SEISMIC RESPONSE OF STRUCTURE USING TUNED MASS DAMPER

A PROJECT REPORT

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF DEGREE
OF

MASTER OF TECHNOLOGY

IN

STRUCTURAL ENGINEERING

Submitted by:

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MAY, 2022

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CANDIDATE'S DECLARATION

I, **Mudit Srivastava**, Roll No. **2K20/STE/14** student of **M.Tech. (Structural Engineering)**, hereby declare that the project dissertation titled "**SEISMIC RESPONSE OF STRUCTURE USING TUNED MASS DAMPER**" which is submitted by me to the Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of degree of **Master of Technology**, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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CERTIFICATE

I, hereby certify that the Project Dissertation titled "**SEISMIC RESPONSE OF STRUCTURE USING TUNED MASS DAMPER**" which is submitted by **Mudit Srivastava, Roll No. 2K20/STE/14**, Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of degree of **Master of Technology**, is a record of the project work carried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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ACKNOWLEDGEMENT

A Major Project at the university level is always a tough nut to crack as it requires days of research, exploration, failures and ultimately success. My project is not exempted in this regard. It would be unfair to dedicate the success of this project to a single individual as it has bits and pieces of several people. I would therefore like to express my gratitude to all those individuals who have played a vital role in one way or another.

First, and foremost my guide **Mr. Hrishikesh Dubey** who had always kept faith in me, no matter what the circumstances were. He was always there to help me whenever I got stuck anywhere in my project and gave me confidence to do the quality of work that I did.

I am grateful to the honourable Head Of Department **Dr.Vijay K. Minocha** for his constant motivation and support to each and every student of the department. He always thought about the interest of the students and gave us necessary guidance whenever we felt dejected.

I would like to thank my fellow classmates and my family members to help me in whatever way they had. Their support was crucial in completing my project on time.

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ABSTRACT

This project illustrates the effect of passive tuned mass damper (PTMD) on multistorey framed structure through various parametric studies that include modification of design parameters of PTMD namely, mass ratio and damping ratio. The effect of increase in number of PTMD on the seismic response of the structure is also demonstrated. A comparative study is adopted to determine the effectiveness of PTMD between a low-rise and a high-rise building through percentage reduction in the seismic responses with the change in the position of PTMD. OPENSEES, serving as an effective tool to perform seismic simulation for all types of structures due to its faster processing speed and accurate results, is used here to perform the designing operations and generating the dynamic responses in the form of storey displacement and acceleration. The results asserted that the increase in mass ratio and the damping ratio of the PTMD helps in suppressing the seismic vibration to the building. The number of PTMDs on the structure also helps in mitigating the effect of vibration caused due to earthquake. Also, for a high-rise building, the variation in responses is more if we shift PTMD along the height of the building as compared to a low-rise building. The application of six different earthquakes of different intensity on the structure, further justified the efficacy of PTMD in reducing the responses of the structure.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND:

Ever since the dawn of civilization, disasters have been an integral part of all life across the globe. Be it humans, animals or even vegetation, disasters have always impacted the life in one way or the another. While some of them are tolerable and have little or no impact, others are hazardous and have led to considerable loss of life and property. The impact of the disaster is more if not apprehended beforehand and, in some case, it would anyway affect the biodiversity due to its large magnitude and less precautionary measures. Among such disasters, Earthquake is the one which has been widely regarded as the most fatal.

Earthquake is a type of natural disaster that has been etched in the mind of humans ever since their very existence. Earthquake occur whenever there is some movement in the tectonic plates beneath, which leads to evolution of tremendous amount of energy in the form of vibration. The intensity of these vibrations as well as the distance from the epicentre decides the magnitude of the earthquake. Across the world, the magnitude of the earthquake is measured by Richter scale which has a range of 0 to 9. Greater the number on the Richter Scale, more is the severity of the Earthquake. An Earthquake of intensity greater than 7 on the Richter Scale has proved to be hazardous in the past leading to considerable loss of life property. The Pacific Ring of Fire is a belt in the Pacific Ocean which experiences maximum Earthquake. All together there are 15 countries in this belt that passes through Pacific Ocean, Japan, Indonesian, Papua New Guinea, Guatemala etc to name a few. If we look at the past Earthquake records, we will see that the majority of the earthquakes have their epicentres in this belt.

Urbanisation has led to construction of several high-rise buildings which are prone to damage by earthquake. Due to increasing population, the need of land is greater than ever before, which has forced us to cut down trees on a large scale or construction of high-rise building. While some are built tall for aesthetic purpose, others are tall to accommodate the increasing population to make up for the less land area available for the humans. It is therefore, the responsibility of an engineer to consider all necessary measures to make the structure earthquake resistant. Every country has its own set of standard codes for the construction of building under lateral load. IS: 1893 (Part 1) is followed in India for the design of earthquake resistant structures.

1.1.1 Vibration suppressing measures

Several modifications in the building have been suggested by the researchers as a result of several years of research and experimentation. While most of them have been implemented in the newly constructed buildings, some are still under trial. Base Isolation, Tuned Mass Damper (TMD), Fluid viscous dampers, Shear wall are some of the techniques necessary to safeguard our structure against the seismic load. In this dissertation, we shall be discussing about the application of Tuned Mass Damper (TMD) as an effective way to reduce the propagation of vibrations in the building.

The concept of Tuned Mass Damper (TMD) was first coined in 1909 by Frahm and from ever since, it has been a matter of study for several researchers all around the world. A TMD consist of a mass, spring and dashpot arrangement, where the spring and the dashpot is connected in parallel to the mass block. This arrangement acts as a secondary structure and is connected to the primary structure, thereby reducing its vibrations by dissipating the kinetic energy. Both primary and secondary structure resonates at a certain frequency allowing the secondary structure to resonates out of phase with the primary one. This concept lays the platform for the design of TMD and serve as an effective vibration dissipator technique.

1.1.2 Practical implementation

The concept of tuned mass damper has been considered as one of the most effective ways to reduce disturbance caused due to lateral load on the building and has already been implemented in several skyscrapers across the world. Few of the examples of the renowned buildings with TMD are **John Hancock tower** in Boston, USA built in the year 1977 with 2 dampers of weight 300 t each. **Burj-Al-Arab** in Dubai built in the year 1999 consisting of 11 dampers, thereby occupying a large amount of space in the building.

Taipei 101 in Taiwan built in the year 2004, consists of a pendulum type TMD with the total weight of the damper equal to 730 t. Another example is the one installed in the **Millennium Bridge** in London having the arrangement quite similar to the one we shall be discussing in the succeeding chapters of our project. In India, the **Air Traffic Control (ATC) Tower** in New Delhi built in the year 2015 has a TMD arrangement with 50 t damper weight.

1.2 OBJECTIVE OF THE WORK:

The objective of the work is as follows:

1) To study the effect of mass ratio of the tuned mass damper in diminishing the vibrations caused due to an earthquake.
2) To study the effect of damping ratio of the tuned mass damper in reducing the vibrations due to the seismic load.
3) To study the effect of multiple tuned mass dampers in protecting a multistorey building against the effect of an earthquake.
4) To study the effect of placement of the tuned mass damper in a multistorey building to safeguard it against the destructive nature of an earthquake.
5) To study the effect of size of the building on the dissipation of dynamic response caused due to installation of TMD in a building.

Therefore, an overall effect of a tuned mass damper on a multistorey building is studied through number of parametric variations thereby giving us the gist of the impact of TMD in safeguarding the modern-day buildings against an earthquake. OPENSEES software, used to achieve our objective is considered to be an advance software by the researchers and provide better seismic simulation than other software available today. Parametric variations included in this work would widen the scope of our study and provide us with ample information regarding the implementation of TMD as a vibration supressing device. The clarity in the work is bought by the use of graphs and tables which would highlight the difference in maximum top storey displacement as well as acceleration of a building with TMD to that of a building without it.

CHAPTER 2

LITERATURE REVIEW

Said Elias and Vasant Matsagar (2015)

The authors have worked on two buildings, one of 76 storeys while the other of 20 storey and analysed the effect of single tuned mass dampers (STMD) at different locations (not necessarily the top floor) under the effect of both the types of dynamic load, namely wind and earthquake. The placement of STMD is based on the fact that the effect of vibrations on the building can be minimised considerably by installing the STMD at the point of highest modal shape amplitude while tuning it to highest modal frequency. Several dynamic parameters such as acceleration, base shear, storey drift etc. are calculated and compared among different cases considered by the author. The effect of increasing the mass ratio was also analysed by the author who therefore concluded that, the disturbance kept on reducing as we increase the mass ratio of the STMD.

Arian Salehiziarani and Reza Karami Mohammadi (2019)

The author of the research paper has basically evaluated the effect of tuned mass damper on a single storey portal frame by varying the mass ratio of the damper and recording the maximum displacement in each case. The frame was subjected to harmonic excitation as well as base acceleration due to different earthquakes. After this, an effort is made to determine the optimal parameters of TMD (mass ratio and damping ratio) using an iterative formula. In the end the results are validated from the several different studies of other authors. While optimising mass ratio called for keeping other parameters like damping ratio, stiffness constant, on the other hand, optimising damping ratio demanded the mass ratio and stiffness to be constant. The suppression in disturbance was always better for harmonic excitation as compared to EQ base acceleration, irrespective of the mass ratio or damping ratio. It was interesting to note that there was a need of large mass in order to optimise mass ratio in case of EQ base excitation while the optimisation of damping ratio desperately needs a semi-active mechanism where there is a meagre increase in damping ratio for obtaining minimum disturbance for harmonic excitation.

Nam Hoang, Yozo Fujino, Pennung Warnitchai (2007)

In the extensive research done by the author, a truss bridge located in Japan with a long span is considered wherein, a tuned mass damping arrangement is suggested for the suppression of seismic vibration, thereby safeguarding the bridge against collapse in the future. The author has recommended to replace the old bearing system with a new one comprising rubber or sliding bearing, which along with bridge deck will make a arrangement resembling a tuned mass damper. Non linearity in programming technique was used to determine the optimised formula for calculating damping ratio and tuning ratio. Previous formulas used by several authors in the past was not applicable here due to excessive mass of the TMD against minute mass of TMD in all other known cases. After several attempts, an optimised formula for damping ratio and tuning ratio was prepared as a function of mass ratio, which varied with different values of ground frequency ratio. The author was therefore able to develop a sturdy arrangement of so-called TMD which showed little or no variation with change in frequency of vibration.

Mohammad Hamayoun Stanikzai, Said Elias, Vasant A. Matsagar, Arvind K. Jain (2019)

The authors have implemented the concept of base isolation along with that of tuned mass damper to provide additional safety to the structures. Two dimensional buildings with variation in number of stories (here 5, 10, 15 storey) are used with a single tuned mass damper placed at varying location of the building. Several different types of isolating materials namely laminated rubber bearing, resilient-friction base isolator, lead rubber bearing, friction pendulum system is used for the purpose of analysis. Parametric study involving the variation in the height of the building, mass ratio, positioning of TMD and use of different isolation material is done in the hybrid system and the results have been compared to draw suitable conclusion. Further, Newmark method of integration has been implemented for formulation and solving the equations of motion. It has been noted that the hybrid system where TMD is coupled with base isolation is more effective in diminishing the mechanical vibration of the system over a wide range of frequencies. The potency of the structure was decreased with an increase in the time period of isolator.

Also, as mentioned by several other researchers, the mass ratio’s increment leads to increase in potency of the TMD, holds true for this work as well. However, it was interesting to note that the position of TMD has its repercussions only for the high-rise building, whereas, the low-rise building is exempted from it.

Chi-Chang Lin, Jin-Min Ueng, Teng-Ching Huang (1998)

The authors in this research have evaluated a 5-storey building by considering the effect of torsional vibration along with translational one, which is generally ignored by the previous authors. Two passive tuned mass dampers (PTMD) were installed in the structure, each responsible for slackening the effect of vibration in both the orthogonal directions. It was ensured by the author that the sum total of mass of both the damper was equal to that of a single damper which therefore, was essential in effective suppression of peak vibration. The optimal location of the PTMD was determined by performing the modal analysis for the structure and carefully considering the mode with the largest participation factor. The peak amplitude of the mode shape gave the authors the location of PTMD, while the direction of it gave the direction of installation of damper. After working on the above-mentioned parameters, the authors found the superlative dampers' parameter. In order to achieve their objective, the authors minimised a parameter in which they calculated the response ratio of the displacement of the modes, which they squared and ultimately took its mean. This allowed them to complete their research by ensuring that the location as well as the optimum parameter was in front of them. The author gave heed to the fact that the highest participation factor of the mode could be different in both the orthogonal direction. Hence to avoid any dispute over the result, they associated one TMD in each direction and designed it accordingly, thereby completing their objective.

Gebrail Bekdas, Sinan Melih Nigdeli (2011)

Harmony search is the core of this paper, where optimised parameters were obtained using this method. The author listed down the advantages of this technique like searching between any variety of real number be it continuous or discrete, a smaller number of iterations in pursuit of global maxima or minima as well as skipping of local minima or maxima and working for global ones, are the few. The author modelled a ten-storey building for this purpose and installed the tuned mass damper at the top of it, while extracting the displacement of top storey and generating the transfer function of acceleration thereby minimising it at the end. The result obtained using this technique was validated using the work of others authentic authors. It was interesting to note that this technique led to the better results than the previous ones by further slackening the value of displacement than the previous work. The optimised values of the tuned mass dampers' parameters were even better in respect to the overall cost of the installation as the values were considerably smaller. This provided the authors with the twin advantage and hence this work improved all those previous works that were done on the building using manual calculations.

S. Pourzeynali, H.H. Lavasani, A.H. Modarayi (2006)

The author has worked on the eleven-storey building and used the concept of genetic algorithm and fuzzy logic for obtaining the superlative values of the parameters. The clubbing ensured that the responses were severely reduced and non-linearity was effectively dealt with. The active tuned mass damper was used which continuously took the power from the external source and diminished the structural response. The final results, thus obtained were compared with that of LQR method. The fuzzy logic takes top storey displacement as well as velocity vector as the input and generate the membership functions through it. As far as the genetic algorithm is concerned, the fitness function is developed in such a way that the storey displacement is diminished. Thus, the combination of fuzzy logic and genetic algorithm turned out to be effective and provided better results than that of LQR method. The use of multiple number of sensors in LQR method is the main drawback of this method. Further, it was observed that the optimised parameters obtained by the author through the use of fuzzy logic and genetic algorithm provided economical arrangement than that obtained from LQR method.

CHAPTER 3

OVERVIEW OF SOFTWARE

3.1 DESIGNING ON OPENSEES:

In order to achieve our objective, the above specified structure is modelled in OPENSEES in the Tcl programming language. The reason being fast processing, open-source nature of the software and the accuracy with which it calculates the results. Following are the steps of modelling our structure in OPENSEES:

a) Defining the number of dimension (ndm) and the number of degrees of freedom per node (ndf) in the very beginning of our program.
b) Next up, we define all the nodes of our structure. Nodes definition includes giving a proper address to each of them through the use of global coordinate system.
c) We define the elements used to create the beams, columns or slabs in the structure. There are several options available in the BasicBuilder package but here we have used elasticBeamColumn as our element.
d) After this we need to define the materials of our members. Here, in our structure we have not specifically defined the material but rather clubbed the characteristics of the member such as area of cross-section (A), modulus of elasticity of the material (E) and moment of inertia of the member (I) in the element itself.
e) We, then, define the boundary condition for our building. In our multi-storey building, we have constrained the ground nodes or the bottom nodes against translation as well as rotation.
f) An all-important step follows called as matrix transformation, where we have different ways to convert all the local coordinates into global coordinates.
g) We therefore, apply all the loads using time series and pattern as well as nodal mass (if any) on the structure.
h) Recorders are used to store the output of our program where a separate file is created at the specifies location containing the specified parameters such as reaction, displacement or drift at different time step of applying the load.

i) The core of the program includes definition of analysis object. It has several key components like constraint, numberer, system, algorithm etc. which needs to be specified carefully depending upon our structure.
j) In the end, we run our analysis in ‘n’ number of steps depending upon the load increment.

After modelling our structure on the OPENSEES, as mentioned in the preceding pages, we applied the gravity load on it. Here in our code the gravity load has been applied in 10 steps with an increment of 0.1 unit per step. These values depend on the programmer, but increasing the number of steps or decreasing the increment per step would lead to increase in processing time.

3.1.1 List of files required:

Several files were prepared along with the main file that contain the above-mentioned steps in order to run our main code. These files include:

a) File containing the basic as well as the derived units.
b) File containing the analysis object to apply the gravity load apart from defining it in the main file.
c) File containing modal analysis to get the frequency of the first few modes of vibrations of the structure.
d) File containing the code to apply Rayleigh damping as well as the unidirectional or bidirectional EQ excitation onto the structure.
e) File containing the code to convert the time-history data obtained from PEER website of a region to the suitable format that the computer understands and access.

CHAPTER 4

STRUCTURE MODELLING

4.1 PROBLEM STATEMENT:

As mentioned above, a 10-storey building needs to be prepared using the specifications written below. Gravity loads are applied and modal analysis is performed. Now the 2 TMD’s are installed at each corner node of the top storey. It is important to note that the TMD’s are tuned to the frequency of the main structure and allowed a phase difference of 90^{o} with the main structure in order to fritter away the kinetic energy of the main structure and overcome the vibrations due to the seismic load. The total mass of the TMD is constant, irrespective of the number of TMD’s used. Here, both the TMD’s will share the mass of the damper equally and other design parameters accordingly.

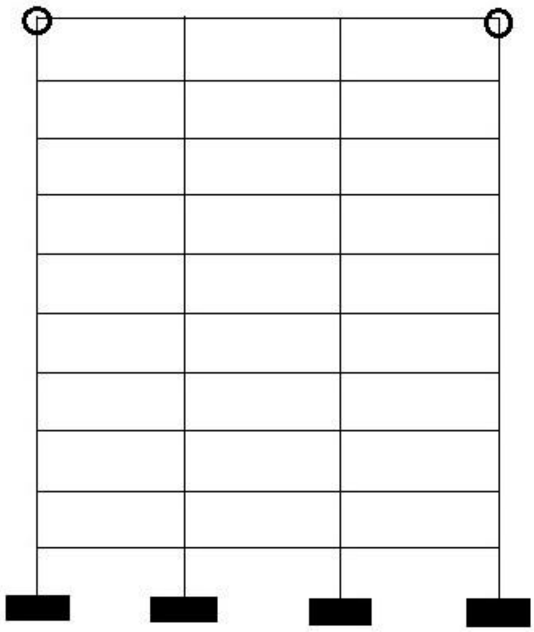

Figure 4.1: 10-storey framed structure with 2 TMDs used for study

4.1.1 STRUCTURE DESCRIPTION:

A 10-storey building is considered with 3 bays wherein, the front frame is shown and the tuned mass damper is attached to that frame. Thus, it can be pronounced to be a framed structure for simplicity and all the parameters, be it design or result, on the plane of the building is only considered.

Following are the properties of the members of the building:

a) Grade of concrete = M40
b) Dimension of the beam = 300 mm * 450 mm
c) Dimension of the column = 300 mm * 450 mm
d) Length of the column = 3.5 m
e) Length of the beam = 6.0 m

4.1.2 GRAVITY ANALYSIS:

Following are the values obtained by the reaction recorder of the OPENSEES along with the summation of the load at all the nodes at a common level.

Time step	**Gravity load at all the base nodes (KN)**				**Sum of the load (KN)**
0.1	22.3801	31.6199	31.6199	22.3801	108
0.2	44.7601	63.2399	63.2399	44.7601	216
0.3	67.1402	94.8598	94.8598	67.1402	324
0.4	89.5203	126.48	126.48	89.5203	432.0006
0.5	111.9	158.1	158.1	111.9	540
0.6	134.28	189.72	189.72	134.28	648
0.7	156.66	221.34	221.34	156.66	756
0.8	179.041	252.959	252.959	179.041	864
0.9	201.421	284.579	284.579	201.421	972
1	223.801	316.199	316.199	223.801	1080

Table 4.1: Gravity load as well as its sum at all the base nodes at each time increment.

4.1.3 MODAL ANALYSIS:

The next step involves performing modal analysis on our structure. Here, modal analysis for first 3 modes have been performed, while the first mode (the dominant mode) having the highest participation factor is considered for designing the TMD required for the building.

Mode No.	Lambda	Omega	Period	Frequency
1	5.401272 E+01	7.349335	8.549325 E-01	1.169683
2	5.065253 E+02	2.250612 E+01	2.791768 E-01	3.58196
3	1.527681 E+03	3.908556 E+01	1.607546 E-01	6.220661

Table 4.2: Parameters recorded on OPENSEES after modal analysis.

After subjecting our building to the gravity load as well as modal analysis, it is then subjected to six different earthquakes occurred at different parts of the world of varying intensity and peak ground acceleration. The basic details regarding them have been presented in the table shown below:

S. No.	Earthquake	Year	Station	Component
1	Imperial Valley	1979	El Centro Array #12	140
2	Kobe	1995	KJMA	000
3	Parkfield	1966	Cholame - Shandon Array #12	DWN
4	Oroville-01	1975	Oroville Seismograph Station	37
5	Hector Mine	1999	Riverside	90
6	Chuetsu-oki	2007	KNG014	EW

Table 4.3: Earthquake records used in the study

A comparative approach has been adopted wherein, dynamic parameters such as top storey displacement as well as top storey acceleration has been compared for the building without tuned mass damper as well as with it.

4.1.4 CASES:

Following are the cases that needed to be done on the building to determine the behaviour of the TMD:

- **CASE I:** The behaviour of the building when it is subjected to several different earthquakes by recording the top storey displacement as well as acceleration.

- **CASE II:** The influence of variation in damping ratio of the TMD on the top storey displacement as well as acceleration keeping the mass ratio and the damping ratio of the structure constant.

- **CASE III:** The influence of variation in mass ratio on the top storey displacement and acceleration keeping the damping ratio of structure and the TMD constant.

4.1.4.1 CASE I: The behaviour of the building when it is subjected to several different earthquakes by recording the top storey displacement as well as acceleration.

4.1.4.1.1 Determination of TMD parameters:

After performing the gravity analysis, we get the value of the total weight of the building at final step to be 1080 KN.

We assume the mass ratio to be 5% i.e., the mass of the damper to be 5% of the total mass of the building

Therefore, the total weight of the damper comes out to be

= (5% of 1080 KN)

= 54 KN

Since, the total mass of the TMD's arrangement is maintained constant, irrespective of the number of TMD's used, therefore we distribute the total weight of the damper equally between the two TMD's.

Therefore, weight of each damper $\boldsymbol{W_d}$ = 54 / 2

=27 KN

Now the mass of each TMD will be

$$\boldsymbol{M_d} = \boldsymbol{W_d} / \boldsymbol{g}$$

= (27 / 9.81)

$= 2.75229$ Kg

In order to calculate the length of the damper, we use the following relation

$$\boldsymbol{T = 2\pi\sqrt{\frac{l}{g}}}$$

Where T is obtained from the modal analysis and is equal to 0.8549325 s.

Therefore, on substituting the values, we get

$$0.8549325 = 2\pi\sqrt{\frac{l}{9.81}}$$

The length of damper comes out to be equal to 0.1816 m.

The stiffness of each TMD is calculated using the following relationship

$$\boldsymbol{K_d = M_d g \;/\; l}$$

$$= (27 / 0.1816)$$

$$= 148.6784 \text{ KN/m}$$

In our building we assume the damping ratio of the building as well as that of tuned mass damper to be 2%.

Since, we have discussed that the tuned mass damper should be in resonance with the structure in order to fritter away the maximum kinetic energy of the structure and itself going out of phase (precisely, 90^0 phase difference with the main structure),

Therefore, we take angular frequency of the TMD to be equal to that of the structure

$$\boldsymbol{\omega_d = \omega}$$

$$\boldsymbol{\omega_d} = 7.349335$$

Finally, the value of damping coefficient is calculated using

$$\boldsymbol{C_d = 2\xi M_d \omega_d}$$

$$= 2 * 0.02 * 2.75229 * 7.349335$$

$$= 0.809102 \text{ Kg/s}$$

Parameters of the TMD	**Values**
Mass of each damper ($\boldsymbol{M_d}$)	2.75229 Kg
Length of each damper **(l)**	0.1816 m.
Stiffness of each damper ($\boldsymbol{K_d}$)	148.6784 KN/m
Damping coefficient of each damper ($\boldsymbol{C_d}$)	0.809102 Kg/s

Table 4.4: TMD parameters used for Case I

4.1.4.1.2 Methodology:

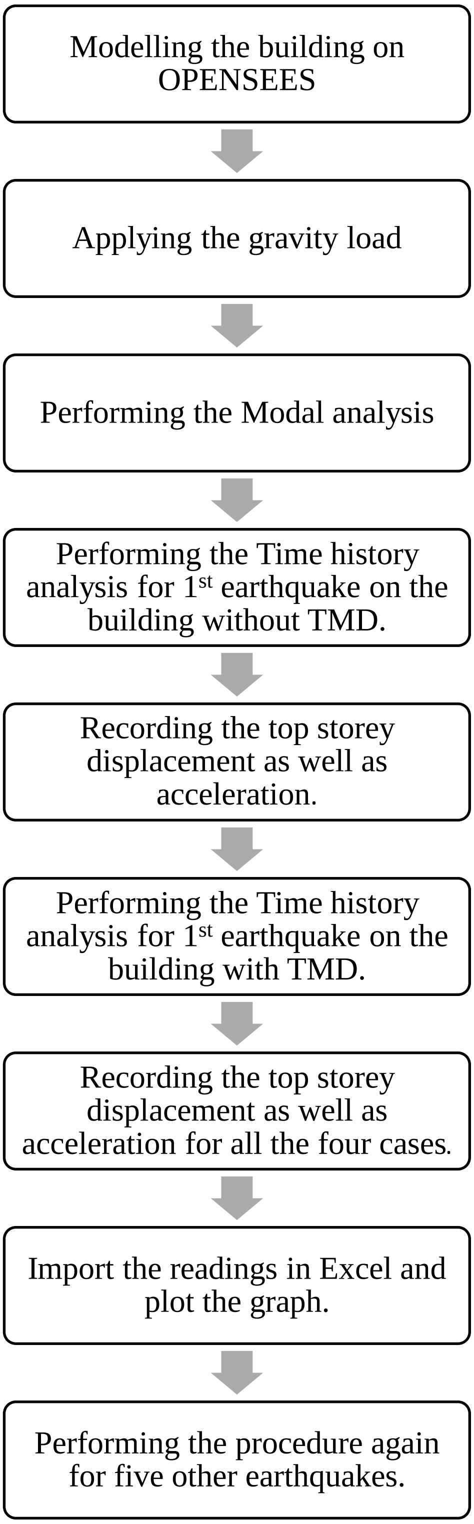

Figure 4.2: Sequence of steps to be followed for CASE I

Imperial Valley earthquake (1979)

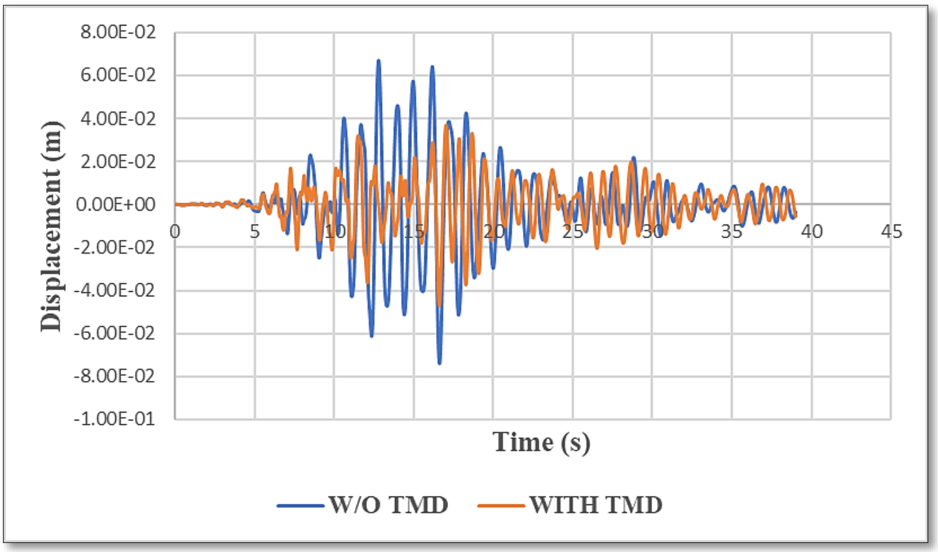

Figure 4.3: Displacement vs time for building under Imperial Valley earthquake

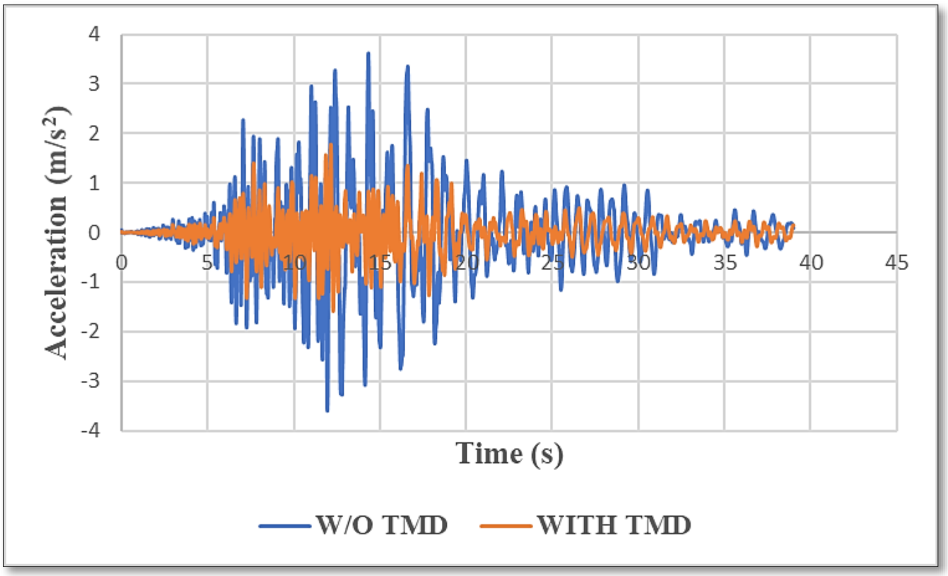

Figure 4.4: Acceleration vs time for building under Imperial Valley earthquake

Kobe earthquake (1995)

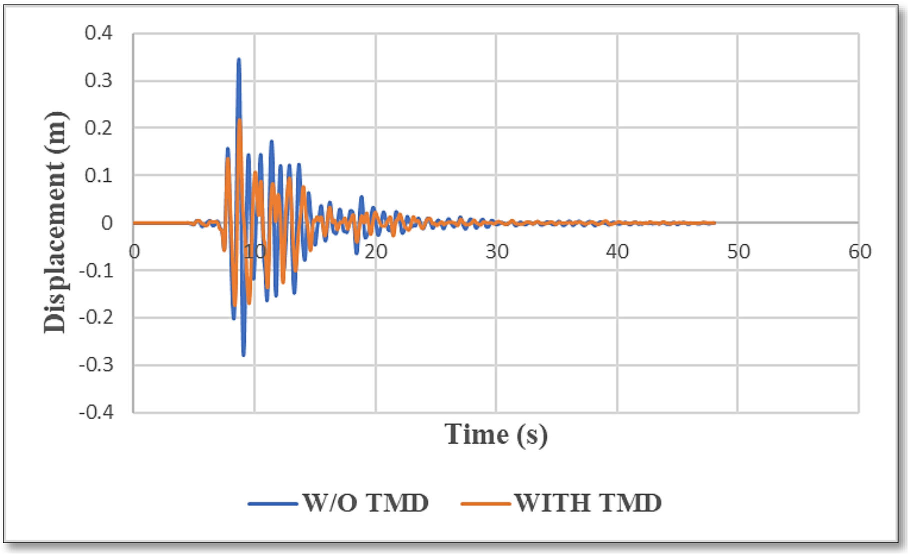

Figure 4.5: Displacement vs time for building under Kobe earthquake

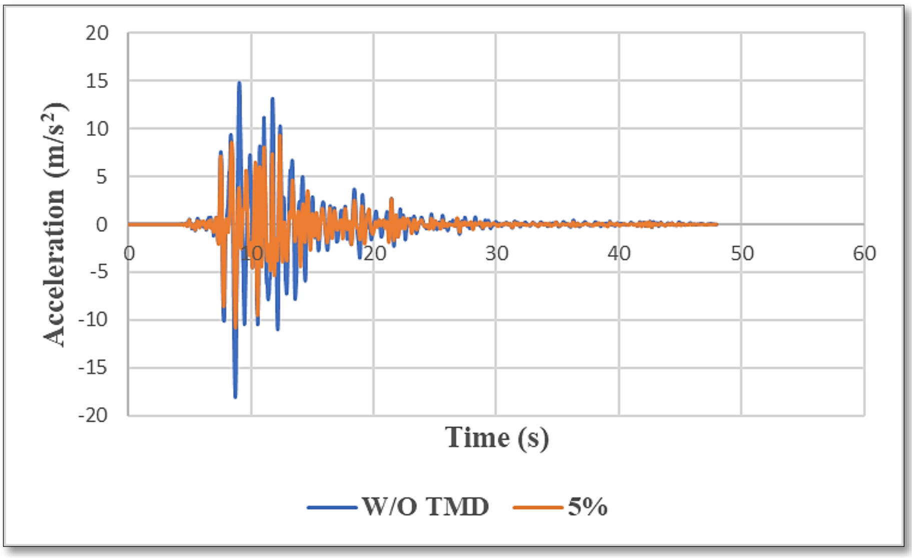

Figure 4.6: Acceleration vs time for building under Kobe earthquake

Parkfield earthquake (1966)

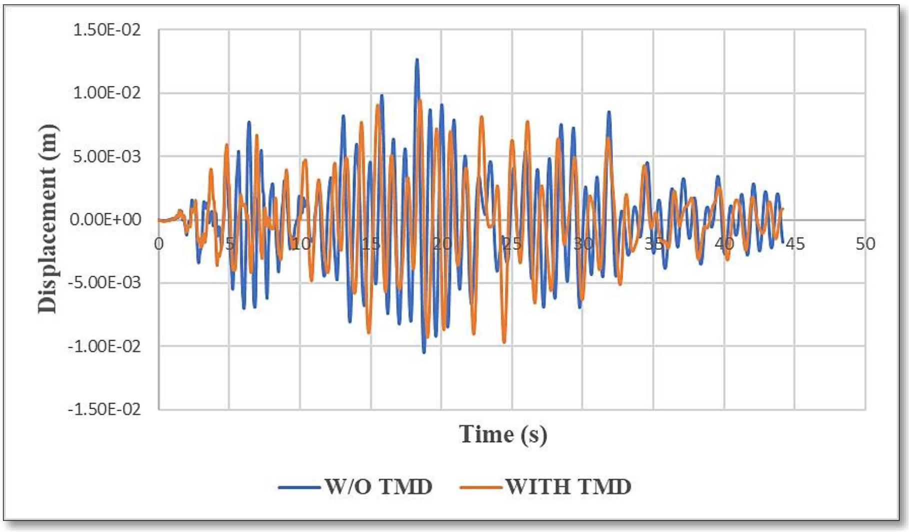

Figure 4.7: Displacement vs time for building under Parkfield earthquake

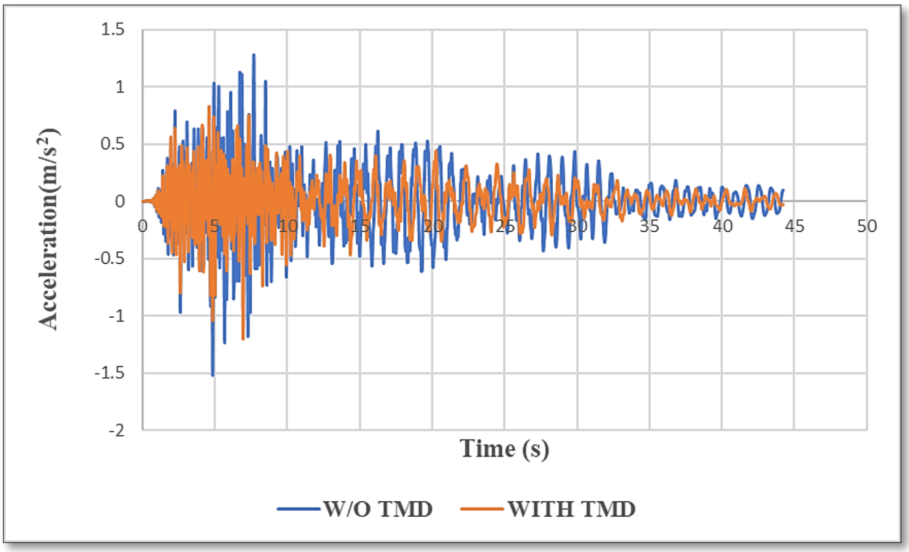

Figure 4.8: Acceleration vs time for building under Parkfield earthquake

Oroville-01 earthquake (1975)

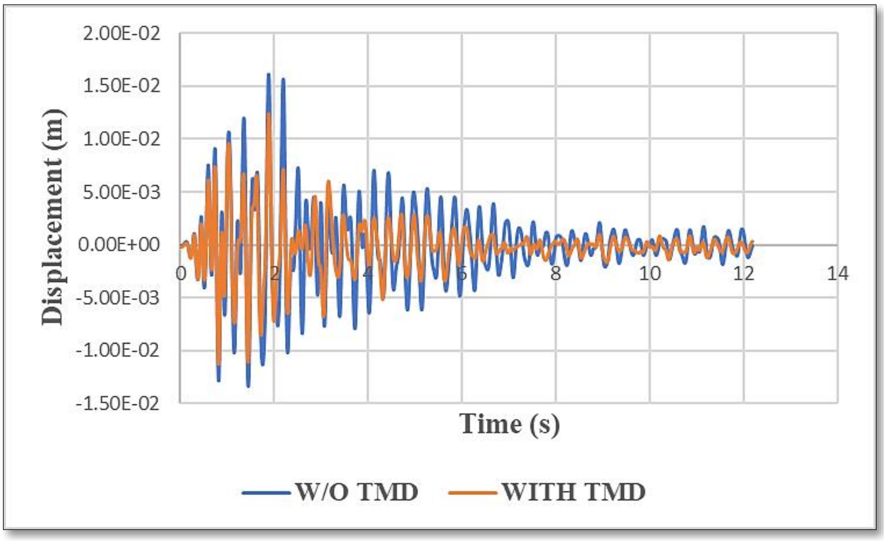

Figure 4.9: Displacement vs time for building under Oroville-01 earthquake

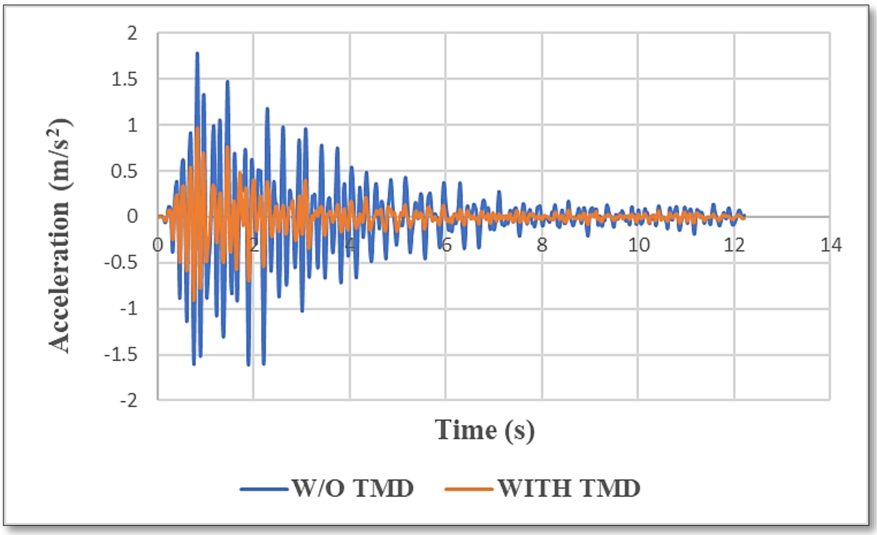

Figure 4.10: Acceleration vs time for building under Oroville-01 earthquake

Hector Mine earthquake (1999)

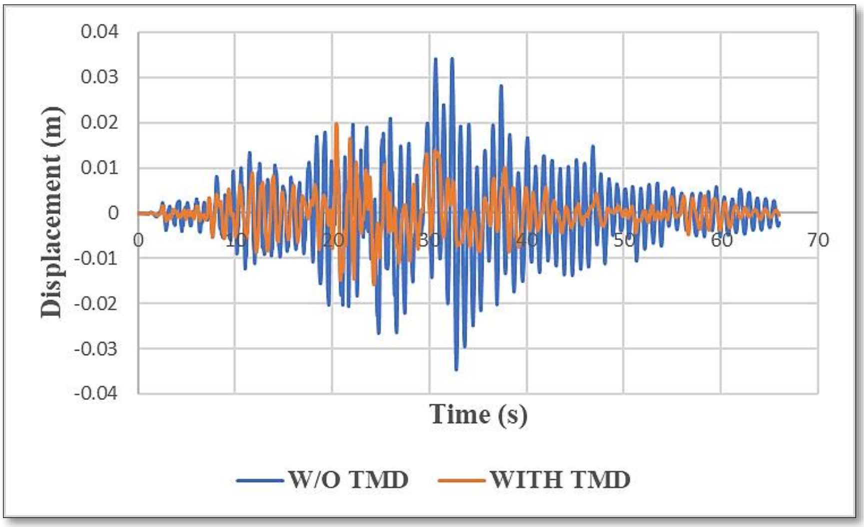

Figure 4.11: Displacement vs time for building under Hector Mine earthquake

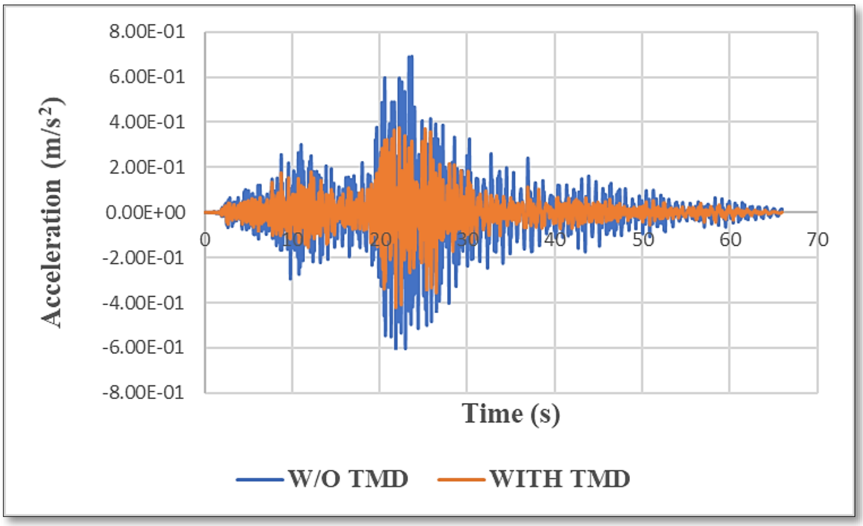

Figure 4.12: Acceleration vs time for building under Hector Mine earthquake

Chuetsu-oki earthquake (2007)

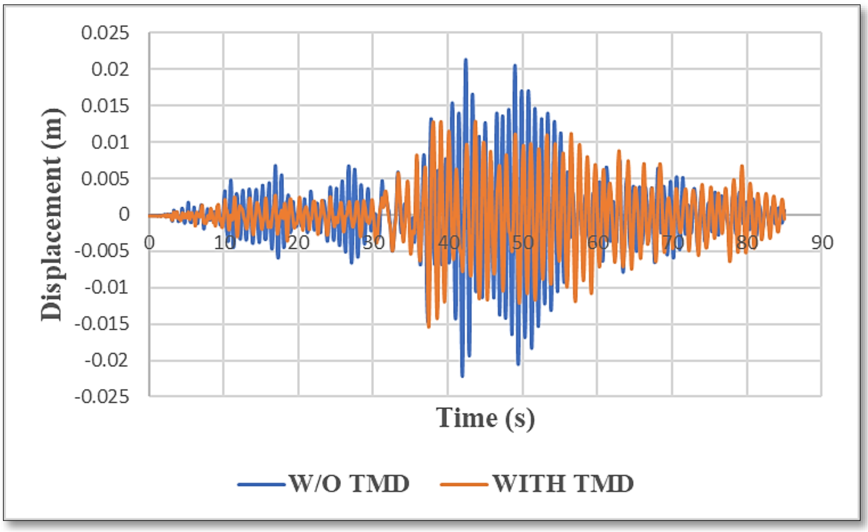

Figure 4.13: Displacement vs time for building under Cheutsu-oki earthquake

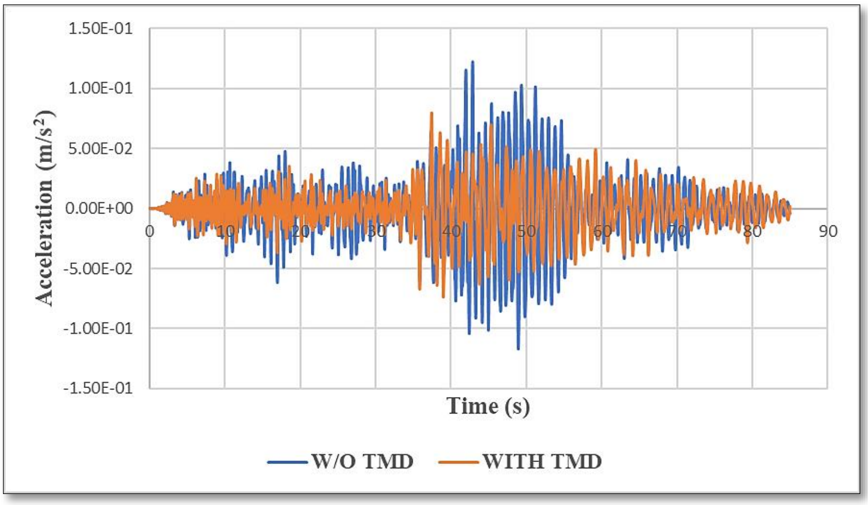

Figure 4.14: Acceleration vs time for building under Cheutsu-oki earthquake

4.1.4.1.3 Results and Discussions:

S.No	Earthquake	Max. Displacement of top storey (m)		% Reduction
		Without TMD	With TMD	
1	Imperial Valley	0.0739	0.0469	36.54
2	Kobe	0.346	0.216	37.57
3	Parkfield	0.0126	0.00947	24.84
4	Oroville-01	0.0161	0.0124	22.98
5	Hector Mine	0.0341	0.0198	41.93
6	Chuetsu-oki	0.0213	0.0127	40.37

Table 4.5: % Reduction of top storey displacement due to 2 TMD's under different earthquakes

It can be seen from the above table that the application of TMD on the building reduces the maximum top storey displacement considerably ranging from 22.98% to 41.93% with an average being 34.04%. Hence, the TMD designed is effective in achieving its objective.

S.No	Earthquake	Max. Acceleration of top storey (m/s^s)		% Reduction
		Without TMD	With TMD	
1	Imperial Valley	3.61853	1.84111	48.12
2	Kobe	18.1418	10.62567	41.43
3	Parkfield	1.51468	1.20201	20.64
4	Oroville-01	1.78817	0.97483	45.47
5	Hector Mine	0.689	0.422	38.75
6	Chuetsu-oki	0.117	0.0794	32.14

Table 4.6: % Reduction of top storey acceleration due to 2 TMD's under different earthquakes

It can be seen from the above table that the application of TMD on the building reduces the maximum top storey acceleration considerably ranging from 20.64% to 48.12% with an average being 37.76%. Hence, the TMD designed is effective in achieving its objective

4.1.4.2 <u>CASE II</u>: The influence of variation in damping ratio of the TMD on the top storey displacement as well as acceleration keeping the mass ratio and the damping ratio of the structure constant.

4.1.4.2.1 Determination of TMD parameters

Here, for this case we assume the mass ratio as well as the damping ratio of the primary structure to be same as that in CASE I (i.e., 5% and 2% respectively).

As discussed before the angular frequency of the TMD is equal to that of the structure

$$\boldsymbol{\omega_d = \omega}$$

$$\boldsymbol{\omega_d} = 7.349335$$

In order to perform the parametric study involving the variation in the damping ratio of the TMD, we take four different cases varying the damping ratio of the TMD from 2 to 5 % with an increment of 1%.

Therefore, the value of damping coefficient for four different cases are as follows:

i. **For $\boldsymbol{\xi = 2}\%$**

   $\boldsymbol{C_d = 2\xi M_d \omega_d}$

   = 2 * 0.02 * 2.75229 * 7.349335

   = 0.809102 Kg / s

ii. **For $\boldsymbol{\xi = 3}\%$**

   $\boldsymbol{C_d = 2\xi M_d \omega_d}$

   = 2 * 0.03 * 2.75229 * 7.349335

   = 1.213652 Kg / s

iii. **For $\boldsymbol{\xi = 4}\%$**

   $\boldsymbol{C_d = 2\xi M_d \omega_d}$

   = 2 * 0.04 * 2.75229 * 7.349335

   = 1.618203 Kg / s

iv. **For $\boldsymbol{\xi = 5}\%$**

$C_d = 2\xi M_d \omega_d$

= 2 * 0.05 * 2.75229 * 7.349335

= 2.022753 Kg / s

<table>
<tr><th>Parameters of the TMD</th><th colspan="4">Values</th></tr>
<tr><td>Mass of each damper (M_d)</td><td colspan="4">2.75229 Kg</td></tr>
<tr><td>Length of each damper (l)</td><td colspan="4">0.1816 m.</td></tr>
<tr><td>Stiffness of each damper (K_d)</td><td colspan="4">148.6784 KN/m</td></tr>
<tr><td>Damping coefficient of each damper (C_d)</td><td>0.809102</td><td>1.213652</td><td>1.618203</td><td>2.022753</td></tr>
</table>

Table 4.7: TMD parameters used for Case II

The procedure remains same as explained long-windedly in the case in the methodology section as well as in CASE I. The storey response in the form of top storey displacement as well as top storey acceleration is calculated as represented in the graphs drawn below clearly depicting the objective of this case.

The flow chart drawn below gives the sequence adopted to achieve the purpose of this case i.e., effect of damping ratio of the TMD on the structural response.

4.1.4.2.2 Methodology

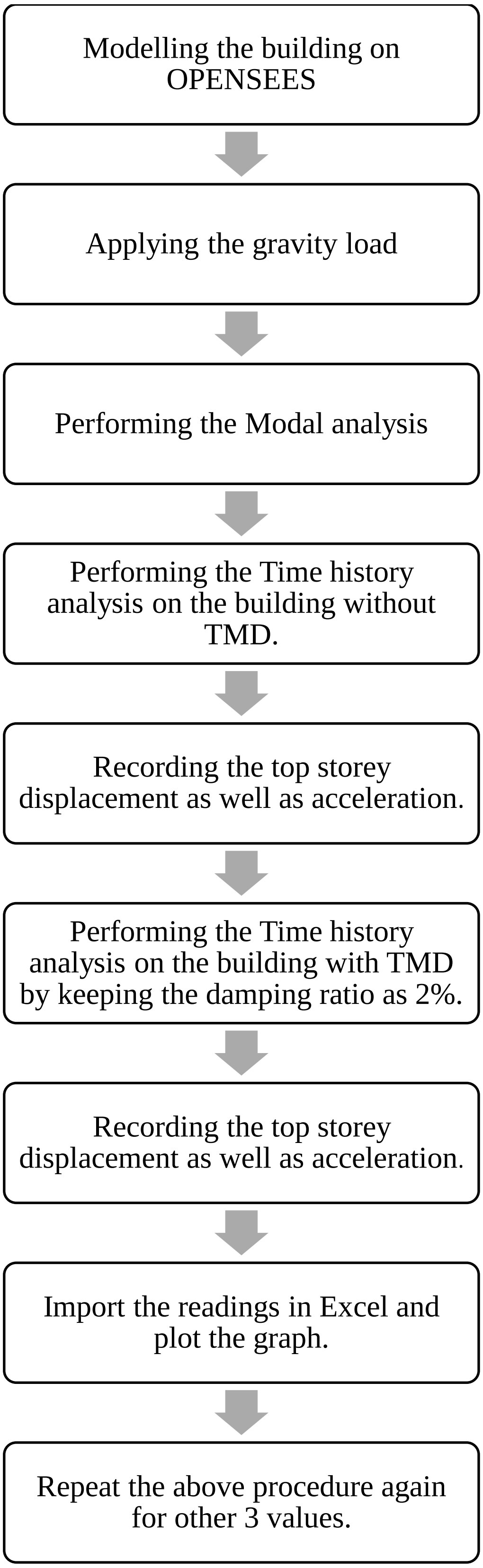

Figure 4.15: Sequence of steps to be followed for CASE II

4.1.4.2.3 Results and discussion:

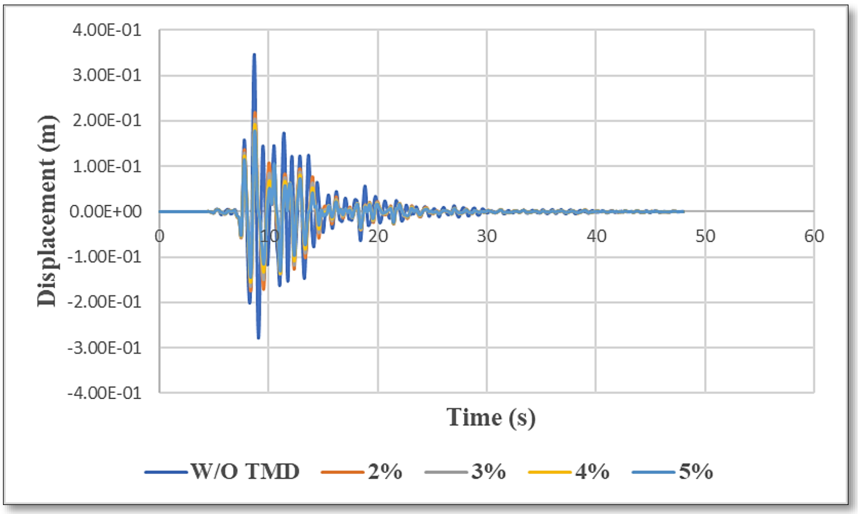

Figure 4.16: Displacement vs time for building under Kobe earthquake with varying damping ratio

As shown in the graph plotted above the maximum top storey displacement in the building without the tuned mass damper arrangement is 0.3462 m.

S.No	Damping ratio of TMD	Maximum top storey displacement (m)	% Reduction
1	2%	0.2160	37.57
2	3%	0.2036	41.19
3	4%	0.1921	44.51
4	5%	0.1751	49.42

Table 4.8: % Reduction of top storey displacement due to TMD with varying damping ratio

It can be seen from the above table that the there is a decrease in the maximum top storey displacement with an increase in the damping ratio of the TMD. This decrease came out to be 3.95% for every 1% increase in damping ratio of TMD. Hence, the damping ratio of the TMD has to be kept at such a value so as to minimise the displacement by maximum amount.

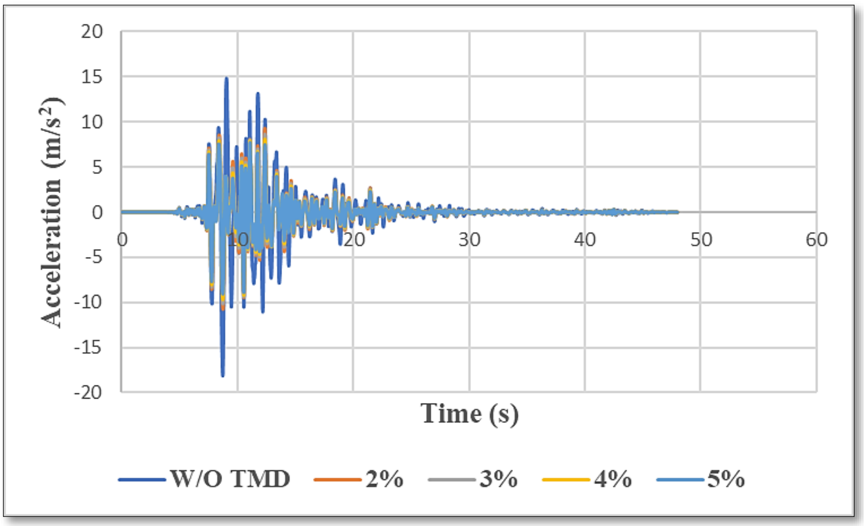

Figure 4.17: Acceleration vs time for building under Kobe earthquake with varying damping ratio

As shown in the graph plotted above the maximum top storey acceleration in the building without the tuned mass damper arrangement is 18.142 m/s^2.

S.No	Damping ratio of TMD	Maximum top storey Acceleration (m/s^s)	% Reduction
1	2%	10.625	41.43
2	3%	10.155	44.02
3	4%	9.680	46.64
4	5%	9.059	50.06

Table 4.9: % Reduction of top storey acceleration due to TMD with varying damping ratio

It can be seen from the above table that the there is a decrease in the maximum top storey acceleration with an increase in the damping ratio of the TMD. This decrease came out to be 2.88% for every 1% increase in damping ratio of TMD. Hence, the damping ratio of the TMD has to be kept at such a value so as to minimise the acceleration by maximum amount.

4.1.4.3 <u>CASE III</u>: The influence of variation in mass ratio of the TMD on the top storey displacement and acceleration keeping the damping ratio of structure and the TMD constant.

4.1.4.3.1 Determination of TMD parameters

Here, for this case we assume the damping ratio of the primary structure as well as the TMD to be same as that in CASE I (i.e., 2% each).

As discussed before the angular frequency of the TMD is equal to that of the structure

$$\boldsymbol{\omega_d = \omega}$$

$$\boldsymbol{\omega_d} = 7.349335$$

In order to perform the parametric study involving the variation in the mass ratio of the TMD, we take four different cases varying the mass ratio of the TMD from 3 to 6 % with an increment of 1%.

Therefore, the value of each Tuned mass damper parameters for four different cases are as follows:

i. For $\boldsymbol{\mu}$ **= 3%**

Total weight of the TMD's = 3% of 1080 KN

= 32.4 KN

Weight of each TMD ($\boldsymbol{W_d}$) = 32.4 / 2

= 16.2 KN

$$\boldsymbol{M_d = W_d \,/\, g}$$

= 16.2 / 9.81

= 1.65137 Kg

$$\boldsymbol{K_d = Mg \,/\, l}$$

= (16.2 / 0.1816)

= 89.2070 KN / m

$$\boldsymbol{C_d = 2\xi M_d \omega_d}$$

= 2 * 0.02 * 1.65137 * 7.349335

= 0.485460 Kg / s

ii. For $\boldsymbol{\mu}$ **= 4%**

Total weight of the TMD's = 4% of 1080 KN

= 43.2 KN

Weight of each TMD ($\boldsymbol{W_d}$) = 43.2 / 2

= 21.6 KN

$\boldsymbol{M_d = W_d \;/\; g}$

= 21.6 / 9.81

= 2.20183 Kg

$\boldsymbol{K_d = Mg \;/\; l}$

= (21.6 / 0.1816)

= 118.9427 KN / m

$\boldsymbol{C_d = 2\xi M_d \omega_d}$

= 2 * 0.02 * 2.20183 * 7.349335

= 0.64728 Kg / s

iii. For $\boldsymbol{\mu}$ **= 5%**

Total weight of the TMD's = 5% of 1080 KN

= 54 KN

Weight of each TMD ($\boldsymbol{W_d}$) = 54 / 2

= 27 KN

$\boldsymbol{M_d = W_d \;/\; g}$

= 27 / 9.81

= 2.75229 Kg

$\boldsymbol{K_d = Mg \;/\; l}$

= (27 / 0.1816)

= 148.6784 KN / m

$\boldsymbol{C_d = 2\xi M_d \omega_d}$

= 2 * 0.02 * 2.75229 * 7.349335

=0.809102 Kg / s

iv. For $\boldsymbol{\mu}$ **= 6%**

Total weight of the TMD's = 6% of 1080 KN

= 64.8 KN

Weight of each TMD ($\boldsymbol{W_d}$) = 64.8 / 2

= 32.4 KN

$\boldsymbol{M_d = W_d \,/\, g}$

= 32.4 / 9.81

= 3.302752 Kg

$\boldsymbol{K_d = Mg \,/\, l}$

= (32.4 / 0.1816)

= 178.4141 KN / m

$\boldsymbol{C_d = 2\xi M_d \omega_d}$

= 2 * 0.02 * 3.302752 * 7.349335

= 0.97092 Kg / s

S.No	Mass ratio of the TMD ($\boldsymbol{\mu}$)	Mass of the TMD ($\boldsymbol{M_d}$) (Kg)	Stiffness of the TMD ($\boldsymbol{K_d}$) (KN/m)	Damping coefficient of TMD ($\boldsymbol{C_d}$) (Kg/s)
1	3 %	1.65137	89.2070	0.485460
2	4 %	2.20183	118.9427	0.64728
3	5 %	2.75229	148.6784	0.809102
4	6 %	3.302752	178.4141	0.97092

Table 4.10: TMD parameters used for Case III

The procedure remains same as explained long-windedly in the case in the methodology section as well as in CASE I. The storey response in the form of top storey displacement as well as top storey acceleration is calculated as represented in the graphs drawn below clearly depicting the objective of this case.

The flow chart drawn below gives the sequence adopted to achieve the purpose of this case i.e., effect of mass ratio of the TMD on the structural responses.

4.1.4.3.2 Methodology

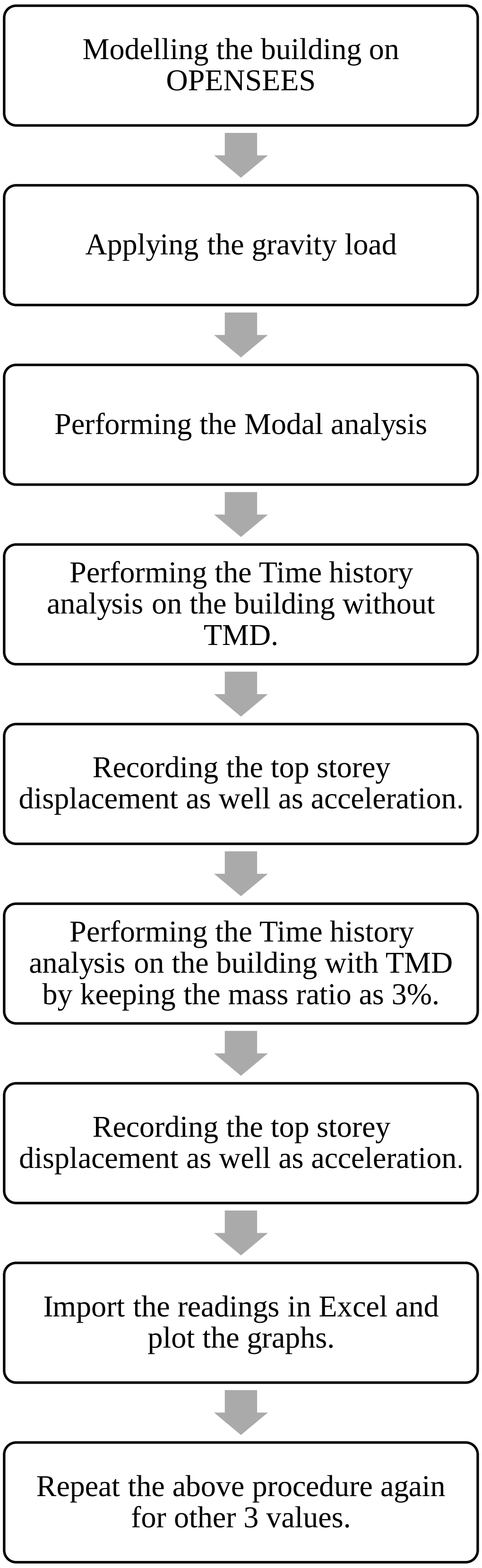

Figure 4.18: Sequence of steps to be followed for CASE III

4.1.4.3.3 Results and discussions

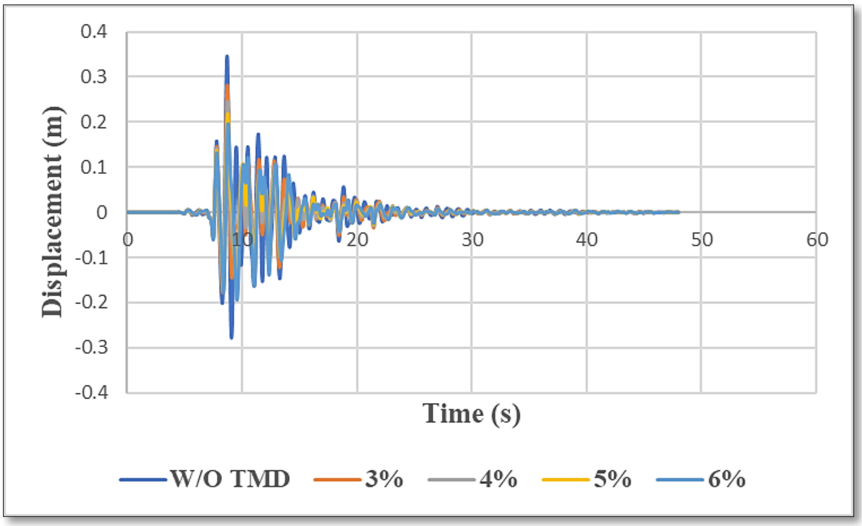

Figure 4.19: Displacement vs time for building under Kobe earthquake with varying Mass ratio

As shown in the graph plotted above the maximum top storey displacement in the building without the tuned mass damper arrangement is 0.346 m.

S.No	Mass ratio of TMD	Maximum top storey displacement (m)	% Reduction
1	3%	0.282	18.50
2	4%	0.246	28.90
3	5%	0.216	37.57
4	6%	0.196	43.35

Table 4.11: % Reduction of top storey displacement due to TMD with varying mass ratio

It can be seen from the above table that the there is a decrease in the maximum top storey displacement with an increase in the mass ratio of the TMD. This decrease came out to be 8.28% for every 1% increase in mass ratio of TMD. Hence, the mass ratio of the TMD has to be kept at such a value so as to minimise the displacement by maximum amount.

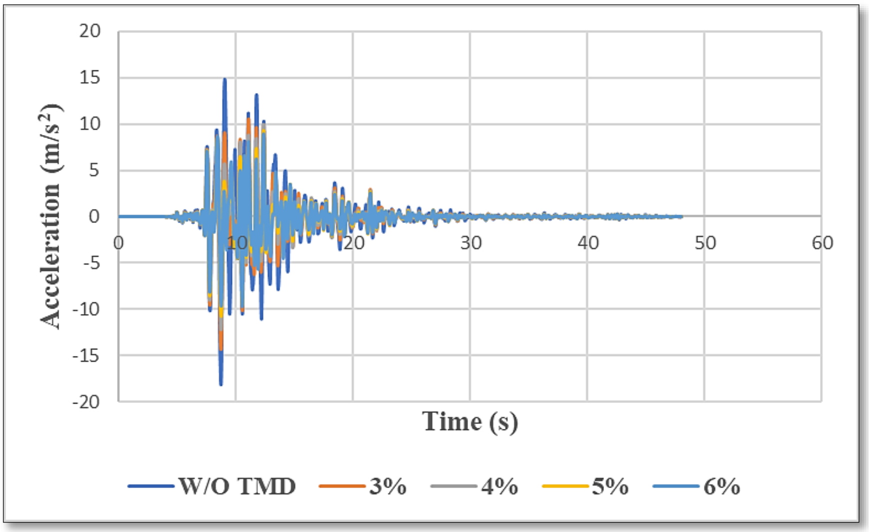

Figure 4.20: Acceleration vs time for building under Kobe earthquake with varying Mass ratio

As shown in the graph plotted above the maximum top storey acceleration in the building without the tuned mass damper arrangement is 18.142 m/s^2.

S.No	Mass ratio of TMD	Maximum top storey Acceleration (m/s^s)	% Reduction
1	3%	14.325	21.03
2	4%	12.179	32.87
3	5%	10.626	41.43
4	6%	9.635	46.89

Table 4.12: % Reduction of top storey acceleration due to TMD with varying Mass ratio

It can be seen from the above table that the there is a decrease in the maximum top storey acceleration with an increase in the mass ratio of the TMD. This decrease came out to be 8.62% for every 1% increase in mass ratio of TMD. Hence, the mass ratio of the TMD has to be kept at such a value so as to minimise the acceleration by maximum amount.

4.2 PROBLEM STATEMENT:

A 10-storey building needs to be prepared using the same specifications as that in problem 1. Gravity loads are applied and modal analysis is performed. Here the 4 TMD's are installed at each node of the top storey. It is important to note that the TMD's are tuned to the frequency of the main structure and allowed a phase difference of 90^o with the main structure in order to fritter away the kinetic energy of the main structure and overcome the vibrations due to the seismic load. The total mass of the TMD is constant, irrespective of the number of TMD's used. Here, all the four TMD's will share the mass of the damper equally and other design parameters accordingly.

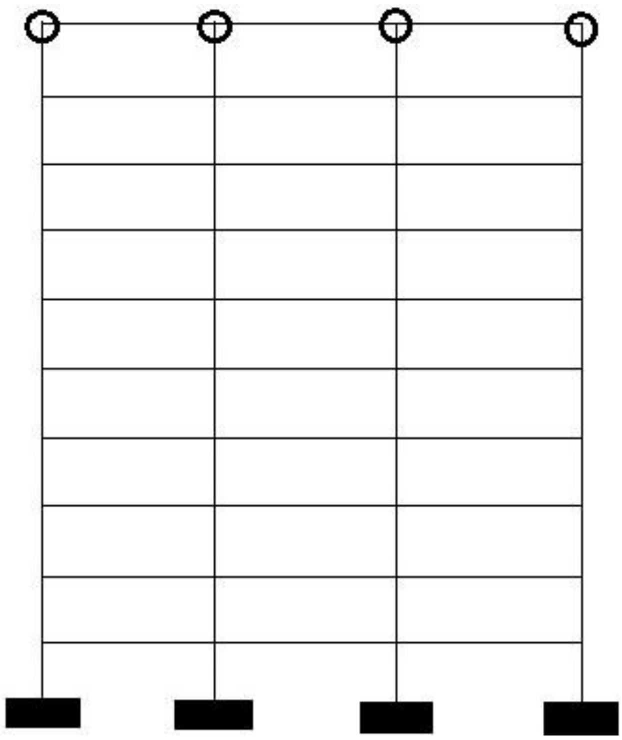

Figure 4.21: 10-storey framed structure with 4 TMDs used for study

4.2.1 STRUCTURE DESCRIPTION:

A 10-storey building is considered with 3 bays wherein, the front frame is shown and the tuned mass damper is attached to that frame. Thus, it can be pronounced to be a framed structure for simplicity and all the parameters, be it design or result, on the plane of the building is only considered.

Following are the properties of the members of the building:

a) Grade of concrete = M40
b) Dimension of the beam = 300 mm * 450 mm
c) Dimension of the column = 300 mm * 450 mm
d) Length of the column = 3.5 m
e) Length of the beam = 6.0 m

4.2.2 GRAVITY ANALYSIS:

Following are the values obtained by the reaction recorder of the OPENSEES along with the summation of the load at all the nodes at a common level.

Time step	Gravity load at all the base nodes (KN)				Sum of the load (KN)
0.1	22.3801	31.6199	31.6199	22.3801	108
0.2	44.7601	63.2399	63.2399	44.7601	216
0.3	67.1402	94.8598	94.8598	67.1402	324
0.4	89.5203	126.48	126.48	89.5203	432.0006
0.5	111.9	158.1	158.1	111.9	540
0.6	134.28	189.72	189.72	134.28	648
0.7	156.66	221.34	221.34	156.66	756
0.8	179.041	252.959	252.959	179.041	864
0.9	201.421	284.579	284.579	201.421	972
1	223.801	316.199	316.199	223.801	1080

Table 4.13: Gravity load as well as its sum at all the base nodes at each time increment.

4.2.3 MODAL ANALYSIS:

The next step involves performing modal analysis on our structure. Here, modal analysis for first 3 modes have been performed, while the first mode (the dominant mode) having the highest participation factor is considered for designing the TMD required for the building.

Mode No.	Lambda	Omega	Period	Frequency
1	5.401272 E+01	7.349335	8.549325 E-01	1.169683
2	5.065253 E+02	2.250612 E+01	2.791768 E-01	3.58196
3	1.527681 E+03	3.908556 E+01	1.607546 E-01	6.220661

Table 4.14: Parameters recorded on OPENSEES after modal analysis.

After subjecting our building to the gravity load as well as modal analysis, it is then subjected to six different earthquakes occurred at different parts of the world of varying intensity and peak ground acceleration. The basic details regarding them have already been mentioned before.

A comparative approach has been adopted wherein, dynamic parameters such as top storey displacement as well as top storey acceleration has been compared for the building without tuned mass damper as well as with it.

4.2.4 CASES:

Following are the cases that needed to be done on the building to determine the behaviour of the TMD:

- The behaviour of the building when it is subjected to several different earthquakes by recording the top storey displacement as well as acceleration.

- The influence of variation in damping ratio of the TMD on the top storey displacement as well as acceleration keeping the mass ratio and the damping ratio of the structure constant.

- The influence of variation in mass ratio on the top storey displacement and acceleration keeping the damping ratio of structure and the TMD constant.

4.2.4.1 CASE I: The behaviour of the building when it is subjected to several different earthquakes by recording the top storey displacement as well as acceleration.

4.2.4.1.1 Determination of TMD parameters

After performing the gravity analysis, we get the value of the total weight of the building at final step to be 1080 KN.

We assume the mass ratio to be 5% i.e., the mass of the damper is 5% of the total mass of the building and damping ratio of the building as well as that of the TMD to be 2% each.

Therefore, the total weight of the damper comes out to be

= (5% of 1080 KN)

= 54 KN

Since, the total mass of the TMD's arrangement is maintained constant, irrespective of the number of TMD's used, therefore we distribute the total weight of the damper equally between the four TMD's.

Therefore, weight of each damper $\boldsymbol{W_d}$ = 54 / 4

=13.5 KN

Now the mass of each TMD will be

$$\boldsymbol{M_d = W_d / g}$$

= (13.5 / 9.81)

= 1.37615 Kg

In order to calculate the length of the damper, we use the following relation

$$\boldsymbol{T = 2\pi\sqrt{\frac{l}{g}}}$$

Where T is obtained from the modal analysis and is equal to 0.8549325 s.

Therefore, on substituting the values, we get

$$0.8549325 = 2\pi\sqrt{\frac{l}{9.81}}$$

The length of damper comes out to be equal to 0.1816 m.

The stiffness of each TMD is calculated using the following relationship

$$\boldsymbol{K_d = M_d g \,/\, l}$$

$$= (13.5 / 0.1816)$$

$$= 74.3392 \text{ KN/m}$$

In our building we assume the damping ratio of the building as well as that of tuned mass damper to be 2%.

Since, we have discussed that the tuned mass damper should be in resonance with the structure in order to fritter away the maximum kinetic energy of the structure and itself going out of phase (precisely, 90^0 phase difference with the main structure),

Therefore, we take angular frequency of the TMD to be equal to that of the structure

$$\boldsymbol{\omega_d = \omega}$$

$$\boldsymbol{\omega_d} = 7.349335$$

Finally, the value of damping coefficient is calculated using

$$\boldsymbol{C_d = 2\xi M_d \omega_d}$$

$$= 2 * 0.02 * 1.37615 * 7.349335$$

$$= 0.404551 \text{ Kg/s}$$

Parameters of the TMD	**Values**
Mass of each damper ($\boldsymbol{M_d}$)	1.37615 Kg
Length of each damper **(l)**	0.1816 m
Stiffness of each damper ($\boldsymbol{K_d}$)	74.3392 KN/m
Damping coefficient of each damper ($\boldsymbol{C_d}$)	0.404551 Kg/s

Table 4.15: TMD parameters used for Case I

4.2.4.1.2 Methodology

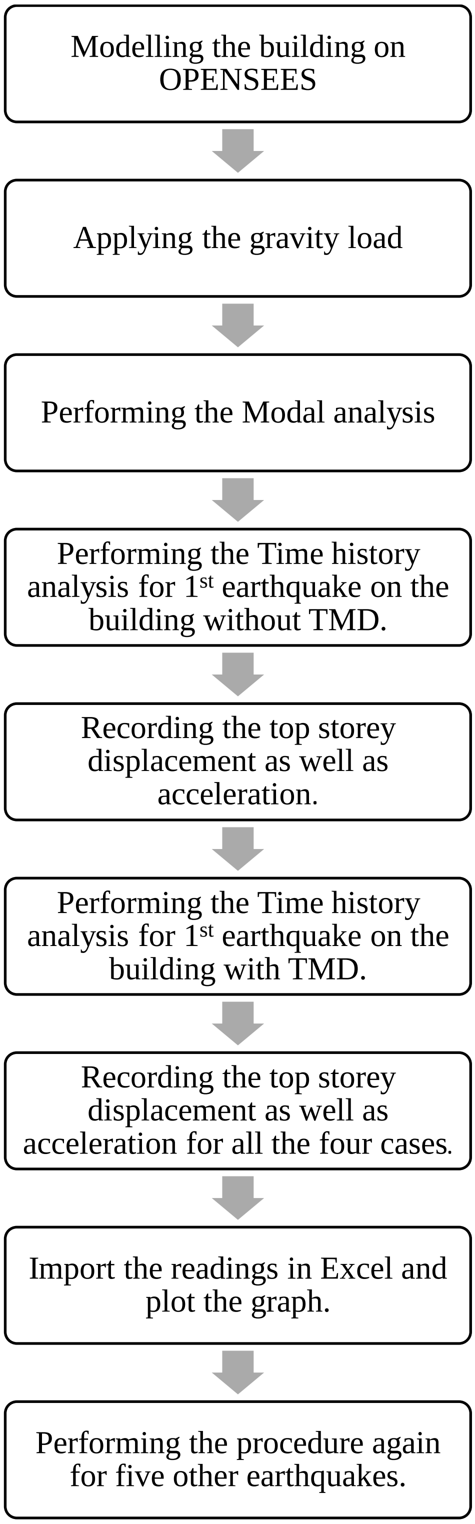

Figure 4.22: Sequence of steps to be followed for CASE I

Imperial Valley earthquake (1979)

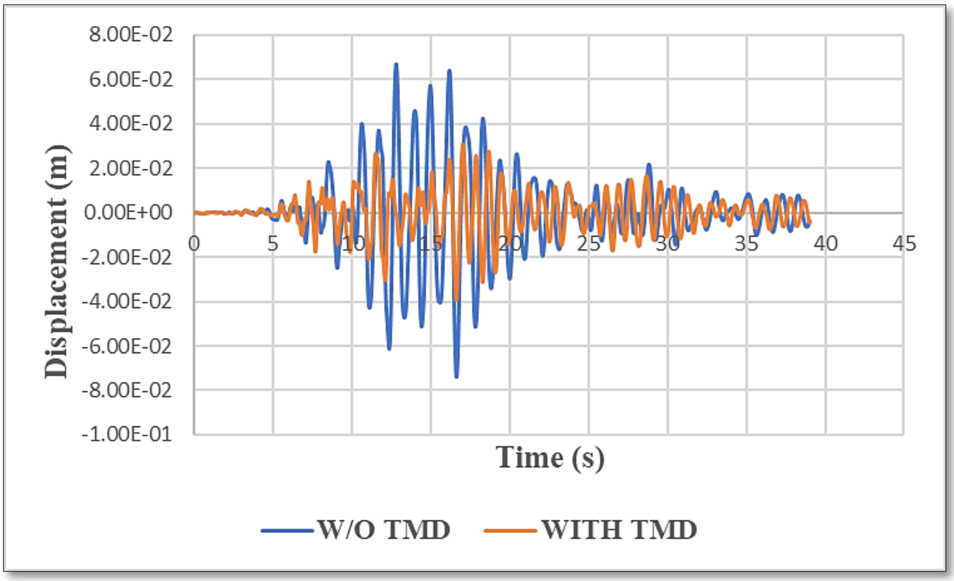

Figure 4.23: Displacement vs time for building under Imperial Valley earthquake

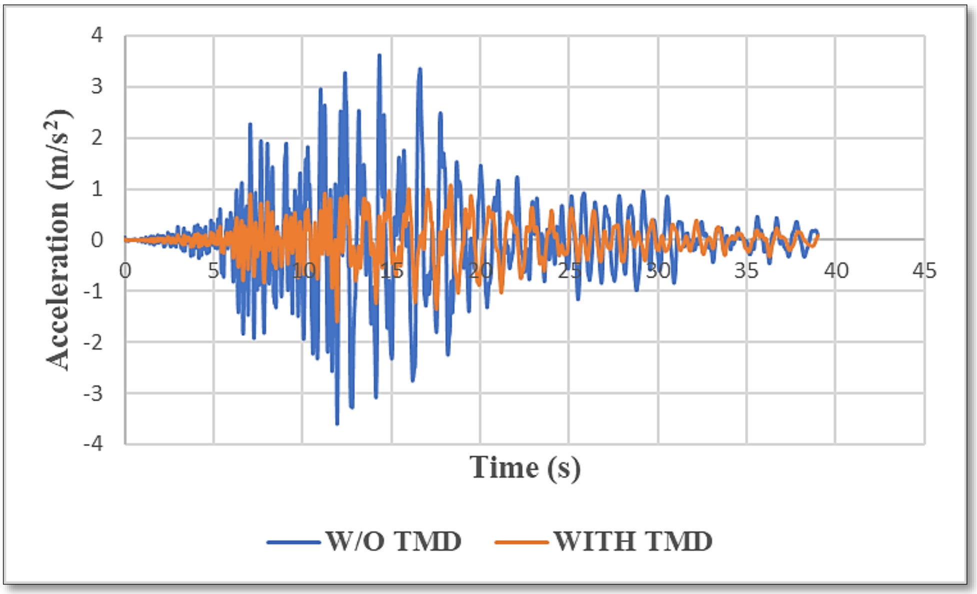

Figure 4.24: Acceleration vs time for building under Imperial Valley earthquake

Kobe earthquake (1995)

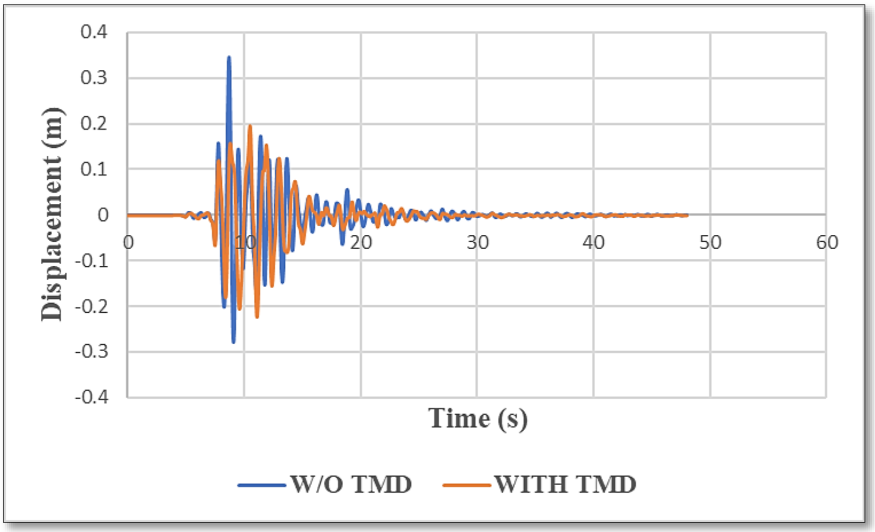

Figure 4.25: Displacement vs time for building under Kobe earthquake

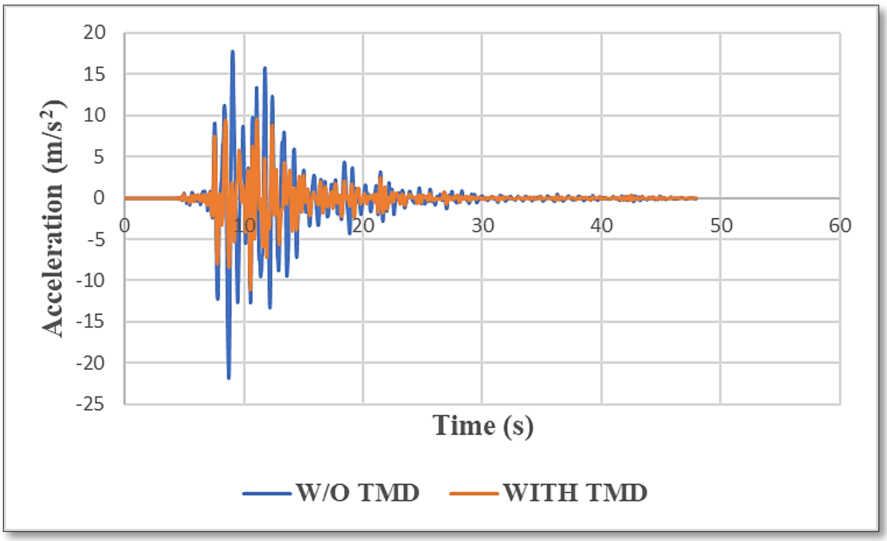

Figure 4.26: Acceleration vs time for building under Kobe earthquake

Parkfield earthquake (1966)

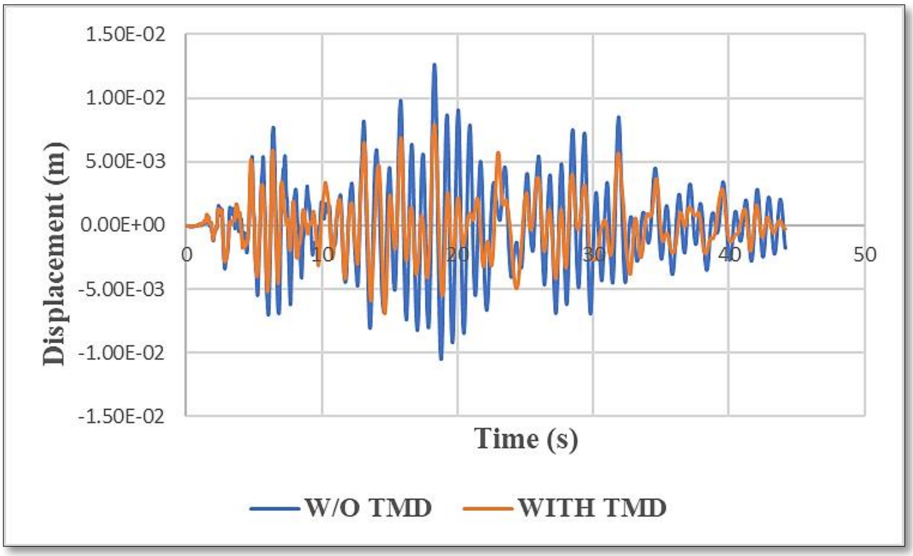

Figure 4.27: Displacement vs time for building under Parkfield earthquake

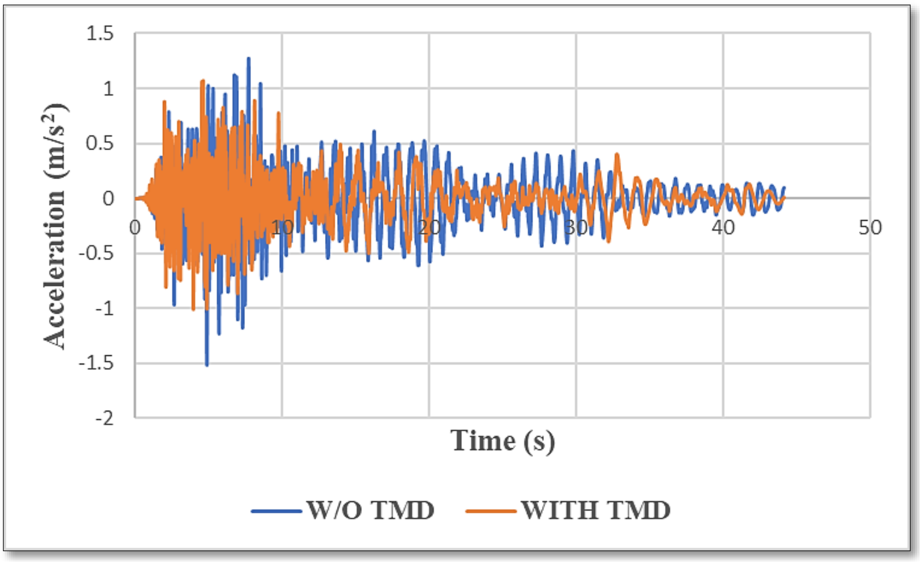

Figure 4.28: Acceleration vs time for building under Parkfield earthquake

Oroville-01 earthquake (1975)

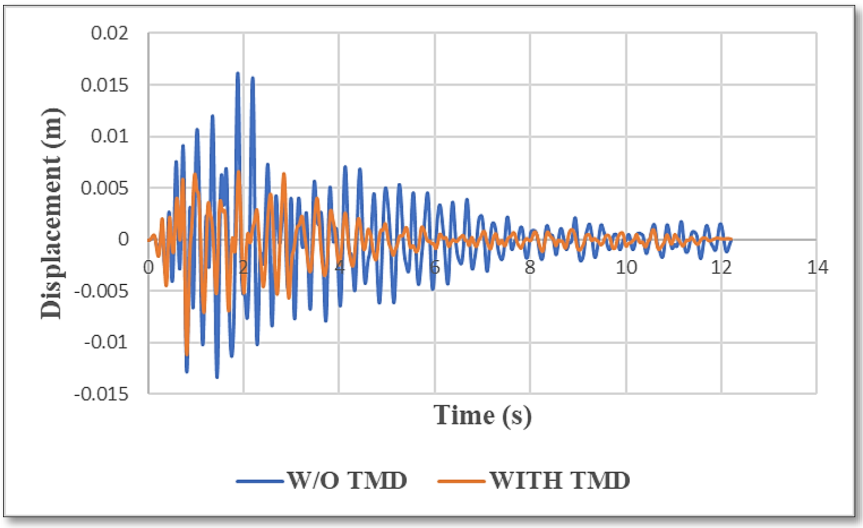

Figure 4.29: Displacement vs time for building under Oroville-01 earthquake

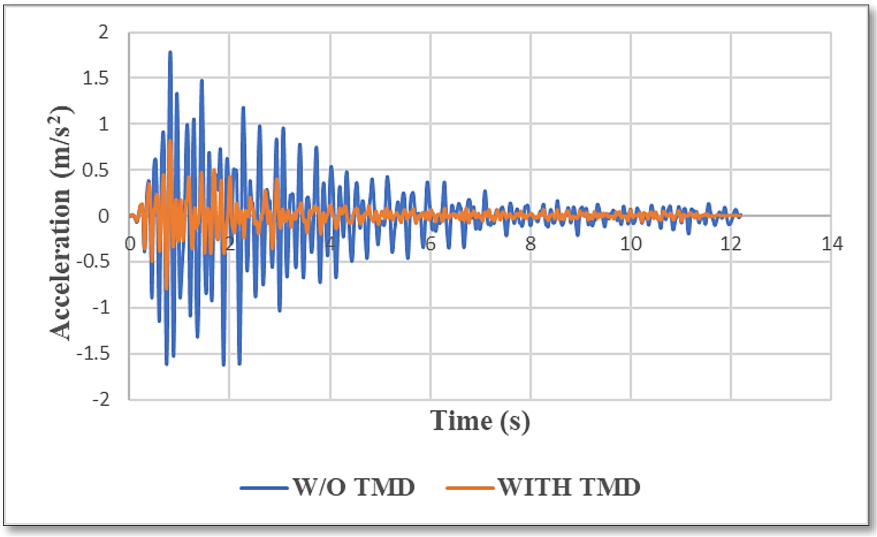

Figure 4.30: Acceleration vs time for building under Oroville-01 earthquake

Hector Mine earthquake (1999)

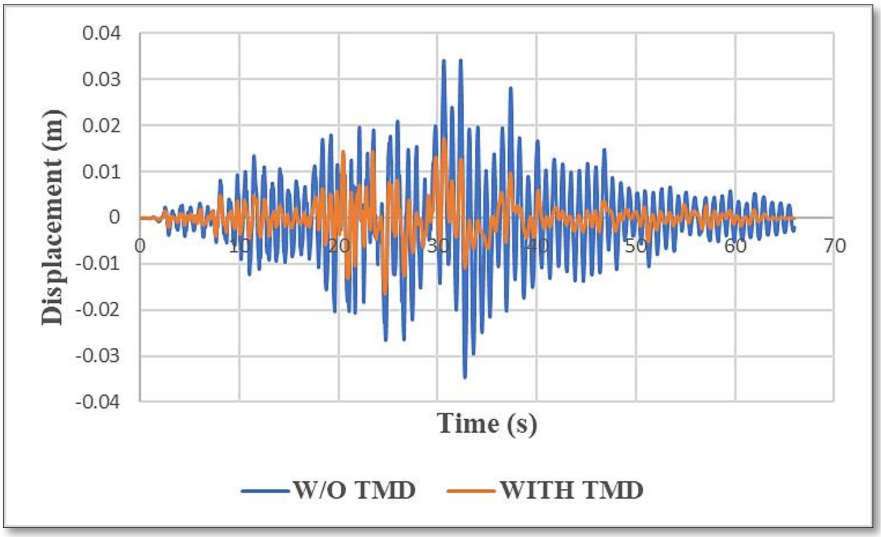

Figure 4.31: Displacement vs time for building under Hector Mine earthquake

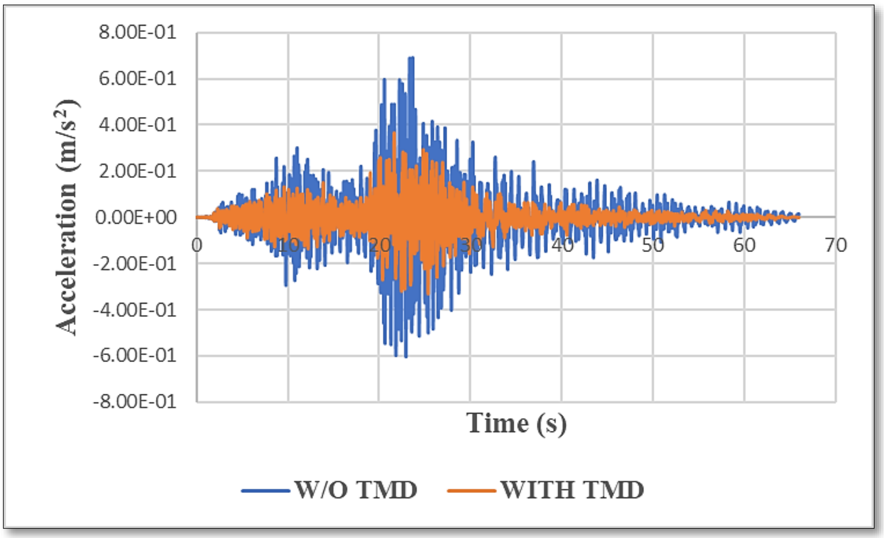

Figure 4.32: Acceleration vs time for building under Hector Mine earthquake

Chuetsu-oki earthquake (2007)

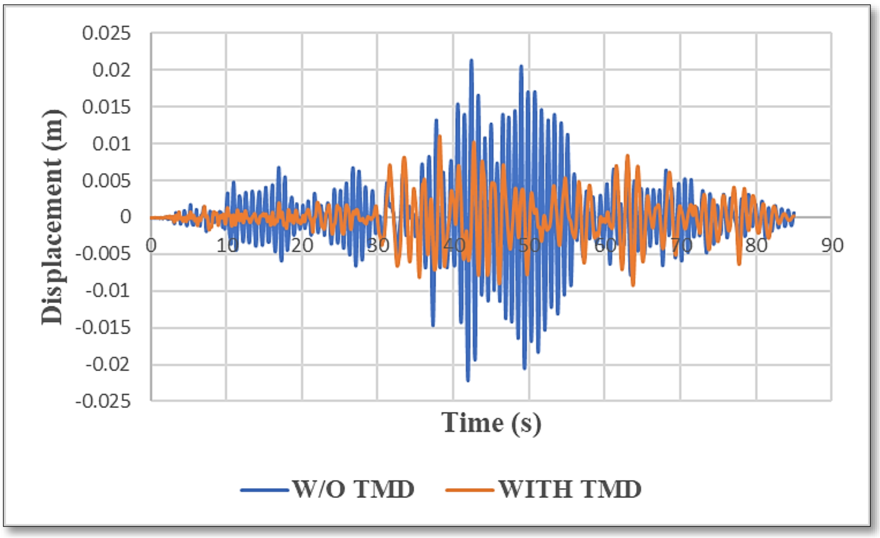

Figure 4.33: Displacement vs time for building under Cheutsu-oki earthquake

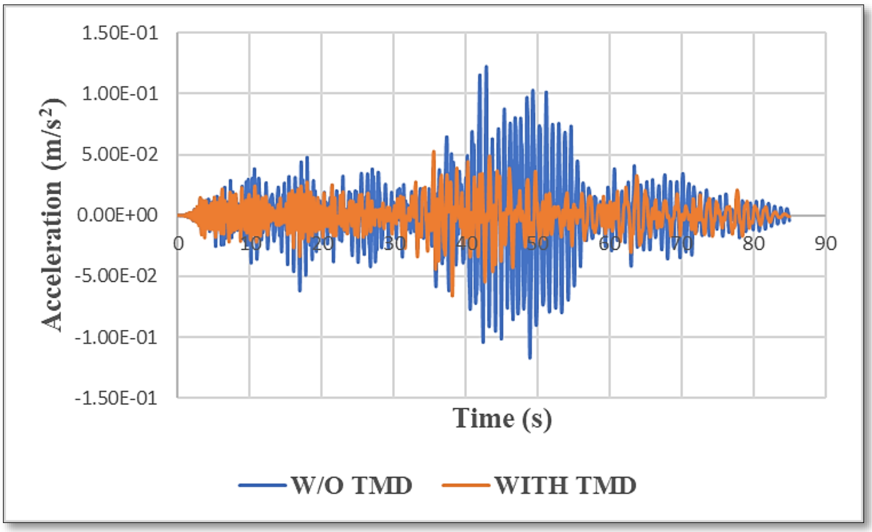

Figure 4.34: Acceleration vs time for building under Cheutsu-oki earthquake

4.2.4.1.3 Results and Discussions:

S.No	Earthquake	Max. Displacement of top storey (m)		% Reduction
		Without TMD	With TMD	
1	Imperial Valley	0.0739	0.0389	47.32
2	Kobe	0.346	0.196	43.35
3	Parkfield	0.0126	0.00787	37.5
4	Oroville-01	0.0161	0.0111	31.06
5	Hector Mine	0.0341	0.0172	49.56
6	Chuetsu-oki	0.0213	0.0110	48.36

Table 4.16: % Reduction of top storey displacement due to 4 TMD's under different earthquakes

It can be seen from the above table that the application of TMD on the building reduces the maximum top storey displacement considerably ranging from 31.06% to 49.56% with an average being 42.86 %. Hence, the TMD designed is effective in achieving its objective.

S.No	Earthquake	Max. Acceleration of top storey (m/s^s)		% Reduction
		Without TMD	With TMD	
1	Imperial Valley	3.61853	1.5947	55.93
2	Kobe	18.1418	9.2831	48.83
3	Parkfield	1.51468	1.0659	29.63
4	Oroville-01	1.78817	0.8186	54.22
5	Hector Mine	0.689	0.3663	46.83
6	Chuetsu-oki	0.117	0.0661	43.49

Table 4.17: % Reduction of top storey acceleration due to 4 TMD's under different earthquakes

It can be seen from the above table that the application of TMD on the building reduces the maximum top storey acceleration considerably ranging from 29.63% to 55.93% with an average being 46.49%. Hence, the TMD designed is effective in achieving its objective

4.2.4.2 <u>CASE II</u>: The influence of variation in damping ratio of the TMD on the top storey displacement as well as acceleration keeping the mass ratio and the damping ratio of the structure constant.

4.2.4.2.1 Determination of TMD parameters

Here, for this case we assume the mass ratio as well as the damping ratio of the primary structure to be same as that in CASE I (i.e., 5% and 2% respectively).

As discussed before the angular frequency of the TMD is equal to that of the structure

$$\boldsymbol{\omega_d = \omega}$$

$$\boldsymbol{\omega_d} = 7.349335$$

In order to perform the parametric study involving the variation in the damping ratio of the TMD, we take four different cases varying the damping ratio of the TMD from 2 to 5 % with an increment of 1%.

Therefore, the value of damping coefficient for four different cases are as follows:

i. **For $\boldsymbol{\xi = 2}\%$**

   $\boldsymbol{C_d = 2\xi M_d \omega_d}$

   = 2 * 0.02 * 1.37615 * 7.349335

   = 0.404551 Kg / s

ii. **For $\boldsymbol{\xi = 3}\%$**

   $\boldsymbol{C_d = 2\xi M_d \omega_d}$

   = 2 * 0.03 * 1.37615 * 7.349335

   = 0.606826 Kg / s

iii. **For $\boldsymbol{\xi = 4}\%$**

   $\boldsymbol{C_d = 2\xi M_d \omega_d}$

   = 2 * 0.04 * 1.37615 * 7.349335

   = 0.809101 Kg / s

iv. **For $\boldsymbol{\xi = 5}\%$**

$$C_d = 2\xi M_d \omega_d$$

= 2 * 0.05 * 1.37615 * 7.349335

= 1.011376 Kg / s

Parameters of the TMD	Values			
Mass of each damper (M_d)	1.37615 Kg			
Length of each damper **(l)**	0.1816 m.			
Stiffness of each damper (K_d)	74.3392 KN/m			
Damping coefficient of each damper (C_d)	0.404551	0.606826	0.809101	1.011376

Table 4.18: TMD parameters used for Case II

The procedure remains same as explained long-windedly in the case in the methodology section as well as in CASE I. The storey response in the form of top storey displacement as well as top storey acceleration is calculated as represented in the graphs drawn below clearly depicting the objective of this case.

The flow chart drawn below gives the sequence adopted to achieve the purpose of this case i.e., effect of damping ratio of the TMD on the structural response.

4.2.4.2.2 Methodology

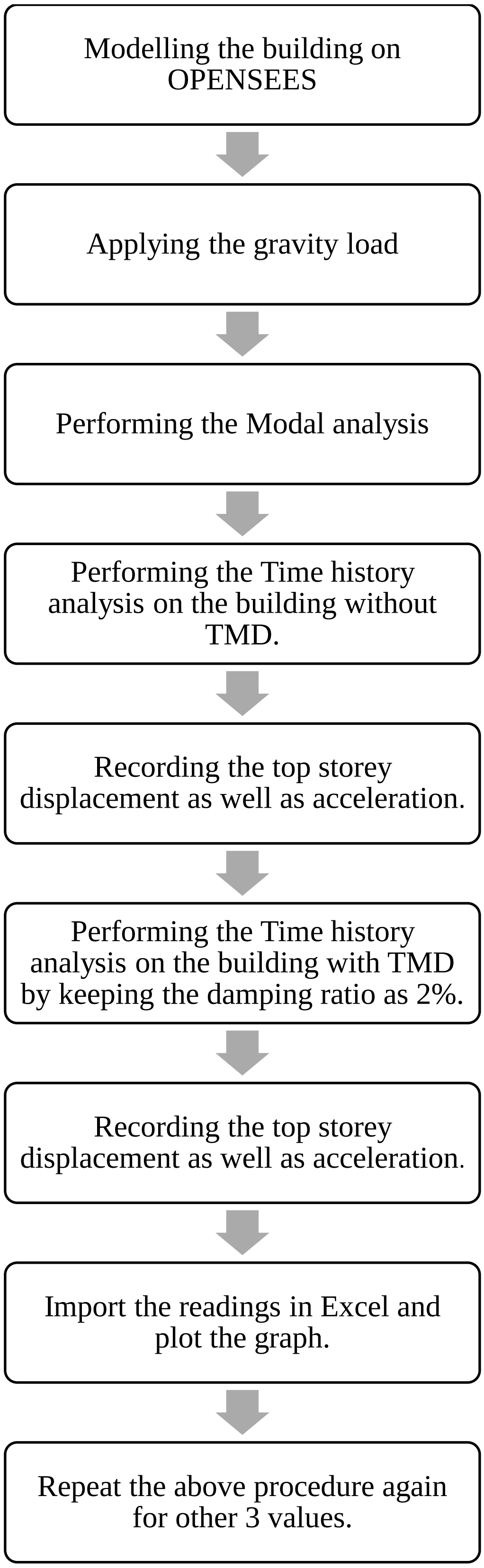

Figure 4.35: Sequence of steps to be followed for CASE II

4.2.4.2.3 Results and discussions:

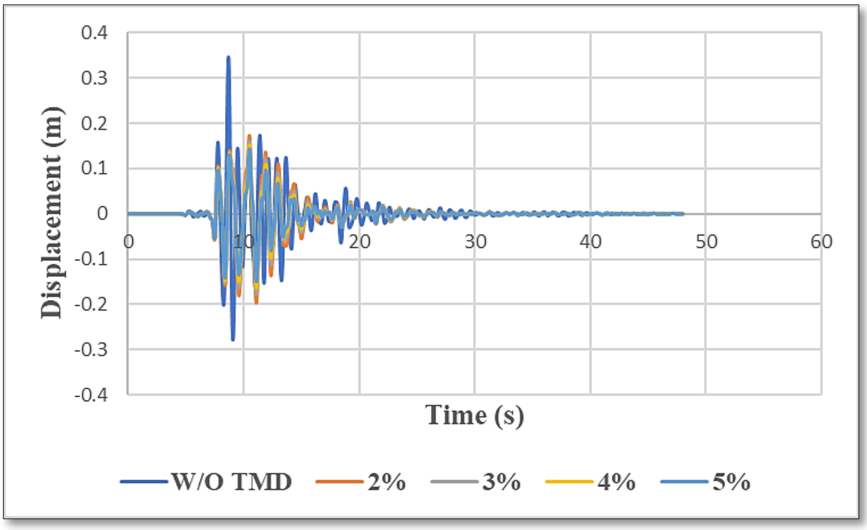

Figure 4.36: Displacement vs time for building under Kobe earthquake with varying damping ratio

As shown in the graph plotted above the maximum top storey displacement in the building without the tuned mass damper arrangement is 0.346 m.

S.No	Damping ratio of TMD	Maximum top storey displacement (m)	% Reduction
1	2%	0.196	43.35
2	3%	0.178	48.42
3	4%	0.164	52.48
4	5%	0.149	56.81

Table 4.19: % Reduction of top storey displacement due to TMD with varying damping ratio

It can be seen from the above table that the there is a decrease in the maximum top storey displacement with an increase in the damping ratio of the TMD. This decrease came out to be 4.49% for every 1% increase in damping ratio of TMD. Hence, the damping ratio of the TMD has to be kept at such a value so as to minimise the displacement by maximum amount.

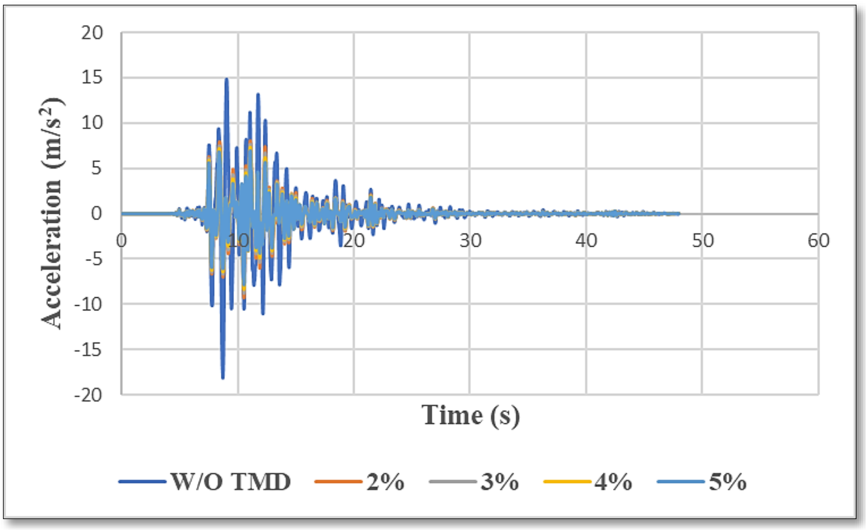

Figure 4.37: Acceleration vs time for building under Kobe earthquake with varying damping ratio

As shown in the graph plotted above the maximum top storey acceleration in the building without the tuned mass damper arrangement is 18.142 m/s^2.

S.No	Damping ratio of TMD	Maximum top storey Acceleration (m/s^s)	% Reduction
1	2%	9.2831	48.83
2	3%	8.7879	51.56
3	4%	8.3507	53.97
4	5%	7.8336	56.82

Table 4.20: % Reduction of top storey acceleration due to TMD with varying damping ratio

It can be seen from the above table that the there is a decrease in the maximum top storey acceleration with an increase in the damping ratio of the TMD. This decrease came out to be 2.66% for every 1% increase in damping ratio of TMD. Hence, the damping ratio of the TMD has to be kept at such a value so as to minimise the acceleration by maximum amount.

4.2.4.3 CASE III: The influence of variation in mass ratio of the TMD on the top storey displacement and acceleration keeping the damping ratio of structure and the TMD constant.

4.2.4.3.1 Determination of TMD parameters

Here, for this case we assume the damping ratio of the primary structure as well as the TMD to be same as that in CASE I (i.e., 2% each).

As discussed before the angular frequency of the TMD is equal to that of the structure

$$\boldsymbol{\omega_d = \omega}$$

$$\boldsymbol{\omega_d} = 7.349335$$

In order to perform the parametric study involving the variation in the mass ratio of the TMD, we take four different cases varying the mass ratio of the TMD from 3 to 6 % with an increment of 1%.

Therefore, the value of each Tuned mass damper parameters for four different cases are as follows:

i. For $\boldsymbol{\mu = 3\%}$

Total weight of the TMD's = 3% of 1080 KN

= 32.4 KN

Weight of each TMD ($\boldsymbol{W_d}$) = 32.4 / 4

= 8.1 KN

$\boldsymbol{M_d = W_d \,/\, g}$

= 8.1 / 9.81

= 0.82568 Kg

$\boldsymbol{K_d = Mg \,/\, l}$

= (8.1 / 0.1816)

= 44.6035 KN / m

$\boldsymbol{C_d = 2\xi M_d \omega_d}$

= 2 * 0.02 * 0.82568 * 7.349335

= 0.24273 Kg / s

ii. For $\boldsymbol{\mu}$ **= 4%**

Total weight of the TMD's = 4% of 1080 KN

= 43.2 KN

Weight of each TMD ($\boldsymbol{W_d}$) = 43.2 / 4

= 10.8 KN

$\boldsymbol{M_d = W_d \;/\; g}$

= 10.8 / 9.81

= 1.10091 Kg

$\boldsymbol{K_d = Mg \;/\; l}$

= (10.8 / 0.1816)

= 59.4713 KN / m

$\boldsymbol{C_d = 2\xi M_d \omega_d}$

= 2 * 0.02 * 1.10091 * 7.349335

= 0.32364 Kg / s

iii. For $\boldsymbol{\mu}$ **= 5%**

Total weight of the TMD's = 5% of 1080 KN

= 54 KN

Weight of each TMD ($\boldsymbol{W_d}$) = 54 / 4

= 13.5 KN

$\boldsymbol{M_d = W_d \;/\; g}$

= 13.5 / 9.81

= 1.37614 Kg

$\boldsymbol{K_d = Mg \;/\; l}$

= (13.5 / 0.1816)

= 74.3392 KN / m

$\boldsymbol{C_d = 2\xi M_d \omega_d}$

= 2 * 0.02 * 1.37614 * 7.349335

=0.404551 Kg / s

iv. For $\boldsymbol{\mu}$ **= 6%**

Total weight of the TMD's = 6% of 1080 KN

= 64.8 KN

Weight of each TMD ($\boldsymbol{W_d}$) = 64.8 / 4

= 16.2 KN

$\boldsymbol{M_d = W_d \,/\, g}$

= 16.2 / 9.81

= 1.651376 Kg

$\boldsymbol{K_d = Mg \,/\, l}$

= (16.2 / 0.1816)

= 89.2070 KN / m

$\boldsymbol{C_d = 2\xi M_d \omega_d}$

= 2 * 0.02 * 1.651376 * 7.349335

= 0.48546 Kg / s

S.No	Mass ratio of the TMD (μ)	Mass of the TMD (M_d) (Kg)	Stiffness of the TMD (K_d) (KN/m)	Damping coefficient of TMD (C_d) (Kg/s)
1	3 %	0.82568	44.6035	0.24273
2	4 %	1.10091	59.4713	0.32364
3	5 %	1.37614	74.3392	0.404551
4	6 %	1.651376	89.2070	0.48546

Table 4.21: TMD parameters used for Case III

The procedure remains same as explained long-windedly in the case in the methodology section as well as in CASE I. The storey response in the form of top storey displacement as well as top storey acceleration is calculated as represented in the graphs drawn below clearly depicting the objective of this case.

The flow chart drawn below gives the sequence adopted to achieve the purpose of this case i.e., effect of mass ratio of the TMD on the structural responses.

4.2.4.3.2 Methodology

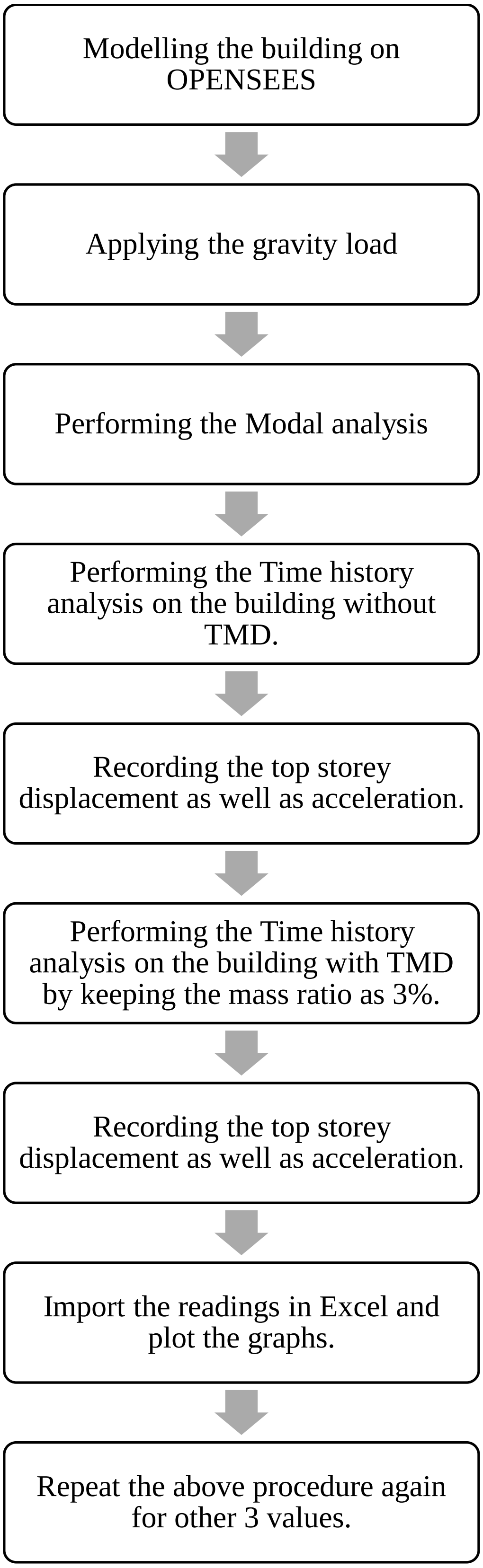

Figure 4.38: Sequence of steps to be followed for CASE III

4.2.4.3.3 Results and discussions

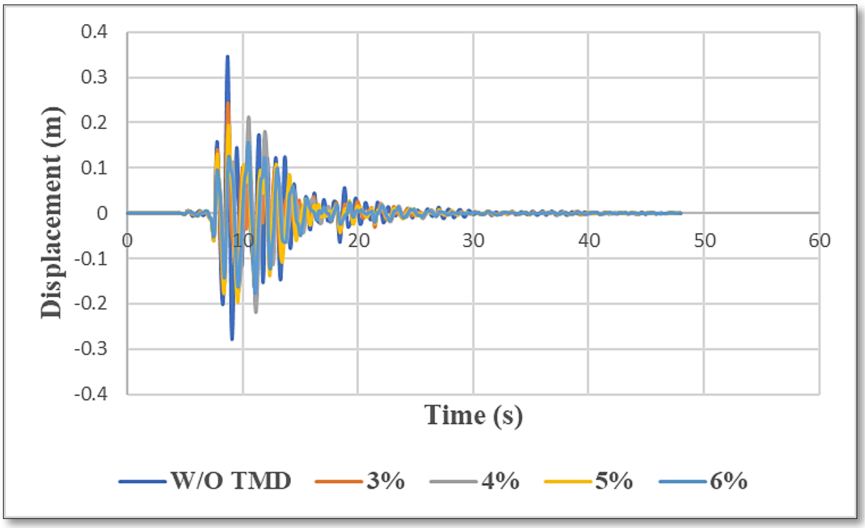

Figure 4.39: Displacement vs time for building under Kobe earthquake with varying Mass ratio

As shown in the graph plotted above the maximum top storey displacement in the building without the tuned mass damper arrangement is 0.346 m.

S.No	Mass ratio of TMD	Maximum top storey displacement (m)	% Reduction
1	3%	0.244	29.48
2	4%	0.2198	36.47
3	5%	0.1961	43.35
4	6%	0.156	54.91

Table 4.22: % Reduction of top storey displacement due to TMD with varying mass ratio

It can be seen from the above table that the there is a decrease in the maximum top storey displacement with an increase in the mass ratio of the TMD. This decrease came out to be 8.48% for every 1% increase in mass ratio of TMD. Hence, the mass ratio of the TMD has to be kept at such a value so as to minimise the displacement by maximum amount.

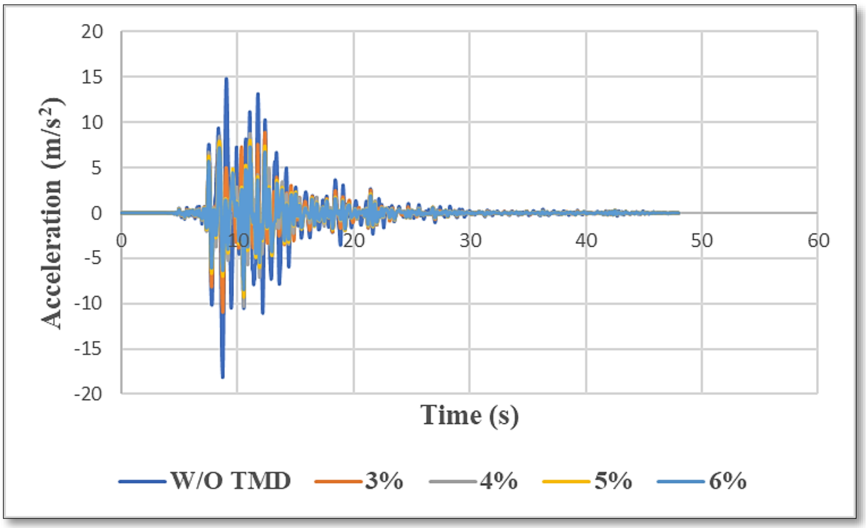

Figure 4.40: Acceleration vs time for building under Kobe earthquake with varying Mass ratio

As shown in the graph plotted above the maximum top storey acceleration in the building without the tuned mass damper arrangement is 18.142 m/s^2.

S.No	**Mass ratio of TMD**	**Maximum top storey Acceleration (m/s^s)**	**% Reduction**
1	3%	10.9467	39.66
2	4%	10.3208	43.11
3	5%	9.2831	48.83
4	6%	8.4432	53.46

Table 4.23: % Reduction of top storey acceleration due to TMD with varying Mass ratio

It can be seen from the above table that the there is a decrease in the maximum top storey acceleration with an increase in the mass ratio of the TMD. This decrease came out to be 4.60% for every 1% increase in mass ratio of TMD. Hence, the mass ratio of the TMD has to be kept at such a value so as to minimise the acceleration by maximum amount.

4.3 PROBLEM STATEMENT:

In this problem, a low-rise building (5-storey building) is compared with a high-rise building (20-storey building) on certain dynamic responses such as top storey displacement and top storey acceleration. Two TMD's are used and their position are changed in each case i.e., starting from top floor to moving down one floor in every case. The specifications of the buildings are given below. Gravity loads are applied and modal analysis is performed. The 2 TMD's are installed at each corner node of the top storey. The total mass of the TMD is constant, irrespective of the number of TMD's used. Here, both the TMD's will share the mass of the damper equally and other design parameters accordingly.

4.3.1 CASE I: For a Low-rise building (5-storey building).

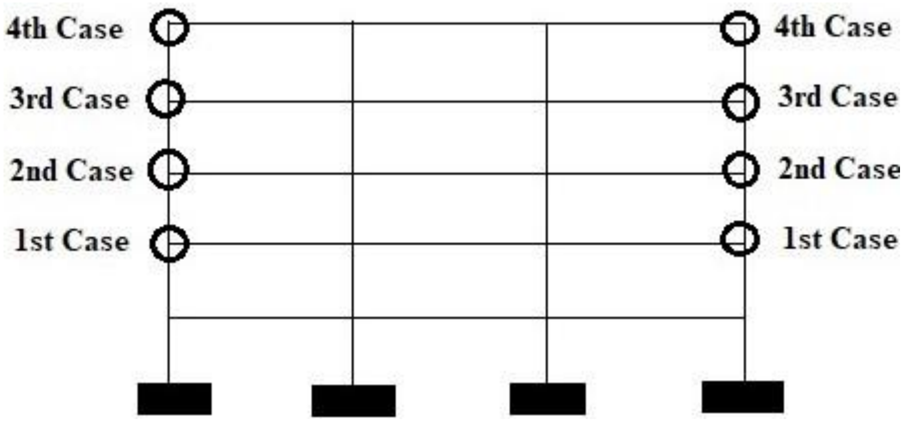

Figure 4.41: 5-storey framed structure with 2 TMDs used for study

4.3.1.1 STRUCTURE DESCRIPTION:

A 5-storey building is considered with 3 bays wherein, the front frame is shown and the tuned mass damper is attached to that frame. Thus, it can be pronounced to be a framed structure for simplicity and all the parameters, be it design or result, on the plane of the building is only considered.

Following are the properties of the members of the building:

a) Grade of concrete = M40
b) Dimension of the beam = 250 mm * 375 mm

c) Dimension of the column = 250 mm * 375 mm

d) Length of the column = 3.5 m

e) Length of the beam = 6.0 m

4.3.1.2 GRAVITY ANALYSIS

Following are the values obtained by the reaction recorder of the OPENSEES along with the summation of the load at all the nodes at a common level.

Time step	**Gravity load at all the base nodes (KN)**				**Sum of the load (KN)**
0.1	7.52645	11.2236	11.2236	7.52645	37.5001
0.2	15.0529	22.4471	22.4471	15.0529	75
0.3	22.5793	33.6707	33.6707	22.5793	112.5
0.4	30.1058	44.8942	44.8942	30.1058	150
0.5	37.6322	56.1178	56.1178	37.6322	187.5
0.6	45.1587	67.3413	67.3413	45.1587	225
0.7	52.6851	78.5649	78.5649	52.6851	262.5
0.8	60.2116	89.7884	89.7884	60.2116	300
0.9	67.738	101.012	101.012	67.738	337.5
1	75.2645	112.236	112.236	75.2645	375.001

Table 4.24: Gravity load as well as its sum at all the base nodes at each time increment.

The next step involves performing modal analysis on our structure. Here, modal analysis for first 3 modes have been performed, while the first mode (the dominant mode) having the highest participation factor is considered for designing the TMD required for the building.

4.3.1.3 MODAL ANALYSIS

Mode No.	Lambda	Omega	Period	Frequency
1	1.613577e+02	1.270266e+01	4.946352e-01	2.021692e+00
2	1.593542e+03	3.991920e+01	1.573976e-01	6.353338e+00
3	5.050180e+03	7.106462e+01	8.841510e-02	1.131029e+01

Table 4.25: Parameters recorded on OPENSEES after modal analysis.

After subjecting our building to the gravity load as well as modal analysis, it is then subjected to Kobe earthquake data of peak ground acceleration (pga) of 0.821g.

A comparative approach has been adopted wherein, dynamic parameters such as top storey displacement as well as top storey acceleration has been compared for the building without tuned mass damper as well as with it.

4.3.1.4 DETERMINATION OF TMD PARAMETERS

After performing the gravity analysis, we get the value of the total weight of the building at final step to be approximately equal to 375 KN.

We assume the mass ratio to be 5% i.e., the mass of the damper to be 5% of the total mass of the building

Therefore, the total weight of the damper comes out to be

= (5% of 375 KN)

= 18.75 KN

Since, the total mass of the TMD's arrangement is maintained constant, irrespective of the number of TMD's used, therefore we distribute the total weight of the damper equally between the two TMD's.

Therefore, weight of each damper $\boldsymbol{W_d}$ = 18.75 / 2

=9.375 KN

Now the mass of each TMD will be

$$\boldsymbol{M_d = W_d / g}$$

= (9.375 / 9.81)

= 0.955657 Kg

In order to calculate the length of the damper, we use the following relation

$$\boldsymbol{T = 2\pi\sqrt{\frac{l}{g}}}$$

Where T is obtained from the modal analysis and is equal to 0.4946352 s.

Therefore, on substituting the values, we get

$$0.4946352 = 2\pi\sqrt{\frac{l}{9.81}}$$

The length of damper comes out to be equal to 0.0608 m.

The stiffness of each TMD is calculated using the following relationship

$$\boldsymbol{K_d = M_d g \,/\, l}$$

= (9.375 / 0.0608)

= 154.1940 KN/m

In our building we assume the damping ratio of the building as well as that of tuned mass damper to be 2%.

Since, we have discussed that the tuned mass damper should be in resonance with the structure in order to fritter away the maximum kinetic energy of the structure and itself going out of phase (precisely, 90^0 phase difference with the main structure),

Therefore, we take angular frequency of the TMD to be equal to that of the structure

$$\boldsymbol{\omega_d = \omega}$$

$$\boldsymbol{\omega_d} = 12.70266$$

Finally, the value of damping coefficient is calculated using

$$\boldsymbol{C_d = 2\xi M_d \omega_d}$$

= 2 * 0.02 * 0.955657 * 12.70266

= 0.485575 Kg/s

Parameters of the TMD	Values
Mass of each damper ($\boldsymbol{M_d}$)	0.955657 Kg
Length of each damper **(l)**	0.0608 m.
Stiffness of each damper ($\boldsymbol{K_d}$)	154.1940 KN/m
Damping coefficient of each damper ($\boldsymbol{C_d}$)	0.485575 Kg/s

Table 4.26: TMD parameters used for Case I

4.3.1.5 METHODOLOGY

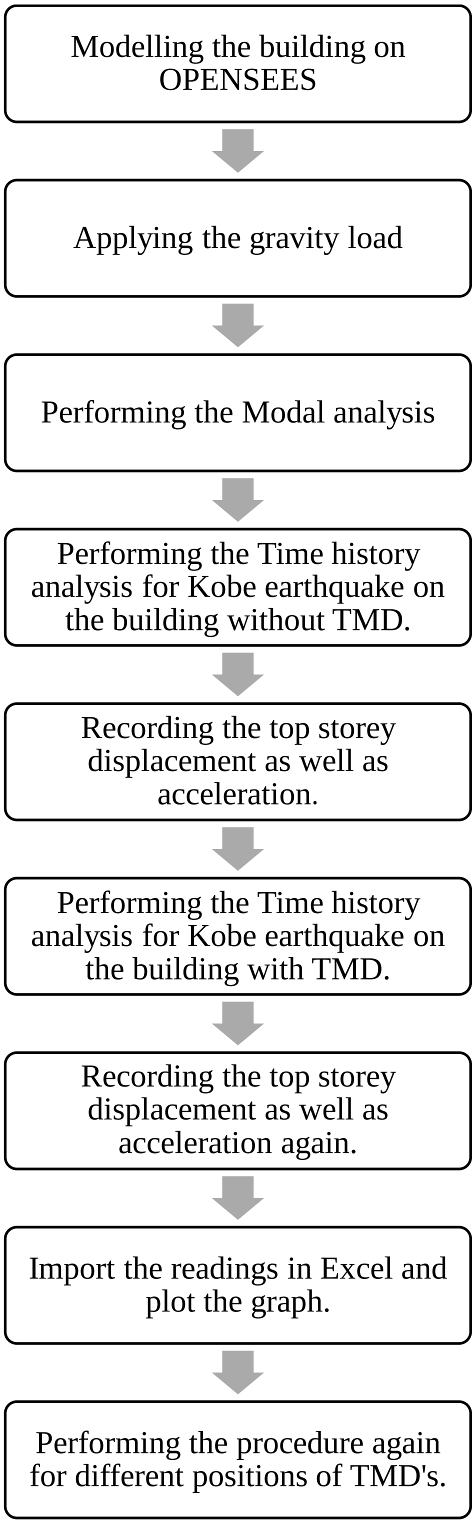

Figure 4.42: Sequence of steps to be followed for CASE I

4.3.1.6 RESULTS AND DISCUSSION

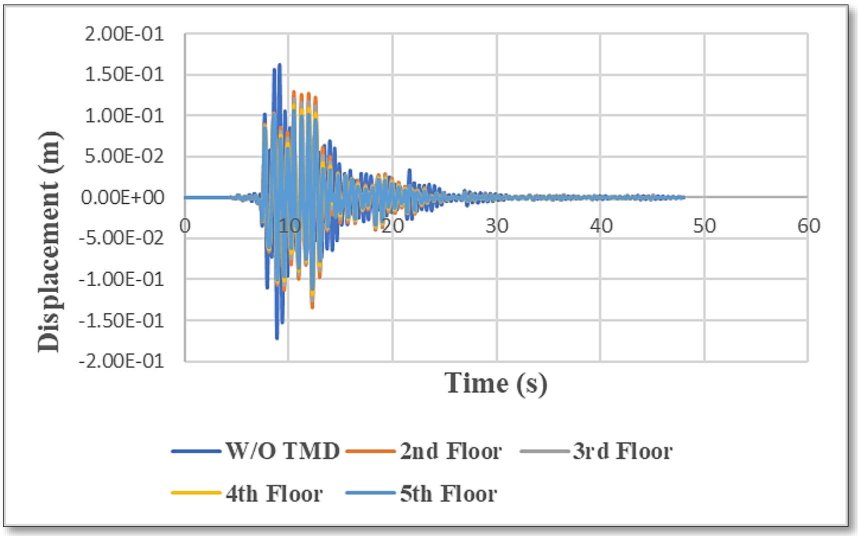

Figure 4.43: Displacement vs time for building under Kobe earthquake with varying TMD's position

As shown in the graph plotted above the maximum top storey displacement in the building without the tuned mass damper arrangement is 0.172 m.

S.No	Position of both the TMDs	Maximum top storey displacement (m)	% Reduction
1	2nd Floor	0.134	22.09
2	3rd Floor	0.126	26.74
3	4th Floor	0.118	31.39
4	5th Floor	0.112	34.88

Table 4.27: % Reduction of top storey displacement due to varying TMDs' position

It can be seen from the above table that there is an average reduction of 28.78% in maximum top storey displacement due to installation of TMD and the increase in reduction is around 4.26 % with change in the position of TMD from bottom of building to top.

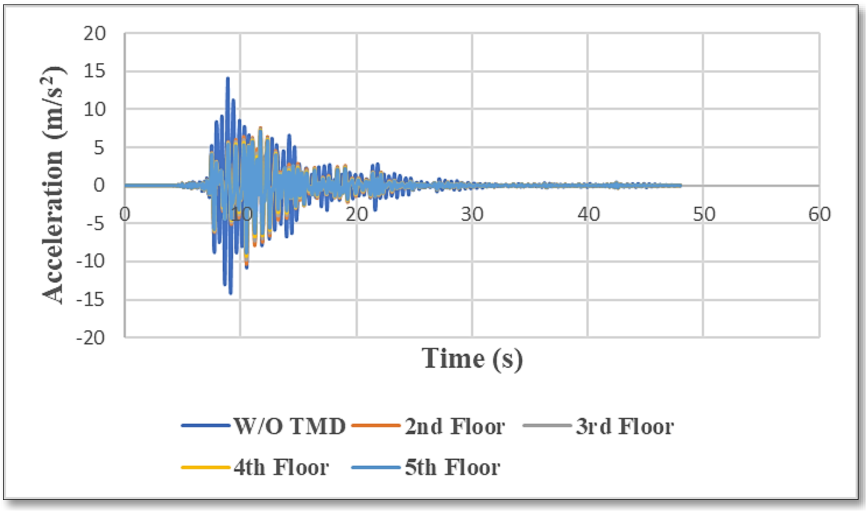

Figure 4.44: Acceleration vs time for building under Kobe earthquake with varying TMDs' position

As shown in the graph plotted above the maximum top storey acceleration in the building without the tuned mass damper arrangement is 14.1553 m/s^2.

S.No	Position of both the TMDs	Maximum top storey Acceleration (m/s^s)	% Reduction
1	2^{nd} Floor	10.3429	26.93
2	3^{rd} Floor	9.7822	30.89
3	4^{th} Floor	9.2875	34.39
4	5^{th} Floor	8.8478	37.49

Table 4.28: % Reduction of top storey acceleration due to varying TMDs' position

It can be seen from the above table that there is an average reduction of 32.43% in maximum top storey acceleration due to installation of TMD and the increase in reduction is around 3.52 % with change in the position of TMD from bottom of building to top.

4.3.2 CASE II: For a High-rise building (20-storey building).

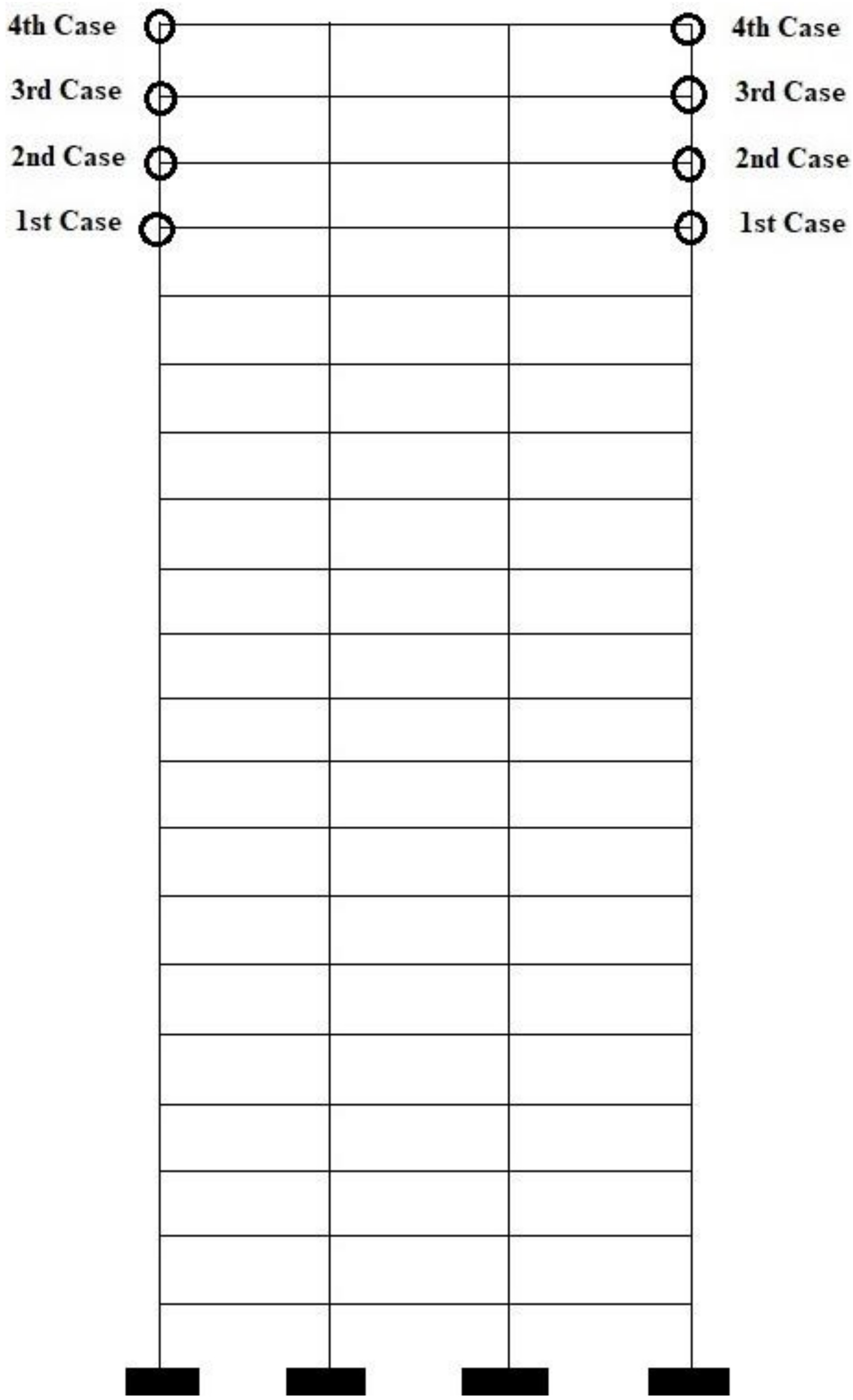

Figure 4.45: 20-storey framed structure with 2 TMDs used for study

4.3.2.1 STRUCTURE DESCRIPTION:

A 20-storey building is considered with 3 bays wherein, the front frame is shown and the tuned mass damper is attached to that frame. Thus, it can be pronounced to be a framed structure for simplicity and all the parameters, be it design or result, on the plane of the building is only considered.

Following are the properties of the members of the building:

a) Grade of concrete = M40
b) Dimension of the beam = 360 mm * 540 mm
c) Dimension of the column = 360 mm * 540 mm
d) Length of the column = 3.5 m
e) Length of the beam = 6.0 m

4.3.2.2 GRAVITY ANALYSIS

Following are the values obtained by the reaction recorder of the OPENSEES along with the summation of the load at all the nodes at a common level.

Time step	**Gravity load at all the base nodes (KN)**				**Sum of the load (KN)**
0.1	69.4811	86.0389	86.0389	69.4811	311.04
0.2	138.962	172.078	172.078	138.962	622.08
0.3	208.443	258.117	258.117	208.443	933.12
0.4	277.924	344.156	344.156	277.924	1244.16
0.5	347.405	430.195	430.195	347.405	1555.2
0.6	416.886	516.234	516.234	416.886	1866.24
0.7	486.367	602.273	602.273	486.367	2177.28
0.8	555.848	688.312	688.312	555.848	2488.32
0.9	625.33	774.35	774.35	625.33	2799.36
1	694.811	860.389	860.389	694.811	3110.4

Table 4.29: Gravity load as well as its sum at all the base nodes at each time increment.

4.3.2.3 MODAL ANALYSIS

The next step involves performing modal analysis on our structure. Here, modal analysis for first 3 modes have been performed, while the first mode (the dominant mode) having the highest participation factor is considered for designing the TMD required for the building.

Mode No.	Lambda	Omega	Period	Frequency
1	1.685076e+01	4.104968e+00	1.530630e+00	6.533259e-01
2	1.583940e+02	1.258547e+01	4.992413e-01	2.003040e+00
3	4.903373e+02	2.214356e+01	2.837477e-01	3.524257e+00

Table 4.30: Parameters recorded on OPENSEES after modal analysis.

After subjecting our building to the gravity load as well as modal analysis, it is then subjected to Kobe earthquake data of peak ground acceleration (pga) of 0.821g.

A comparative approach has been adopted wherein, dynamic parameters such as top storey displacement as well as top storey acceleration has been compared for the building without tuned mass damper as well as with it.

4.3.2.4 DETERMINATION OF TMD PARAMETERS

After performing the gravity analysis, we get the value of the total weight of the building at final step to be approximately equal to 3110.4 KN.

We assume the mass ratio to be 5% i.e., the mass of the damper to be 5% of the total mass of the building

Therefore, the total weight of the damper comes out to be

= (5% of 3110.4 KN)

= 155.52 KN

Since, the total mass of the TMD's arrangement is maintained constant, irrespective of the number of TMD's used, therefore we distribute the total weight of the damper equally between the two TMD's.

Therefore, weight of each damper $\boldsymbol{W_d}$ **=** 155.52 / 2

=77.76 KN

Now the mass of each TMD will be

$$\boldsymbol{M_d} = \boldsymbol{W_d} \,/\, \boldsymbol{g}$$

= (77.76 / 9.81)

= 7.92660 Kg

In order to calculate the length of the damper, we use the following relation

$$\boldsymbol{T = 2\pi\sqrt{\frac{l}{g}}}$$

Where T is obtained from the modal analysis and is equal to 1.53063 s.

Therefore, on substituting the values, we get

$$1.53063 = 2\pi\sqrt{\frac{l}{9.81}}$$

The length of damper comes out to be equal to 0.5822 m.

The stiffness of each TMD is calculated using the following relationship

$$\boldsymbol{K_d = M_d g \,/\, l}$$

= (77.76 / 0.5822)

= 133.5623 KN/m

In our building we assume the damping ratio of the building as well as that of tuned mass damper to be 2%.

Since, we have discussed that the tuned mass damper should be in resonance with the structure in order to fritter away the maximum kinetic energy of the structure and itself going out of phase (precisely, 90^0 phase difference with the main structure),

Therefore, we take angular frequency of the TMD to be equal to that of the structure

$$\boldsymbol{\omega_d = \omega}$$

$$\boldsymbol{\omega_d} = 4.104968$$

Finally, the value of damping coefficient is calculated using

$$\boldsymbol{C_d = 2\xi M_d \omega_d}$$

= 2 * 0.02 * 7.92660 * 4.104968

= 1.30154 Kg/s

Parameters of the TMD	**Values**
Mass of each damper ($\boldsymbol{M_d}$)	7.92660 Kg
Length of each damper **(l)**	0.5822 m.
Stiffness of each damper ($\boldsymbol{K_d}$)	133.5623 KN/m
Damping coefficient of each damper ($\boldsymbol{C_d}$)	1.30154 Kg/s

Table 4.31: TMD parameters used for Case II

4.3.2.5 METHODOLOGY

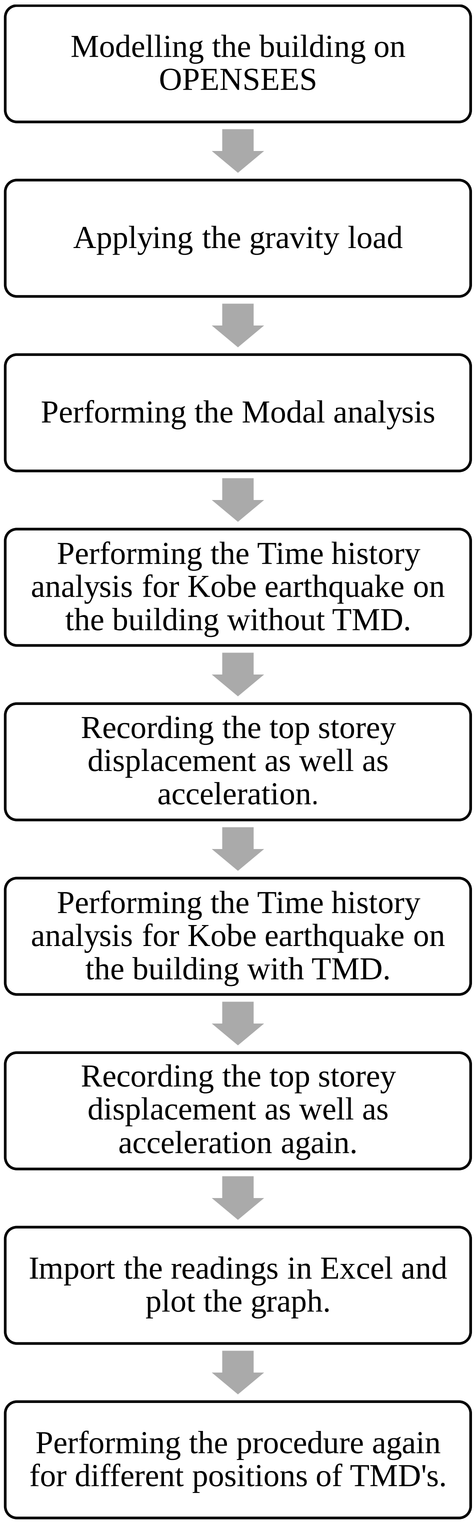

Figure 4.46: Sequence of steps to be followed for CASE II

4.3.2.6 RESULTS AND DISCUSSION

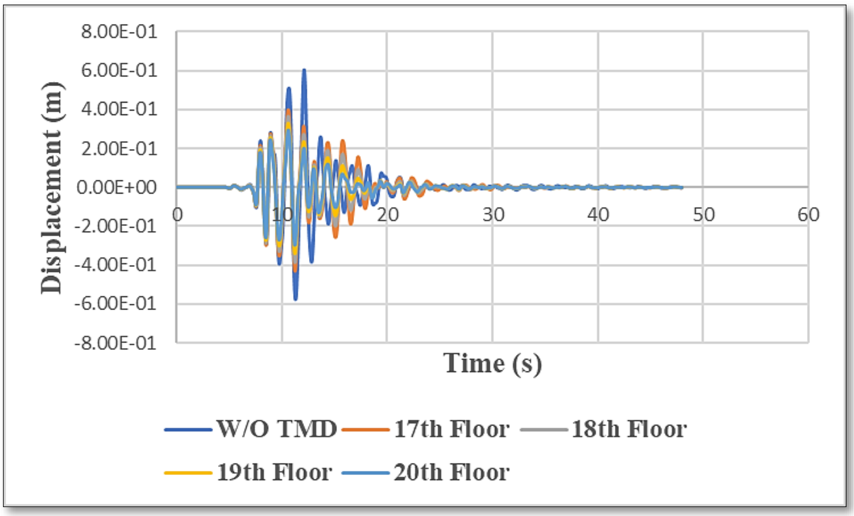

Figure 4.47: Displacement vs time for building under Kobe earthquake with varying TMD's position

As shown in the graph plotted above the maximum top storey displacement in the building without the tuned mass damper arrangement is 0.604 m.

S.No	Position of both the TMDs	Maximum top storey displacement (m)	% Reduction
1	17th Floor	0.429	28.97
2	18th Floor	0.386	36.09
3	19th Floor	0.341	43.54
4	20th Floor	0.297	53.59

Table 4.32: % Reduction of top storey displacement due to varying TMDs' position

It can be seen from the above table that there is an average reduction of 40.55% in maximum top storey displacement due to installation of TMD and the increase in reduction is around 8.21 % with change in the position of TMD from bottom of building to top.

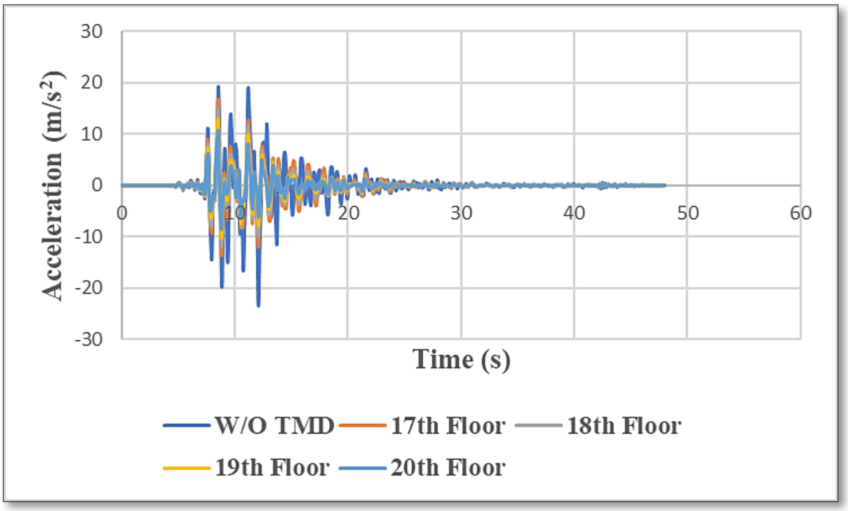

Figure 4.48: Acceleration vs time for building under Kobe earthquake with varying TMDs' position

As shown in the graph plotted above the maximum top storey acceleration in the building without the tuned mass damper arrangement is 23.4628 m/s^2.

S.No	Position of both the TMDs	Maximum top storey Acceleration (m/s^s)	% Reduction
1	17th Floor	16.7947	28.42
2	18th Floor	15.0490	35.86
3	19th Floor	13.0523	44.37
4	20th Floor	10.7553	54.16

Table 4.33: % Reduction of top storey acceleration due to varying TMDs' position

It can be seen from the above table that there is an average reduction of 40.70% in maximum top storey acceleration due to installation of TMD and the increase in reduction is around 8.58 % with change in the position of TMD from bottom of building to top.

CHAPTER 5

CONCLUSION & FUTURE WORK

5.1 CONCLUSION:

After thorough research on the topic of Tuned Mass Damper and working on the software for designing a building equipped with it, we can conclude that:

1) Decrease in structural responses such as maximum top storey displacement by 34.04% and maximum top storey acceleration by 37.76% for a building equipped with 2 TMD's makes tuned mass damper, an effective way of reducing the structural vibrations on a building caused by an earthquake.
2) There is a decrease of maximum top storey displacement by 3.95% and maximum top storey acceleration by 2.88% for every 1% increase in damping ratio of the TMD. Hence, increase in damping ratio of the tuned mass damper leads to an increase in the dissipation of vibrational energy in the building.
3) A decrease of maximum top storey displacement by 8.28% and maximum top storey acceleration by 8.62% is observed for every 1% increase in mass ratio of the TMD. Therefore, increase in mass ratio of the tuned mass damper leads to an increase in the reduction of the vibration of the building.
4) Greater decrement in structural responses such as maximum top storey displacement by 42.86% and maximum top storey acceleration by 46.49% is observed for a building equipped with 4 TMD's. Thus, greater number of tuned mass damper with a constant total mass would lead to greater reduction in dynamic responses.
5) A high-rise building equipped with passive tuned mass damper shows a greater reduction in dynamic responses as compared to that of a low-rise building. The difference being 11.77% for maximum top storey displacement and 8.27% for maximum top storey acceleration.
6) As we change the position of TMD's from bottom of the building to top, the average increase in reduction of maximum top storey displacement is more for a high-rise building than a low-rise building (8.21% against 4.26%). Same goes with the maximum top storey acceleration (8.58% against 3.52%).

5.2 FUTURE SCOPE OF WORK:

The concept of Passive tuned mass damper has been deeply studied through the medium of this project and several parametric variations has been implemented to decipher the gist of the mechanism of the TMD. However, the TMD is a broad topic and involve several other concepts to be understood, if one wants to effectively implement it in the real-world scenarios.

Therefore, the future scope of the work remaining in this topic is as follows:

1) The concept of active tuned mass damper in suppressing the vibrational energy transmitted to the building and its comparison with the passive tuned mass damper that we did in our study.
2) Optimisation of the tuned mass dampers parameters (mass ratio and damping ratio to be precise) to obtain a system that dissipates the maximum Kinetic energy to the atmosphere, thereby safeguarding the structure.

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