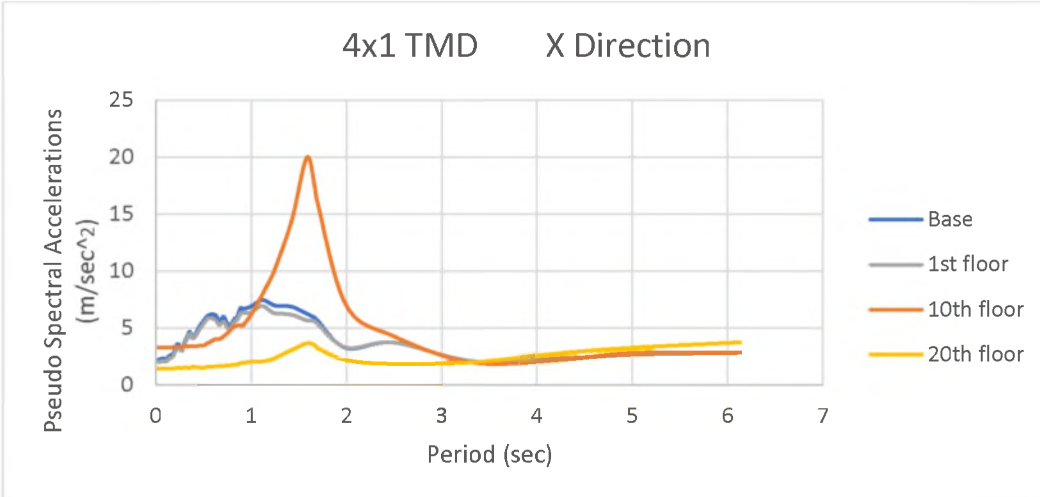


Figure 26. Period vs. Pseudo Acceleration Spectral using 1x1 TMD



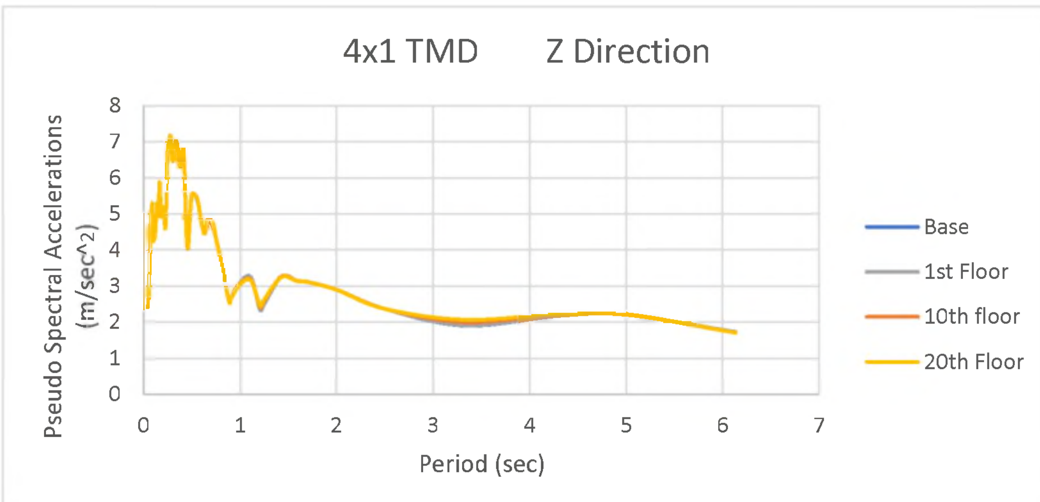


Figure 27. Period vs. Pseudo Acceleration Spectral using 4x1 TMD

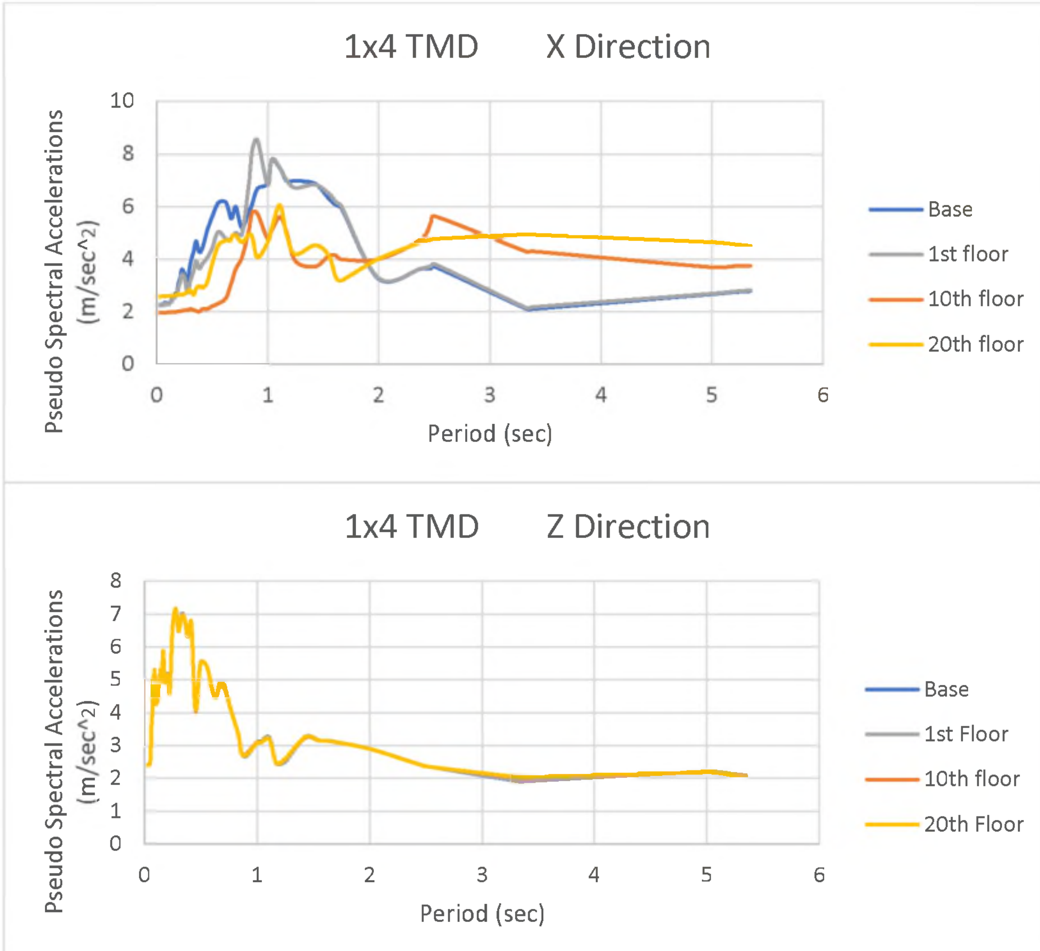


Figure 28. Period vs. Pseudo Acceleration Spectral using 1x4 TMD

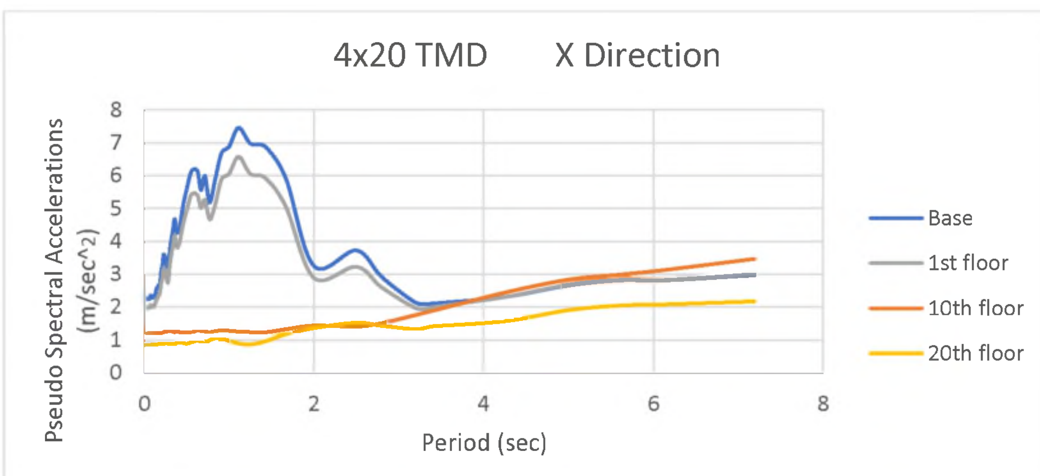


Figure 29. Period vs. Pseudo Acceleration Spectral using 4x20 TMD

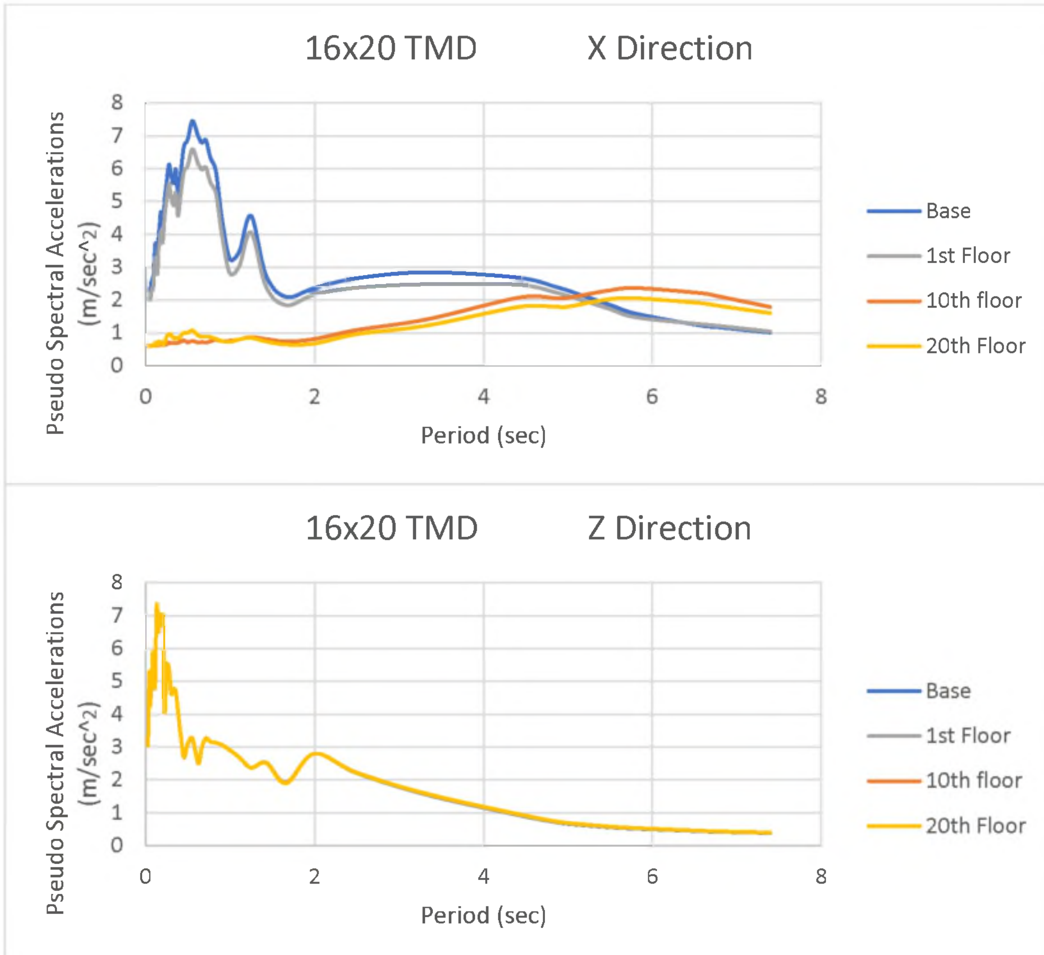


Figure 30. Period vs. Pseudo Acceleration Spectral using 16x20TMD

6. Conclusion

In this paper, I tested the efficiency of utilizing MTMD in a 20 story height building, and quantified the changes in seismic response due to the distribution of TMDs across a given story and through the elevation using time history analysis. The following conclusions can be drawn from the present study:

1. The response of structures, such as displacement, shear force, and acceleration, can be dramatically mitigated by using MTMD.

2. Adding TMD devices to the structure without increasing the total TMD mass doesn't reduce the dynamic behavior of structure. In other words, whatever the amount of total TMD mass increases, the reduction in dynamic response also increases.

3. The systems with TMDs that are distributed vertically along the elevation of the model, are more effective in controlling the performance of structures than the TMDs systems that are distributed horizontally on the floor plan of the model, especially under earthquakes with short wavelength.

4. Two directional TMD can control the behavior of structure in the third direction, only under ground motions with short period.

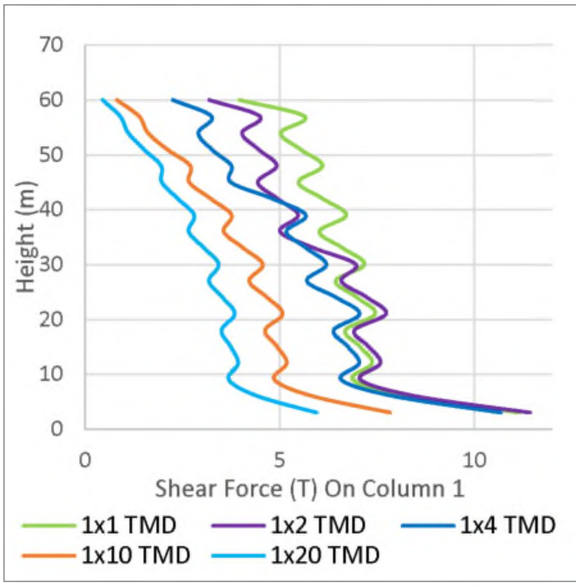
5. Group 16 TMDs are very efficient in mitigating the dynamic behavior of structures than any lateral resistance method, such as shear wall. The most optimum distribution of TMDs is on the floor plan and through the elevation of the model at the same time.

Utilizing up to 320 TMD devices in a structure is effective but could be uneconomical. I recommend for future research in the field of applying TMD, to find the most cost-effective materials for each component of the TMD. I also recommend testing the effectiveness of MTMD using a shaking table, and see if similar observation could be made experimentally compared to my computational simulation results.

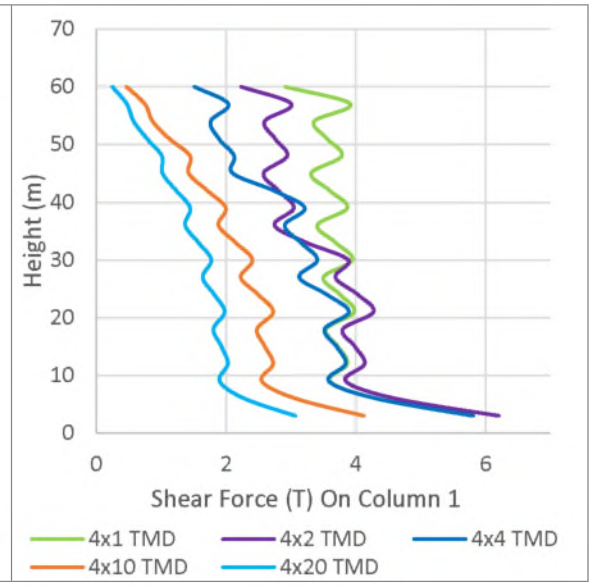
Appendices

Appendix A:

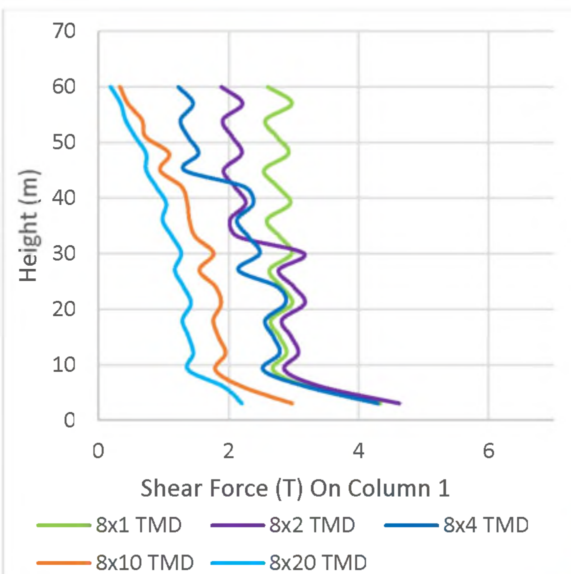
Comparison of shear forces of the model under (El Centro) Seismic load with different arrangements of TMDs



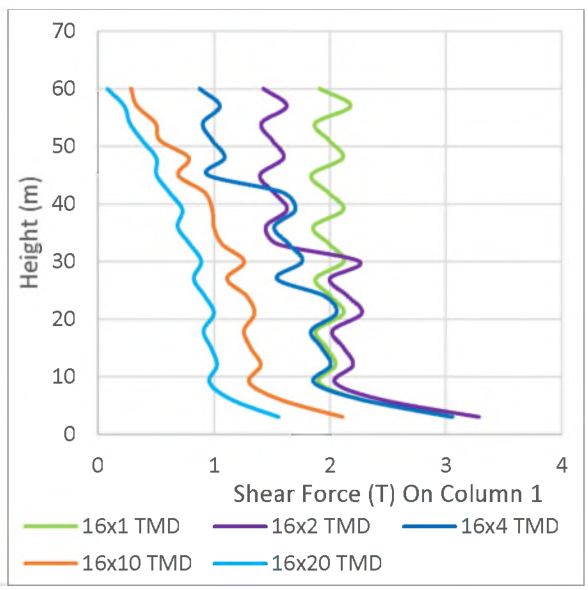
(i) One Group TMD (Scenario 1-5)



(ii) Four Group TMD (Scenario 6-10)

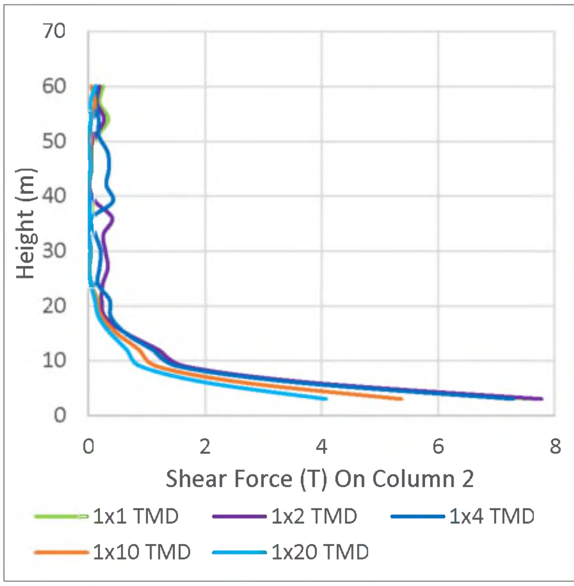


(iii) Eight Group TMD (Scenario 11-15)



(iv) Sixteen Group TMD (Scenario 16-20)

(a) Shear force column (1)



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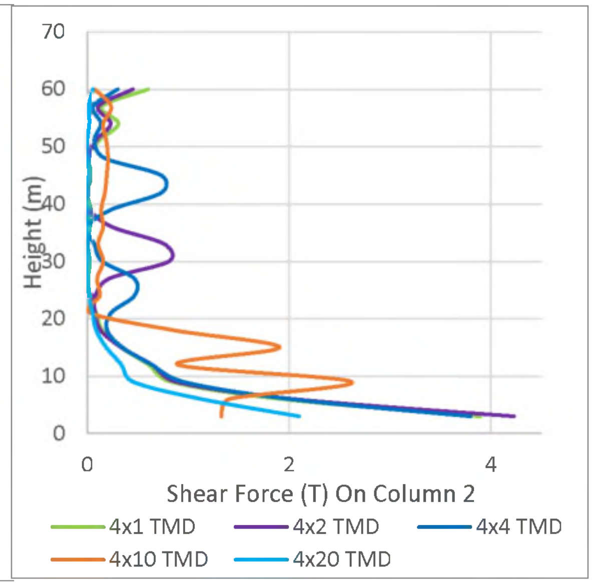
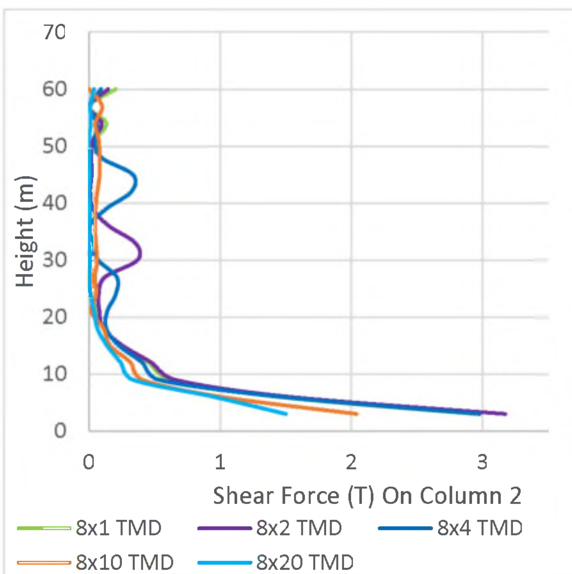
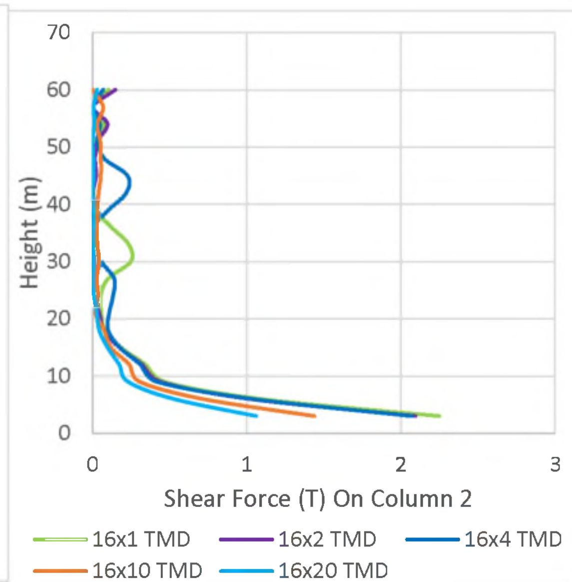


(ii) Four Group TMD (Scenario 6-10)

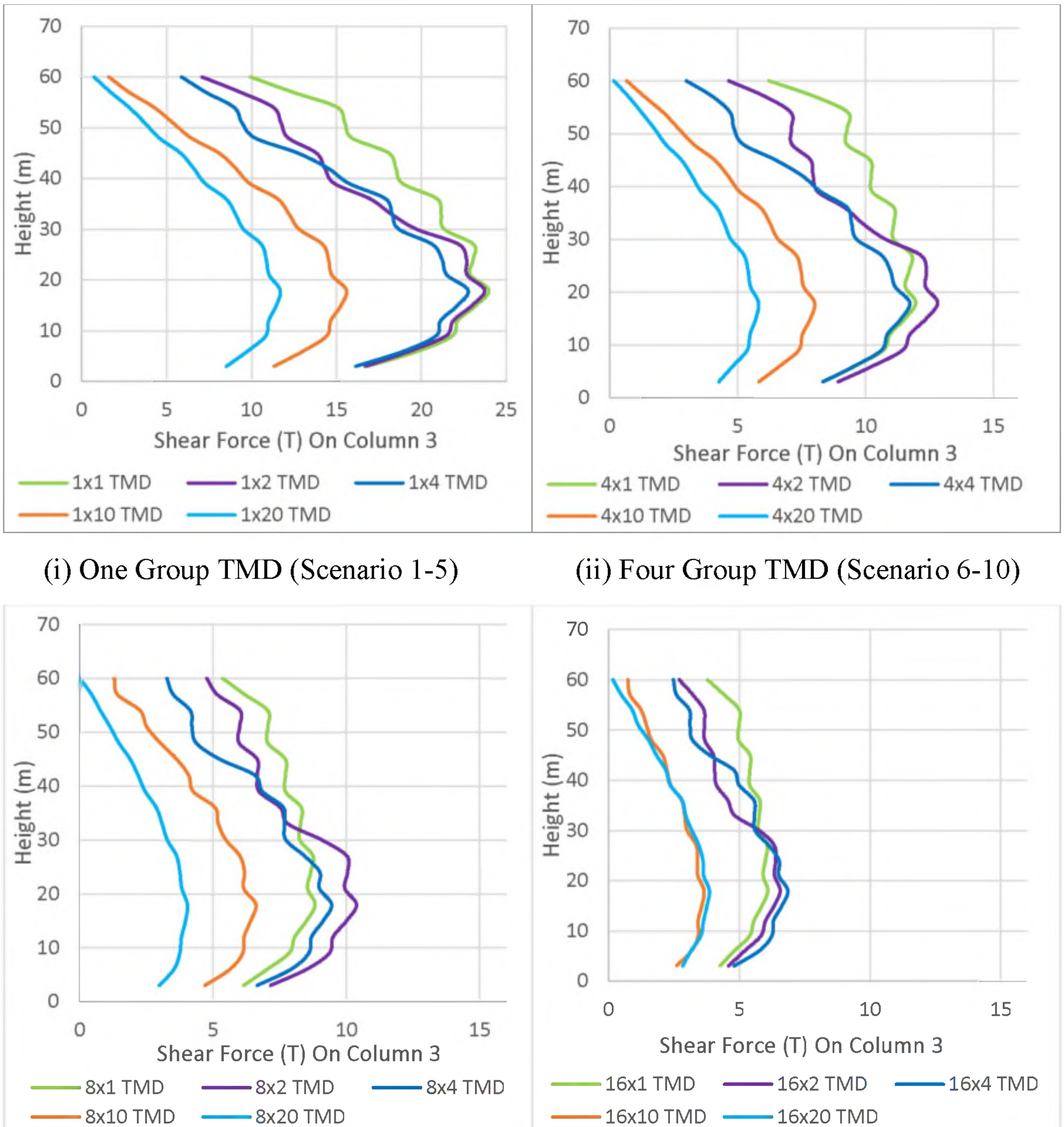


(iii) Eight Group TMD (Scenario 11-15)



(iv) Sixteen Group TMD (Scenario 16-20)

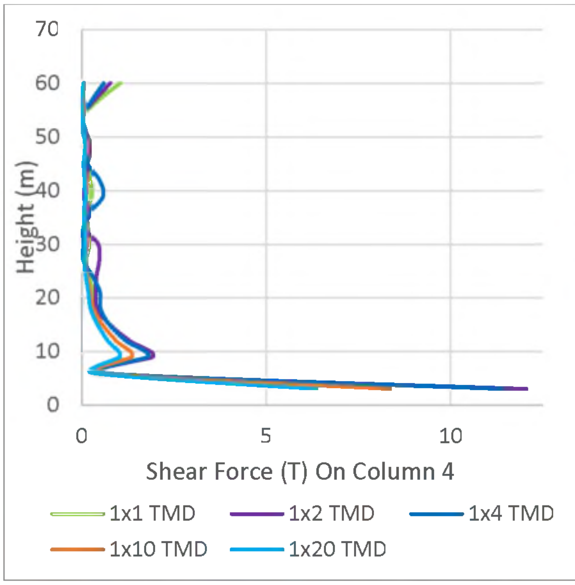
(b) Shear force column (2)



(i) One Group TMD (Scenario 1-5) (ii) Four Group TMD (Scenario 6-10)

(iii) Eight Group TMD (Scenario 11-15) (iv) Sixteen Group TMD (Scenario 16-20)

(c) Shear force column (3)



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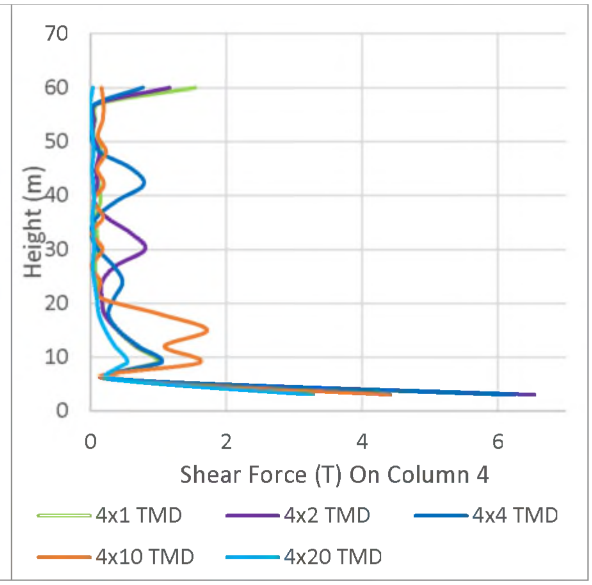
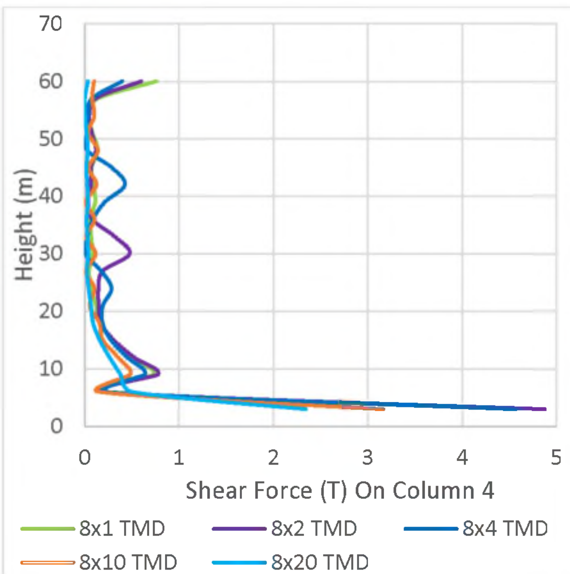
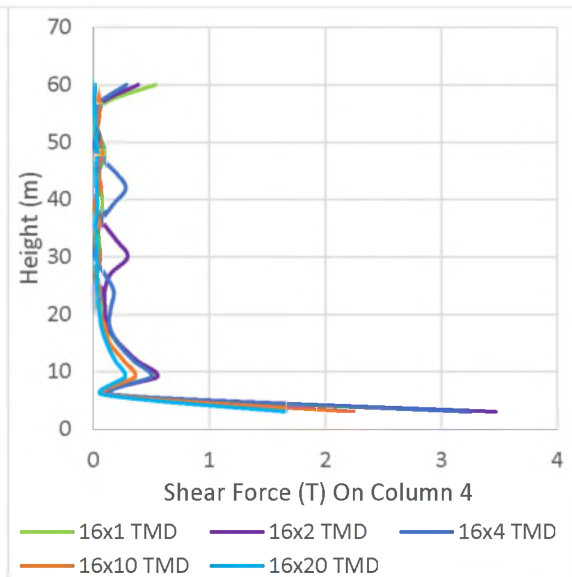


(ii) Four Group TMD (Scenario 6-10)

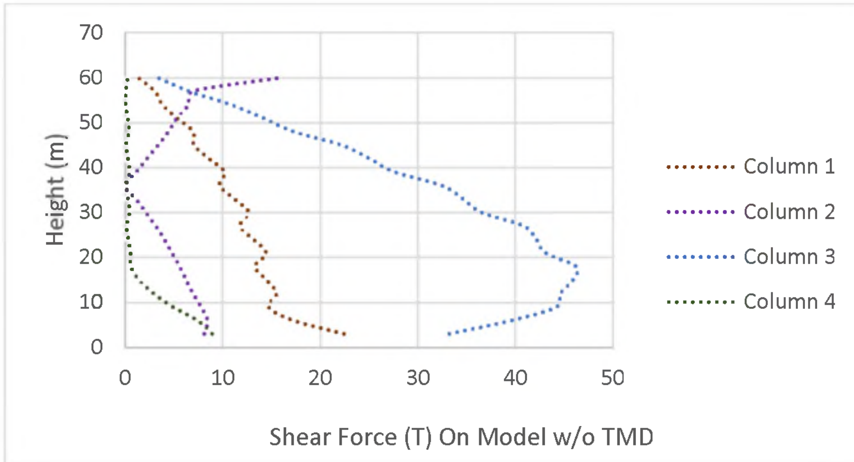


(iii) Eight Group TMD (Scenario 11-15)

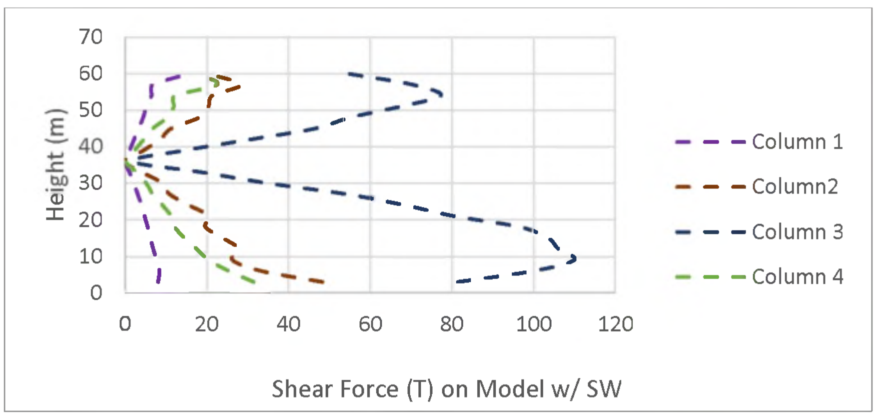


(iv) Sixteen Group TMD (Scenario 16-20)

(d) Shear force column (4)



(e) Shear force on Model without TMD



(f) Shear force on Model with Shear Wall

Appendix B:

Period vs. pseudo acceleration spectral under El Centro ground motion

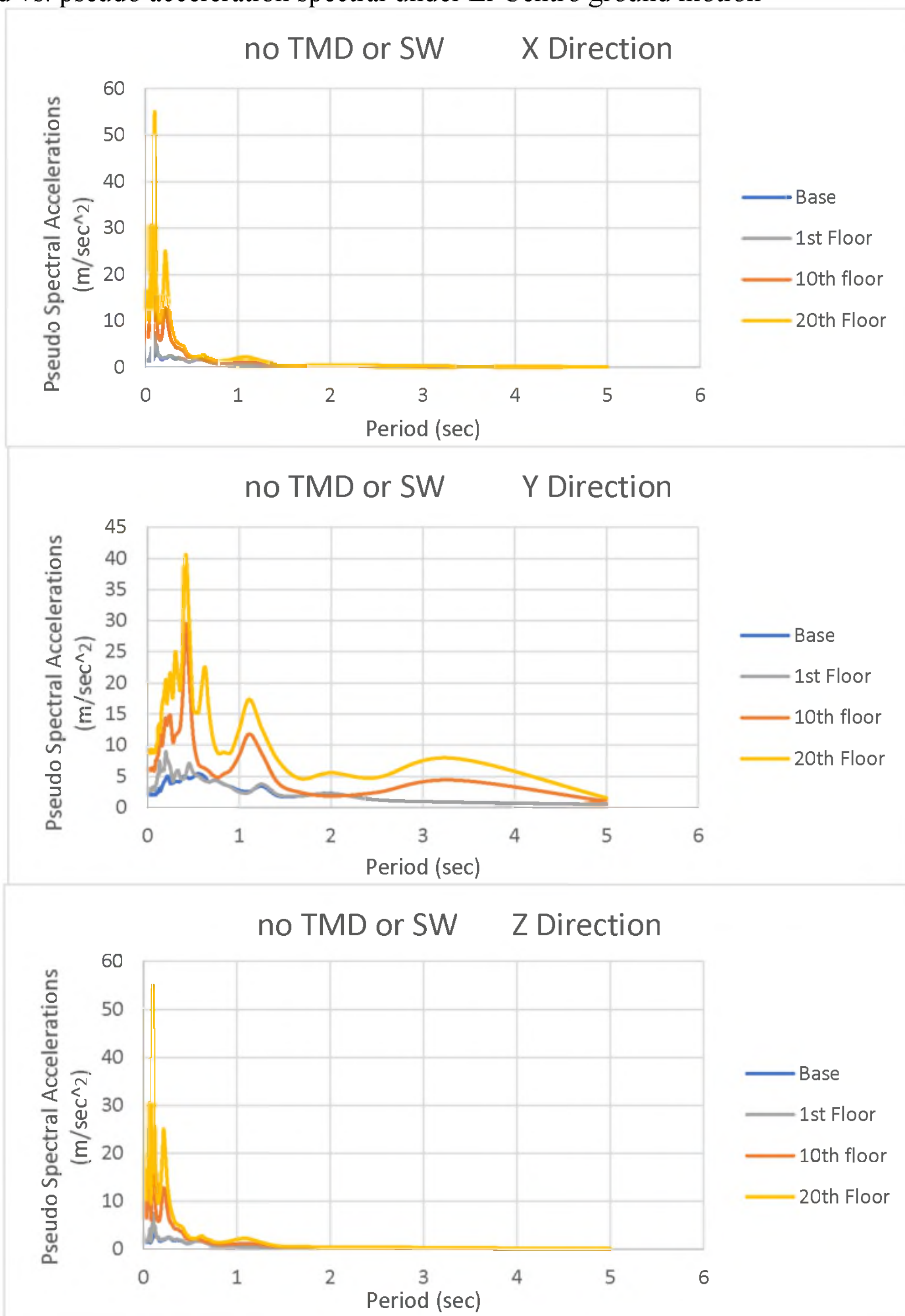


Figure 15. Period vs. Pseudo Acceleration Spectral using No TMD and SW

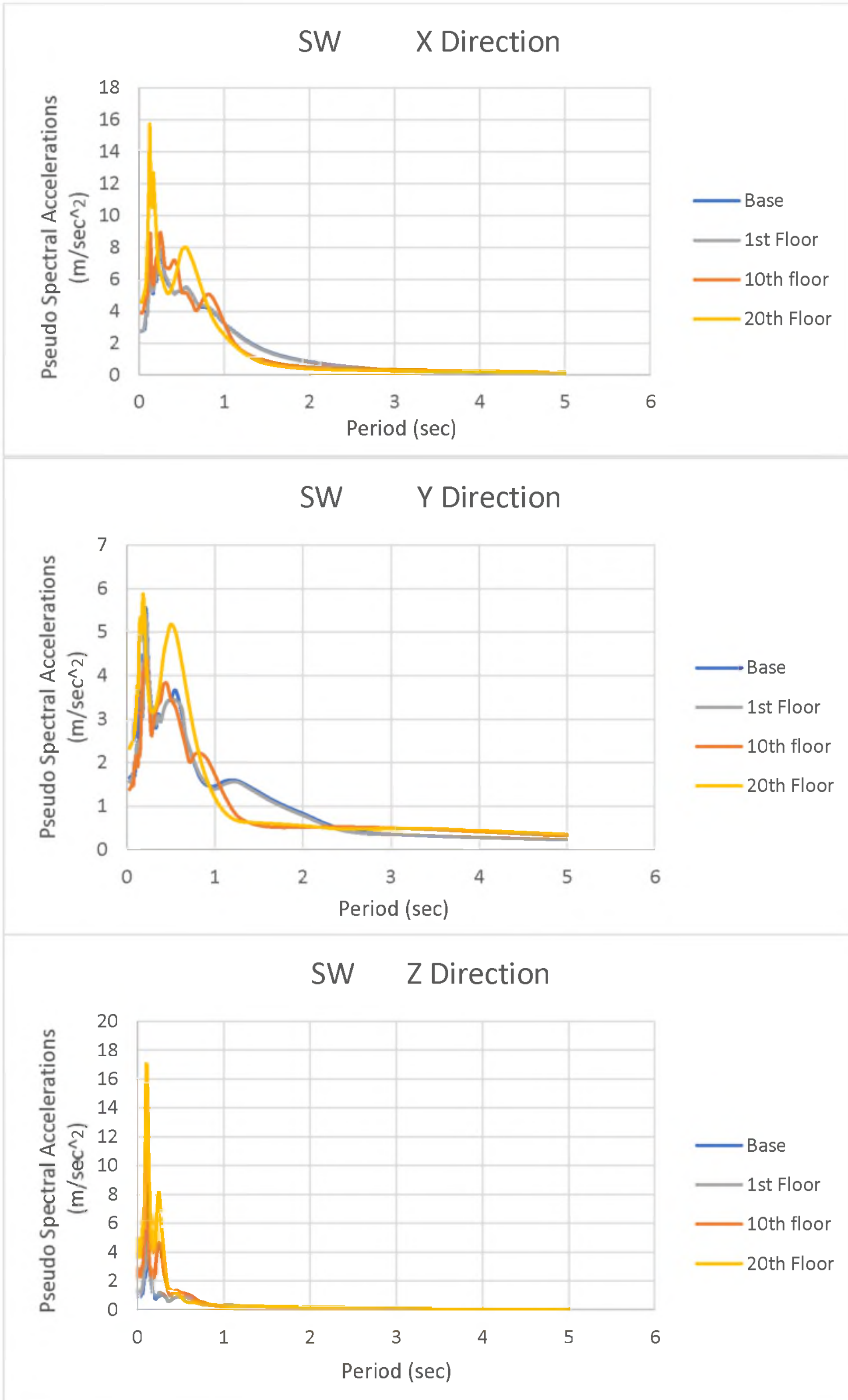


Figure 16. Period vs. Pseudo Acceleration Spectral using Shear Wall

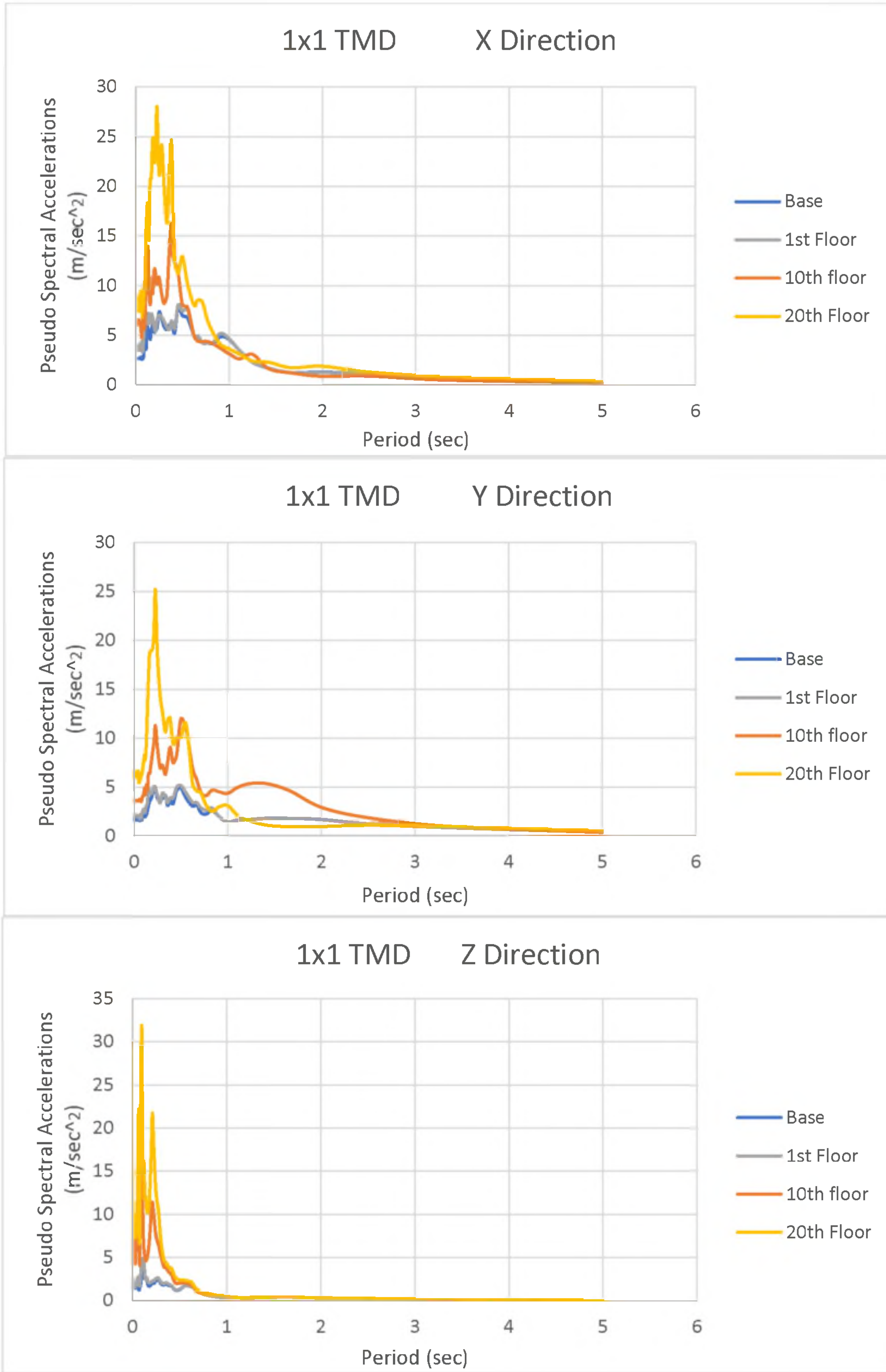


Figure 17. Period vs. Pseudo Acceleration Spectral using 1x1 TMD

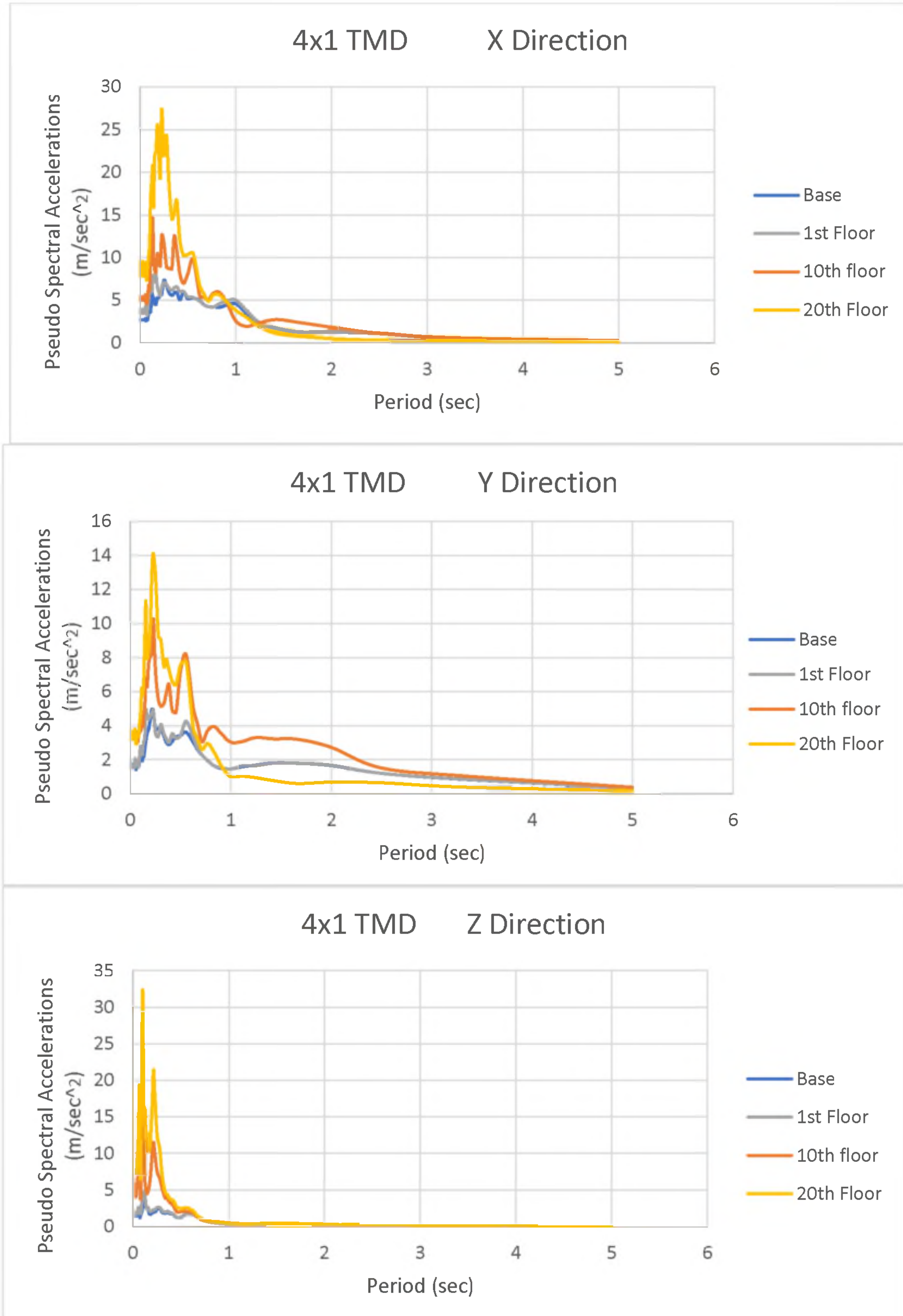


Figure 18. Period vs. Pseudo Acceleration Spectral using 4x1 TMD

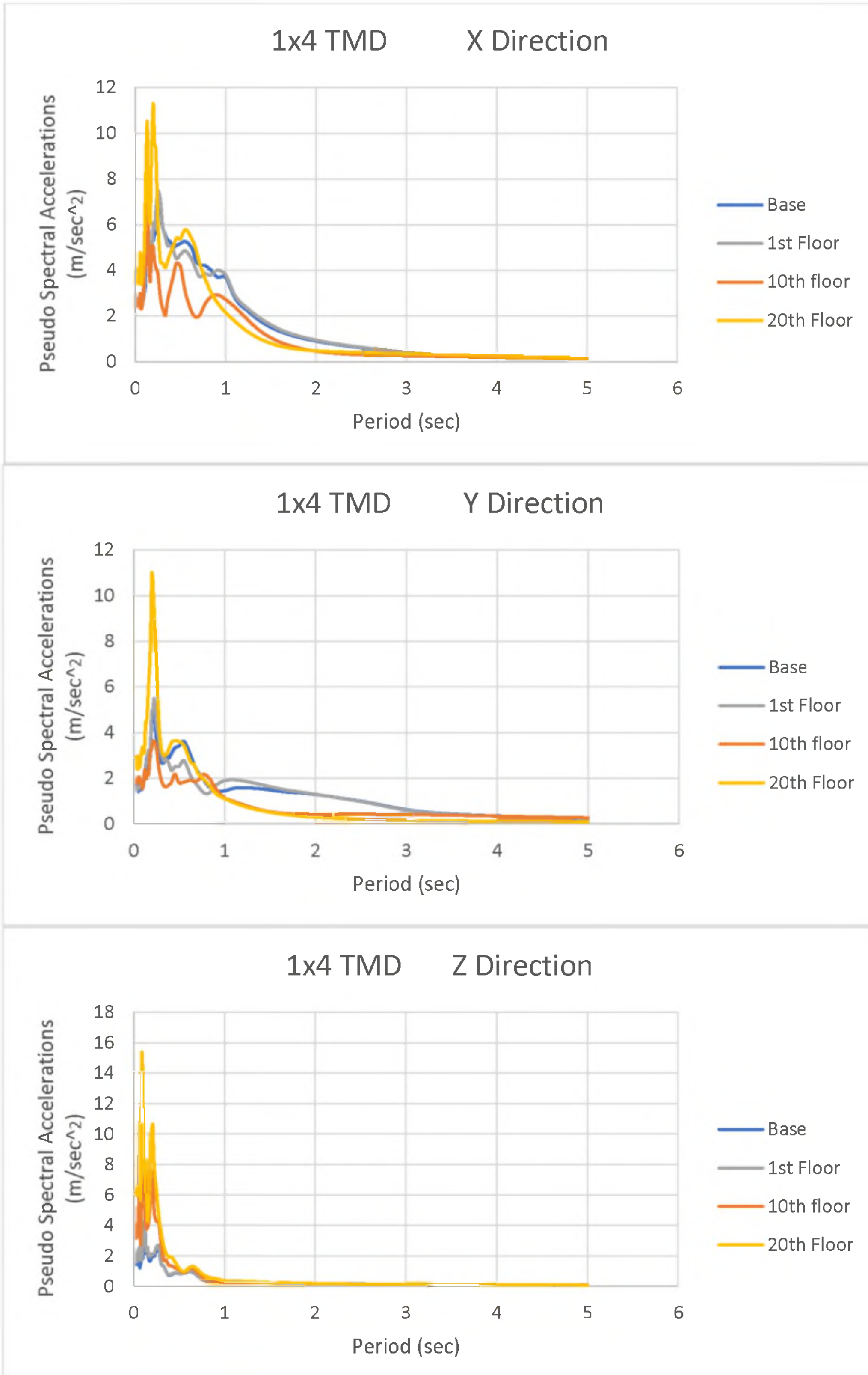


Figure 19. Period vs. Pseudo Acceleration Spectral using 1x4 TMD

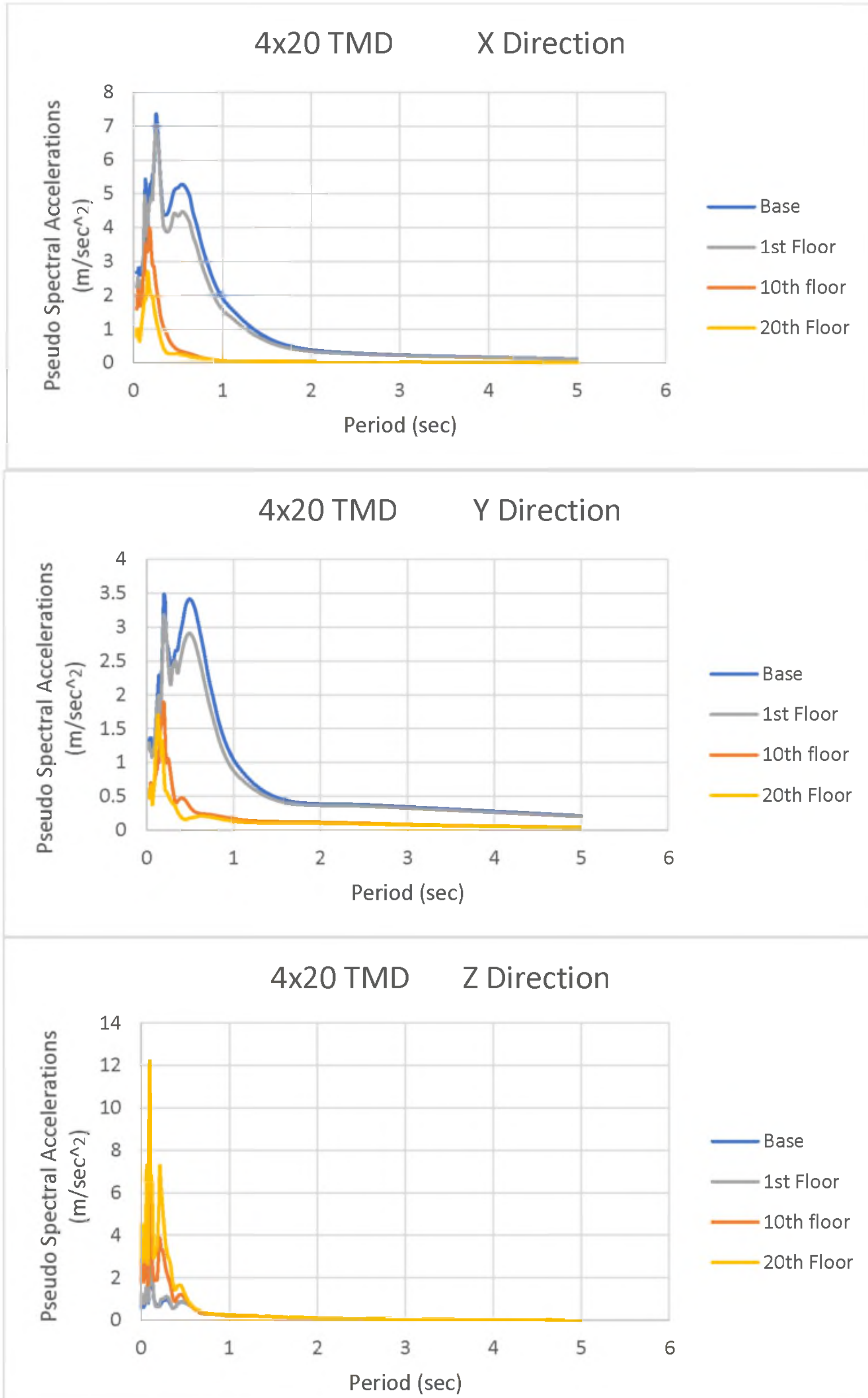


Figure 20. Period vs. Pseudo Acceleration Spectral using 4x20 TND

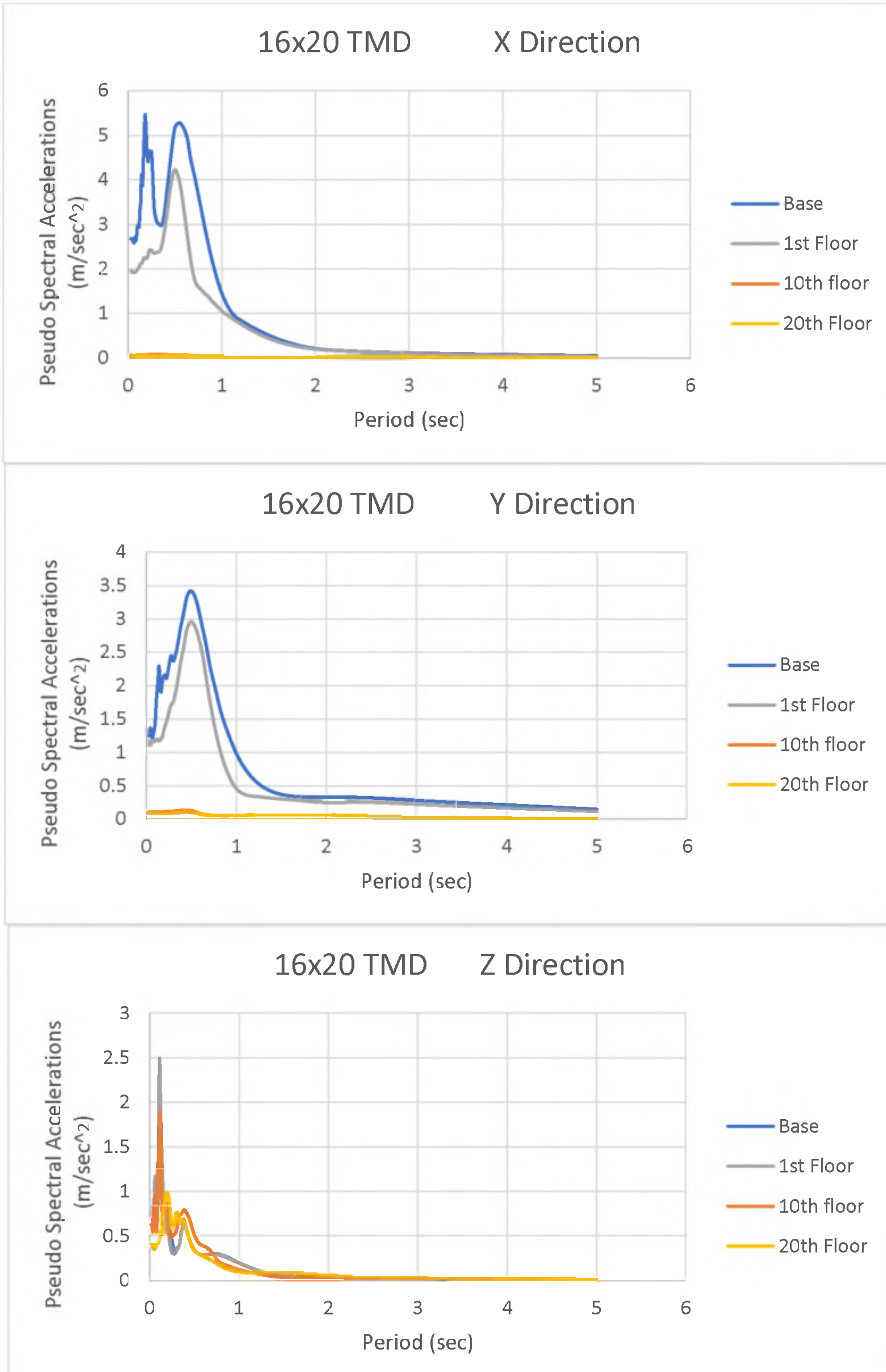
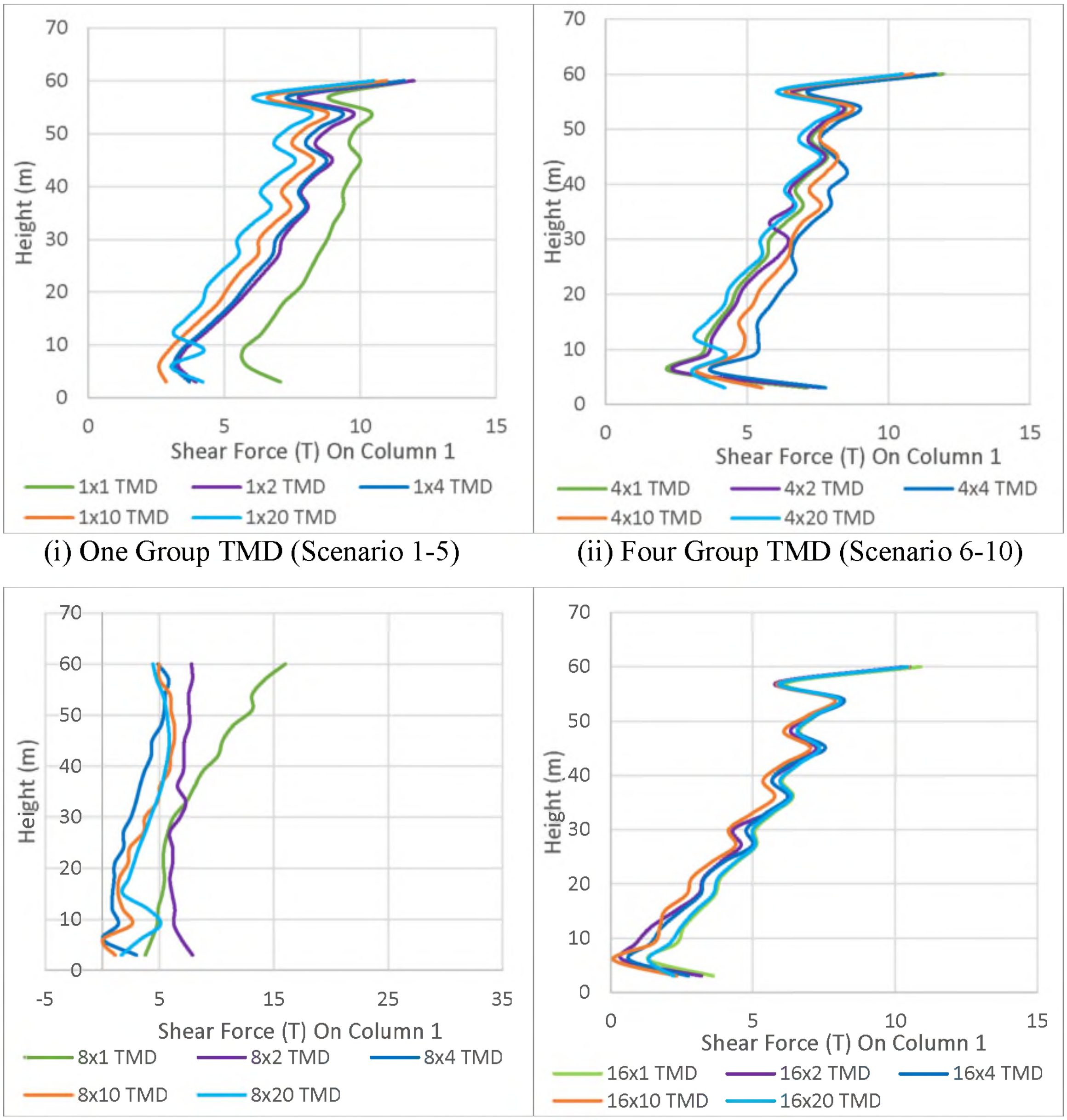


Figure 21. Period vs. Pseudo Acceleration Spectral using 16x20 TMD

Appendix C:

Comparison of shear forces of the model under (Kocaeli) Seismic load with different arrangements of TMDs



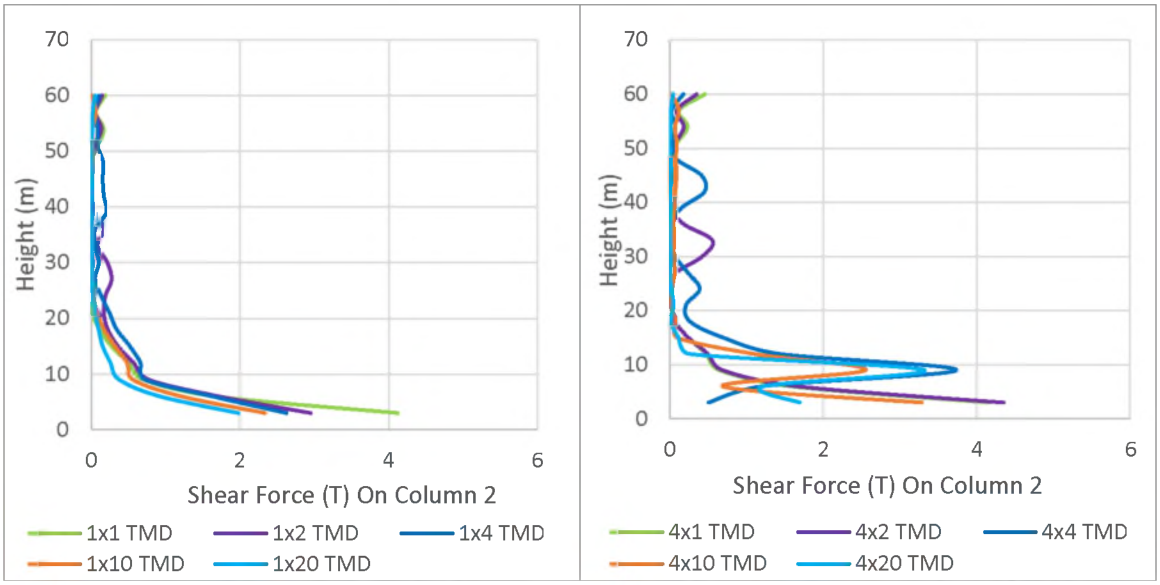
(i) One Group TMD (Scenario 1-5)

(ii) Four Group TMD (Scenario 6-10)

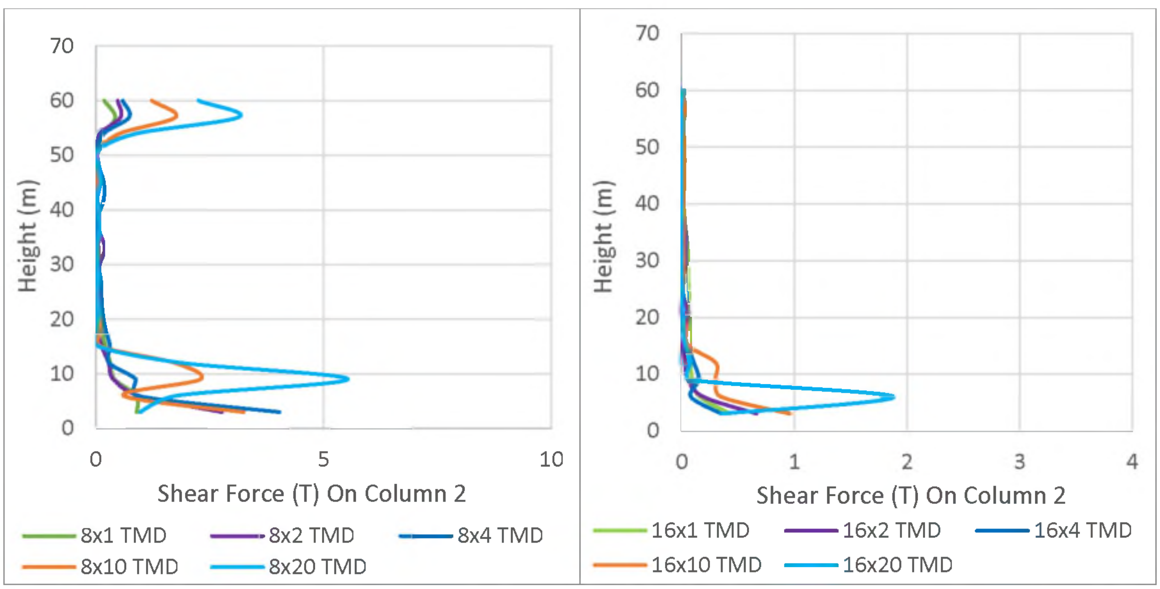
(iii) Eight Group TMD (Scenario 11-15)

(iv) Sixteen Group TMD (Scenario 16-20)

(a) Shear force column (1)

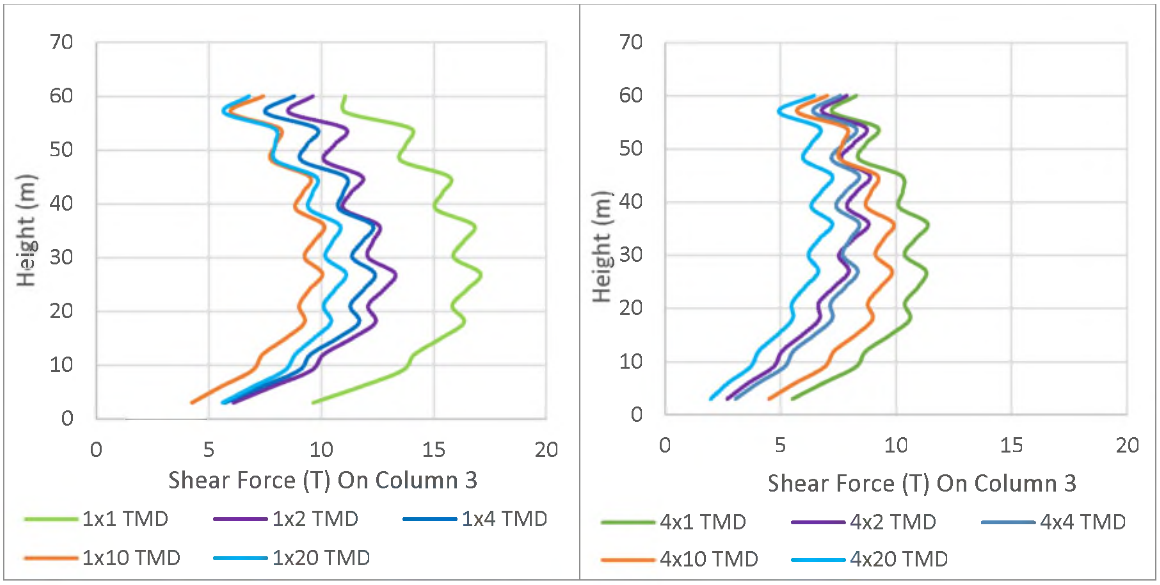


(i) One Group TMD (Scenario 1-5) (ii) Four Group TMD (Scenario 6-10)

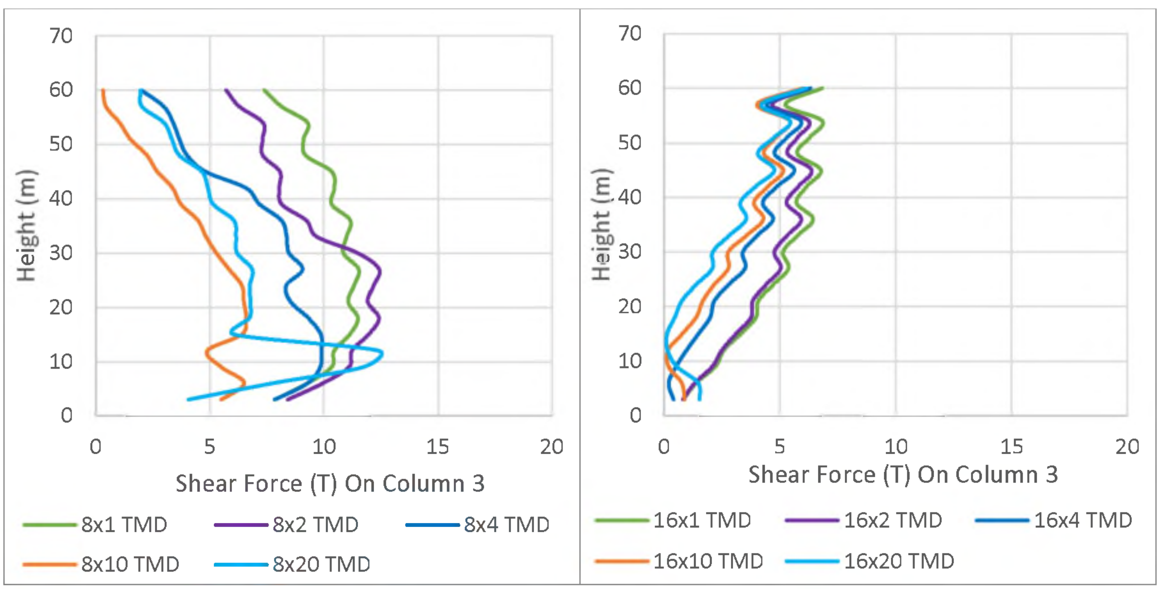


(iii) Eight Group TMD (Scenario 11-15) (iv) Sixteen Group TMD (Scenario 16-20)

(b) Shear force column (2)

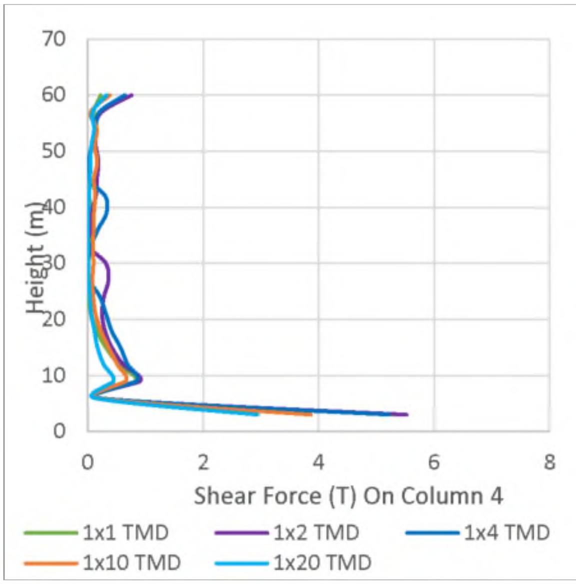


(i) One Group TMD (Scenario 1-5) (ii) Four Group TMD (Scenario 6-10)

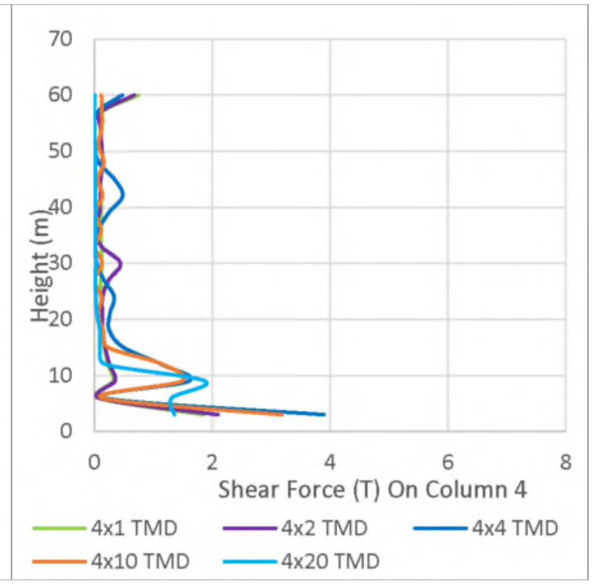


(iii) Eight Group TMD (Scenario 11-15) (iv) Sixteen Group TMD (Scenario 16-20)

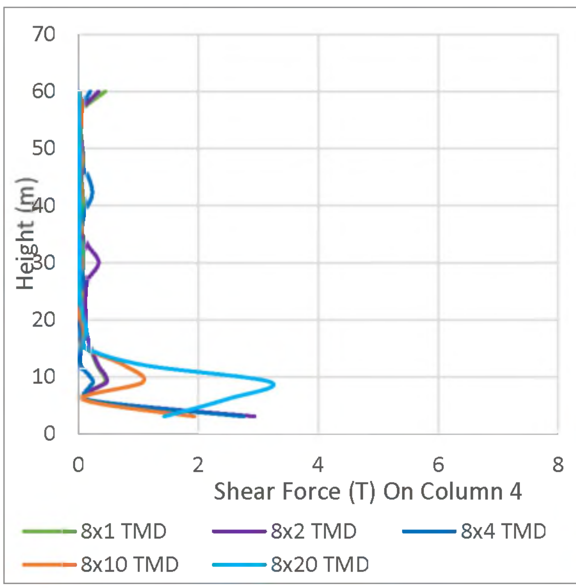
(c) Shear force column (3)



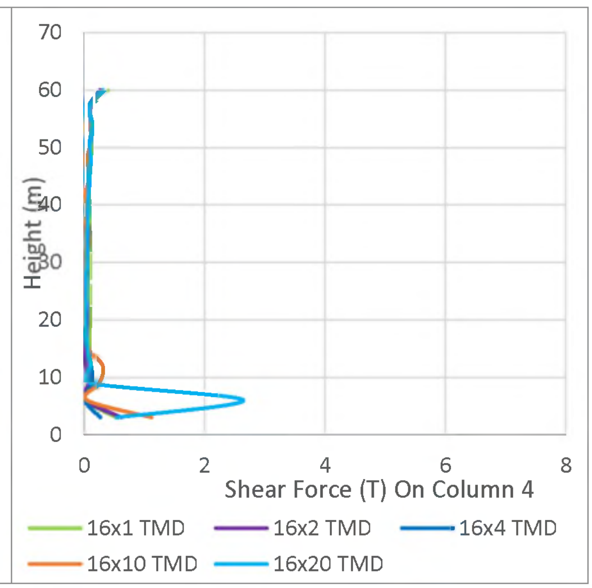
(i) One Group TMD (Scenario 1-5)



(ii) Four Group TMD (Scenario 6-10)

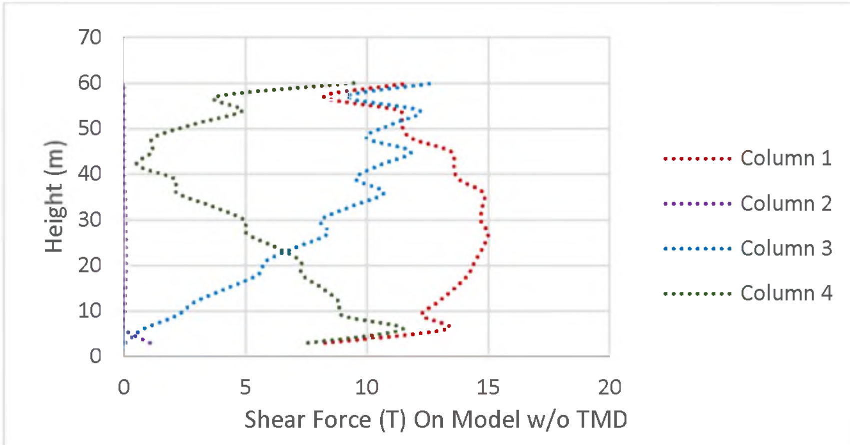


(iii) Eight Group TMD (Scenario 11-15)

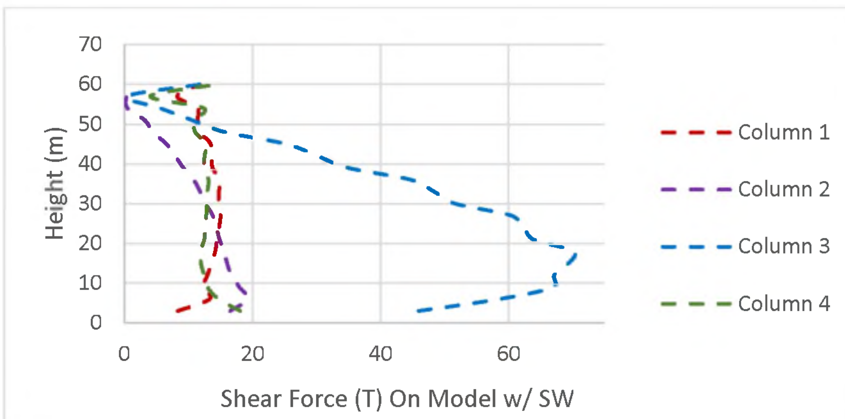


(iv) Sixteen Group TMD (Scenario 16-20)

(d) Shear force column (4)



(e) Shear force on Model without TMD



(f) Shear force on Model with Shear Wall

Appendix D:
Period vs. pseudo acceleration spectral under Kocaeli ground motion

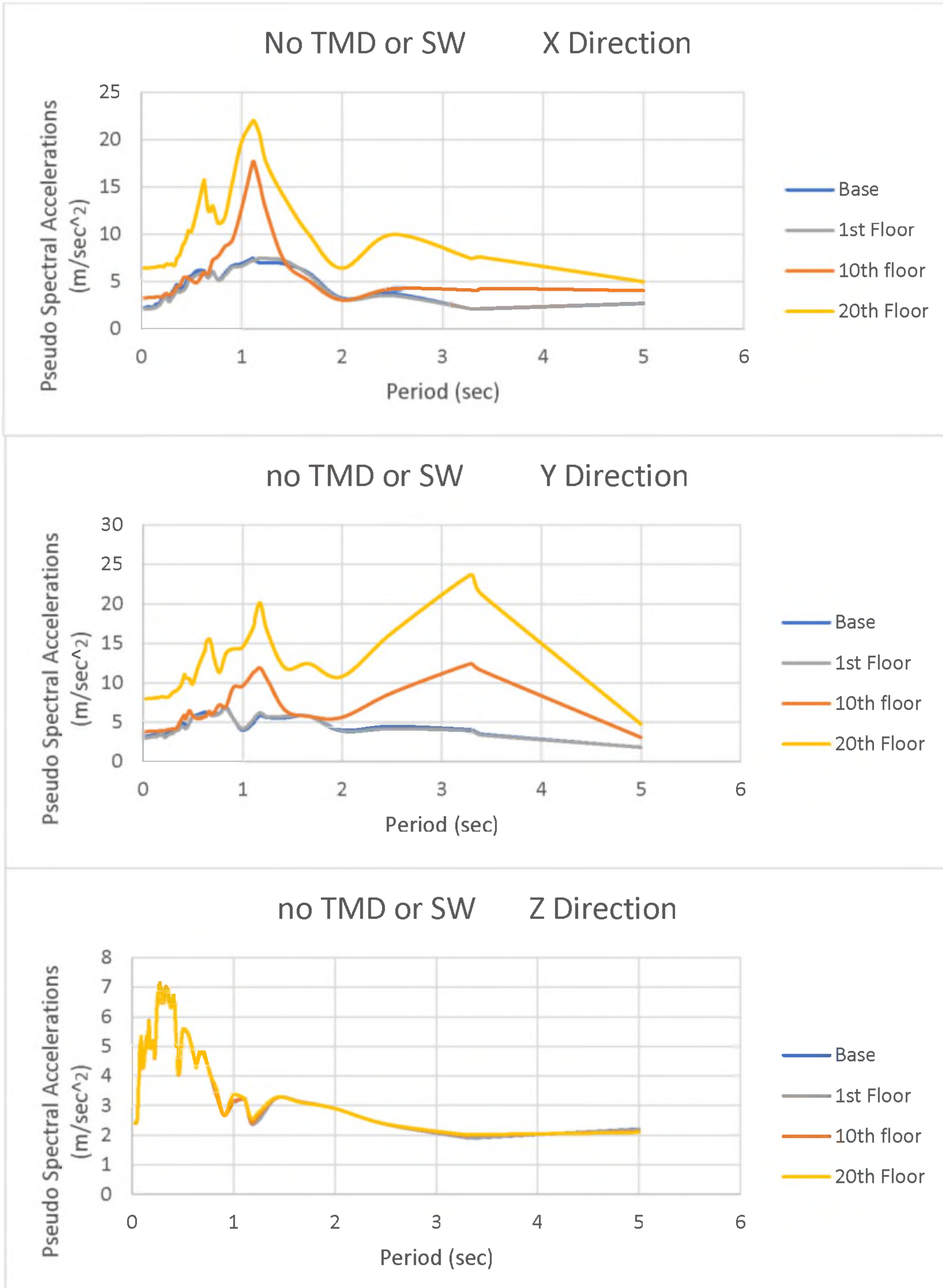


Figure 24. Period vs. Pseudo Acceleration Spectral using No TMD and SW

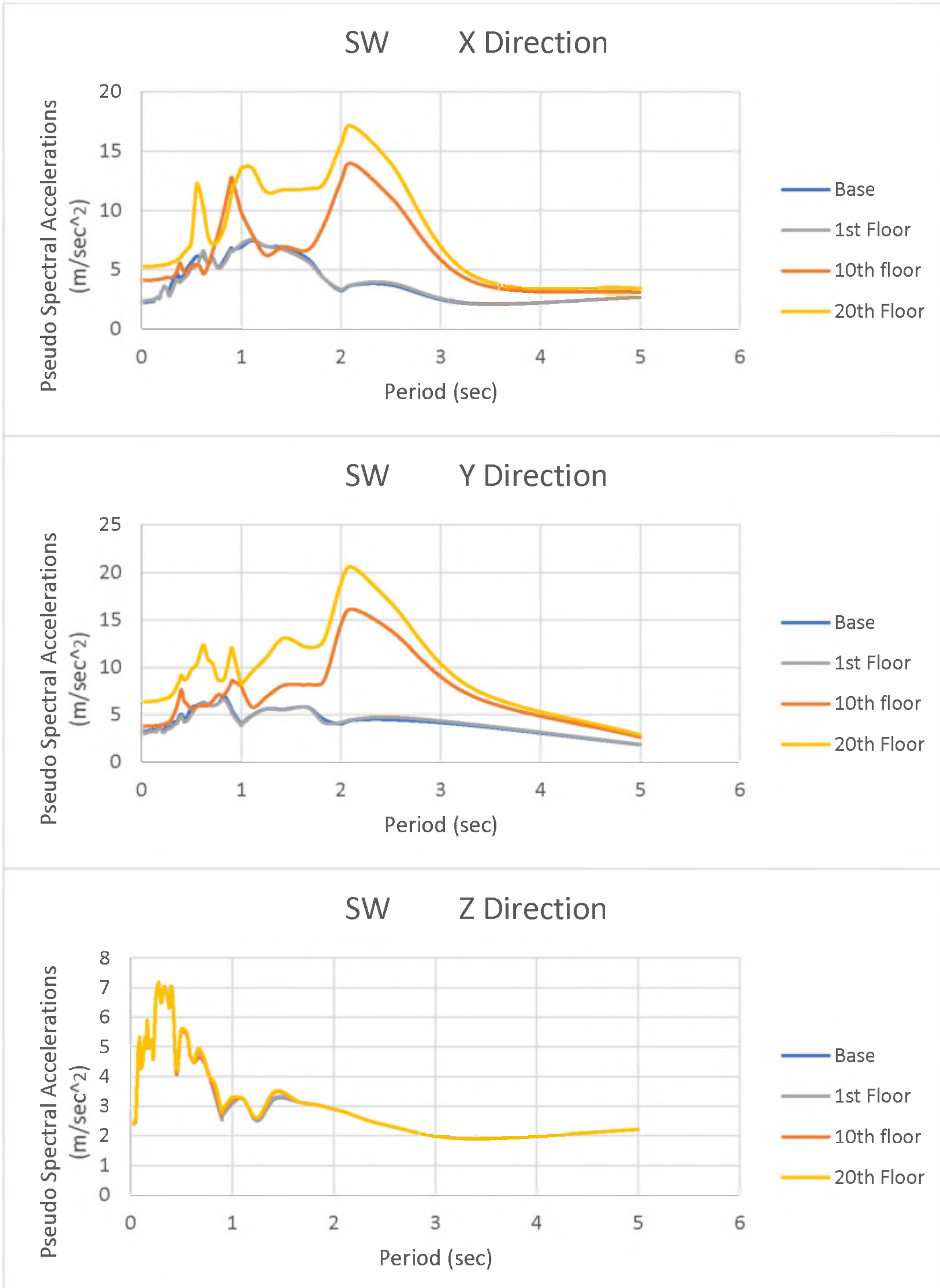


Figure 25. Period vs. Pseudo Acceleration Spectral using Shear Wall

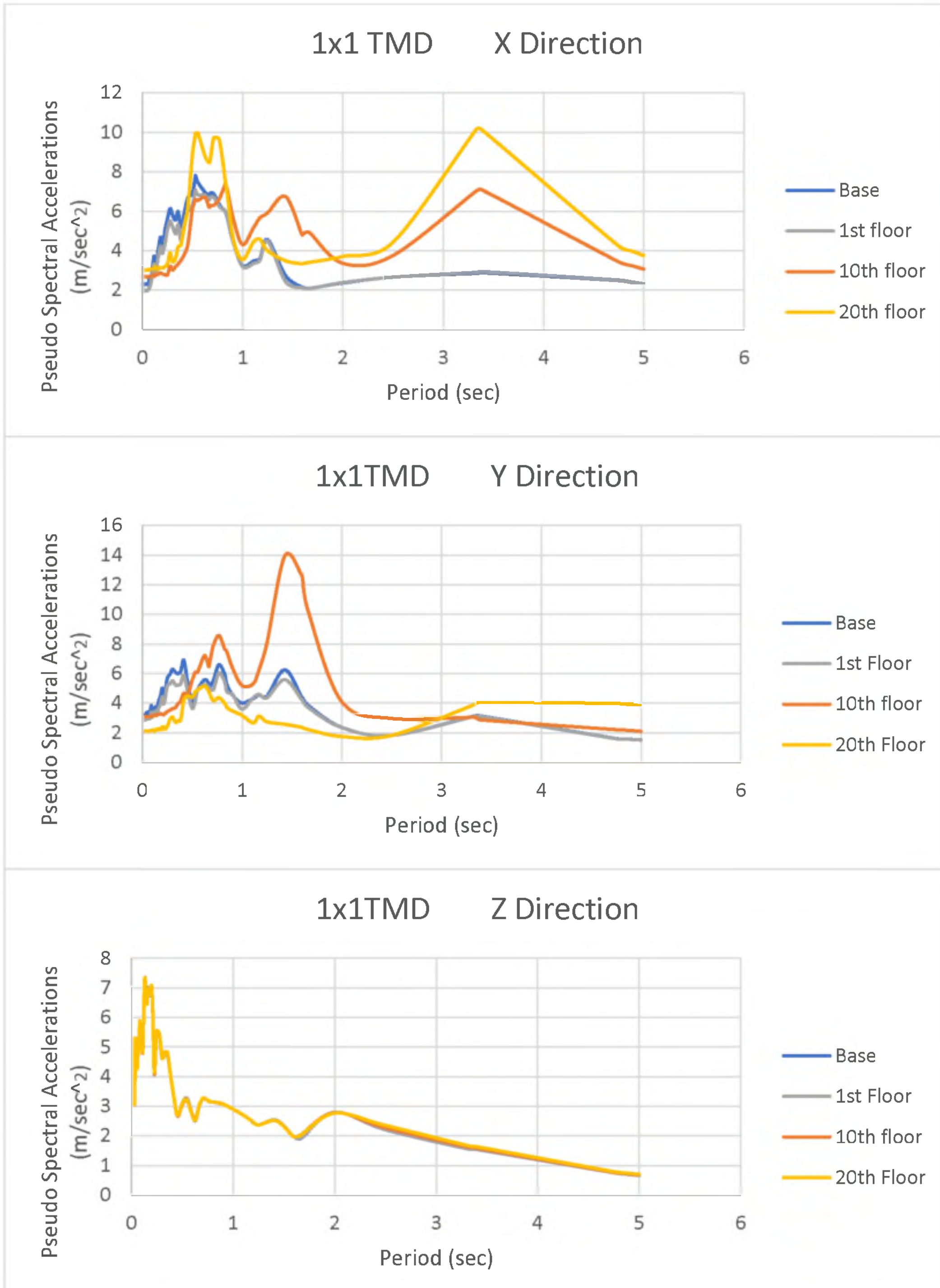


Figure 26. Period vs. Pseudo Acceleration Spectral using 1x1 TMD

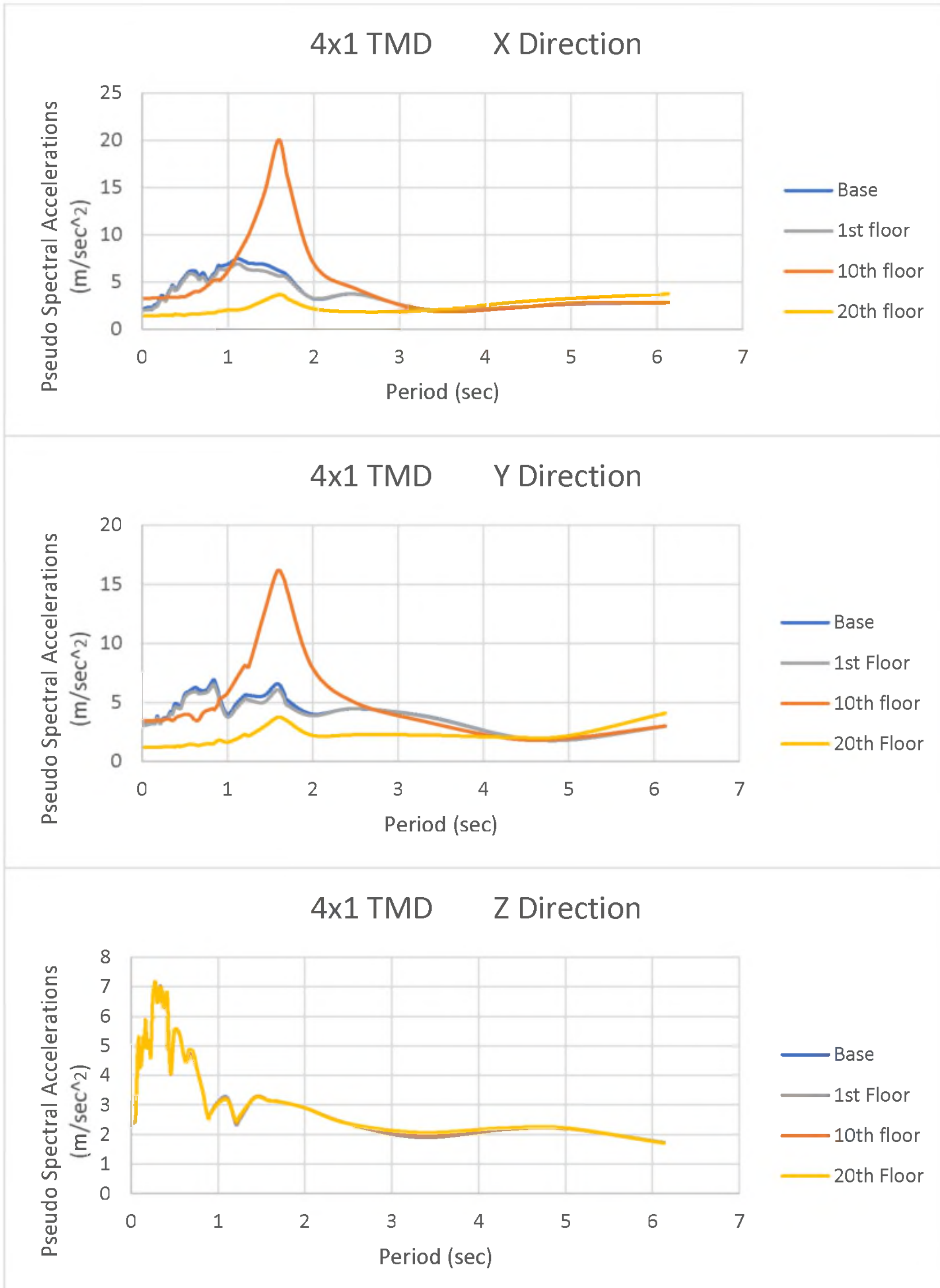


Figure 27. Period vs. Pseudo Acceleration Spectral using 4x1 TMD

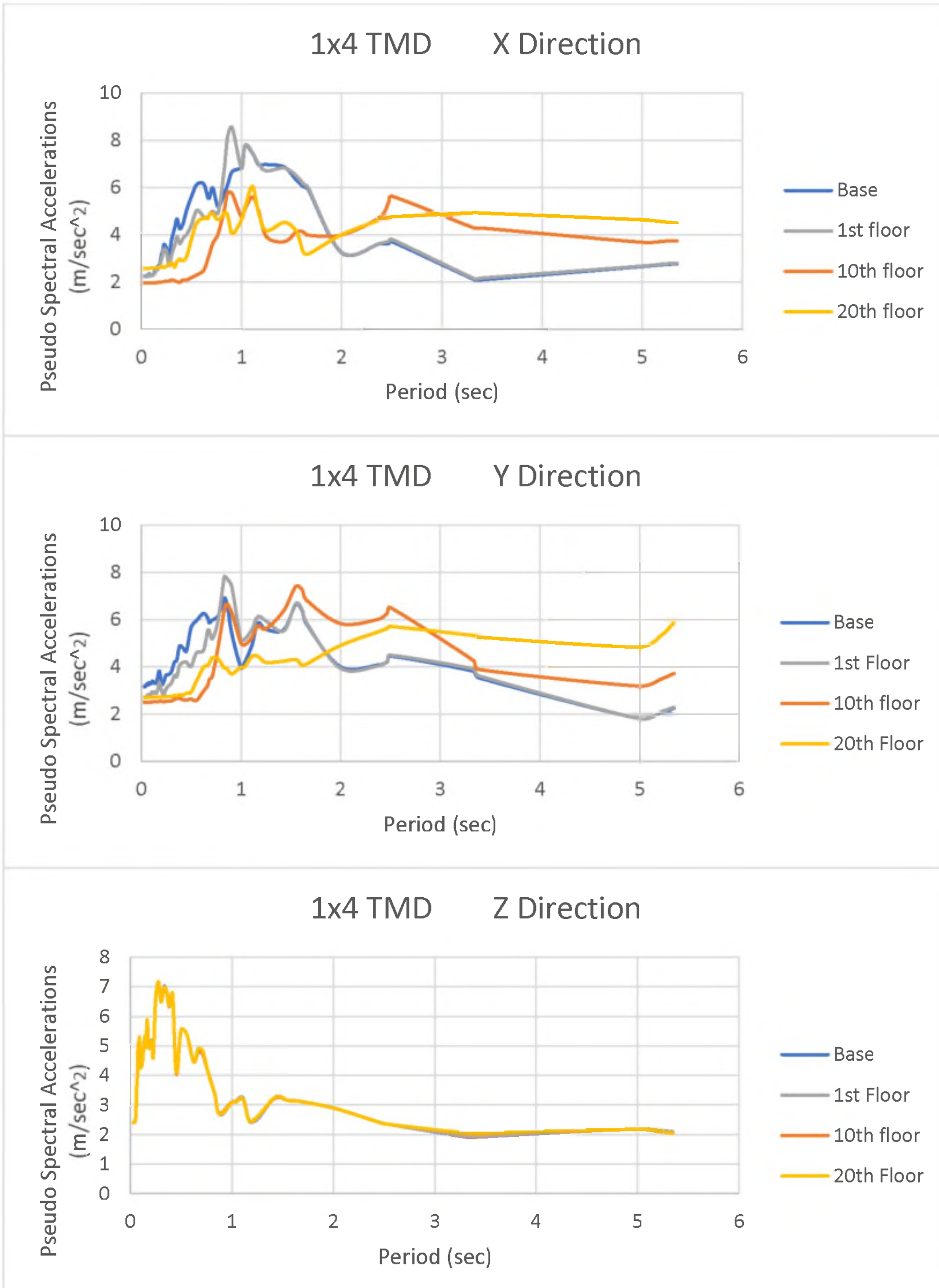


Figure 28. Period vs. Pseudo Acceleration Spectral using 1x4 TMD

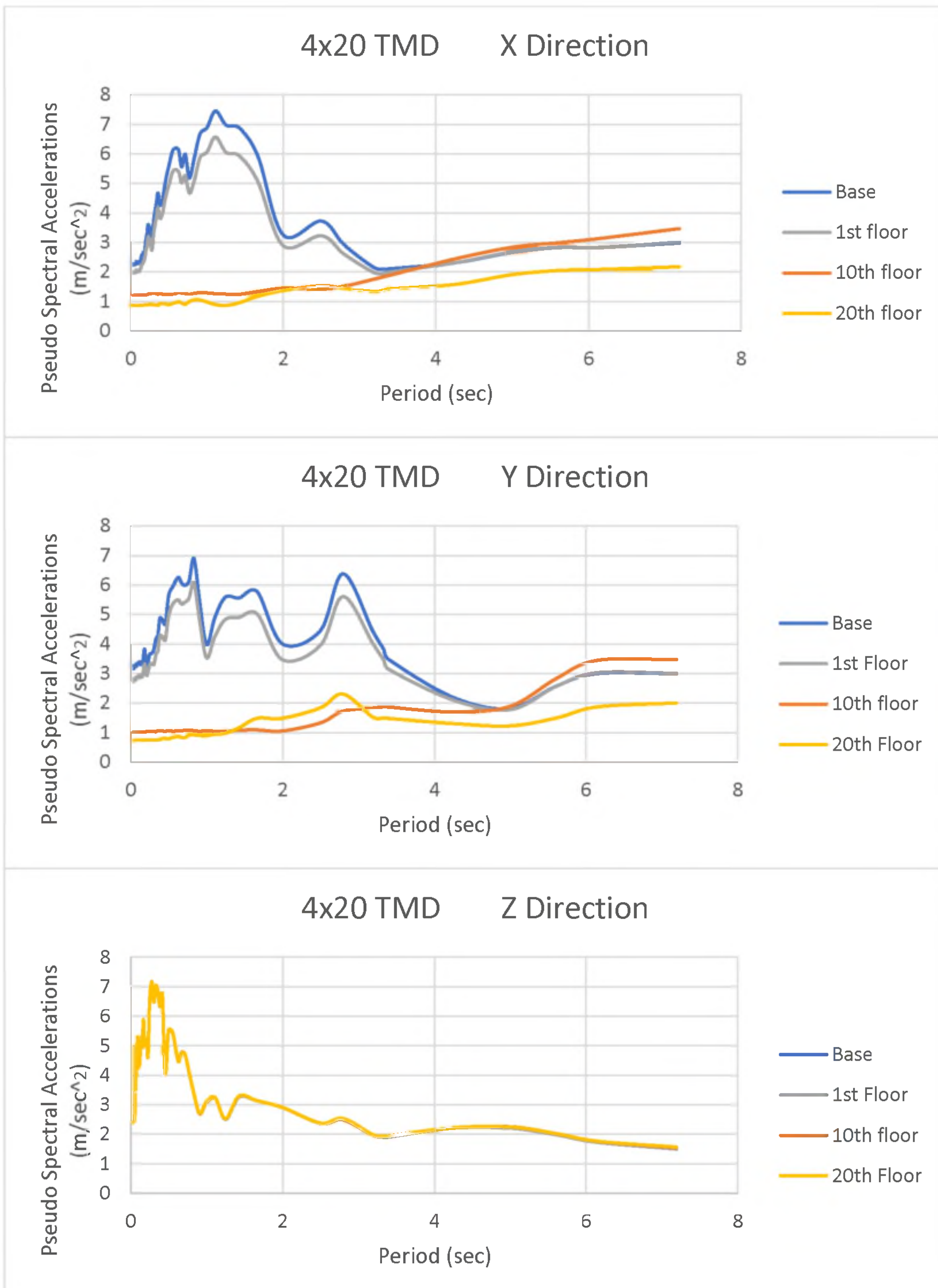


Figure 29. Period vs. Pseudo Acceleration Spectral using 4x20 TMD

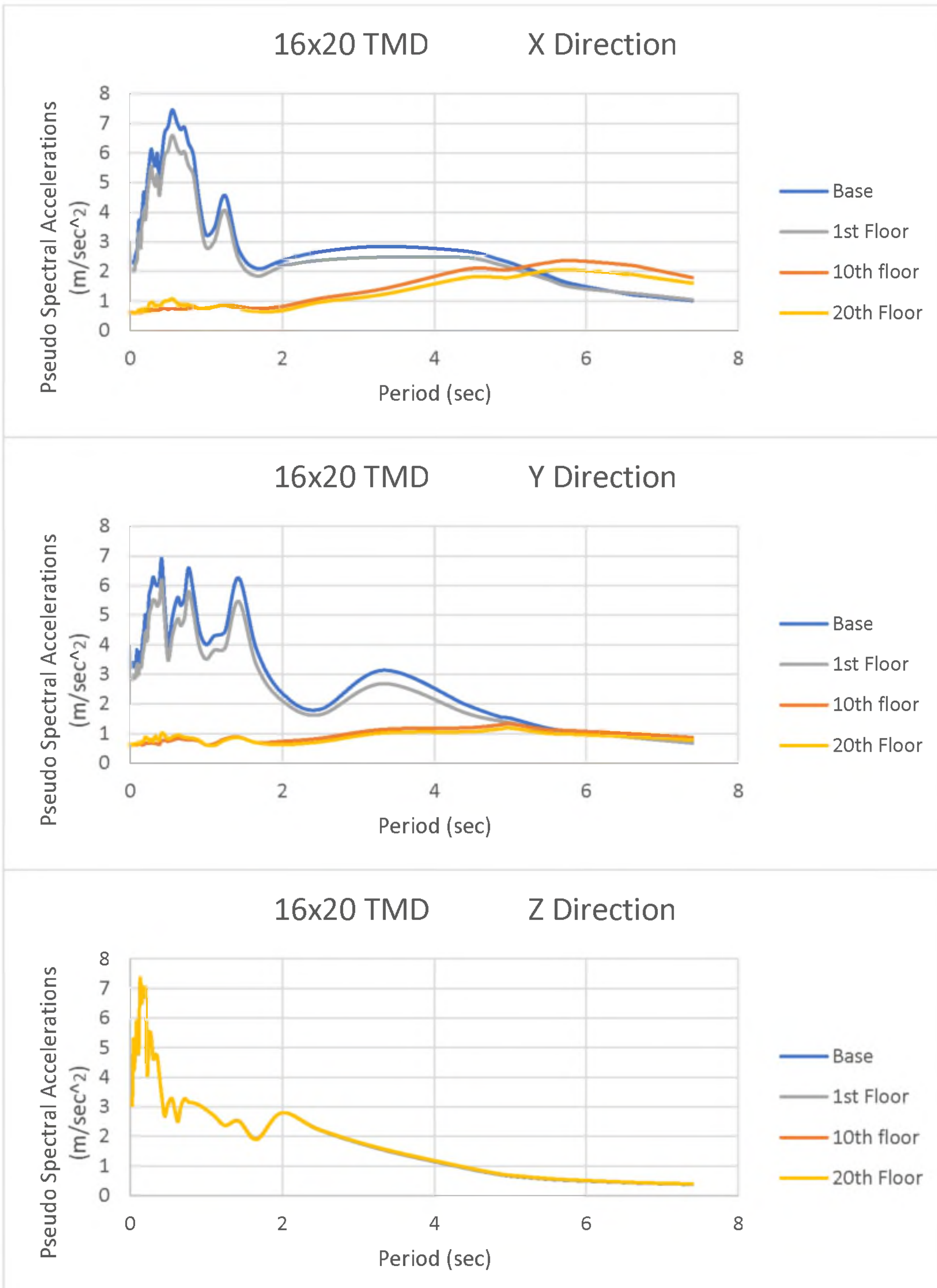


Figure 30. Period vs. Pseudo Acceleration Spectral using 16x20TMD

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