Optimization of Multiple Tuned Mass Damper Parameters Using Evolutionary Operation Algorithm Considering Soil-Structure Interaction

by

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DEPARTMENT OF CIVIL ENGINEERING

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY

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The thesis titled **“Optimization of Multiple Tuned Mass Damper Parameters Using Evolutionary Operation Algorithm Considering Soil-Structure Interaction”** Submitted by **Bushra Islam, Roll: 1009042354, Session: October 2009,** has been accepted as satisfactory in partial fulfillment of requirement for the degree of Master of Science in Civil Engineering (Structure).

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It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

November, 2013

Bushra Islam

DEDICATION

To My Parents, Brother and Husband

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I would also like to express my heartfelt gratitude to Almighty Allah for all my achievements.

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ABSTRACT

Vibration control is an important issue for structures subjected to dynamic loading like earthquake and wind. It is necessary to keep structural response within desirable limit and achieve desirable performance of structures. Among different structural control techniques Tuned Mass Damper (TMD) is a popular and good practical option because of its simple principle and easier implementation on existing buildings with comparatively modest rehabilitation. Appropriate selection of damper parameters is required for the structural system to perform efficiently. In the present study a methodology has been developed to optimize Multiple Tuned Mass Damper (MTMD) parameters considering soil-structure interaction. A global optimization algorithm named Evolutionary Operation (EVOP) has been applied for optimization. Generalized equation of motion has been proposed for building frames with any number of stories associated with any number of Tuned mass Damper (TMD) at different story level subjected to seismic excitation. A computer program has been developed in C++ to analyze Structure-TMD system for optimization problem formulation and has been linked with EVOP. In the optimization problem optimization criterion is defined as minimization of top displacement and maximum inter-story drift. The study has been conducted to explore EVOP in vibration control of structures using TMD. EVOP is found effective in minimizing structural performance with higher percentage of reduction in sway and choice of smaller TMD parameters. Also different combinations of TMDs have been optimized for regular and irregular frames to minimize top displacement and maximum inter-story drift in two different optimization problems. It is found possible for TMDs to minimize structural response even if bottom story stiffness is less. Optimum TMD parameters vary with the irregularity of structural system. Finally, Soil-Pile interaction has been modeled using a program TLEM (Thin Layered Element Method) for different soil-pile systems. Later soil-pile interaction has been incorporated into superstructure and optimization has been performed. The result shows, excluding the SSI effect in optimization overestimates the TMD's performance.

Chapter 1 INTRODUCTION

1.1 GENERAL

The rapid and historic growth of urbanization created a surge in the construction of high-rise buildings. Excessive vibration due to external forces like earthquake and wind is an expected phenomenon in high-rise buildings. The induced vibration may result into structural damage and undesirable performance of structures. Also human exposure to vibration induced in structure can cause discomfort. As a result vibration control of structural system in order to provide safety and functionality against induced vibration has always been considered as major relevant technological challenges for the designers.

A number of technologies have been invented and adopted to control excessive vibration and to reduce structural response and keep it within tolerable limit during unexpected events like earthquake. Primarily vibration control devices can be classified into passive, active and hybrid control systems. The technologies commonly adopted to control vibration in order to minimize damage and improve structural performance include damping, vibration isolation, control of excitation forces, vibration absorber and so forth. Each system has limitations and advantages in different perspective. The selection of a particular control system and technique is governed by a number of factors such as effectiveness, convenience, life cycle costs and so on. Among vibration absorbers Tuned Mass Damper (TMD), Active Mass Damper (AMD), Hybrid Mass Damper (HBD) have been studied and installed in high rise buildings to control their behaviour under excitations. Among these systems still TMD is popular due to its simple principle and a number of successful applications in recent days.

Tuned Mass Damper (TMD) has been widely used to minimize mechanically induced vibration. Recently the principle has been applied to control structural vibration caused by seismic event and wind. Use of Tuned Mass Damper (TMD) which is a passive energy dissipation device, consisting of mass, spring and damping elements increases the damping in the primary structure. The device is installed in the structure to reduce the dynamic response. In the cases where single TMD was placed on the top, it was found to be more effective in controlling the first mode of building structure under excitation. From that point of view the concept of Multi Tuned Mass Damper (MTMD) has been generated to have a better control under seismic load without any vulnerability to power failure.

When the external forces, such as earthquakes, act on a structural system, neither the structural displacements nor the ground displacements, are independent of each other. The response of the soil influences the motion of the structure and the motion of the structure influences the response of the soil which results in soil-structure interaction. This effect plays a significant role in the response of the system to external loads. In conventional approaches soil-structure interaction effect is neglected in structural design methods. The effect, however, becomes prominent for heavy structures resting on relatively soft soils. In fact, the soil-structure interaction effect can be significant in identifying the structural response, and neglecting the effects in the analysis may lead to inaccurate design.

1.2 BACKGROUND AND PRESENT STATE OF PROBLEM

Frahm (1909) first invented the basic form of tuned mass dampers which itself did not have any damping property. So the system was effective only when its natural frequency matched with that of the excitation force. Ormondroyd and Den Hartog (1928) introduced internal damping in TMD. Optimum choices of damper parameters were not considered until Den Hartog (1947) proposed closed form expressions of frequency ratio and damping ratio of the TMD for an undamped single degree of freedom (SDOF) system. Later damping in the main system was included through several researches performed by Bishop and Welboum (1952), Snowdon (1959), Falcon et al. (1967), Ioi and Ikeda (1978). With time a number of studies were made by Warburton and Ayorinde (1980), Thompson (1981), Warburton (1982), Villaverde et al. (1985, 1993 and 1995), Sadek et al. (1997) to obtain optimum TMD parameters in different conditions. Rana and Soong (1998) simplified the design of TMD to control a single mode of a MDOF system. In addition they also inspected the prospect of controlling multiple structural modes with multi-tuned mass dampers (MTMD). Afterward some more studies were made on determining optimal parameters of MTMDs to reduce dynamic response of structural system, by Yau and Yang (2004), Lee et al. (2006), Li and Qu (2006) and Carotti and Turci (1999). Chang (1999) studied and compared the performance of TMD, tuned liquid column damper (TLCD) and liquid column vibration absorber (LCVA). He also established generalized building mass damper equations by considering the building as SDOF system and derived some optimum design formulas in closed forms for both wind and earthquake. Lin et al. (2001) applied an extended random decrement method to reduce dynamic responses of a MDOF system subjected to seismic load. Lee et al. (2006) proposed an optimal design theory for buildings associated with TMDs at different story level and power spectral density (PSD) function of environmental disturbances. Optimal design parameters were expressed in terms of damping coefficients and spring constants through minimization of structural responses. A numerical algorithm was also developed to search optimal design parameters of MTMDs. Bakre and Jangid (2007) developed explicit mathematical expressions for optimum TMD parameters using numerical searching technique. Rudinger (2007) included nonlinear viscous damping elements to TMD and analyzed the effect. Unlike previous studies related to TMD optimization where TMD mass ratio was a preselected parameter, Marano et al. (2010) optimized TMD mass ratio along with other parameters.

Metaheuristic methods like genetic algorithm (GA), particle swarm, ant algorithm, simulated annealing, big bang big crunch and harmony search (HS) were applied to solve different optimization problems. A wide application of genetic algorithm for tuning of TMDs was made in studies of Hadi and Arfiadi (1998), Singh et al. (2002), Desu et al. (2006), Pourzeynali et al. (2007). Leung et al. used particle swarm optimization technique of tuned mass dampers. Gebrail and Sinan (2011) used harmony search to obtain optimum TMD parameters. They considered maximum acceleration transfer function and first story displacement as optimization criterion under harmonic loading. A global optimization algorithm named EVOP (Evolutionary Operation) was used by Ahsan et al. (2011) to optimize the design of simply supported, post-tensioned, prestressed concrete I-girder bridge. This optimization tool was found to be capable of locating global minimum directly with high probability and without any requirement of information related to gradient or sub-gradient of objective function. Also computational time needed for optimization was less which is really advantageous.

Wu et al. (1999) investigated the effectiveness of Tuned Mass Damper under seismic excitation considering Soil-Structure Interaction for structure with flexible base and concluded on the fact that strong soil-structure interaction extensively reduces effectiveness of TMD in minimizing maximum structural response of structures.

It is very important to search for the optimum parameters to control the dynamic response due to first mode of structural system effectively using Tuned Mass Damper (TMD). In case of controlling multi modal dynamic response of a system under seismic excitation Multiple Tuned Mass Damper (MTMD) can be a solution. Considering this fact the prospect of applying Multiple Tuned Mass Damper (MTMD) technique for controlling structures associated with soft-story which have vertical stiffness irregularity can be studied. Again soil-structure interaction plays an influential role in defining structural response. Hence it is desirable to include this effect into structural system while searching for the most effective optimum parameters of Tuned Mass Damper to control vibration. In present study soil-structure interaction will be taken into account to obtain behavior of structural system associated with tuned mass dampers and a global optimization algorithm Evolutionary Operation (EVOP) (Ghani, 1989) will be used for optimization to explore the tool in the study of dynamic control.

1.3 OBJECTIVES OF THE PRESENT STUDY

The aim of the study is to obtain optimum Tuned Mass Damper parameters for structural frame systems to minimize response of the structure. In this study a global optimization technique, called EVOP, has been applied to minimize structural response in terms of top deflection and maximum inter-story drift and to obtain the optimum Single and Multiple Tuned Mass Damper (TMD and MTMD) parameters which include mass, stiffness and damping. The objective of the present study includes,

(i) Simulation of behavior of building structures associated with Multiple Tuned Mass Dampers (MTMD) considering soil-structure interaction effect.

(ii) Optimization of Multiple Tuned Mass Dampers (MTMD) parameters to minimize building response using Evolutionary Operation (EVOP) algorithm.

1.4 SCOPE AND METHODOLOGY OF THE STUDY

Present study develops an approach to find out the optimum parameters of TMDs installed in different story level of a multi-storied building for minimum structural response caused by lateral excitation. Structural response is defined as top deflection and maximum inter-story drift in two different optimization problems. In the proposed approach optimum values of TMD parameters can be determined without specifying the modes to be controlled. A generalized equation of motion for a linear Multi Degree of Freedom (MDOF) system is formulated using principles of dynamics. This equation of motion for building with any number of stories associated with TMD in different story level is used in developing the computer program for structural response minimization. The entire optimization problem has been formulated by developing a program using C++ language. The analysis of the system including soil-structure interaction effect is performed by following Sub-Structure method. For this purpose a program named TLEM, based on Thin Layer Element Method, is used to analyze pile foundation which is considered to be situated in a homogeneous layered semi-infinite soil medium. The support condition has been incorporated into superstructure to achieve the ultimate behavior of the system subjected to seismic excitation considering lateral component of soil-structure interaction. Subsequently optimization of structural response is performed using global optimization algorithm Evolutionary Operation (EVOP). This algorithm is capable of locating the global minimum with high probability. In the optimization problem objective function defines either the top deflection or maximum inter-story drift of the building to be minimized.

After the problem formulation is complete and all the parameters are set as input, the program is linked to the optimization method to obtain optimum solution of the problem. The optimization approach is applied on regular and irregular soft-story structures with single and multiple TMDs incorporating Soil-Structure Interaction effect. The study explores EVOP in the study of dynamic control of structural system with TMD. This study would be beneficial for future extended studies in vibration control of structures using EVOP.

The study intends to determine the optimum parameters of TMDs installed at different story in a multistoried building with the objective of minimization of dynamic responses of the structure. The scope of the present study include

- Formulation of general equation of motion for multistoried building frame associate with TMDs at any story level.
- Development of algorithm to obtain optimum TMD parameters to minimize structural response.
- Development of analysis program on C++ platform
- Verification of the computer program
- Incorporation of SSI into the methodology
- Application of the methodology for regular and irregular frame
- Analysis of parameters and comparison

1.5 ORGANIZATION OF THE THESIS

Apart from this chapter, the remainder of the thesis has been divided into five chapters.

Chapter 2 presents literature review concerning past research on the field of vibration control of building, structural optimization and soil-structure interaction. It includes literature related to TMD theory, optimization in vibration control, solution principle of EVOP, incorporation of Soil-Structure Interaction in vibration control, etc.

Chapter 3 presents the methodology developed in the present study to search optimum Tuned Mass Damper parameters using Evolutionary Operation Algorithm (EVOP). It also presents extended methodology to find optimum TMD parameters considering soil-structure interaction effect.

Chapter 4 presents the formulation and analysis of optimization problem to obtain optimum solution for all the case studies studied in present work.

Chapter 5 presents the optimized results and comparisons among obtained optimum TMD parameters. This chapter also presents minimum structural response obtained from the optimum solutions and discussion on the results.

Chapter 6 presents the concluding remarks of the study and also provides recommendations for future study.

Chapter 2 LITERATURE REVIEW

2.1 GENERAL

Structural control under lateral excitation is one of the major concerns and a growing field of study. Any structure subjected to dynamic loading like seismic excitation or wind may result into high amplitude motion. Induced excessive vibration of structure can cause two adverse effects. First effect is related to structure and second one is related to its inhabitants. In case of structure, long term fatigue can occur due to uncontrolled vibration of the structural system which can play a significant role to cause material failure and develop fracture. This phenomenon can ultimately lead to a weakened structure or structural failure which is undesirable to happen. Repair and maintenance is required to improve the performance of the damaged structure. Except the impact on structure, vibration also affects the normal activity of the inhabitants of the building since people are highly sensitive to vibrations. Considering these issues mitigation of excessive vibration of structures is considered as a focus of research in order to protect structure and keep them serviceable. Additionally application of optimization approach is necessary to determine an effective system of controlling vibration. Moreover like any other structural analysis it is important to incorporate Soil-Structure Interaction into the structural system to predict the actual behavior.

Present study focuses on minimizing building vibration using optimum Tuned Mass Damper (TMD) and Multiple Tuned Mass Damper (MTMD) considering soil-structure interaction (SSI). A tuned mass damper is a passive control device. It includes a lumped mass with a spring dashpot system attached to the primary structure. This arrangement reduces undesirable vibration of the structural system induced by lateral excitation. Here a global optimization tool Evolutionary Operation (EVOP) algorithm has been applied. This chapter presents a literature of related studies on structural vibration control, Tuned Mass Damper, optimization of Tuned Mass Damper and vibration control considering soil-structure interaction. Also this section includes brief description of EVOP.

2.2 VIBRATION CONTROL OF STRUCTURES

Structures are usually susceptible to vibrations in case it is not possible for the vibration to be damped out and energy to be dissipated. Structural control is an alternative way to ensure structural safety and keep vibration within tolerable limit besides conventional design methods. A number of approaches are available to control the induced vibration of structural system. Researchers have developed structural control systems which can protect structures and improve their performance during earthquake. Passive or active stabilizing forces can be applied on the structure using external dampening device to mitigate the effect of structural vibrations (Gerges and Vickery 2005). One of the examples of this type of control system is Tuned Mass Damper. Different earthquake protective systems including Tuned Mass Damper have been applied to structures in several seismically active countries of the world.

A number of researches have been taken place to develop different structural control systems to alleviate structural responses under seismic excitation and wind load. Still numerous research works are going on to advance the effectiveness of these systems. The following sections provide a brief overview of structural vibration control systems. Later a review of the principles of Tuned Mass Damper (TMD) and studies made on controlling building vibration using Tuned Mass Damper subjected to various dynamic loading such as earthquakes and wind are presented in this section. Finally overview of some practical applications of Tuned Mass Damper (TMD) on structures has been provided.

2.2.1 Vibration Control Techniques

Vibration control techniques can be broadly classified into four major groups based on their operational mechanism (Cheng et al., 2008; Constantinou et al., 1998; Housner et al., 1997; Spencer and Nagarajaiah, 2003). These include passive, semi-active, active, and hybrid control approaches Details classification of structural control system is presented in Figure 2.1 (Saeed et al., 2013). A brief description of different structural control systems based on the operational mechanism is presented in this section.

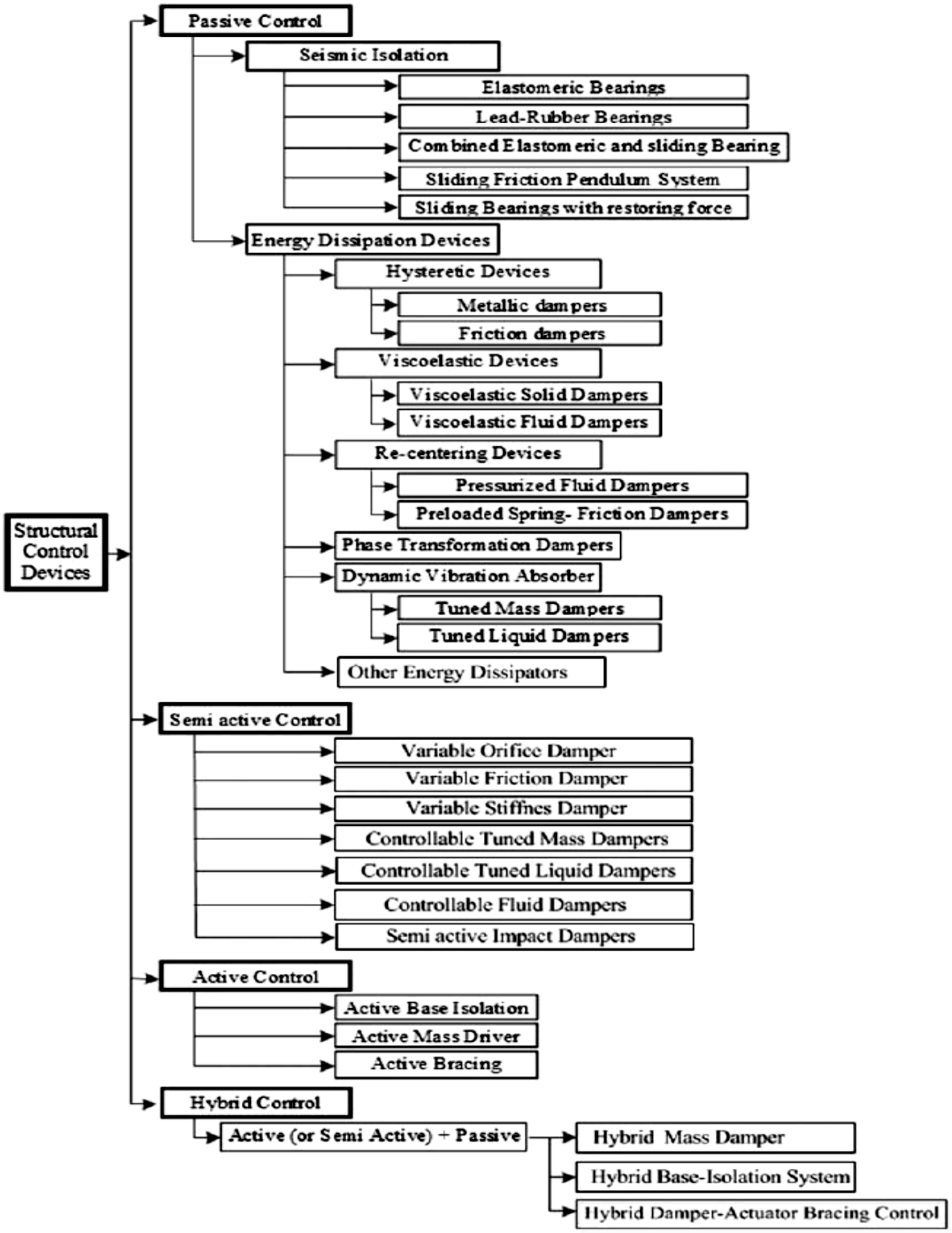

Figure 2.1 Classification of Structural Control System

(a) Passive Control Systems

Passive control systems are the most common among structural control devices. Passive systems work by dissipating the input energy causing vibration. This category includes mainly seismic isolation and energy dissipation devices. This system was considered as smart system in the past since they can generate a higher damping force when the structural response becomes higher (Cheng et al., 2008). Usually passive control systems are effective only for specific dynamic loading they have been designed and tuned for and considered as system with limited control capacity. In other words structures associated with specific passive control systems are not able to adapt different types of excitation. Their efficiency will be optimum only to protect structure from a specified dynamic loading. But over this factor passive control systems have stable nature and do not require external energy source to operate during excitation. Also design and construction of passive control devices are simpler (Christenson, 2001).Energy dissipation and seismic isolation devices are briefly described below.

Energy Dissipation Device

Energy dissipation devices control the effect of structural vibration by absorbing or diverting part of the input energy. This type of device reduces the energy dissipation demand in the primary structure. Energy dissipation devices are installed between the primary structure and bracing system. Dynamic vibration absorbers are passive devices which are installed in primary structure to minimize the demand of energy dissipation generated in the structure during application of dynamic loading. In case of vibration absorbers some of the vibration energy is transferred to the absorber rather than direct dissipating. This type of device consists of a mass, stiffness and damping component. Their dynamic properties are tuned in a manner to control vibration induced by specific dynamic loading. Common types of dynamic vibration absorbers are Tuned Mass Dampers (TMDs), Tuned Liquid Dampers (TLDs) and Tuned Liquid Column Dampers (TLCDs) (Constantinou et al., 1998).

Another type of passive control system is hysteretic devices. Metallic dampers and friction dampers are hysteretic devices which dissipate the energy by a mechanism that is independent of loading rate. Metallic dampers dissipate energy by yielding of metal and friction dampers dissipate energy by heat generation from dry sliding friction (Constantinou et al., 1998). Viscoelastic devices dissipate energy in a rate-dependent way. They are usually used in structures where it is expected to have shear deformations. Re-centering devices work based on its inherent re-centering capability. In phase transformation dampers a novel and smart material named shape memory alloy (SMA) is used in passive dampers. This material has the ability its ability to undergo large deformations and return to their undeformed shape by removal of stresses. It can transform between martensitic and austenitic crystalline phases due to reversible stress or temperature.

Seismic Isolation Device

In seismic isolation devices a layer in inserted which is flexible in horizontal direction and very stiff in vertical direction. Its working principle is to increase the horizontal flexibility and rocking stability to absorb the part of the input energy prior to dissipation energy. These devices are effective for buildings of short to medium height. Seismic isolation can control effects of vibration transmitted through the ground. They cannot control vibration caused by wind load efficiently due to the flexibility in the horizontal direction.

(b) Semi-Active Control Systems

Semi-active control devices are an advanced form of passive devices. These devices have adaptive capacity. Adaptive system of these devices controls the damper behavior based on the collected information of excitation and response of the structure. These devices consist of sensors, control computer, control actuator and a passive damping device. Small power source is required to operate semi-active control systems. This system does not have full control capacity since it works depending on the capacity of installed passive devices. In spite of this limitation semi-active control system has potential in controlling vibration because advantages of both passive and active systems are present in these devices.

(c) Active Control Systems

Active control devices have been developed to overcome the limitations of passive and semi-active control systems in seismic structural response control (Cheng et al., 2008). Active system has the enhanced control effectiveness to withstand the unpredictable vibrations due to different excitations. Significant energy source is required for active system to function during natural hazard event. In case power supply fails during the hazard phenomena active system will become inoperative. Also system setup and its components are complicated. Active mass damper system, active base isolation system and active bracing system are examples of active control devices.

(d) Hybrid Control Systems

Hybrid control system is the combination of passive, active and semi-active devices connected into series or parallel manner. This system has become a promising solution since this system possesses the advantage of passive, active and semi-active control systems. Passive part works to reduce the structural response and keep performance of the structure within desirable limit. Active part is applied to tune and adjust the response. Hybrid control systems are effective to protect structures subjected to different types of excitation with dissimilar intensity and frequency range (Wu, 2011).

2.2.2 Principles of Tuned Mass Damper (TMD)

A Tuned Mass Damper (TMD) works as a passive control device. This device is used to reduce the amplitude of structural and mechanical vibrations. It composed of three major components namely a concentrated mass, a spring and a viscous damper. These components are attached and tuned to the primary structure to reduce undesirable vibration. Lumped mass of TMD moves relative to the main structure during excitation. This mass is attached to the structural system with a spring and damper in parallel connection. A Tuned Mass Damper attached to a Single Degree of Freedom (SDOF) system is presented in Figure 3.2. Spring attached to the system provides stiffness and the damper works as a dissipative energy system.

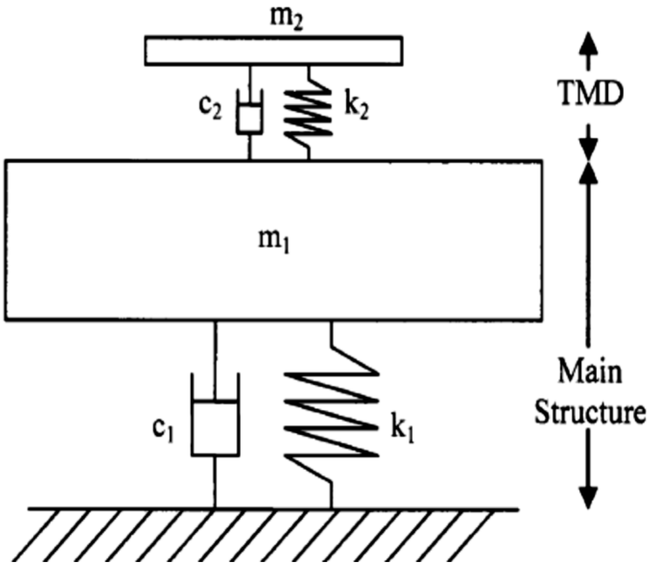

Figure 2.2 A Tuned Mass Damper (TMD) attached to a SDOF system

In the presence of dynamic loading causing lateral excitation, Structure-TMD system will be excited and will generate kinetic energy which needs to be transferred to reduce the structural response. The TMD is tuned close to the natural frequency of the structural mode of interest which results into the resonance of TMD. In this way the kinetic energy produced from structural vibration is transferred to the TMD attached to the primary structure. This transferred energy is absorbed by the viscous damper of the TMD.

A significant amount of energy can be dissipated by properly selecting TMD system parameters. The most significant design variable of Tuned Mass Damper is the mass ratio (μ) which is the ration between mass of TMD and mass of the primary structure (Den Hartog, 1947). Generally the mass ratio is selected to be in the range of 1–10% (Farghaly and Ahmed, 2012).

A system with Multiple Tuned Mass Dampers (MTMD) consists of a number of lumped mass dampers. In this system TMDs are installed at different levels of primary structure to control multiple mode of vibration.

2.2.3 Structural Vibration Control using TMD

The concept of Tuned Mass Damper (TMD) was first proposed by Frahm (1911). Later a theory for the Tuned Mass Damper (TMD) was presented by Ormondroyd and Den Hartog (1928). Clark (1988) extended the classic work of Den Hartog from SDOF to MDOF system and proposed a design methodology for Multiple Tuned Mass Damper (MTMD).

Igusa and Xu (1994) investigated Multiple Tuned Mass Damper (MTMD) with natural frequencies distributed over a range of frequency. They developed an integral form to express the impedence. Later TMD was designed optimally based on Euler-Lagrange equations from the calculus of variations. They also derived a closed form analytical solution for optimal design parameters of TMD.

Rana and Soong (1998) performed a parametric study to demonstrate a better understanding on detuning effect of TMD parameters. They also studied the application of Multiple Tuned Mass Damper (MTMD) to multiple structural modes.

Dynamic analysis of building structure associated with Multiple Tuned Mass Damper was performed under wind exposure (Lewandowski and Grzymisławska, 2009). The analysis was done to find out the possibility of the system to reduce vibration of structure.

Zuo (2009) studied a TMD system where multiple absorbers are connected to the primary system in series. They used decentralized H2 and H control method for the optimization of parameters for spring stiffness and damping coefficient for random and harmonic vibration. They showed that the TMDs in series are more effective and robust compared to other TMD system of same mass ratio and also the TMDs in series are less sensitive to parameter variations in primary system.

Shariatmadar and Razavi (2010) studied and presented the effectiveness of multi-tuned mass dampers to reduce acceleration and RMS acceleration of building under seismic excitation.

2.3 OPTIMIZATION IN VIBRATION CONTROL USING TMD

Optimization is a technique to minimize or maximize some functions of system variables subject to specified performance measures. A number of optimization models proposed to obtain optimum Tune Mass Damper (TMD) parameters for minimum structural response. Different optimization techniques have been applied in this regard.

An approach to evaluate the performance of both passive and active TMD's is parametric study. Many researchers put their effort in parametric study to select the optimal parameters for TMDs. A few experimental studies have been conducted on active control system to verify TMD theory and the experimental results were well compared with those from parametric studies. Some researcher conducted full scale experiments through the installation of TMDs in tall buildings and other structures and found significant effectiveness of TMDs in reduction of dynamic responses of those structures (Kwok and Samali, 1995).

Chang (1997) conducted a comparative study on three different types of mass dampers. He proposed a set of mass-dampers relationships for SDOF system and derived a set of closed formed formulas for optimal properties and design of three types of mass dampers for both earthquake and wind load.

Joshi and Jangid (1997) investigated the optimal parameters of MTMD to alleviate the dynamic response of a base excited (modeled as a stationary white noise random process) structure in a particular mode. They used minimization of Root Mean Square (R.M.S.) of displacement of primary structure as the objective function. The damping ratio, the tuning frequency ratio, and the frequency bandwidth of the MTMD system were the parameters in this study. They claimed that the optimally designed MTMD perform better than single TMD with respect to efficiency of the damper system.

Hadi and Arfiadi (1999) considered MDOF primary system instead of usual SDOF system considered in early studies for the optimum design of TMD under seismic excitation. Genetic Algorithm (GA) was used for the optimization of TMD parameters.

Optimal placement of multistage and multimodal TMD for building under seismic excitation was studied by Chen and Wu (2001). Optimal location indices were suggested and a procedure of practical design and placement of dampers was proposed in this study.

A number of researchers have investigated the characteristics of MTMDs associated With SDOF systems. Several authors incorporated some parameter optimization relying on restrictive assumptions. Zuo and Nayfeh (2005) proposed a numerical algorithm that optimizes the stiffness and damping of each TMD in MTMD associated with SDOF systems. They demonstrated that the optimal designs have not yielded uniformly spaced tuning frequencies and identical damping coefficients. They also stated that the optimization individual parameter in MTMD system has significant positive impact on performance and the performance is not substantially affected by the distribution of mass among the TMDs.

Lee et al. (2006) proposed an optimal design theory for Tuned Mass Damper. In the study MDOF structural system with multiple TMDs installed at different level of building were chosen as structural system. They determined optimal design parameters of TMD in terms of stiffness and damping coefficient. Also a numerical approach is developed for searching optimal MTMD parameters.

A study was performed to obtain optimum parameters of TMD attached to a viscously damped SDOF system subjected to non-stationary base excitation using Particle Swarm Optimization (PSO) algorithm (Leung et al., 2008). In this optimization problem cost function was defined as the displacement or the acceleration mean square response or their combination.

Bekdas and Nigdeli (2011) applied a metaheurestic optimization method named Harmony Search (HS) to propose optimum parameters of Tuned Mass Dampers (TMD) under seismic excitation. They used peak values of first story displacement and acceleration transfer function as optimization criterion.

2.4 EVOLUTIONARY OPERATION ALGORITHM (EVOP)

Evolutionary Operation Algorithm (EVOP) is a global optimization tool for constrained parameter optimization. It has the ability to locate the global minimum directly with high probability. This tool can deal with possible finite number of discontinuities in the nonlinear objective and constraining functions. It can minimize an objective function without information on gradient or sub-gradient. EVOP can work with objective functions which contain a mix of integer, discrete and continuous variables as arguments. EVOP can perform optimization even when more than one of the difficulties mentioned above are simultaneously present. It checks whether the obtained minimum is the global minimum by automatic restarts in the next step. Evaluation of objective function in the infeasible region keeps the plant or system always in safe zone. Capacity of optimizing without gradient or sub-gradient information ensures that noise in measurement will not be accentuated to negatively affect the optimization process. It can cope with realistic hard time constraint requirement imposed by real-time systems. EVOP has successfully minimized internationally recognized test problems (Ghani, 1995). The problems include unconstrained, constrained, multiple minima and mixed variable problems.

The algorithm of EVOP has been developed to minimize a defined objective function. The numbers of independent variables involved in the objective function are subjected to explicit constraints with specific upper and lower limit of each constraint. If any explicit constraint causes the vector-space non-convex it is then set into the group of implicit constraints with fixed upper and lower limit of each of them. These limits are either constant values or function of independent variables.

The algorithm works and progresses through six fundamental process Ghani (1989). The processes are

(i) Generation of a 'complex',
(ii) Selection of a 'complex' vertex for penalization,
(iii) Testing for collapse of a 'complex',
(iv) Dealing with a collapsed 'complex',
(v) Movement of a 'complex' and

(vi) Convergence tests.

The algorithm of EVOP is presented in Figure 2.3.

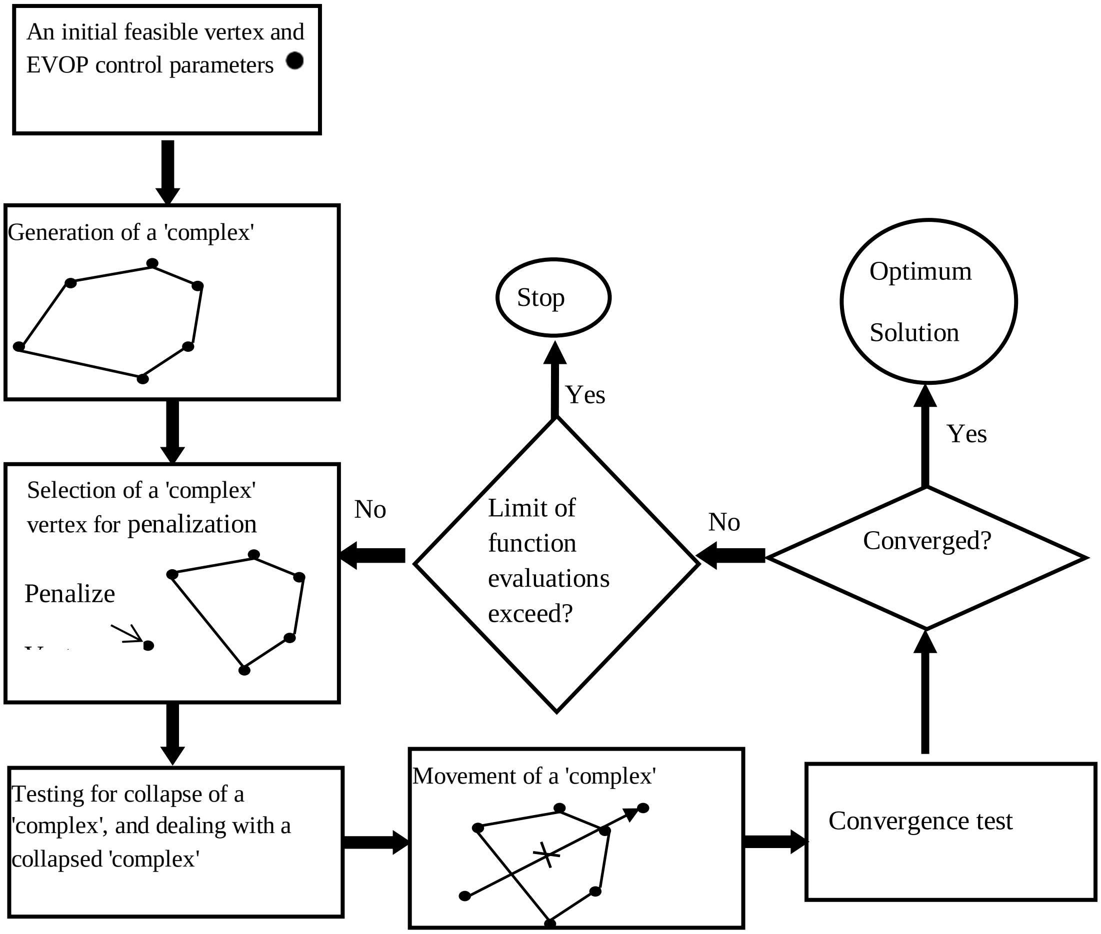

Figure 2.3 Algorithm of EVOP (Ahsan et al., 2011)

Six fundamental processes of EVOP to find out the global minima of an objective function are briefly described below.

1. *Generation of 'Complex'*: A complex is an object comprises of k vertices spanning on n- dimensional space (k>=n+1) capable of moving towards global minima located on the boundary or within the feasible region through changing shape and size. This

complex is generated using an initial starting point and randomly generated points satisfying explicit and implicit constraints.

A complex with four vertices in a two dimensional parameter space is shown in figure 3.4. Lower case letters a, b, c and d denotes the complex vertices in an ascending order of function values, i.e. f(a)<f(b)<f(c)<f(d). Straight lines drawn parallel to the co-ordinate axes represent fixed upper and lower limits of explicit constraints. The curved lines represent upper and lower limits of implicit constraints. The hatched area shown in Figure 2.4 is the two dimensional feasible search spaces to search the minimum.

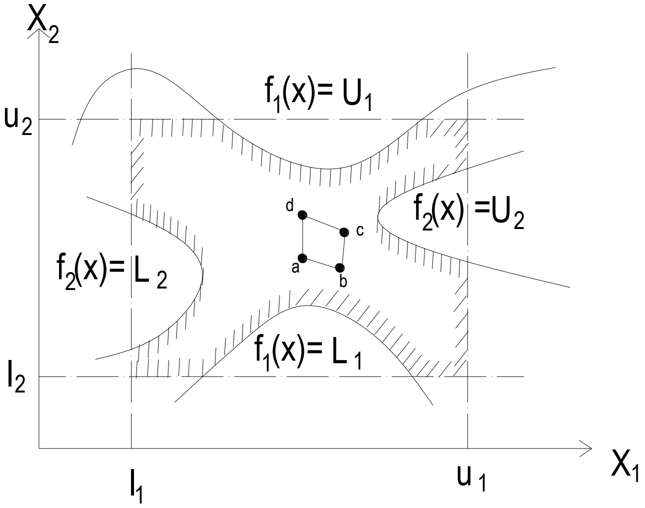

Figure 2.4 A "complex" with four vertices (Ahsan et al., 2011)

2. *Selection of a vertex of complex for penalization:* In this step, a vertex of the complex generated in the first process, with highest objective function value is selected for penalization. The penalization is done by over reflecting the vertex on centroid on the complex.

3. *Testing for a collapsed complex:* the collapsed complex is defined as a complex having centroid with a coordinate identical to the same coordinate for all vertices. The collapsed complex is need to be detected as a complex that collapsed into subspace

cannot span original space. The EVOP detects a collapsed complex by comparing the numerical values of points within the resolution of a parameter. This parameter is called the parameter for detection of collapsed complex (Φcpx).

4. *Dealing with collapsed complex:* If EVOP identifies a collapsed complex, it either generates a new complex for the full feasible spaces or creates a new complex spanning smaller feasible spaces.

5. *Movement of a complex:* this process involves with the movement of a complex to attain the global minima of the defined objective function. EVOP initiates the process by over reflecting the selected penalization point (worst vertex) of the complex on the centroid of the complex comprises of all vertices except selected point. EVOP defines a coefficient, called reflection coefficient to generate a trial vertex (α). This trial vertex replaces the selected penalization vertex (worst vertex), if over-reflection is found successful. If the reflection step becomes unsuccessful, EVOP applies a contraction step. There are three stages in contraction step which depend on the value of the objective function at the feasible trial vertex of the reflection step. Stage 1 of the contraction step is applied, if the function value at feasible trial vertex after over reflection is less than the function value at the worst vertex but greater than the value at vertex having second highest function value (under reflection). A coefficient of contraction (β) is used to estimate a new trial vertex in the stage of contraction step. If the objective function value at the trial vertex of the reflection step is greater or equal to the function value at worst vertex of current complex, EVOP calls stage 2 of contraction step. Stage 3 of contraction step is called only after Stages 1 and/or 2 have been previously applied consecutively for more than '2k' times. If on over-reflection the trial point has not violated any constraints, has a function value lower than the function value at vertex having lowest objective function value' of the current complex and the previous move was not a contraction step, this over-reflection is considered over-successful. Under this situation an expansion step is applied to generate a new trial point using a coefficient called expansion coefficient (γ). If the

expansion step becomes unsuccessful, then EVOP creates a new complex with new reflection scheme.

6. *Convergence tests:* EVOP runs tests for convergence in parallel with the movement of complex after a certain specified number calls of objective function. EVOP applies two levels of tests to ensure convergence. EVOP uses a convergence parameter (Φ) in the first level of tests, which indicates whether the specified numbers of consecutive function value are identical. Upon the success of first level of tests, EVOP implements the second level of tests.. This second test for convergence validates whether function values at all vertices of the current 'complex' are also identical within the resolution of convergence parameters

2.5 VIBRATION CONTROL CONSIDERING SOIL-STRUCTURE INTERACTION

Different studies have been conducted from the realization of necessity of incorporating soils-structure interaction effect into the analysis of structural control system. A brief literature of studies related to analyze the performance of structural control system considering soil-structure interaction is stated in this section.

Samali et al. (1992) performed a study to find out the effectiveness of Tuned Liquid Column Dampers (TLCD) in reducing structural vibration induced by seismic loads and compared with Tuned Mass Damper (TMD considering soil-structure interaction effect. They observed that natural frequencies of soil-structure system and tuning of dampers are affected by soil flexibility.

Xu and Kwok (1992) investigated vibration of tall structures associated with Tuned Mass Damper induced by wind considering soil-structure interaction. Analysis of soil-structure-mass damper interaction was performed in frequency domain using transfer matrix formulation.

The effect of soil-structure interaction on the performance of Tuned Mass Dampers

(TMD) attached to structure with flexible base under seismic excitation was studied by Wu et al. (1999). In the study soil-structure system was presented by a generic frequency-independent model and a stationary random excitation was considered as input motion. TMD performance was defined in terms of root-mean-square responses. It was observed from extensive parametric study that strong oil-structure interaction considerably reduces the seismic effectiveness of TMD. It was shown that the TMD becomes less effective with the decrease of shear wave velocity of soil

Chouw (2004) focused on the effect of Tuned Mass Damper on the response of frame structure during near-source ground excitations considering soil-structure interaction. It is revealed from the study that the SSI and ground motion's attributes may affect the effectiveness of TMD substantially. Detailed investigations are required to draw a generalized conclusion.

Garcia and Schmid (2004) studied the influence of plate foundations, pile foundation and soil improvement blocks on earthquake induced vibration reduction of structures. The study shows that deep foundation can reduce amplitude of vibration in comparison with those occurred at ground surface in the absence of any structure. Also deep foundations can shift first resonance frequency of soil-structure system.

Patel and Jangid (2008) studied influence of soil-structure interaction on response of adjacent SDOF structures connected by viscous damper. Response of connected structural system was found more critical on soft soil than response of the structural system located on stiff soil. Also other energy dissipating control systems were suggested as solutions.

The effect of soil-structure interaction on the performance of a number of 3D steel moment resisting fames with different eccentricities in orthogonal direction associated with Tuned Mass Damper (TMD) locating on soft soil are investigated (Rofooei and Shamsi, 2008). Structural system was considered to be founded on rigid concrete mat footing and soil is modelled as s homogeneous half-space. In this study TMD performance was measured in terms of maximum real story drift.

Kenarangi1 and Rofooei (2010) considered Soil-Structure Interaction effect in analyzing the performance of Tuned Mass Dampers (TMD) to reduce nonlinear response of irregular buildings. Bi-directional horizontal ground motions were considered in their study. A discrete model of underlying infinite soil medium was made for the study using concept of Cone Models.

Chapter 3 METHODOLOGY

3.1 GENERAL

The present study developed an approach for optimization of Tuned Mass Damper parameters using Evolutionary Operation (EVOP) algorithm considering Soil-Structure Interaction effect. In this approach the behavior of building structures installed with Multiple Tuned Mass Dampers (MTMD) at different story levels has been simulated. Then the optimization problem has been formulated to link with EVOP and to obtain optimum solution. The solution looks for optimum Tuned Mass Damper Parameters to achieve minimum response of the building. Later Soil-Structure Interaction effect was incorporated into the simulated behavior of the entire system to model actual behavior under earthquake excitation. The simulation was done considering flexible pile foundation beneath the superstructure and different soil profile. Optimization is performed for the structural system considering Soil-Structure Interaction to obtain effective optimum parameters of TMD.

3.2 METHODOLOGY WITHOUT SOIL-STRUCTURE INTERACTION EFFECT

A general methodology of analyzing a MDOF structure associated with Multiple Tuned Mass Dampers (MTMD) installed at different story levels and solving the system to search optimum parameters for each TMD has been formulated. A code has been developed using C++ to analyze the whole system subjected to earthquake. The code has been validated for systems with known response. Then the optimization problem for controlling the vibration of a building structure using principle of MTMD has been formulated. In this approach mass, stiffness and damping coefficient of individual TMD are considered as target parameters to be optimized. Formulated problem was coded in C++ and linked with the optimization tool EVO chosen for this study, to obtain optimum parameters of each TMD resulting into minimum structural response. The methodology developed in this study has been shown in Figure 3.1.

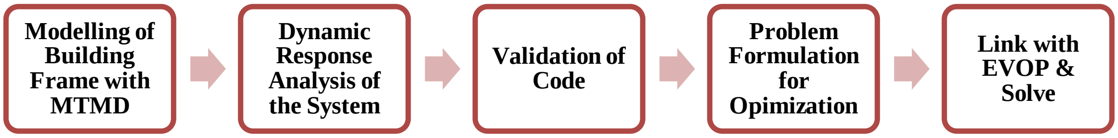

Figure 3.1 Methodology of TMD parameter optimization using EVOP

Based on this methodology and formulation, structural response under seismic activity can be evaluated and the target parameters can be optimized efficiently.

3.2.1 Modeling of Frame Structure with Tuned Mass Damper

For this study a linear model of MDOF building system associated with Multiple Tuned Mass Damper (MTMD) installed in different story level has been developed. Tuned Mass Dampers located at different story locations are modeled as single SDOF Tuned Mass Damper system. The combined structural system is shown in Figure 3.2 below. The model can be used to simulate response of a multistoried building occupied with vertically distributed Tuned Mass Dampers under lateral excitation.

The model has been expressed with a generalized equation of motion. This equation of motion has been formulated considering a building system with ‘n’ number of stories associated with total ‘m’ number of TMDs subjected to ground excitation. These TMDs are distributed in selected story locations. One single TMD is placed in each desired story position to minimize the response of the primary system. The mass of primary system is considered to be lumped on the level of building floors. The primary structure is idealized as linear elastic spring elements and dashpots. The dynamic degrees of freedom considered for the analysis are lateral displacements of floors. Individual Tuned Mass Dampers with one degree of freedom consist of a rigid mass are idealized as spring element and dashpot. Base of the structure is assumed to be fixed to the ground. Earthquake acceleration time history is the force applied on the ground causing vibration.

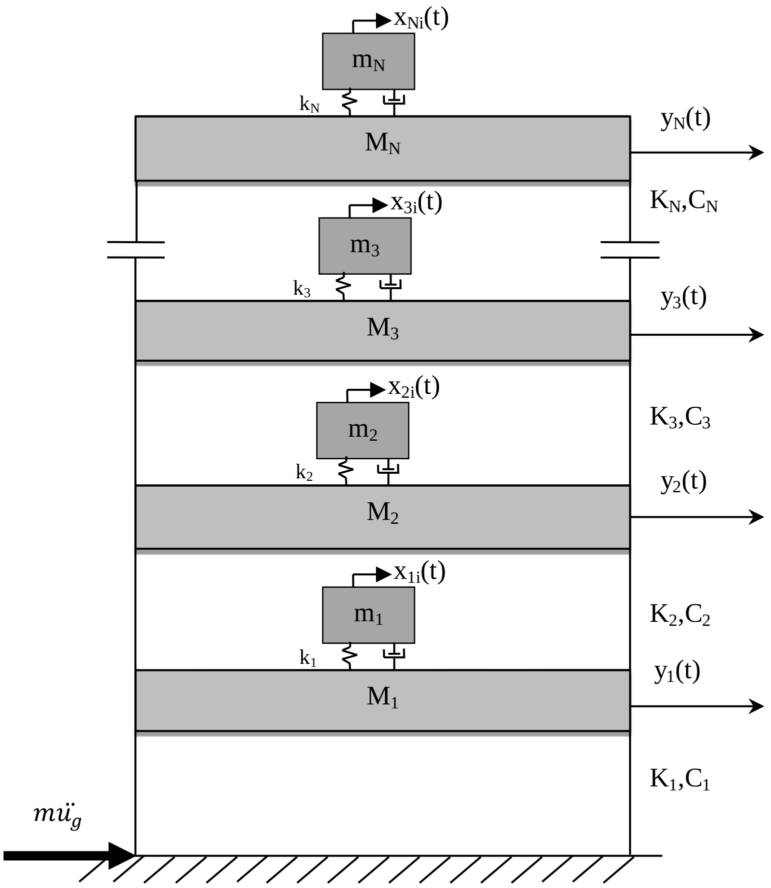

Figure 3.2 Multiple Tuned Mass Dampers attached to Building

In the developed approach the Structure-MTMD system has been characterized by a set of differential equations of motion. The equation of motion of the combined system has been expressed in two parts.

The equation of motion at any story level of the primary system is stated in Eqn. 3.1.

$$M_i\ddot{X}_i + K_i(X_i - X_{i+1}) + K_{i-1}(X_i - X_{i-1}) + C_i(\dot{X}_i - \dot{X}_{i+1}) + C_{i-1}(\dot{X}_i - \dot{X}_{i-1}) + k_j(X_i - x_j) + c_j(\dot{X}_i - \dot{x}_j) = -M_i\ddot{u}_g \qquad (3.1)$$

Where, i=1, 2, 3.....n. Notation 'n' is the number of total story of the building. In the above equation of motion M, K, C denotes mass, stiffness and damping respectively of i^{th} story of the primary superstructure. X is the lateral displacement with respect to ground.

$\dot{X}$ is single derivative of displacement which is velocity and $\ddot{X}$ is double derivative which is acceleration of the structure with respect to base. $\ddot{u}_g$ is the horizontal ground acceleration due to lateral seismic excitation.

The equation of motion at the free end of TMD is given in Eqn. 3.2.

$$m_j\ddot{x}_j + k_j\left(x_j - X_i\right) + c_j\left(\dot{x}_j - \dot{X}_i\right) = -m_j\ddot{u}_g \qquad (3.2)$$

Where, j=1, 2, 3.....m. Notation ‘m’ is the number of total TMD in the system.

In the above equation symbols m, k, c represents mass, stiffness and damping of j^{th} Tuned Mass Damper. x, $\dot{x}$ and $\ddot{x}$ represents the lateral displacement, velocity and acceleration of the damper with respect to ground.

3.2.2 Dynamic Analysis of the Structural System

The proposed approach uses the central difference method to analyze the structural system by solving equation of motion developed for the system. This numerical time stepping method solves the system by integration of differential equation. A program has been developed in C++ language based on the system equation of motion developed in section 3.1.1 and central difference method (Chopra, 2002). This code simulates behavior of the structural system and analyzes the system to find out lateral displacement at each story level and inter-story drift. Steps of how the computer program works are described below.

1. Input parameters for the code
    a. Concentrated mass of each story, stiffness and damping coefficient provided by frame at each story
    b. Initial feasible starting point for EVOP: Mass, stiffness and damping ratio of each tuned mass damper
    c. TMD location
    d. Earthquake acceleration time history and time step

2. Create global mass matrix
    a. For determination of each element of the global mass matrix, the program checks whether it is a TMD node or primary structure node
    b. For TMD node equation of motion of TMD is applied to calculate the mass element
    c. For structural node equation of motion for primary system is used to determine the mass element
3. Create global stiffness matrix
    a. For determination of each element of the global stiffness matrix, the program checks whether it is a TMD node or primary structure node
    b. For TMD node equation of motion of TMD is applied to calculate the stiffness element
    c. For structural node equation of motion for primary system is used to determine the stiffness element
4. Create global damping matrix
    d. For each For determination of each element of the global damping matrix, the program checks whether it is a TMD node or primary structure node
    e. For TMD node equation of motion of TMD is applied to calculate the damping element
    f. For structural node equation of motion for primary system is used to determine the damping element
5. Create force matrix
6. Solve using central difference method (each time step calculation)
7. Determination of lateral displacement vector at each node
8. Determination of inter-story drift vector at each node

$$\text{Interstory drift} = \frac{\text{Lateral Displacement } (\text{i}+1)^{\text{th}} \text{ story} - \text{Lateral Displacement } \text{i}^{\text{th}} \text{ story}}{\text{Story Height}}$$

9. Calculate maximum inter-story drift
10. Define objective function
11. Define explicit constraints and maximum, minimum limits
12. Define implicit Constraints and maximum, minimum limits

13. Input EVOP control parameters
14. Link the program with EVOP

Using this computerized approach developed in this study the interaction of building system installed with any number of passive TMD at a desired position can be simulated and optimum parameters of TMD can be determined using EVOP to achieve minimum structural response.

3.2.3 Verification of Code

The program developed for the dynamic analysis of shear building with ‘n’ number of story associated with ‘m’ number of TMDs in different story level has been validated for two shear building frames associated with Tuned Mass Damper. Among two frames, one frame is installed with one TMD on top and another frame is installed with four TMDs at different story location.

The first structural system was taken from Hadi anr Arfiadi (1998). The code developed for current study analyzed the ten story shear building with a Tuned Mass Damper (TMD) installed on the top and calculated response of the system. El Centro earthquake excitation was put as seismic input. The obtained response matched to that of the system presented in the original study. The building and TMD parameters are presented in Table 3.1 and the lateral displacement with respect to ground obtained from developed code and original study are shown in Table 3.2.

The second structural system was taken from the study of Clark (1988). In that study a tall building was considered with 4 TMD located at 3rd, 5th, 6th and 8th story. The code developed for current study analyzed the eight story shear building with Multiple Tuned Mass Damper (MTMD) installed at specified locations. Structural response matched to that of the system presented in the original study. The building and TMD parameters are presented in Table 3.3. The responses of the top floor of the primary system without TMD, with single TMD and with all 4 TMDs obtained using the developed code are shown in Figure 3.3, Figure 3.4 and Figure 3.5 respectively.

Table 3.1 Parameters of Structure and TMD for the 1st structural system (Hadi & Arfiadi, 1998)

Parameters	Structure (each story)	TMD
Mass (t)	360	108
Stiffness (kN/m)	650000	3750
Damping (kNs/m)	6200	151.5

Table 3.2 Verification of Code developed for present study

Story level	Displacement (m)	
	Hadi & Arfiadi	Present Study
Story 1	0.019	0.019
Story 2	0.037	0.037
Story 3	0.058	0.054
Story 4	0.068	0.069
Story 5	0.082	0.082
Story 6	0.094	0.094
Story 7	0.104	0.104
Story 8	0.113	0.113
Story 9	0.119	0.119
Story 10	0.122	0.122
Story TMD	0.358	0.359

Table 3.3 Parameters of Structure and MTMD for the 2nd structural system (Clark, 1988)

Parameters	Structure (each story)	TMD (3rd story)	TMD (5th story)	TMD (6th story)	TMD (8th story)
Mass (t)	510	53	53	53	53
Stiffness (kN/m)	42400	135	5760	3150	1190
Damping (kNs/m)	0	27.6	148	109	67.1

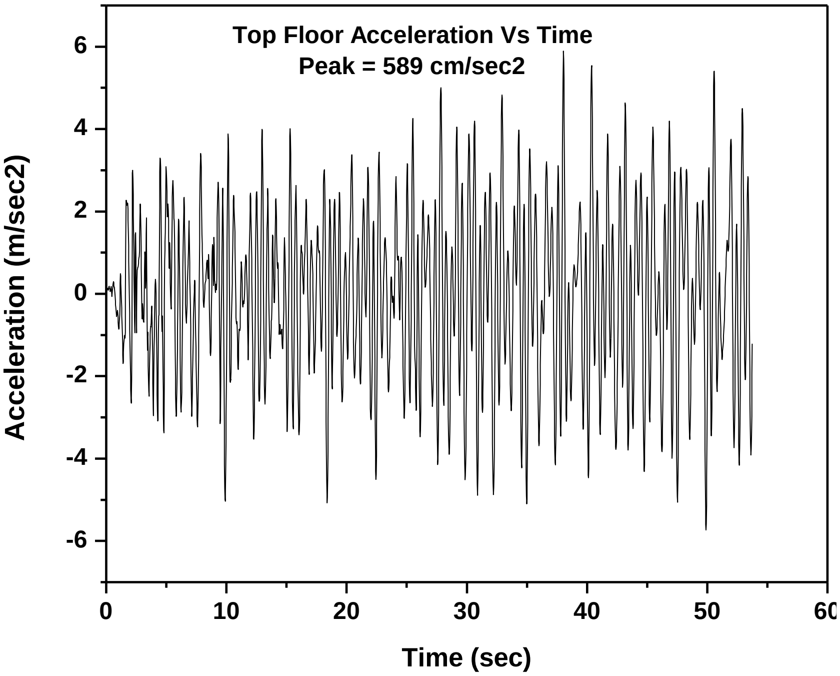

Figure 3.3 Top floor response of structure without TMD obtained using developed program

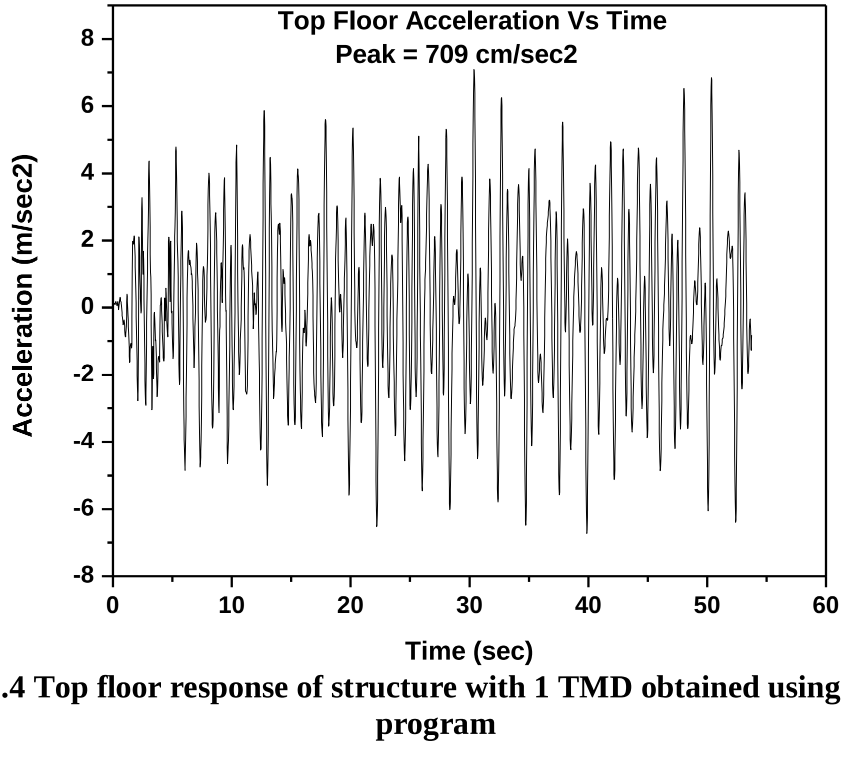

Figure 3.4 Top floor response of structure with 1 TMD obtained using developed program

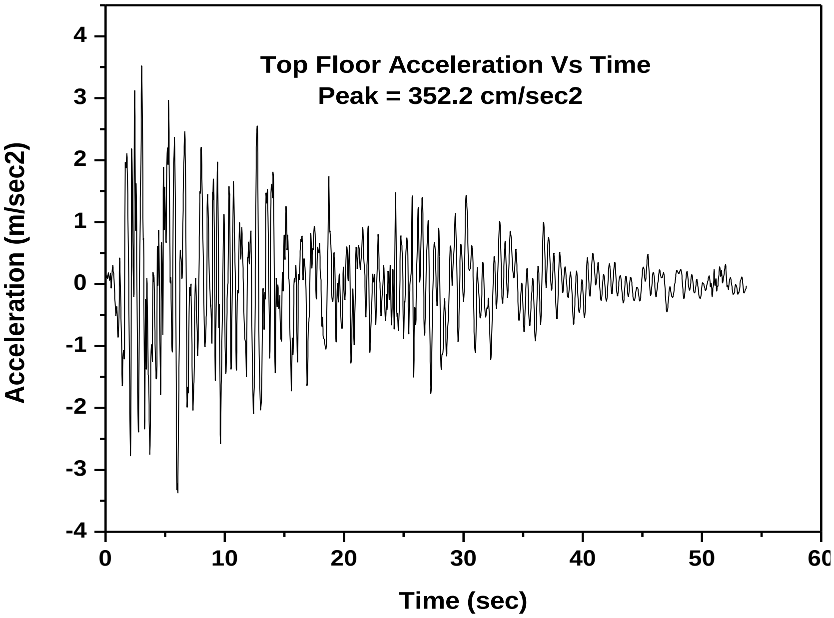

Figure 3.5 Top floor response of structure with 4 TMDs obtained using developed program

3.2.4 Problem Formulation for Optimization

In order to optimize the Tuned Mass Damper (TMD) parameters for achieving minimum response of an MDOF structural system, extensive evaluation of dynamic response is required which also have to satisfy the limit of variables and other constraints. For the present problem the variables used are of continuous type. This highly complex problem of dynamics with multiple local minima needs a global optimization tool for searching the global minimum. The current problem has been constructed to solve the optimization problem using EVOP. This global optimization tool has been assessed for optimization of numerous test problems and has succeeded in locating global minimum directly. It is capable of minimizing an objective function without asking information on gradient or sub-gradient. It is facilitated with automatic restarts to check whether the previously obtained minimum is the global minimum.

For the present case, the entire problem has been constructed by identifying the independent variables, setting objective function to be minimized along with selecting the explicit and implicit constraints to be satisfied. After simulating the related expressions for dynamic analysis of current structural system chosen for optimization, a feasible starting point and control parameters required for EVOP has been selected and then linked the formulated problem with EVOP algorithm to perform the ultimate optimization operation. The systematic flow of the formulation steps of selected optimization problem and linking it with EVOP is illustrated in Figure 3.6.

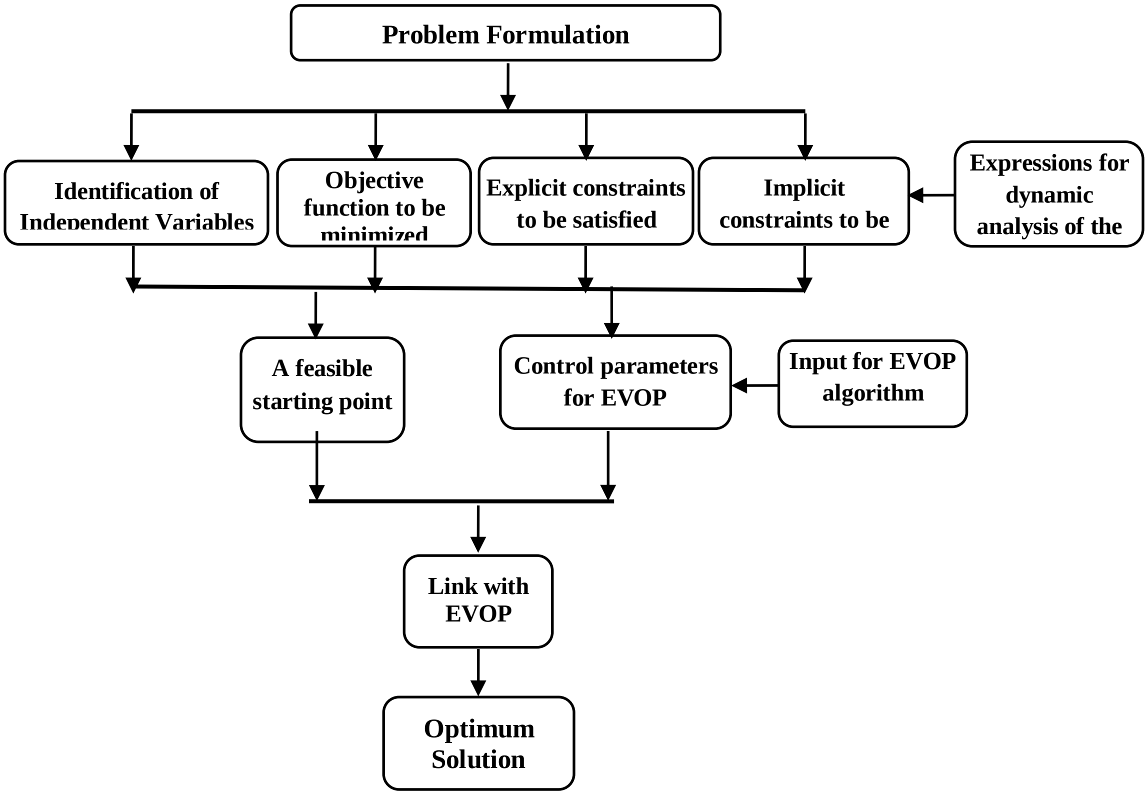

Figure 3.6 Problem formulation process

The entire optimization problem for structural response minimization using EVOP and to search for the optimum parameters of TMDs subjected to seismic excitation has been formulated by developing a program using C++ language.

3.2.4.1 Objective Function

To analyse the problem using EVOP the objective function is selected to minimize the response of the primary structure.

In this study, two separate optimization problem have been formulated. In case of first problem, the objective function is considered as the minimization of top deflection of the TMD-Structure systems.

$F_{obj} = \text{Min}\ (umax_{top})$

Where, F_{obj} = Objective function, $umax_{top}$ = Maximum top displacement

In case of second optimization problem formulation, the objective function is chosen as the minimization of maximum inter-story drift of the structural system.

$F_{obj} = \text{Min}\ (maxstdrift)$

Where, maxstdrift = Maximum inter-story drift

3.2.4.2 Independent Variables

For a specific Structure-MTMD system, optimum parameters of each Tuned Mass Damper (TMD) are required to control and minimize the vibration of the primary system. For the current study and optimization problem, independent variables identified are mass, stiffness and damping values of each TMD. The independent variables and variable type considered in the study are enlisted in Table 3.4.

Table 3.4 Design variables with variable type

Independent variables	**Variable type**
Mass of each TMD (m_j) (ton)	Continuous
Stiffness of each TMD ($k_{j)}$ (kN/m)	Continuous
Damping coefficient of each TMD (c_j) (kNs/m)	Continuous

N.B. j = 1,2,3……m

3.2.4.3 Explicit Constraint

Explicit constraints are specified limitation (upper or lower limit) on independent variables chosen for optimization problem. The constraint is defined as

$$X_L \leq X \leq X_U$$

Where, X = Design variable, X_L = Lower limit of the variable, X_U = Upper limit of the variable.

Limits of design variables are chosen from geometric requirements, minimum practical value, code restriction, feasibility and so on. For the present optimization problem, mass, stiffness and damping coefficient of each TMD are independent variables. Depending on the optimization problem upper limit of the mass of each tuned mass damper has been varied within the range of 3% to 5% of total mass of the primary structure. Upper limit of stiffness and damping coefficient of each TMD are set to a random feasible maximum value. Lower limit of the mass, stiffness and damping coefficient of each TMD is set as zero.

3.2.4.4 Implicit Constraint

Implicit constraints characterize the performance requirements or response of the structural system. Total four implicit constraints are considered for solving current optimization problem.

(a) In case of optimization problem with objective function set as top deflection, maximum inter-story drift is chosen as first implicit constraint. The upper limit and lower limit are set as 0.1 and 0.000001 respectively. The constraint can be defined as

$$0.000001 \leq \text{maximum inter-story drift} \leq 0.1$$

In case of optimization problem with objective function set as maximum inter-story drift, top deflection is chosen as implicit constraint. The upper limit and lower limit are set as 0.4 and 0.000001 respectively. The constraint can be defined as

$$0.000001 \leq \text{top deflection} \leq 0.4$$

(b) The next implicit constraint states that the summation of the masses of all TMD’s installed in the primary structure must not be greater than 3% to 5% of the mass of the primary structure depending on the optimization problem. The constraint can be defined as

$$0.000001 \le \sum_{j=1}^{m} m \le (3\% \text{ to } 5\%)\ (\sum_{i=1}^{n} M)$$

(c) The next implicit constraint ensures that the summations of stiffness of all TMD's in the primary structure should be within a feasible specified range.

(d) The next implicit constraint ensures that the summations of damping coefficient of all TMD's in the primary structure should be within a feasible specified range.

3.2.4.5 Linking Optimization Problem with EVOP and Solve

The non-convex optimization problem considered in this study has multiple local minima and requires an optimization method to derive the global optimum. As a result the global optimization algorithm named EVOP (Ghani 1989) is used.

The optimization algorithm EVOP requires three user written functions to link the problem formulation code with EVOP. These are objective function, explicit constraint function and implicit constraint function. Also some user input control parameters and a starting point inside the feasible space are required. The objective function calculates the functional value using the coordinates of a feasible point in an N-dimensional space. Explicit constraint function evaluates the upper and the lower limits of the explicit constraints. Implicit constraint function evaluates the implicit constraints values and their upper and lower limits. The input control parameters with their default values and ranges are shown is Table 3.5.

The other parameters relevant to the usage of the program EVOP are as follows.

IJK --- For first entry, this variable should always be set to 1. It will subsequently be changed by 'EVOP'.

K --- Number of 'complex' vertices. If 'n' is the dimension of the parameter space, for n <= 5, k = 2n; and for n > 5, k >= (n + 1).

KNT --- Number of consecutive times the objective function is called after which tests are conducted for convergence. Typically, the KNT is equal to 25.

LIMIT --- Maximum number of times the three functions: the objective function, the explicit constraint function and the implicit constraint function can be collectively called.

NRSTRT --- Number of automatic restart of EVOP to check that the previously obtained value is the global minimum. If NRSTRT = 5, the EVOP program will execute 5 times. For first time execution a starting point of the complex inside the feasible space has to be given. For further restart the complex is generated taking the coordinates of the previous minimum (values obtained from previous execution of EVOP) as the starting point of the complex.

IER --- Error flag.

> = 1 indicates user provided starting point is violating upper limit of an explicit constraint.
>
> = 2 indicates user provided starting point is violating lower limit of an explicit constraint.
>
> = 3 indicates user provided starting point is violating upper limit of an implicit constraint.
>
> = 4 indicates user provided starting point is violating the lower limit of an implicit constraint.
>
> = 5 indicates randomly generated (k – 1) tests points not obtainable in the ‘LIMIT’ to which the three functions can be collectively called.
>
> = 6 indicates minimum of the objective function not obtainable within the desired accuracy of convergence. The results are those obtained after exceeding ‘LIMIT’.
>
> = 7 indicates final ‘complex’ has not reduced its size to satisfy convergence test2. Results are those obtained after exceeding ‘LIMIT’.

= 8 indicates minimum of the objective function has been located to the desired degree of accuracy to satisfy both convergence tests.

XMAX(N) --- Array of dimension ‘N’ containing the upper limits of the explicit constraints. They are calculated and supplied by the explicit constraint function for a given trial point provided by ‘EVOP’.

XMIN(N) --- Array of dimension ‘N’ containing the lower limits of the explicit constraints. They are calculated and supplied by the explicit constraint function for a given trial point provided by ‘EVOP’.

XT(N) --- Array of dimension ‘N’ containing the coordinates of the trial point. On first entry ‘XT(N)’ contains the feasible trial point, and at the end of minimization it returns with the coordinates of the minimum located.

XX(NIC) --- Array of dimension ‘NIC’ containing the implicit constraint function values. They are calculated and supplied by the implicit constraint function, for a given trial point ‘XT(N)’ provided by ‘EVOP’.

XXMAX(NIC) --- Array of dimension ‘NIC’ containing the upper limit of the implicit constraints. They are calculated and supplied by the implicit constraint function, for a given trial point ‘XT(N)’ provided by ‘EVOP’.

XXMIN(NIC) --- Array of dimension ‘NIC’ containing the lower limit of the implicit constraints. They are calculated and supplied by the implicit constraint function, for a given trial point ‘XT(N)’ provided by ‘EVOP’.

A computer program coded in C++ (Appendix A) is developed to formulate the optimization problem and to link it with EVOP. Optimization problem is formulated in the developed code by providing input of EVOP control parameters, defining three functions: an objective function, explicit constraint function and implicit constraint function. First the values of the control parameters are assigned with their default values and other input parameters are set to specific numerical values. These other input parameters for the present optimization problem are: number of complex vertices, K;

maximum number of times the three functions can be collectively called, limit = 100000; dimension of the design variable space, N; number of implicit constraint, NIC and number of EVOP restart, NRSTRT = 10.

Table 3.5 EVOP control parameters and input parameters

EVOP Control Parameters	**Default values**	**Range**	**Input Parameters**
Reflection coefficient, α	1.2	1.0 to 2.0	Number of complex vertices, K
Contraction coefficient, β	0.5	0 to 1.0	Maximum number of times the three functions can be collectively called, LIMIT = 100000
Expansion coefficient, γ	2.0	>1.0	
Convergence parameter, Φ	10^{-13}	10^{-16} to 10^{-8}	Dimension of the design variable space, N
Φcpx	10^{-9}	10^{-16} to 10^{-8}	

At first the starting point is checked whether it satisfies all explicit constraints. If it passes then it is tested for all implicit constraints. If these constraints are also satisfied the function EVOP is called otherwise the process is repeated until a feasible starting point is found. Next suitable values of the control parameters are obtained by varying the parameters within the range sequentially. Then the program is rerun using optimum design variables obtained from previous run setting as starting point with same values of control parameters to check whether a better minimum is obtained.

3.3 METHODOLOGY WITH SOIL-STRUCTURE INTERACTION

Seismic behavior of a structure is influenced not only by the response of the superstructure, but also by the response of the foundation and the ground as well. Therefore it is necessary to evaluate the pile-soil-pile interaction and incorporate into the analysis. In this study an approach of controlling the vibration of a building structure using principle of MTMD incorporating soil-structure interaction effect has been developed.

Once structure-MTMD model has been developed using the methodology described in above section, soil-structure interaction effect has been included in the system. The structure-TMD-soil-pile model considered in this study is shown in Figure 3.7.

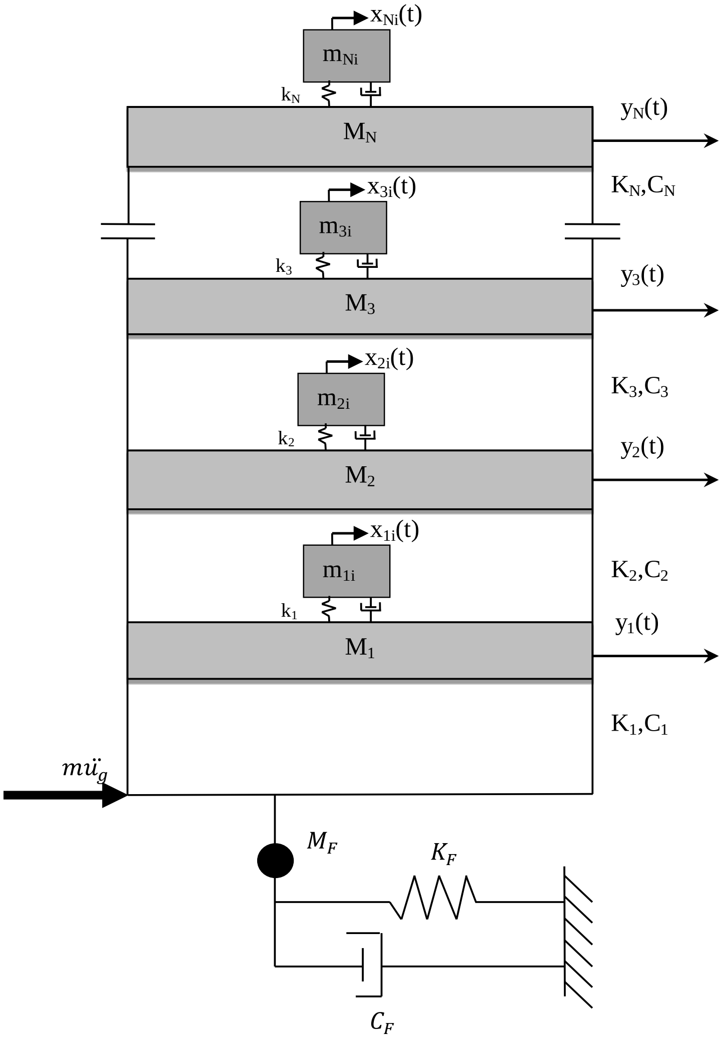

Figure 3.7 Building-MTMD system with Soil-Structure Interaction

The equation of motion of the system considering soil-structure interaction is given in the matrix form in equation 3.3.

$$\begin{bmatrix} M_S & M_{SF} \\ M_{SF}^T & M_F \end{bmatrix} \begin{Bmatrix} \ddot{X}_S \\ \ddot{X}_F \end{Bmatrix} + \begin{bmatrix} C_S & C_{SF} \\ C_{SF}^T & C_F \end{bmatrix} \begin{Bmatrix} \dot{X}_S \\ \dot{X}_F \end{Bmatrix} + \begin{bmatrix} K_S & K_{SF} \\ K_{SF}^T & K_F \end{bmatrix} \begin{Bmatrix} X_S \\ X_F \end{Bmatrix} = \begin{bmatrix} M_S \\ M_F \end{bmatrix} \{\ddot{u}_g\} \qquad (3.3)$$

Where,

M_S = Mass sub-matrix of super-structure with or without TMD

K_S = Stiffness Mass sub-matrix of super-structure with or without TMD

C_S = Damping coefficient sub-matrix of super-structure with or without TMD

M_F = Mass sub-matrix of foundation

K_F = Stiffness sub-matrix of foundation

C_F = Damping coefficient sub-matrix of foundation

M_{SF} = Mass interaction sub-matrix between super-structure and foundation

M_{FS}^T = Transpose of mass interaction sub-matrix between super-structure and foundation

K_{SF} = Stiffness interaction sub-matrix between super-structure and foundation

K_{FS}^T = Transpose of Stiffness interaction sub-matrix between super-structure and foundation

C_{SF} = Damping interaction sub-matrix between super-structure and foundation

C_{FS}^T = Transpose of damping interaction sub-matrix between super-structure and foundation

X_S = Displacement sub-vector of super-structure with respect to base

X_F = Displacement sub-vector of foundation

In this system only lateral component of soil-structure interaction effect is taken into consideration. Soil-structure interaction component is represented with inertia mass, stiffness and damping. Structural system is considered to be located in soft soil and flexible group pile foundation beneath it. Soil-pile interaction has been modeled and analyzed using a program TLEM which works based on Thin Layered Element Method (Tajimi and Shimomura, 1976). Here foundation is considered to be situated in a homogeneous layered semi-infinite soil medium. From the analysis of soil-pile interaction, lateral component of soil-structure interaction effect is taken corresponding to predominant earthquake frequency. Using the principle of sub-structure method this SSI component put as the support condition. Then the whole structural system considering SSI effect has been simulated based on the equation of motion developed. Dynamic analysis of the whole system is performed to find out the response and formulate the optimization problem incorporating SSI effect. The code developed for the problem formulation is then linked with EVOP to search for optimum TMD parameters and minimize the structural response. This methodology of solving the optimization problem is shown in Figure 3.8.

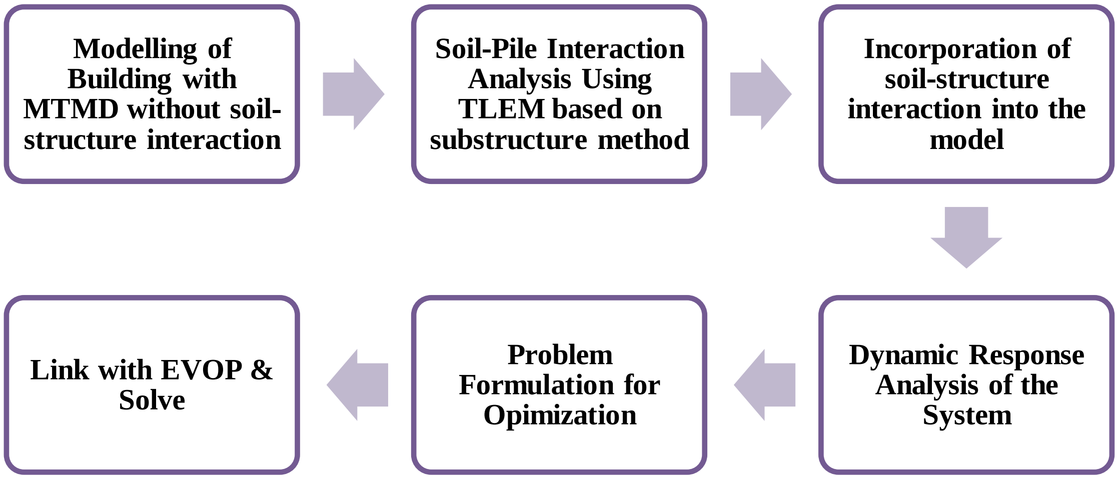

Figure 3.8 Methodology of TMD parameter optimization using EVOP incorporating soil-structure interaction effect

Chapter 4 ANALYSIS

4.1 GENERAL

The approach developed for optimization of Tuned Mass Damper parameters using EVOP has been applied for different building frame systems. The study has been explored for both regular and irregular building frames. The following subsections describe the case studies in details.

4.2 EARTHQUAKE RESPONSE

The structural response analysis for all the systems have been performed for El Centro (1940) NS earthquake excitation. The input motion was collected from http://www.vibrationdata.com/elcentro.htm. The earthquake record is shown in Figure 4.1. Fast Fourier Transform was performed over this acceleration time history record to obtain the predominant frequency of the excitation. The FFT of earthquake acceleration history is shown in Figure 4.2. From the analysis the predominant frequency of the earthquake is obtained as 1.46 Hz.

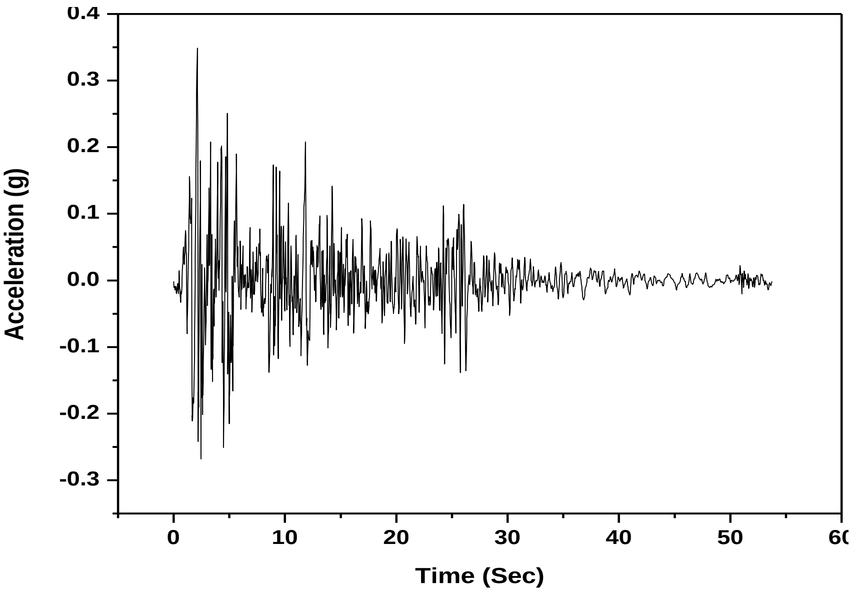

Figure 4.1 El Centro (1940) NS Acceleration Response

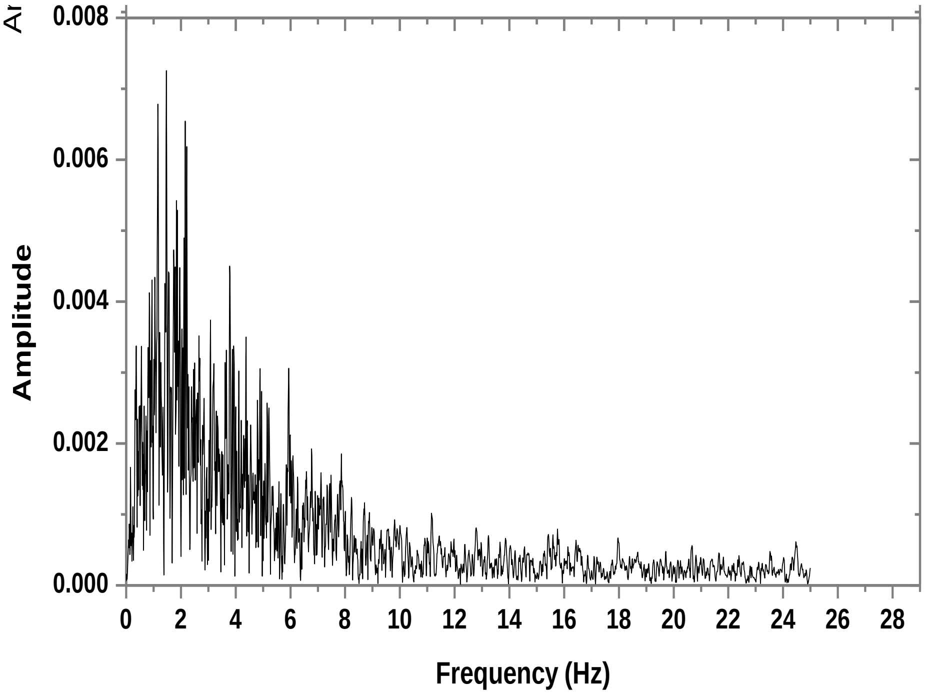

Figure 4.2 FFT of El Centro (1940) NS Earthquake Acceleration Response

4.3 EVOP IN TMD OPTIMIZATION

To explore EVOP for the optimization of TMD parameters, a ten story shear building was chosen from problems analyzed by Hadi and Arfiadi (1998). The building has uniform mass of 360 t, stiffness of 650 MN/m, and damping coefficient of 6.2 MNs/m at each story. For the purpose of calculating inter-story drift, height of each story was assumed as 3 m (10.0 ft). To analyze the problem using EVOP the objective function is selected as minimization of top deflection of the structure. The structural response has been simulated under lateral excitation and solved using central difference method. The independent variables identified are mass, stiffness and damping values of TMD. In the expressions written for constraints, the explicit constraints are defined as mass, stiffness and damping of TMD and implicit constraint is set to maximum inter-story drift. The selected values for initial feasible vertex and limit of constraints are presented in the following Table 4.1

Table 4.1 Initial feasible values of independent variable and limits of constraints

TMD	Initial feasible value	Upper limit	Lower limit
Mass (t) (Explicit Constraint)	105	108 (3% of total story mass of primary structure)	0
Stiffness (kN/m) (Explicit Constraint)	3750	5000	0
Damping (kNs/m) (Explicit Constraint)	151.5	200	0
Inter-sotry Drift (m) (Implicit Constraint)	-	0.1	0

After setting the initial values and constraint limits for the problem, the maximum story displacement with respect to ground were calculated by the developed program due to El Centro (1940) NS earthquake and the obtained maximum top displacement was defined as the objective function for minimization. Finally optimum TMD parameters were obtained for minimum top displacement applying the proposed methodology. Results of the analyses are discussed in the next chapter.

4.4 EVOP IN MTMD OPTIMIZATION

EVOP has been applied for the optimization of MTTD parameters. In this case a hypothetical tall building modeled as a shear building was selected for optimization from the work of Clark (1988). In that study a tall building was considered with 4 TMD located at 3rd, 5th, 6th and 8th story. The code developed for current study analyzed the eight story shear building with Multiple Tuned Mass Damper (MTMD) installed at specified locations. The building parameters at each story are presented in Table 4.2.

Table 4.2 Parameters at each story of the Primary Structure (Clark, 1988)

Parameters	Structure (each story)
Mass (t)	510
Stiffness (kN/m)	42400
Damping (kNs/m)	0

Height of each story was assumed as 3 m (10.0 ft) in order to calculate inter-story drift. To formulate the optimization problem using EVOP the objective function is selected as the minimization of top deflection of the structure. The structural response has been simulated under lateral excitation and solved using developed methodology. The independent variables identified are mass, stiffness and damping values of four TMDs. In the expressions written for constraints, the explicit constraints are defined as mass, stiffness and damping value of each TMD. The selected values for initial feasible vertex and limit of constraints are presented in Table 4.3.

Table 4.3 Initial feasible values of independent variable and limits of constraints

MTMD	Initial feasible value (All TMDs)	Upper limit (All TMDs)	Lower limit (All TMDs)
Mass (t) (Explicit Constraint)	3rd Story - 40	55	0
	5th Story – 40		
	6th Story – 40		
	8th Story - 40		
Stiffness (kN/m) (Explicit Constraint)	3rd Story - 1190	6000	0
	5th Story – 3150		
	6th Story – 5760		
	8th Story - 135		
Damping (kNs/m) (Explicit Constraint)	3rd Story - 67.1	150	0
	5th Story – 109		
	6th Story – 148		
	8th Story - 27.6		
Intersotry Drift (m) (Implicit Constraint)	-	0.1	0

After setting the initial values and constraint limits for the problem, the maximum story displacement with respect to ground were calculated by the developed program due to El

Centro (1940) NS earthquake. Finally optimum TMD parameters were obtained for minimum top displacement applying the proposed methodology.

4.5 EVOP IN TMD AND MTMD OPTIMIZATION – IRREGULAR FRAMES

The methodology developed for optimization of Tuned Mass Damper Parameters using EVOP has been applied for irregular frames. Frame with soft-story at ground floor is vulnerable to earthquake action. The vibration of such primary structure can be minimized and performance can be improved by applying vibration control techniques. In this study the developed methodology of controlling vibration applying Tuned Mass Damper in an optimal way using EVOP is explored for such soft-story frames.

For the case study one regular and two irregular 8 story structural frames have been chosen. The optimization is performed for regular and soft-story frames. All frames are considered as undamped. All of them have uniform mass of 510 ton at each story and stiffness 42400 kN/m at upper stories. Bottom story stiffness of the 8 story frame is reduced in different ranges with respect to the regular frame for this part to explore EVOP in MTMD optimization. Bottom story stiffness of the frames chosen to explore soft-story case using EVOP for TMD optimization is mentioned in Table 4.4.

Table 4.4 Stiffness of irregular soft-story frames

Frame	Type	Bottom Story Stiffness (kN/m)
Frame 1	Regular frame	42400
Frame 2	70% Stiffness of Upper Story at bottom story	29680
Frame 3	50% Stiffness of Upper Story at bottom story	21200

All three frames have been studied considering three cases. In the first case, one Tuned Mass Damper was placed on the roof of the frame. In the second case, four Tuned Mass Dampers were placed 3rd, 5th, 6th and 8th story of the frame. Last case considers tuned mass dampers are installed in each story. In every case El Centro 1940 NS seismic motion was given as input excitation. Each Tuned Mass Damper parameter has been optimized for two optimization problems. One is to minimize the top displacement and another is to minimize maximum inter-story drift. Height of each story was assumed as 3 m (10.0 ft) in order to calculate inter-story drift TMD parameter of Frame 1 which is a regular frame has been optimized for top displacement minimization in the previous section. The selected values for initial feasible vertex and limit of constraints are presented in Table 4.5.

Table 4.5 Initial feasible values of independent variable and limits of constraints

MTMD	**Initial feasible value (All TMDs)**	**Upper limit (All TMDs)**	**Lower limit (All TMDs)**
Mass (t) (Explicit Constraint)	3rd Story - 40	220	0
	5th Story – 40		
	6th Story – 40		
	8th Story - 40		
Stiffness (kN/m) (Explicit Constraint)	3rd Story - 1190	24000	0
	5th Story – 3150		
	6th Story – 5760		
	8th Story - 135		
Damping (kNs/m) (Explicit Constraint)	3rd Story - 67.1	600	0
	5th Story – 109		
	6th Story – 148		
	8th Story - 27.6		
Inter-story Drift (Implicit Constraint) (Top displacement - Objective function)	-	0.1	0
Top displacement (Implicit Constraint) (Inter-Story Drift - Objective function)		0.4	0
Sum of all TMD mass (Implicit Constraint)	-	220	0
Sum of all TMD stiffness (Implicit Constraint)	-	24000	0
Sum of all TMD damping (Implicit Constraint)	-	600	0

After the initial values and constraint limits are set in the optimization problem, the maximum story displacement with respect to ground and maximum inter-story drift were calculated by the developed program due to El Centro (1940) NS earthquake. Finally optimum TMD parameters were obtained for minimum structural response applying the proposed methodology.

4.6 EVOP IN TMD AND MTMD OPTIMIZATION CONSIDERING SOIL-STRUCTURE INTERACTION EFFECT

Seismic excitation causes piles underneath the soil to sway resulting in soil-structure interaction effects. Soil-structure interaction is an important phenomenon in dynamic analysis of structural system. Dynamic behavior of a structure is controlled by the response of the superstructure and response of the foundation and the ground as well. Conventional practice of ignoring the dynamic pile-soil-pile interaction effects in design procedure may lead to inaccurate response analysis of the structure.

Dynamic pile-soil-pile interaction often affects the motion of the superstructure to a considerable extent. Therefore it is necessary to evaluate the pile-soil-pile interaction and incorporate into the analysis. Hence a simplified approach for the evaluation of such dynamic pile-soil-pile interaction can be helpful in considering the dynamic behavior of an entire soil-foundation-structure system.

In this study the soil-structure interaction analysis has been performed using substructure method. This method allows the complicated soil-structure system to be analyzed by breaking down into manageable parts. The force-displacement relationship of the degrees of freedom of the contact nodes with the structure is determined. The dynamic stiffness coefficients can physically be expressed as a generalized spring, a spring-dashpot system. After determining the dynamics stiffness coefficients, the structure supported on this spring-dashpot system is analyzed for earthquake excitation.

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4.6.1 Soil-Structure Interaction Analysis using TLEM

In this study the soil-pile interaction is analyzed using a computer program based on TLEM method. The numerical scheme presented by Tajimi and Shimomura (1976) allows soil-embedded foundation interaction effects to be rigorously evaluated. In Thin-

Layered Element Method, a soil deposit is treated as an infinite stratified medium with the inclusion of a cylindrical hollow in which the foundation is fitted. The piles are assumed to be upright Timoshenko beam. The evaluation of pile-soil-pile interaction effects in this program is based on the superposition method that was originally proposed by Poulos (1968, 1971). Kanya and Kausel (1982) have shown that reasonable results for both static loads and dynamic loads can be obtained from superposition schemes.

The simplified expression produced by Konagai et al. (2000) is used here for a linear analysis of the interaction between soil and pile foundation. In the simplified expression the mass, damping and stiffness parameters are frequency invariant. The overall dynamic stiffness k_{XX} of the pile cap for sway motion can be expressed as the following simple form with frequency-independent stiffness k_o and damping and mass parameters c_o and m_o respectively:

$$k_{xx} = k_o + ic_o\omega - m_o\omega^2 \tag{4.1}$$

Where,

k_{xx} = dynamic stiffness;

k_o = static stiffness of equivalent soil-pile system;

c_o = damping coefficient of equivalent soil-pile system;

m_o = mass of equivalent soil-pile system; and

ω = circular frequency.

To determine the value of dynamic stiffness parameters, pile-soil interaction effects are analyzed using the computer program TLEM. Group pile is designed for chosen structural system considering different homogeneous soil profile. For any soil-pile system with specific pile dimensions and shear wave velocity, the properties are considered to be homogeneous through all horizontal slices. The parameters that describe mechanical features of soil slices and representative of pile properties are provided as inputs for sliced elements.

4.6.2 Parameters of Frame, Pile Foundation and Soil Profile

To formulate optimization problem for a building frame associated with TMD considering soil-structure interaction, an 8 story RC frame has been modeled in ETABS. 3D view of the model and 2D view of an interior frame are shown in Figure 4.3.

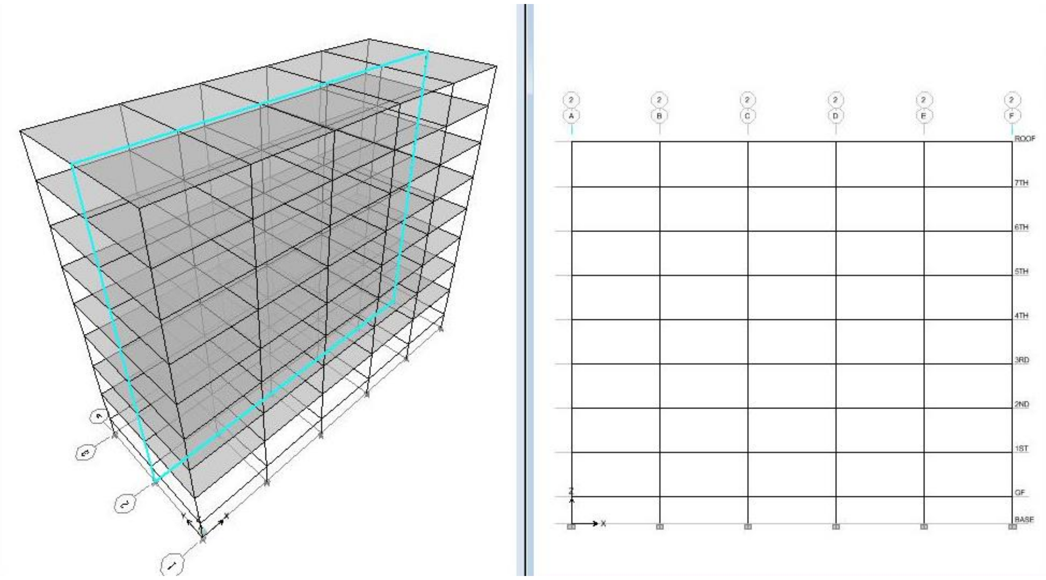


Figure 4.3 3D view and 2D view of the model in ETABS

The frame has been idealized as an MDOF system. Shear model of the structure has been presented by spring-dashpot and lumped mass at each story. 5% inherent damping of the structure is assumed. Height of each story is 3 m (10.0 ft). The building parameters are presented in Table 4.6.

For the structural system, circular reinforced concrete group pile is designed to support the load of the system and transfer it to the ground. Pile foundation is designed considering the possible structure location in four different types of soil condition. Soil profile considered and corresponding group pile information are presented in Table 4.7. Each pile length is taken as 12 m (40 ft).

Table 4.6 Parameters of primary structure

Parameter	Value at each story
Mass (t)	318.403
Stiffness (kN/m)	694824.623
Damping (kNs/m)	134.575

Table 4.7 Soil and Pile parameters

SPT Value of Soil	Total Number of Pile	Pile Arrangement (X-Y direction)	Each Pile diameter (m)
2	16	4x4	0.6096
6	9	3x3	0.6096
10	9	3x3	0.6096
14	6	2x3	0.6096

4.6.3 Determination of Dynamic Stiffness Parameters

From the obtained outputs of analysis using TLEM, dynamic stiffness versus circular frequency curves are developed for each soil-pile systems. Plots for all soil-pile systems mentioned in Table 4.7 are shown in Figure 4.4 and Figure 4.5.

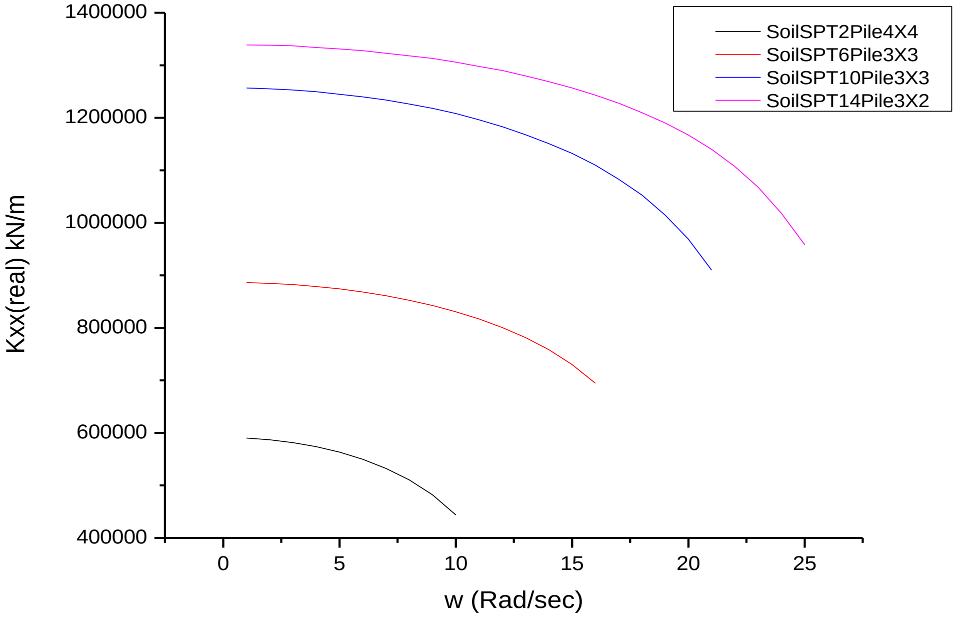


Figure 4.4 Real part of dynamic stiffness Vs circular frequency curves

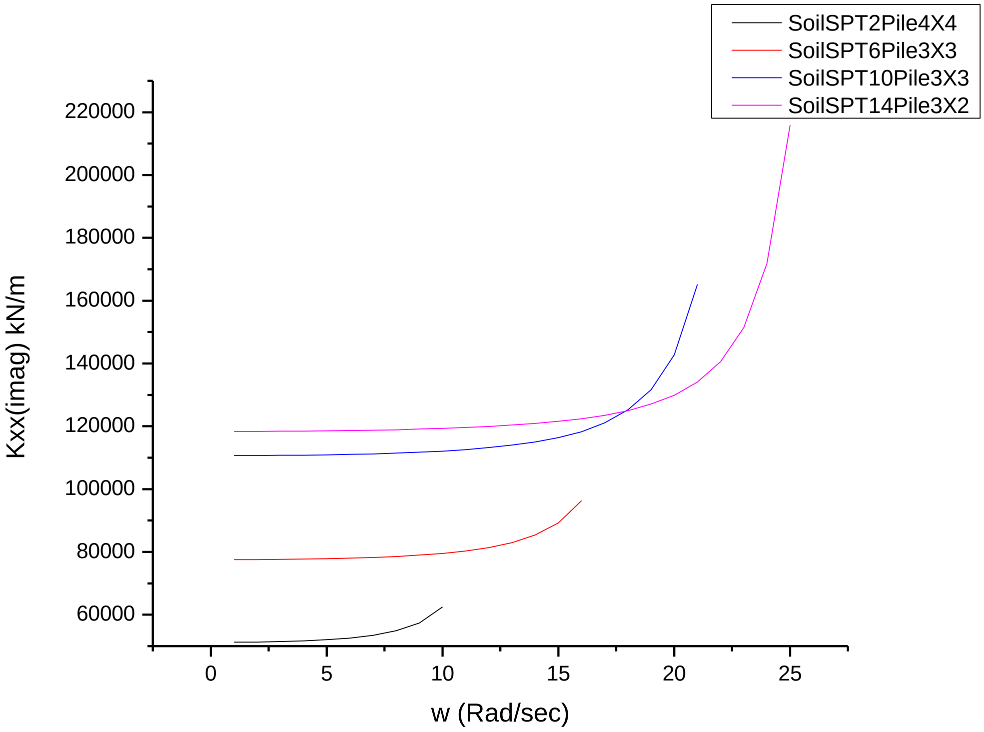


Figure 4.5 Imaginary part of dynamic stiffness Vs circular frequency curves

The real part of dynamic stiffness represents the stiffness of the pile can be written from Eqn. 4.1 is shown below in Eqn. 4.2.

$$((\mathrm{k}_{\mathrm{xx}})_{\mathrm{real}} = \mathrm{k}_{\mathrm{o}} - \mathrm{m}_{\mathrm{o}}\omega^2 \qquad (4.2)$$

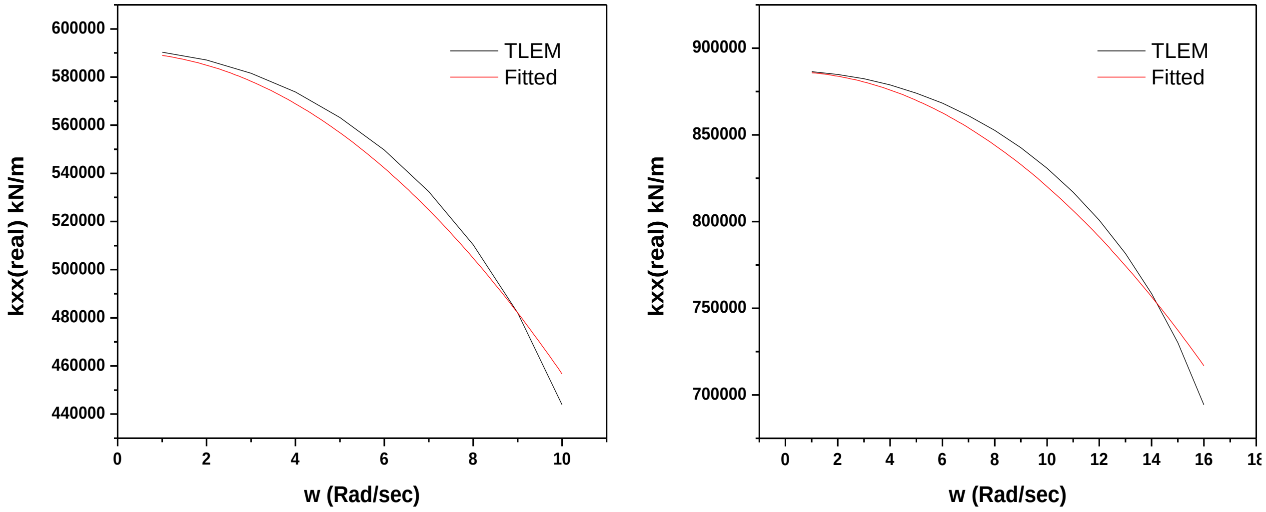
The real part of the stiffness versus circular frequency curve is fitted to a parabola of the form expressed in Eqn. 4.3,

$$y = b - kx^2 \qquad (4.3)$$

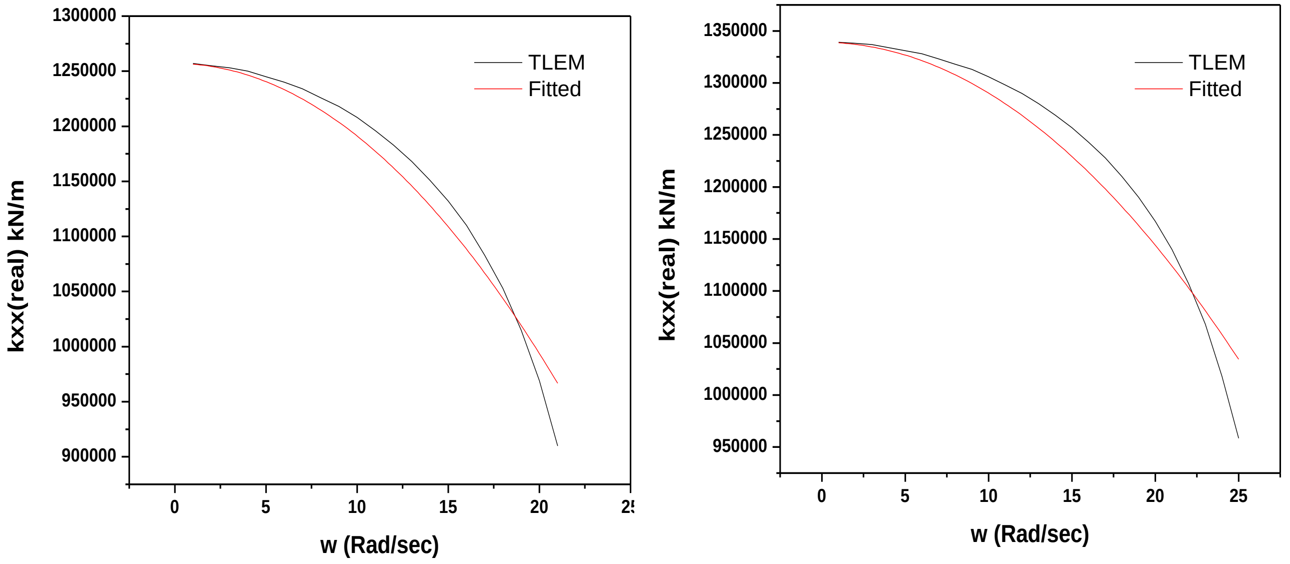
Where,

$b = \mathrm{k}_{\mathrm{o}}, k = \mathrm{m}_{\mathrm{o}}$

Figure 4.6 includes parabolic fitted curves for each soil-pile system mentioned in Table 4.7.



(a) SPT=2,Pile 4X4 (b) SPT=6, Pile 3X3



(c) SPT=10,Pile 3X3 (d) SPT=14, Pile 3X2

Figure 4.6 Non-linear curve fit of real part for different SPT and pile configurations

The parameter stiffness of the spring-dashpot system representing Soil-Structure Interaction is the value obtained corresponding to the predominant frequency of applied earthquake excitation. In the present study El Centro 1940 NS earthquake is chosen as input excitation. The predominant frequency of this earthquake motion is 1.46 Hz ais obtained by performing FFT shown in Figure 4.2. The dynamic stiffness parameter 'm' is obtained from the value 'k' of Eqn. 4.3.

The imaginary part of dynamic stiffness represents the radiation damping. From Eqn. 4.1 it can be written as in Eqn. 4.4,

$$((\mathrm{k_{xx}})_{\mathrm{imag}} = \mathrm{c_o}\omega \qquad (4.4)$$

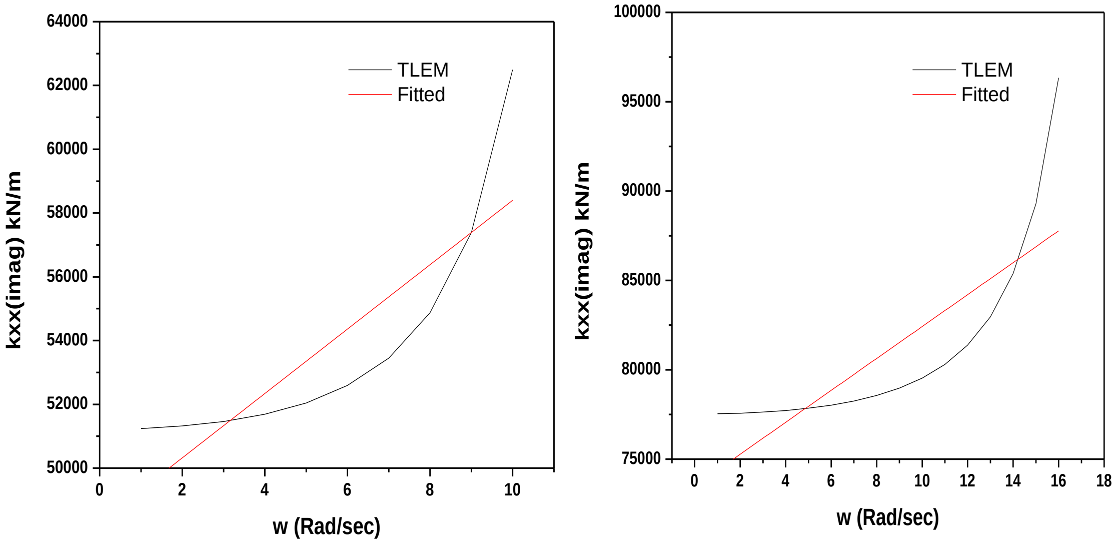
The imaginary part of the dynamic stiffness versus circular frequency curve is fitted to a straight line. Figure 4.7 includes linearly fitted curves for each soil-pile system mentioned in Table 4.7. The slope of this line gives the value of c_o.

The values of dynamic stiffness parameters obtained from the curves fitted according to Eqn. 4.3 and Eqn. 4.4, for each soil-pile system analyzed are given in Table 4.8.

All four soil-structure systems have been studied for three cases. In the first case, one Tuned Mass Damper was placed on the roof of the frame. In the second case, four Tuned Mass Dampers were placed 3rd, 5th, 6th and 8th story of the frame. And finally it has been considered that TMD is installed at each floor of the frame. In every case El Centro 1940 NS seismic motion was put as input excitation.

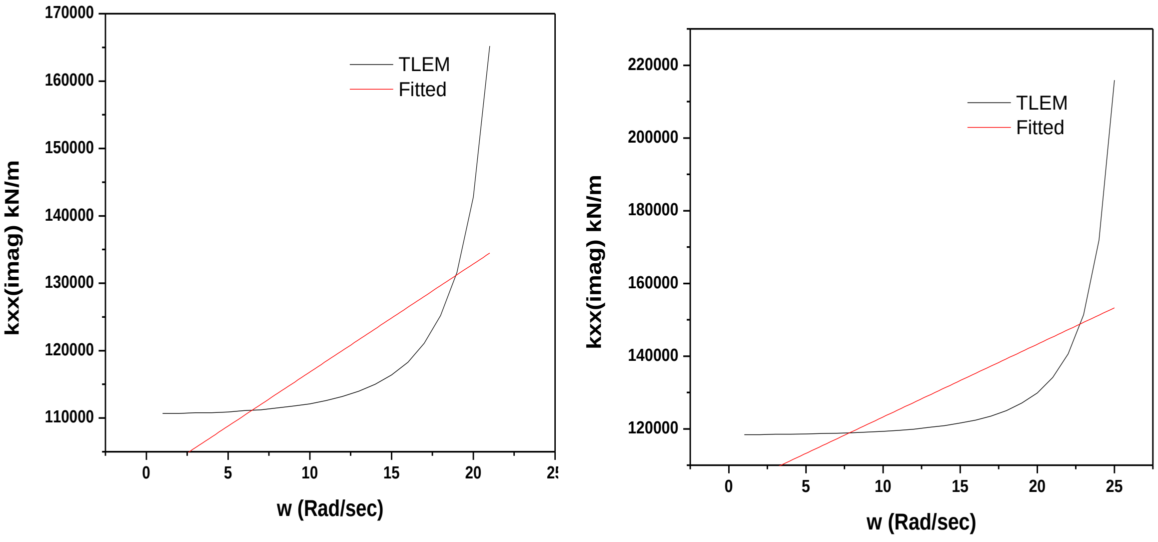
In the formulation of the optimization problem using EVOP, the objective function is selected as the minimization of top deflection of structure. The structural response has been simulated under lateral excitation and solved using the methodology developed in the present study as explained in Chapter 3. Mass, stiffness and damping values of each TMD are selected as the independent variables for optimization problem. In the expressions written for constraints, the explicit constraints are defined as mass, stiffness and damping value of all TMDs. The selected values for initial feasible vertex and limit of constraints are presented in the following Table 4.9.

After setting the initial values and constraint limits for the problem, the maximum story displacement with respect to ground were calculated by the developed program due to El Centro (1940) NS earthquake. Finally optimal TMD parameters were obtained for minimum top displacement applying the proposed methodology.



(a) SPT=2,Pile 4X4

(b) SPT=6,Pile 3X3



(c) SPT=10,Pile 3X3

(d) SPT=14,Pile 3X2

Figure 4.7 Linear fit of imaginary part for different SPT and pile configurations

Table 4.8 Dynamic stiffness parameters

Soil profile	Pile	Mass (t)	Stiffness (kN/m)	Damping (kNs/m)
SPT 2	4x4	1336.486	482000	1009.818
SPT 6	3x3	662.7444	842600	892.9706
SPT 10	3x3	658.4203	1.22E+06	1604.026
SPT 14	3x2	487.3631	1.31E+06	2000.769

Table 4.9 Initial feasible values of independent variable and limits of constraints for optimization problem considering soil-structure interaction

MTMD	Initial feasible value (All TMDs)	Upper limit (All TMDs)	Lower limit (All TMDs)
Mass (t) (Explicit Constraint)	50 – 1 TMD case 25 – 4 MTMD case 15 – 8 MTMD case	127	0
Stiffness (kN/m) (Explicit Constraint)	1000 – All cases	24000	0
Damping (kNs/m) (Explicit Constraint)	30 – All cases	600	0
Inter-story Drift (Implicit Constraint) (Top displacement - Objective function)	-	0.1	0
Top displacement (Implicit Constraint) (Inter-Story Drift - Objective function)		0.4	0
Sum of all TMD mass (Implicit Constraint)	-	127	0
Sum of all TMD stiffness (Implicit Constraint)	-	24000	0
Sum of all TMD damping (Implicit Constraint)	-	600	0

Chapter 5 RESULTS AND DISCUSSIONS

5.1 OPTIMIZATION OF SINGLE TUNED MASS DAMPER (TMD) PARAMETERS

The structural system associated with one Tuned Mass Damper (TMD) installed on top of the building described in section 4.2 is solved by following the developed methodology as explained in Chapters 3 and 4. After simulating the related expressions for dynamic analysis of current structural system chosen for optimization, a feasible starting point and control parameters required for EVOP has been selected and then linked the formulated problem with EVOP algorithm to perform the ultimate optimization operation. EVOP control parameters and input parameters used for the present case study are shown in Table 5.1.

Table 5.1 EVOP control parameters and input parameters

EVOP Control Parameters	**Values**	**Range**	**Input Parameters with values**
Reflection coefficient, α	1.6	1.0 to 2.0	Number of complex vertices, K = 6
Contraction coefficient, β	0.5	0 to 1.0	Maximum number of times the three functions can be collectively called, LIMIT = 100000
Expansion coefficient, γ	2.0	>1.0	
Convergence parameter, Φ	10^{-13}	10^{-16} to 10^{-8}	Dimension of the design variable space, N = 3
Parameter for determining collapse of a complex Φ_{cpx}	10^{-16}		

Optimum TMD parameters are obtained after formulating the optimization problem and solving it using EVOP. To evaluate the effectiveness of present approach of optimization minimized structural response and optimum TMD parameters which are TMD mass, stiffness and damping obtained using EVOP were compared to those obtained using two different approaches - genetic algorithm (GA) (Hadi and Arfiadi, 1998) and numerical alogorithm proposed by Lee et al. (2006). In case of optimizing dynamic parameters of TMD, Hadi and Arfiadi (1998) and Lee et al. (2006) only considered stiffness and damping of TMD. But in current methodology optimum value of TMD mass has also been searched along with stiffness and damping while performing the optimization process.

The comparison among optimum TMD parameters and maximum story displacements with respect to ground obtained using three optimization approaches are enlisted in Table 5.2 and Table 5.3 respectively.

From the above comparison it can be observed that, using EVOP the structural response which is taken as story displacement has been minimized more efficiently with the accomplishment of better and more economic choice of selected TMD parameters. Optimum parameters of TMD obtained using EVOP are found to be smaller than those obtained by Hadi & Arfiadi (1998) using GA and Lee et al. (2006). The percentage of reduction of displacement is also higher compared to other two approaches selected for comparison. Maximum inter-story drift at the point of optimum value is found to be 1 in 167. However allowable limit of inter-story drift can be set depending on the design consideration of structural system.

Table 5.2 Comparison among TMD parameters for different optimization approaches

Optimum Parameters	**Without TMD**	**With TMD (GA)**	**With TMD (Lee et al.)**	**With TMD (EVOP)**
Mass (t)	-	108	108	107.995
Stiffness (kN/m)	-	3750	4126.93	3346.406
Damping (kNs/m)	-	151.5	271.79	66.024

Table 5.3 Comparison among story displacement in meter with respect to ground for different optimization approaches

Story	No TMD	TMD (GA)	TMD (Lee et al.)	TMD (EVOP)	%Reduction (GA)	%Reduction (Lee et al.)	%Reduction (EVOP)
Story 1	0.031	0.019	0.02	0.0187	38.71	35.48	39.58
Story 2	0.06	0.037	0.039	0.0365	38.33	35.00	39.07
Story 3	0.087	0.058	0.057	0.0530	33.33	34.48	39.11
Story 4	0.112	0.068	0.073	0.0677	39.29	34.82	39.54
Story 5	0.133	0.082	0.087	0.0816	38.35	34.59	38.62
Story 6	0.151	0.094	0.099	0.0937	37.75	34.44	37.92
Story 7	0.166	0.104	0.108	0.1038	37.35	34.94	37.49
Story 8	0.177	0.113	0.117	0.1115	36.16	33.90	37.00
Story 9	0.184	0.119	0.123	0.1170	35.33	33.15	36.41
Story 10	0.188	0.122	0.126	0.1197	35.11	32.98	36.34
TMD	-	0.358	0.282	0.4140	-	-	-

5.2 OPTIMIZATION OF MULTIPLE TUNED MASS DAMPER (MTMD) PARAMETERS

Optimization of Multiple Tuned Mass Damper (MTMD) parameters was performed for the structural system described in section 4.3. A feasible starting point and control parameters required for EVOP has been chosen to link the formulated problem with EVOP algorithm. Control parameters of EVOP used for the present case are given in the Table 5.4.

Optimum parameters of each Tuned Mass Dampers are solved by EVOP and given as solution. Optimum MTMD parameters found from the solution for the minimum structural response are compared to those obtained from the study of Clark (1988). The study of Clark is an extension of classic work of Den Hartog (1947). The comparison among optimum MTMD parameters is presented in Table 5.5.

Minimized displacement responses of the top story under El Centro (NS) excitation obtained using methodology of Clark and present approach with EVOP are shown in Figure 5.1 and Figure 5.2. The peak displacement of top story obtained from the study of Clark and present study are 0.27762 m and 0.25357 m respectively. It can be observed that reduced peak response has been achieved by applying Evolutionary Operation Algorithm (EVOP). Maximum inter-story drift at the point of optimum value is found as 0.028.

Table 5.4 EVOP control parameters and input parameters

EVOP Control Parameters	**Values**	**Range**	**Input Parameters with values**
Reflection coefficient, α	1.6	1.0 to 2.0	Number of complex vertices, K = 13
Contraction coefficient, β	0.5	0 to 1.0	Maximum number of times the three functions can be collectively called, LIMIT = 100000
Expansion coefficient, γ	2.0	>1.0	--
Convergence parameter, Φ	10^{-13}	10^{-16} to 10^{-8}	Dimension of the design variable space, N = 12
Φ_{cpx}	10^{-17}		

Table 5.5 Comparison among MTMD parameters

TMD Location	Optimum MTMD Parameters	Clark (1988)	EVOP
3rd Story	Mass (t)	53	54.99
	Stiffness (kN/m)	135	1738.51
	Damping (kNs/m)	27.6	0.004
5th Story	Mass (t)	53	0.04
	Stiffness (kN/m)	5760	1.09
	Damping (kNs/m)	148	150.00
6th Story	Mass (t)	53	40.57
	Stiffness (kN/m)	3150	6000.00
	Damping (kNs/m)	109	0.008
8th Story	Mass (t)	53	54.99
	Stiffness (kN/m)	1190	1752.49
	Damping (kNs/m)	67.1	0.01

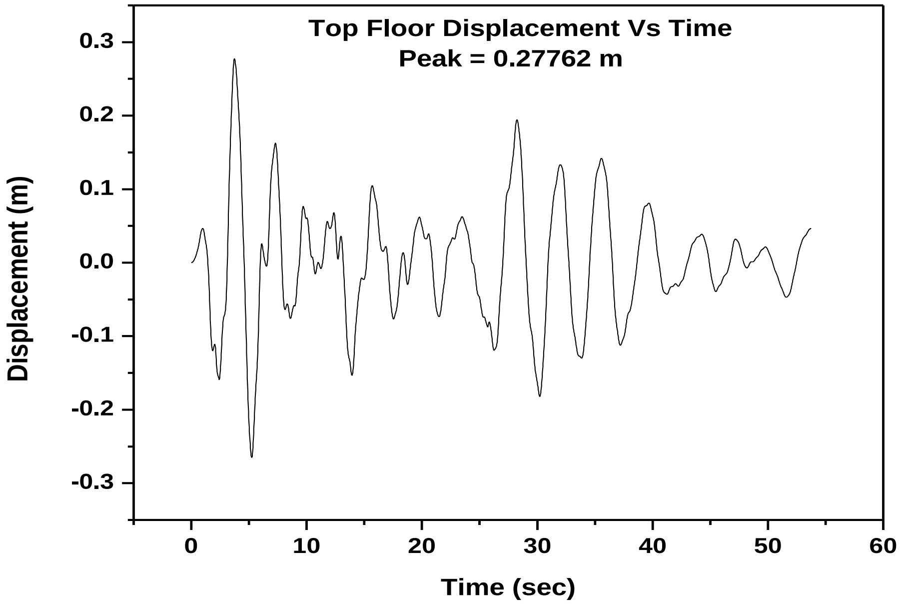


Figure 5.1 Displacement response history of top floor using approach of Clark (1988)

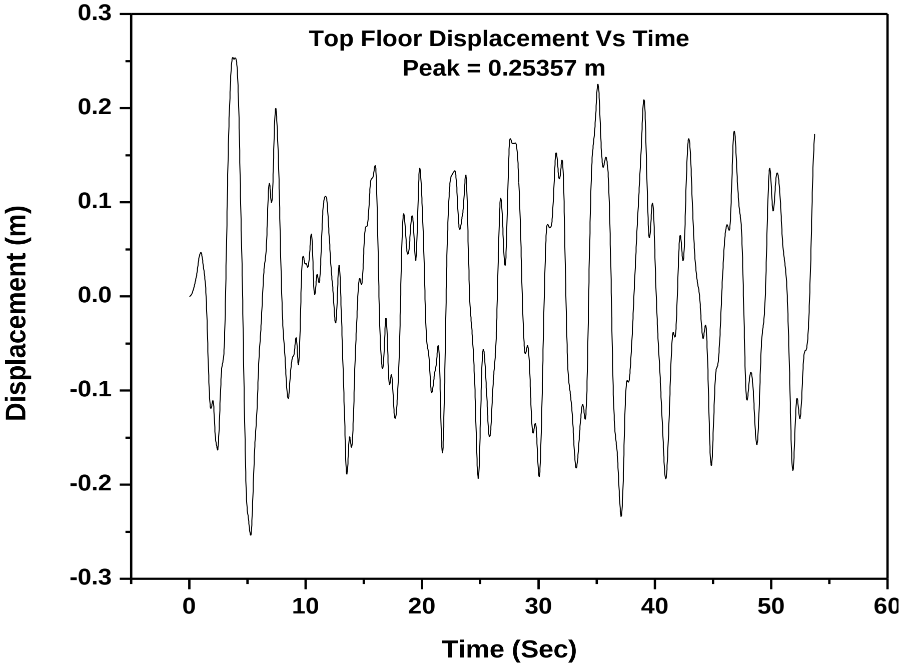


Figure 5.2 Displacement response history of top floor using EVOP

EVOP control parameters for optimization of the Multiple Tuned Mass Damper parameter system for the case described in this section and the output summary of final complex generated by EVOP program are demonstrated briefly in Appendix B.

5.3 OPTIMIZATION OF TUNED MASS DAMPER (TMD) PARAMETERS - IRREGULAR FRAME

Optimization was performed for irregular structural systems associated with one or multiple tuned mass dampers. The structural systems chosen for this study are described in section 4.4. Feasible starting point and control parameters of EVOP used for the present case are given in the Table 5.6.

Table 5.6 EVOP control parameters and input parameters

EVOP Control Parameters	Values	Range	Input Parameters with values
Reflection coefficient, α	1.6	1.0 to 2.0	Number of complex vertices, K = 6 (TMD case), K = 13 (4 TMD case), K = 25 (8 TMD case)
Contraction coefficient, β	0.5	0 to 1.0	Maximum number of times the three functions can be collectively called, LIMIT = 100000
Expansion coefficient, γ	2.0	>1.0	
Convergence parameter, Φ	10^{-13}	10^{-16} to 10^{-8}	Dimension of the design variable space, N= 3 (TMD case), N = 12 (4 TMD case), N = 24 (8 TMD case)
Φ_{cpx}	10^{-17}		

5.3.1 Minimization of Top Displacement

First optimization problem was constructed where the objective function was set as the minimization of top displacement of the structural system under selected earthquake excitation. In this optimization problem three cases were considered. In the first case one Tuned Mass Damper was considered to be installed on the top of story. Optimum parameters of TMD were obtained from the solution provided by EVOP. The optimum parameters for all the frames are enlisted in Table 5.7. Frames are classified according to Table 4.4.

Table 5.7 Optimum TMD Parameters for top displacement minimization using single TMD

Optimum TMD Parameters	Frame 1	Frame 2	Frame 3
Mass (t)	220.00	220.00	220.00
Stiffness (kN/m)	687.7574	1056.00	5393.9972
Damping (kNs/m)	147.0006	30.00	0.00

In the second case four TMDs have been considered to be installed in the structural system. Graphical representations of the optimum MTMD parameters for different frames are shown in Figure 5.3 - Figure 5.5.

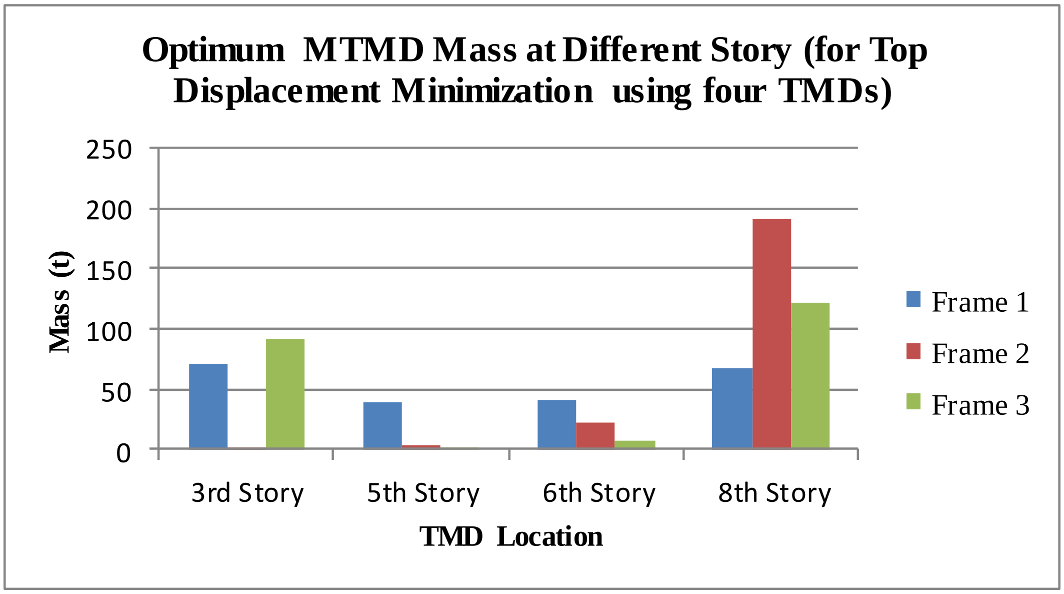


Figure 5.3 Optimum TMD mass at different story for minimization of Top displacement using four TMDs

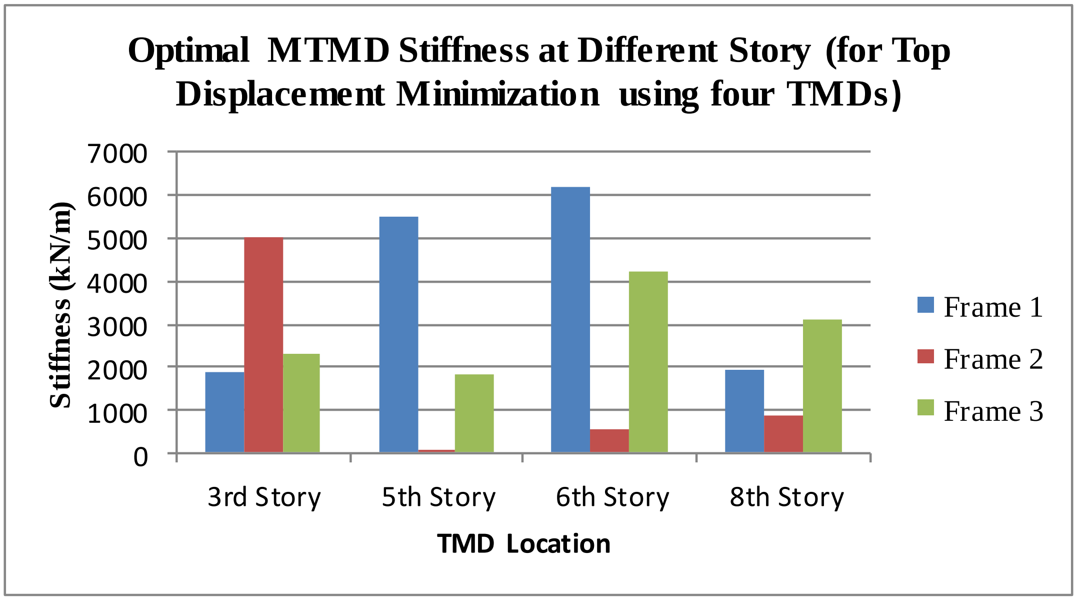


Figure 5.4 Optimum TMD Stiffness at different story for minimization of Top displacement using four TMDs

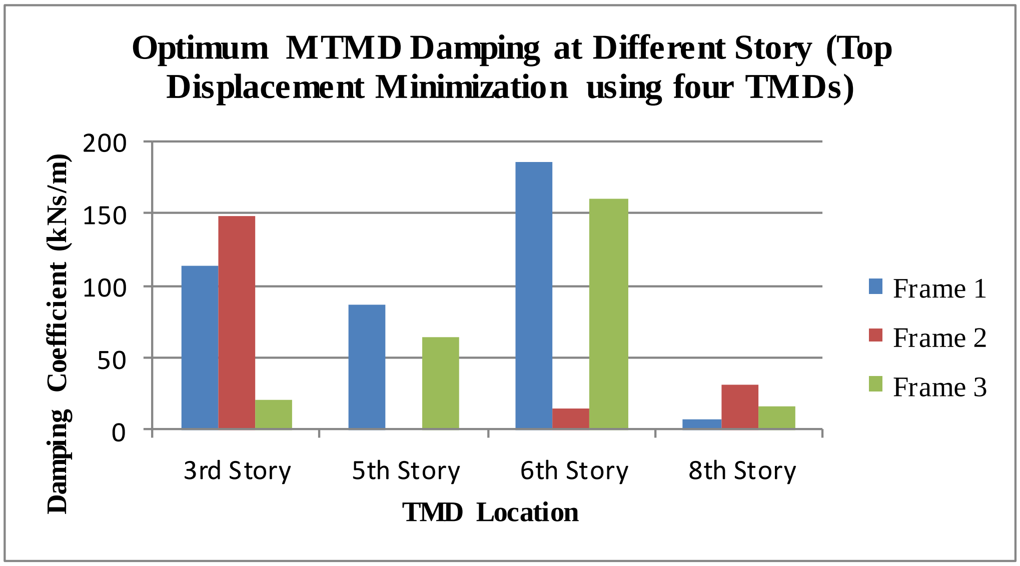


Figure 5.5 Optimum TMD Damping at different story for minimization of Top displacement using four TMDs

Finally the structural systems were modeled with TMD at each floor. Optimum mass, stiffness and damping values of TMDs for three chosen frames are presented in Figure 5.6 – Figure 5.8.

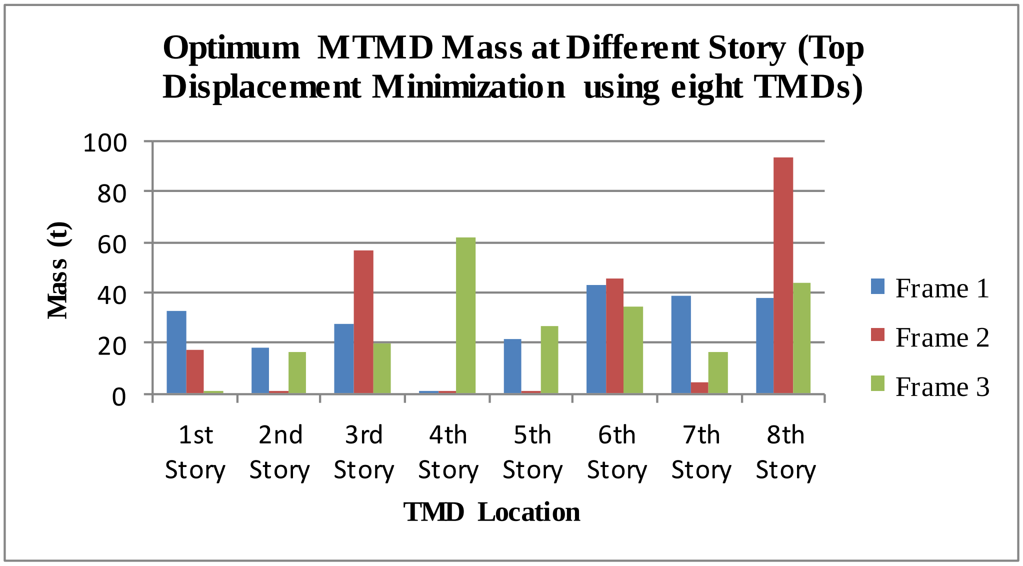


Figure 5.6 Optimum TMD mass at different story for minimization of Top displacement using eight TMDs

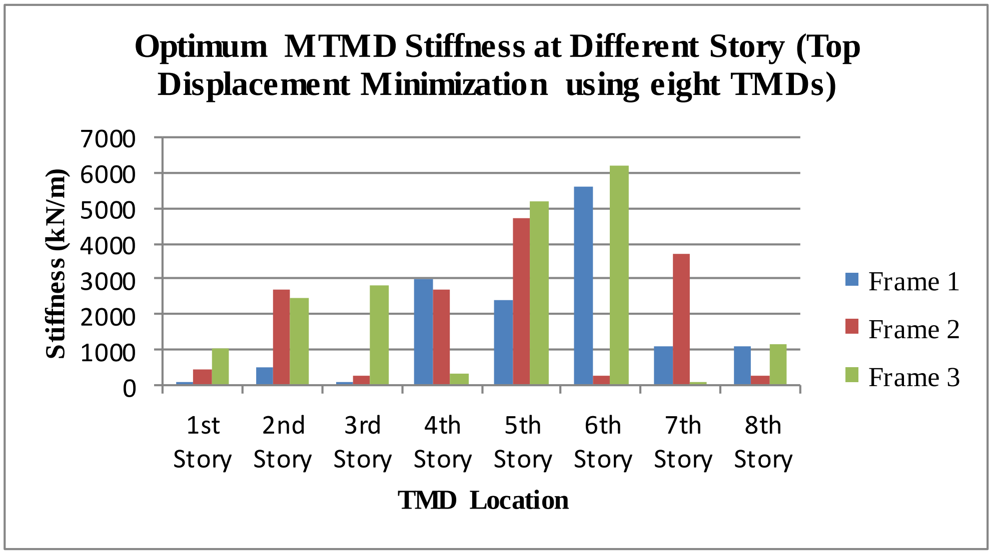


Figure 5.7 Optimum TMD stiffness at different story for minimization of Top displacement using eight TMDs

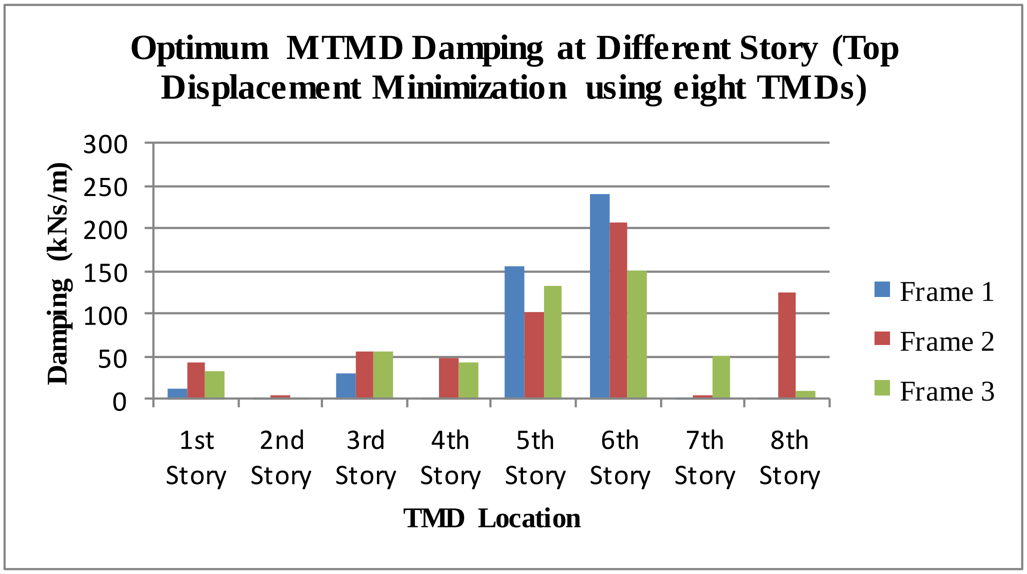


Figure 5.8 Optimum TMD damping at different Story for minimization of Top displacement using eight TMDs

Minimum structural responses obtained at optimum solution for structural frames with considered combination of TMD are shown in Table 5.8. A graphical representation of minimized top displacement of structures (Δ) with respect to top displacement of regular frame without TMD (Δ_o) for each frame is shown in Figure 5.9.

Table 5.8 Minimized top displacement of structural frames for optimum TMD parameters

	Optimal Top Displacement (m)			
Frame Type	**No TMD**	**1 TMD**	**4 TMD**	**8 TMD**
Frame 1	0.315241	0.2576	0.2547	0.2634
Frame 2	0.349821	0.2404	0.2439	0.261111
Frame 3	0.363875	0.2207	0.2274	0.2426

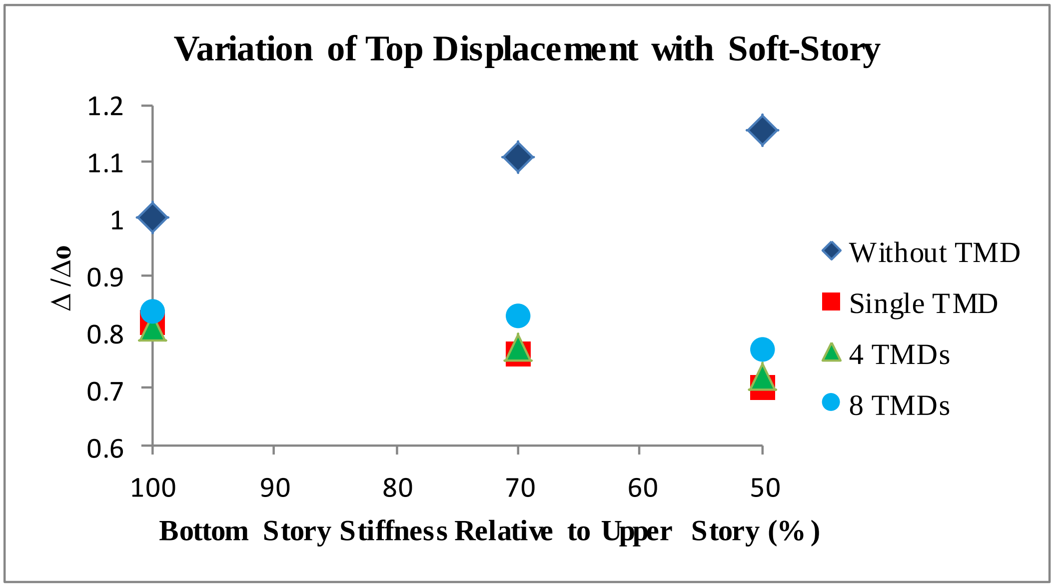


Figure 5.9 Variation of top displacement with soft-story

From the comparison it can be observed that the top displacement of both regular and soft story frames can be reduced effectively with TMD. Application of Tuned Mass Damper becomes more effective in case of irregular soft-story frames. It can be seen that effectiveness of TMD in reducing top displacement increases with the increase of story softness. In case of regular frame single TMD and MTMD performance are almost same. For irregular frames single TMD and 4 MTMD application reduces the top displacement of structure approximately in same quantity. Installation of TMD at each story shows comparatively less reduction of top displacement of soft-story frames.

5.3.2 Minimization of Maximum Inter-story Drift

Second optimization problem was formulated to find out the optimum Tuned Mass Damper parameters to minimize maximum inter-story drift of the structural system subjected to earthquake excitation. Same as the previous optimization problem of minimizing top displacement, this problem was also studied for three cases. At first optimization has been performed considering one Tuned Mass Damper was installed on the top story. Optimum TMD parameters obtained from the analysis for all the frames are enlisted in Table 5.9. Classification of frames is given in Table 4.4.

Table 5.9 Optimum TMD parameters for maximum inter-story drift minimization using single TMD

Optimum TMD Parameters	Frame 1	Frame 2	Frame 3
Mass (t)	219.9725	220.0000	219.9998
Stiffness (kN/m)	9204.9656	816.9074	1302.7500
Damping (kNs/m)	425.0110	600.0001	600.0001

In the second case same structural systems were considered with four TMDs installed in different story level. Optimum mass, stiffness and damping values of TMDs for three chosen frames are presented in Figure 5.10 – Figure 5.12.

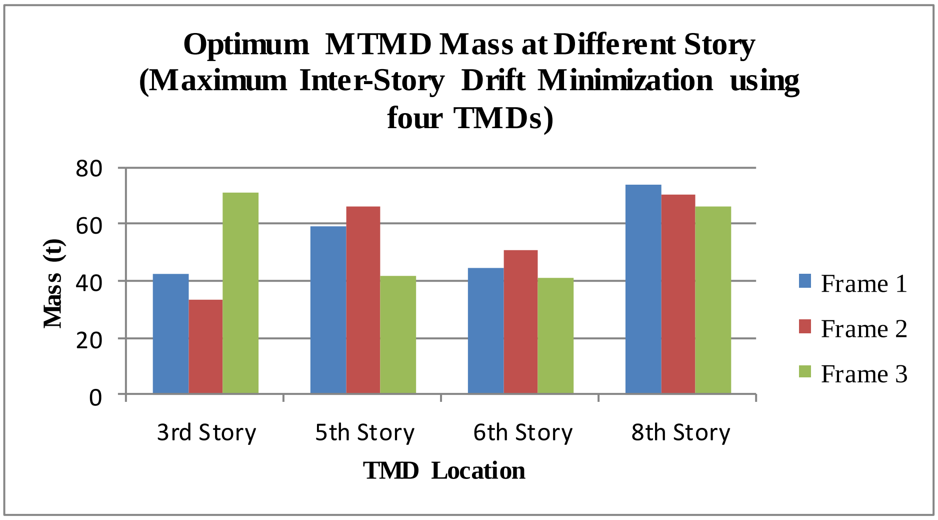


Figure 5.10 Optimum TMD Mass at different story for minimization of maximum inter-story drift using four TMDs

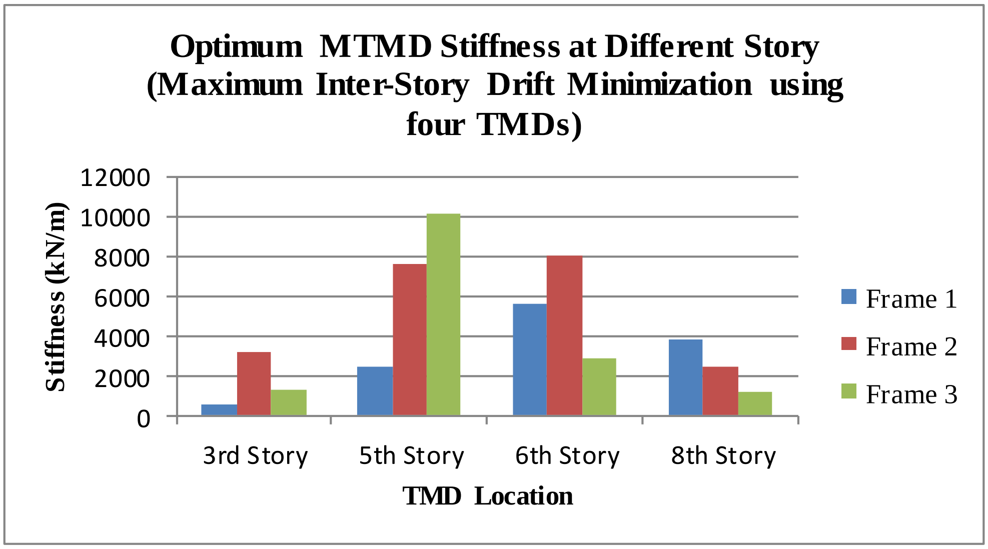


Figure 5.11 Optimum TMD stiffness at different story for minimization of maximum inter-story drift using four TMDs

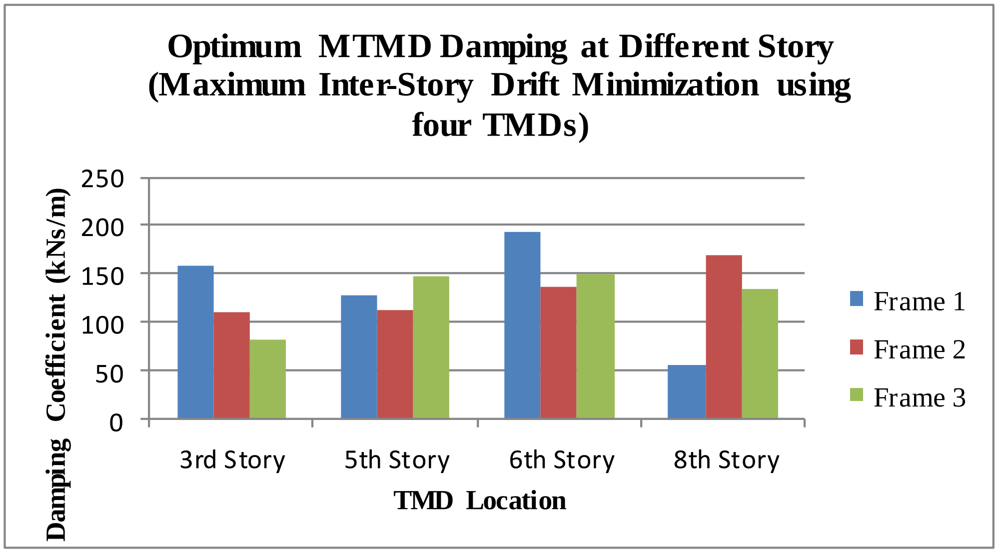


Figure 5.12 Optimum TMD damping at different story for minimization of maximum inter-story drift using four TMDs

Next the structural systems were considered with TMD installed at each floor. The comparison among the optimum mass, stiffness and damping values for three chosen frames are presented in Figure 5.13 – Figure 15.

Minimum inter-story drift of structural frames with considered combination of TMD are obtained from EVOP solution is shown in Table 5.10. A graphical representation of minimized maximum inter-story drift of structures (δ) with respect to maximum inter-story drift of regular frame without TMD (δ_o) for each frame is shown in Figure 5.16.

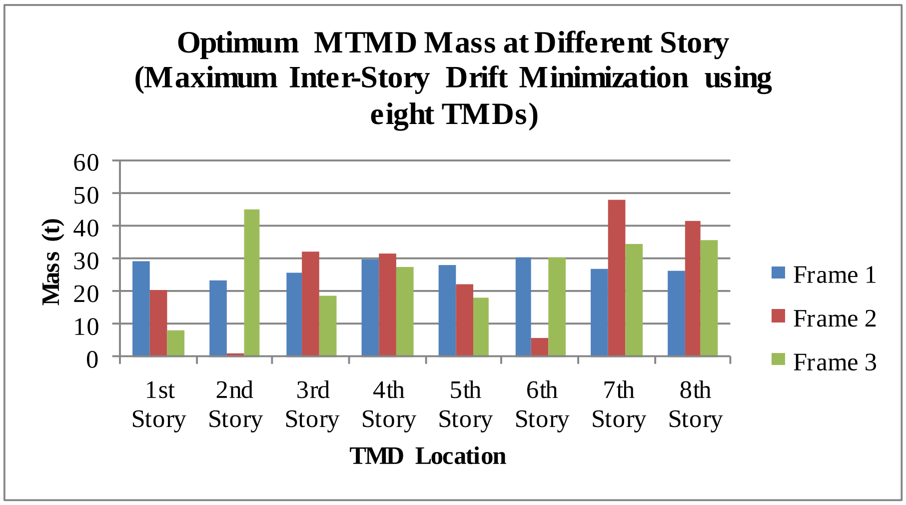


Figure 5.13 Optimum TMD mass at different story for minimization of maximum inter-story drift using eight TMDs

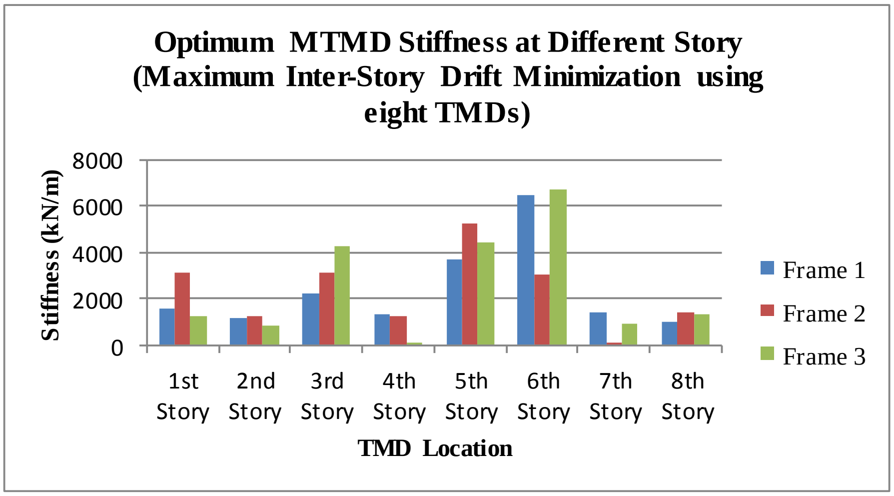


Figure 5.14 Optimum TMD stiffness at different story for minimization of maximum inter-story drift using eight TMDs

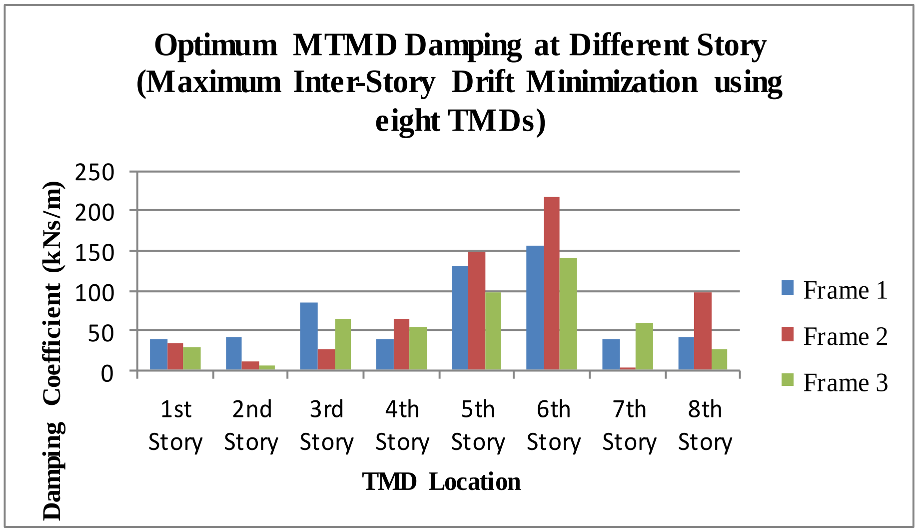


Figure 5.15 Optimum TMD dampingat different story for minimization of maximum inter-story drift using eight TMDs

Table 5.10 Minimum Inter-Story Drift of structural frames obtained for optimum TMD parameters

	Optimal Inter-Story Drift			
Frame Type	**No TMD**	**1 TMD**	**4 TMD**	**8 TMD**
Frame 1	0.040275	0.0196	0.0201	0.0216
Frame 2	0.039654	0.0234	0.0260	0.0193
Frame 3	0.071161	0.0225	0.0234	0.0229

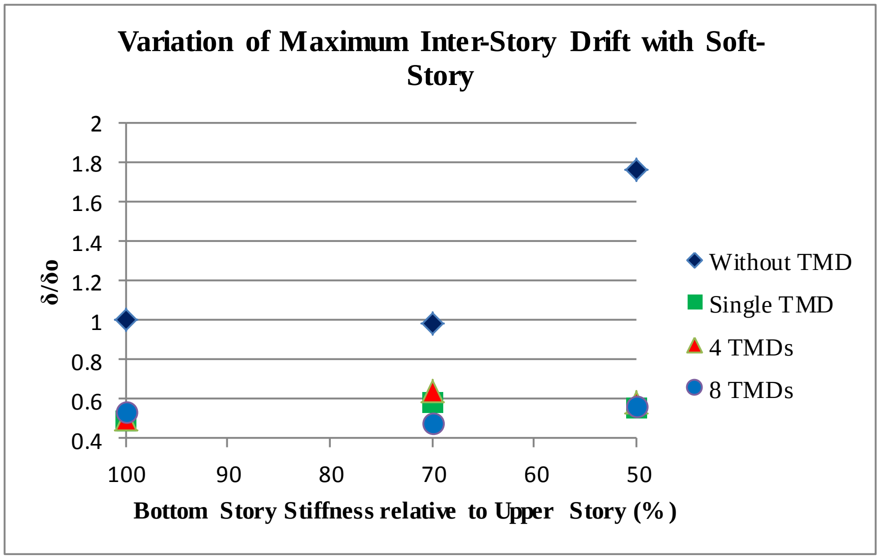


Figure 5.16 Variation of optimum maximum inter-story drift with soft-story

It can be stated from the above comparison that the maximum inter-story drift of both regular and soft-story frames can be effectively reduced with the application of Tuned Mass Damper. It can be observed that effectiveness of TMD in reducing maximum inter-story drift increases with the increase of story softness. In case of regular frame single TMD and MTMD performance are almost same. For irregular frames single TMD and 4 MTMD application reduces the top displacement of structure approximately in same quantity. Installation of TMD at each story shows better performance in case of 30 percent story stiffness. However in case of 50 percent story softness it shows approximately same performance as singular TMD and 4 MTMD.

5.4 OPTIMIZATION OF TUNED MASS DAMPER (TMD) PARAMETERS CONSIDERING SOIL-STRUCTURE INTERACTION

Optimization was performed for structural systems described in section 4.5.2 considering soil-structure interaction. The structural system has been considered to be associated with one or multiple tuned mass dampers. The Feasible starting point and control parameters of EVOP used for the present case are given in the Table 5.11.

Table 5.11 EVOP control parameters and input parameters

EVOP Control Parameters	**Values**	**Range**	**Input Parameters with values**
Reflection coefficient, α	1.6	1.0 to 2.0	Number of complex vertices, K = 6 (TMD case), K = 13 (4 TMD case), K = 25 (8 TMD case)
Contraction coefficient, β	0.5	0 to 1.0	Maximum number of times the three functions can be collectively called, LIMIT = 100000
Expansion coefficient, γ	2.0	>1.0	
Convergence parameter, Φ	10^{-13}	10^{-16} to 10^{-8}	Dimension of the design variable space, N= 3 (TMD case), N = 12 (4 TMD case), N = 24 (8 TMD case)
Φ_{cpx}	10^{-17}		

Two types of optimization problem were formulated. One is to minimize the top deflection of the structure and another is to minimize the maximum inter-story drift of the system. For both optimization problems, at first TMD parameters were optimized to minimize the structural response without taking soil-structure interaction into consideration. Then the same optimization problem was solved considering soil-structure interaction effect and optimum TMD parameters are obtained. Also a case study was made to observe the effect of traditional practice of avoiding SSI effect in the analysis. In this purpose performance of TMD-Structure system, where optimum TMD parameters obtained without considering SSI effect, was determined incorporating SSI effect. This part was studied to observe how the optimum system chosen without considering the effect will perform in the presence of SSI effect.

5.4.1 Minimization of Top Displacement

Tuned Mass Damper parameters were optimized for structural system considering soil-structure interaction. Optimization problem was formulated to minimize the top displacement of the structure under seismic excitation.

In the first case one Tuned Mass Damper was considered on the top floor of the frame. Optimum parameters of TMD were obtained from the solution provided by EVOP. Cases of soil-pile profiles considered in the study are enlisted in Table 5.12. Graphical representation of optimum TMD parameters are shown is Figure 5.17 – Figure 5.19.

Table 5.12 Optimum Tuned Mass Damper parameters for minimization of top displacement considering soil-structure interaction

Soil-Pile Profile		
Profile Name	**SPT Value of Soil**	**Pile Arrangement (X-Y direction)**
Without SSI	-	
Profile 1	2	4x4
Profile 2	6	3x3
Profile 3	10	3x3
Profile 4	14	3x2

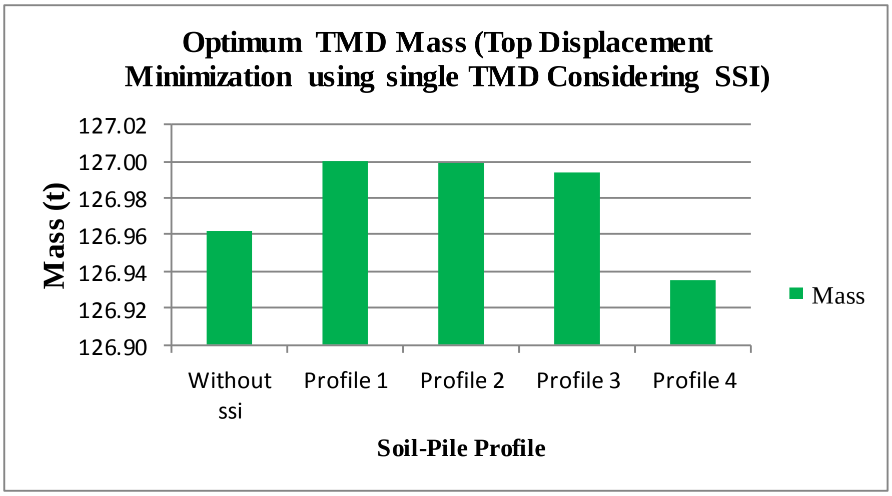


Figure 5.17 Optimum TMD mass for different soil pile profile for minimization of top displacement using single TMD

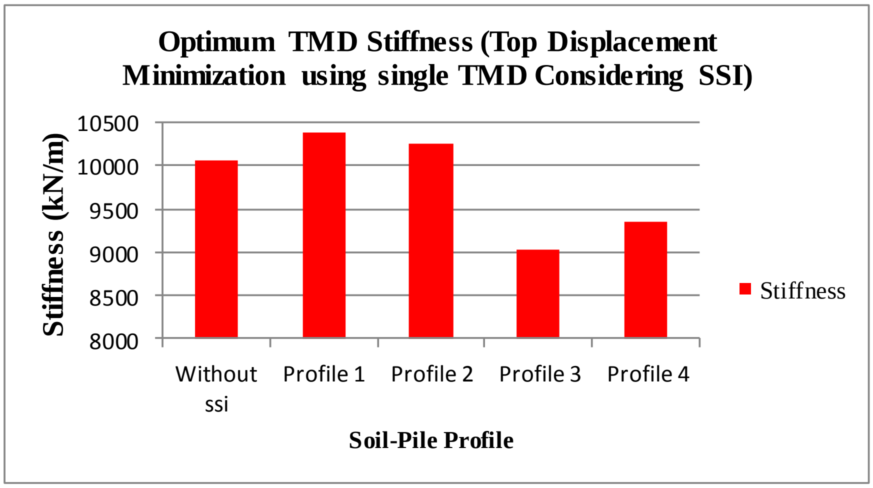


Figure 5.18 Optimum TMD stiffness for different soil pile profile for minimization of top displacement using single TMD

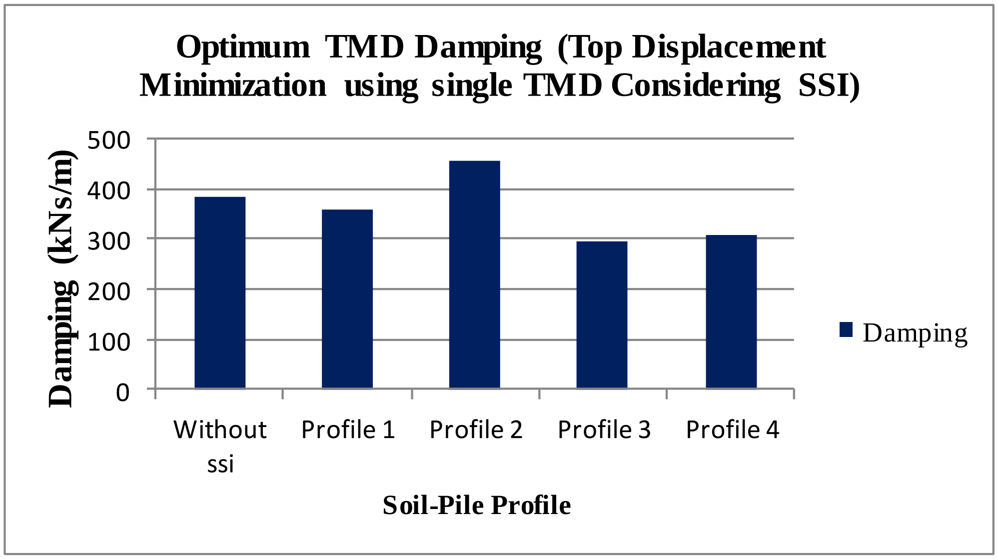


Figure 5.19 Optimum TMD damping for different soil pile profile for minimization of top displacement using single TMD

In the second case four TMDs have been considered to be installed in the structural system. Soil-Pile systems are classified according to Table 5.12. Graphical representations of the comparison among the parameters for different frames are shown in Figure 5.20 – Figure 5.22.

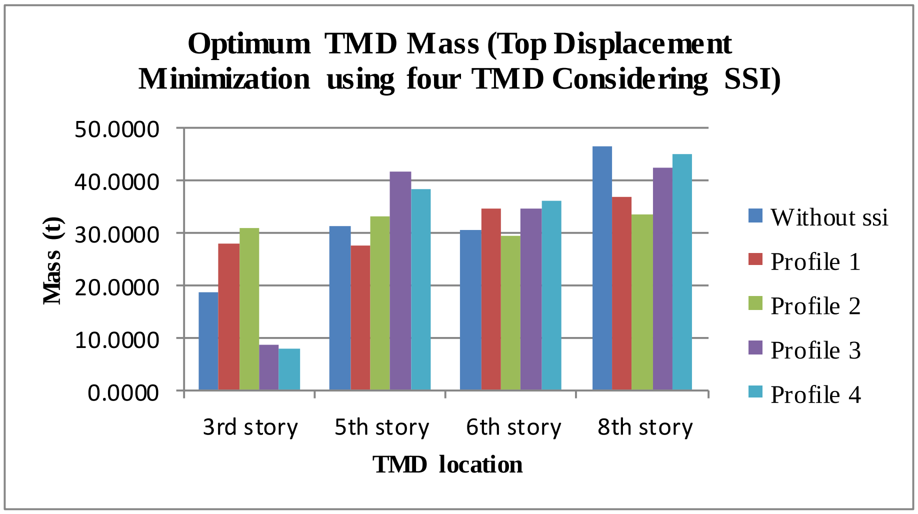


Figure 5.20 Optimum TMD mass at different story level for different soil-pile profile using four TMDs for minimization of top displacement

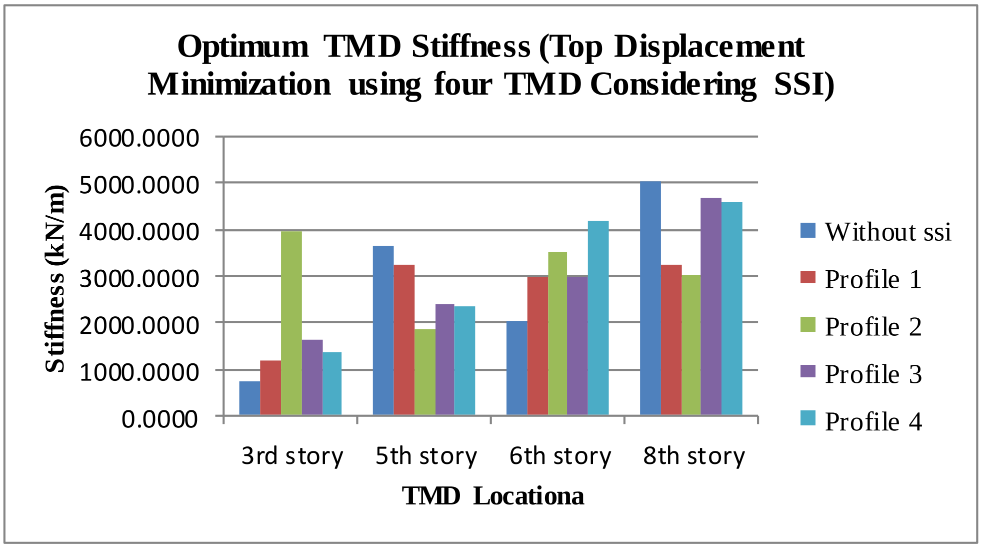


Figure 5.21 Optimum TMD stiffness at different story level for different soil-pile profile using four TMDs for minimization of top displacement

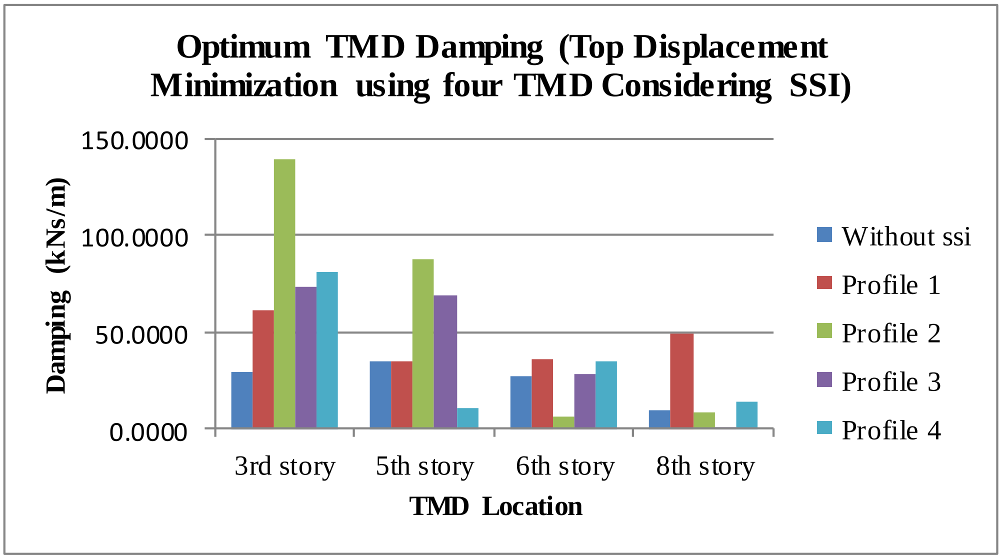


Figure 5.22 Optimum TMD damping at different story level for different soil-pile profile using four TMDs for minimization of top displacement

Finally the structural systems were modeled with TMD at each floor considering soil-structure interaction effect. Comparison among the optimum mass, stiffness and damping values of TMD for structural system with different soil-pile profile are presented in Figure 5.23 – Figure 5.25. The soil-pile profiles are classified according to Table 5.12.

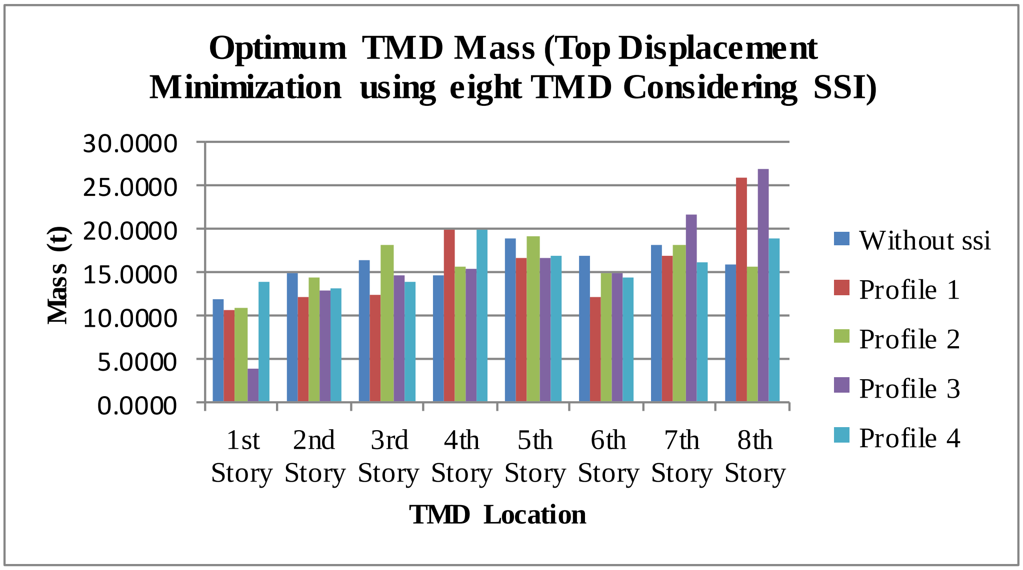


Figure 5.23 Optimum TMD mass at different story level for different soil-pile profile using eight TMDs for minimization of top displacement

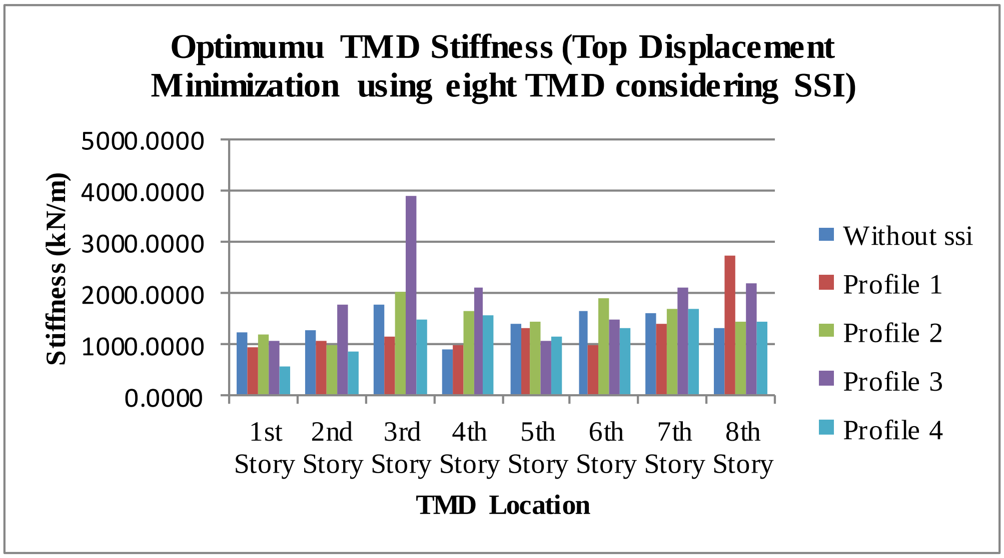


Figure 5.24 Optimum TMD stiffness at different story level for different soil-pile profile using eight TMDs for minimization of top displacement

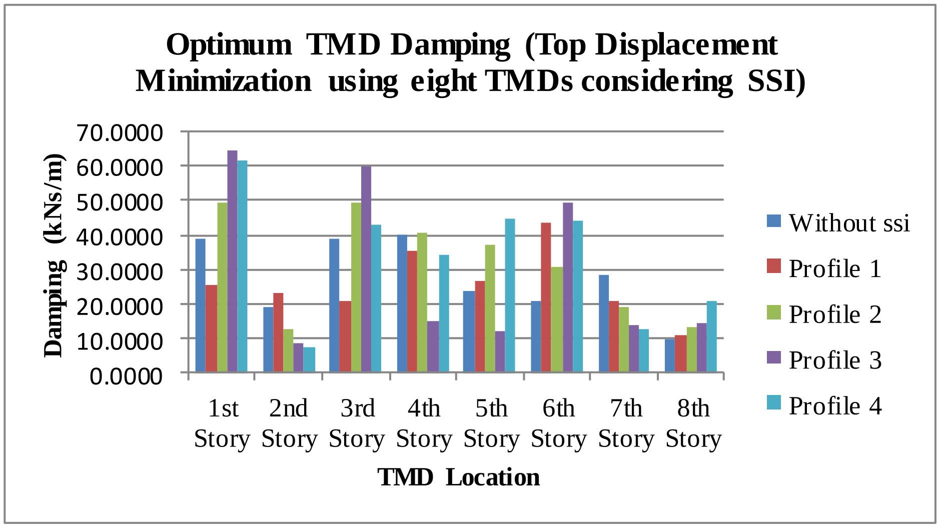


Figure 5.25 Optimum TMD damping at different story level for different soil-pile profile using eight TMDs for minimization of top displacement

Minimum top deflection obtained at optimum solution for the structural frame with different soil-pile profiles and for different combinations of TMD is shown in Table 5.13. A graphical representation of minimized top displacement of structures with optimum Tuned Mass Damper parameters for each case is shown in Figure 5.26.

Table 5.13 Minimized top displacement of structural frame obtained at optimum for different soil-pile profile

	Minimized Top Displacement (m)			
Profile	**No TMD**	**1 TMD**	**4 TMD**	**8 TMD**
Without SSI	0.1361	0.1005	0.0964	0.1092
Profile 1	0.3828	0.1291	0.1314	0.1343
Profile 2	0.2067	0.1108	0.1127	0.1201
Profile 3	0.1834	0.1071	0.1061	0.1153
Profile 4	0.1847	0.1046	0.1026	0.1171

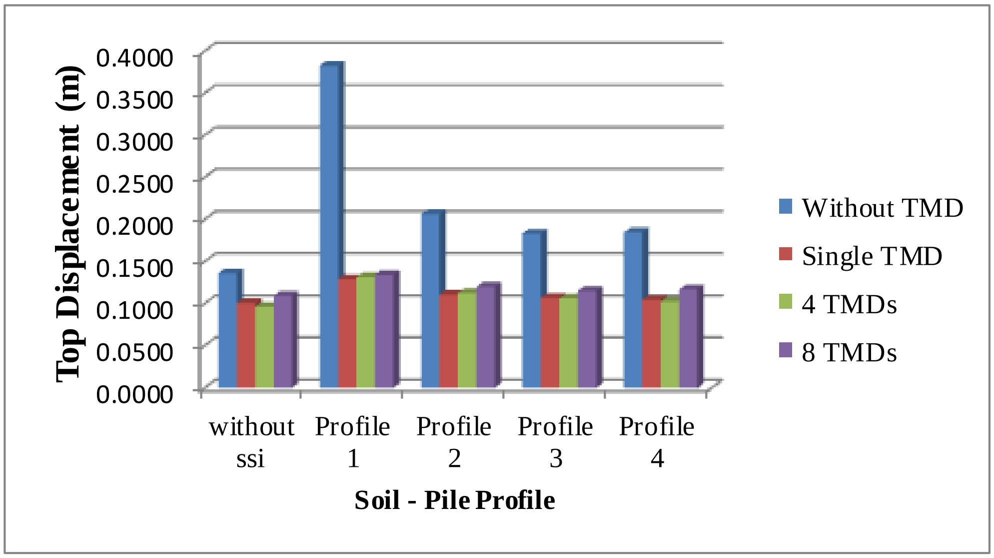


Figure 5.26 Top displacements of structural systems with optimum TMD paramters for different soil-pile profiles

It can be observed from the above comparison that the performance of the primary structure considering soil-structure interaction varies from that of the structure which does not take SSI into account. In case of structure without TMD application, top displacement is found to be higher when SSI is incorporated into the analysis. Top displacement of structure without TMD decreases with the increase of stiffness of soil-pile system. Application of TMD improves the performance of structure by reducing the top displacement of the frame. Minimum top displacement of the structure obtained using optimum TMD parameters is higher when soil-structure interaction effect is considered. The rate of increase is higher in case of more flexible soil-pile system. Performance of the structural system remains almost same with the increase of number of TMD.

Later the performance of the optimum TMD-structure system obtained from the problem formulated without considering soil-structure interaction effect was determined in the presence of soil-structure interaction effect. This study was made to see the performance of the structure installed with optimum TMD parameters, determined in traditional way by avoiding SSI analysis, in real condition. The comparison among the performance of structure under following conditions is shown in Figure 5.27 – Figure 5.30.

(a) Case 1 – Top displacement of structure with optimum TMD system obtained without considering SSI effect.

(b) Case 2 – Top displacement of structure with optimum TMD system from case -1, under soil-structure interaction.

(c) Case 3 – Top displacement of structure with optimum TMD system obtained considering SSI effect.

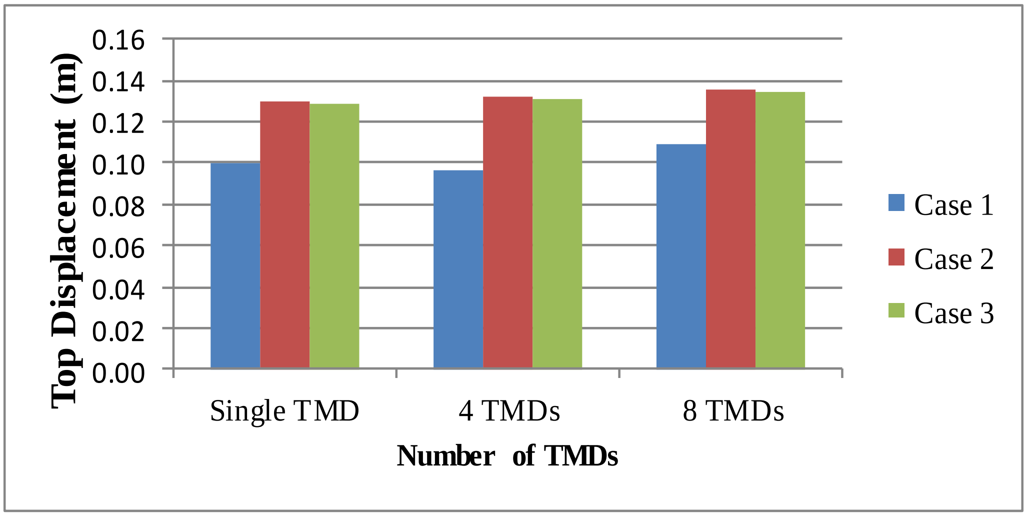


Figure 5.27 Top displacement of structure with optimum TMD system for different cases of soil-structure interaction (for Soil-Pile Profile 1)

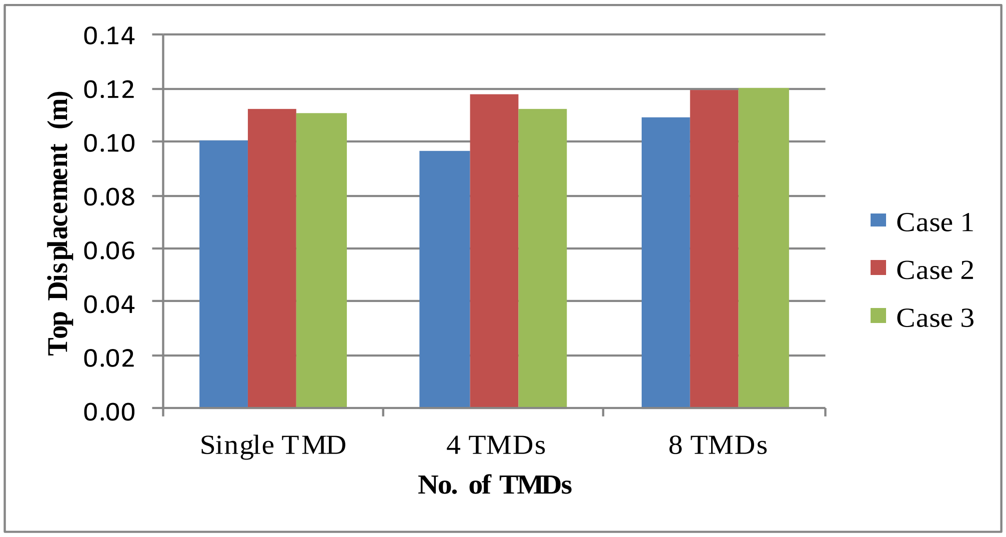


Figure 5.28 Top displacement of structure with optimum TMD system for different cases of soil-structure interaction (for Soil-Pile Profile 2)

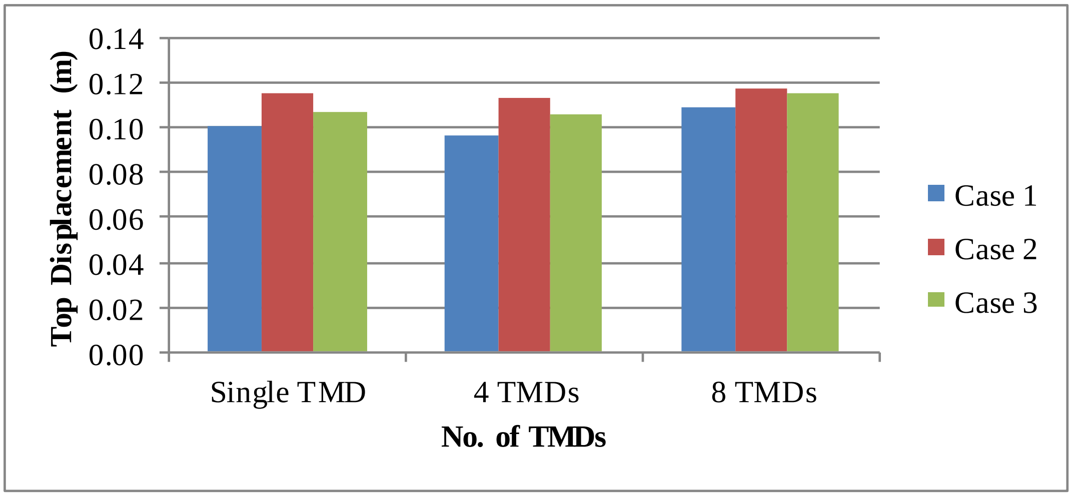


Figure 5.29 Top displacement of structure with optimum TMD system for different cases of soil-structure interaction (for Soil-Pile Profile 3)

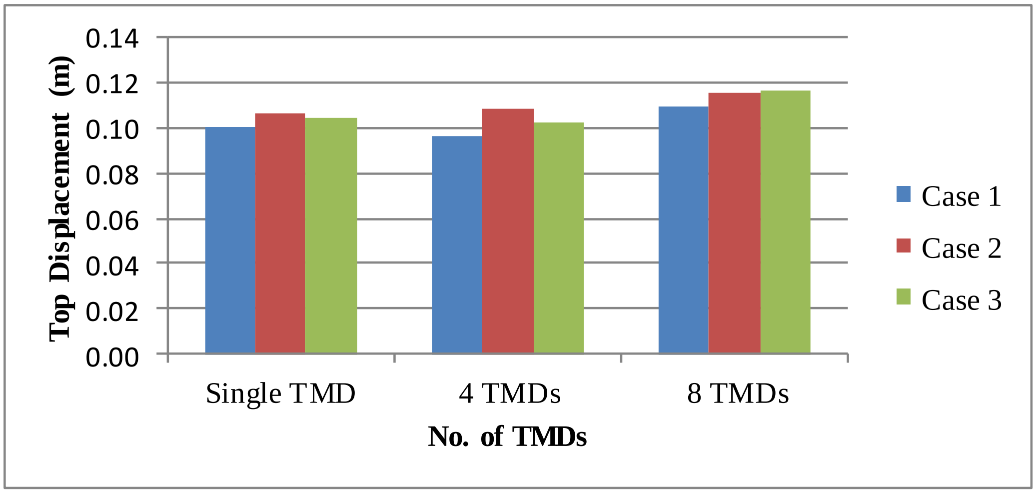


Figure 5.30 Top displacement of structure with optimum TMD system for different cases of soil-structure interaction (for Soil-Pile Profile 4)

From the above comparison it can be seen that the performance evaluated for the optimum TMD-structure system without considering SSI effect varies in real condition where SSI exists. The top displacement determined without incorporating SSI effect is less than the actual displacement which will occur during earthquake when interaction between the substructure and soil will take place.

5.4.2 Minimization of Maximum Inter-Story Drift

In this case optimization problem was formulated to minimize the maximum inter-story drift of the structure under seismic excitation. At first optimization was performed for one Tuned Mass Damper installed on the top floor of the frame. Optimum parameters of TMD were obtained from the solution provided by EVOP. Graphical representations of the comparison among the parameters for all cases are shown in Figure 5.31 – Figure 5.33. Soil-pile profiles are classified according to Table 5.12.

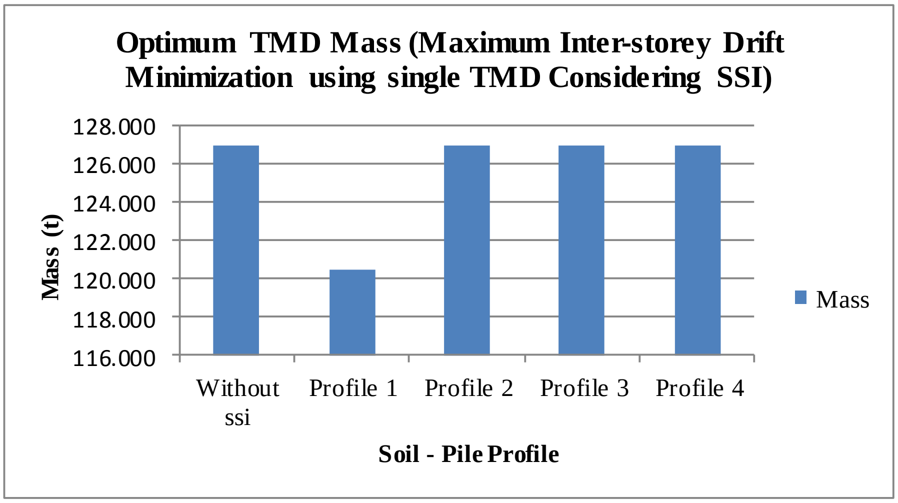


Figure 5.31 Optimum TMD mass for different soil pile profile for minimization of maximum inter-story drift using single TMD

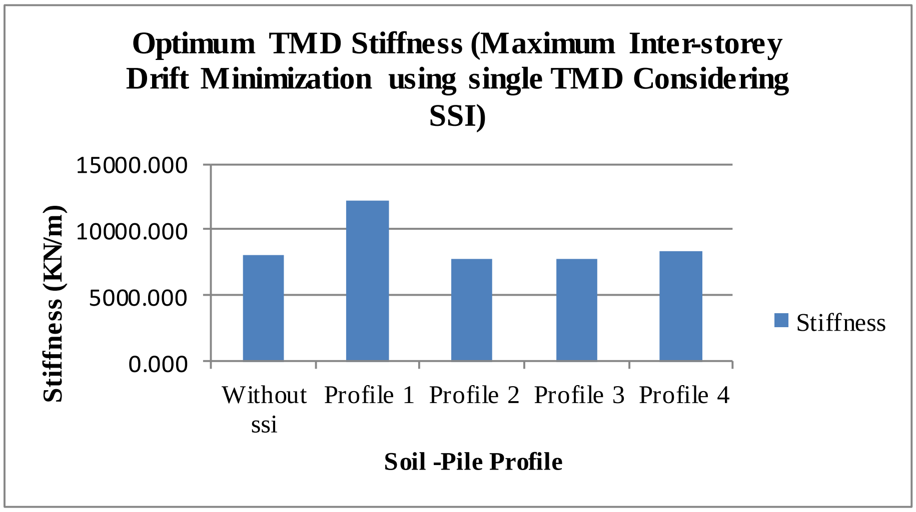


Figure 5.32 Optimum TMD Stiffness for different soil pile profile for minimization of maximum inter-story drift using single TMD

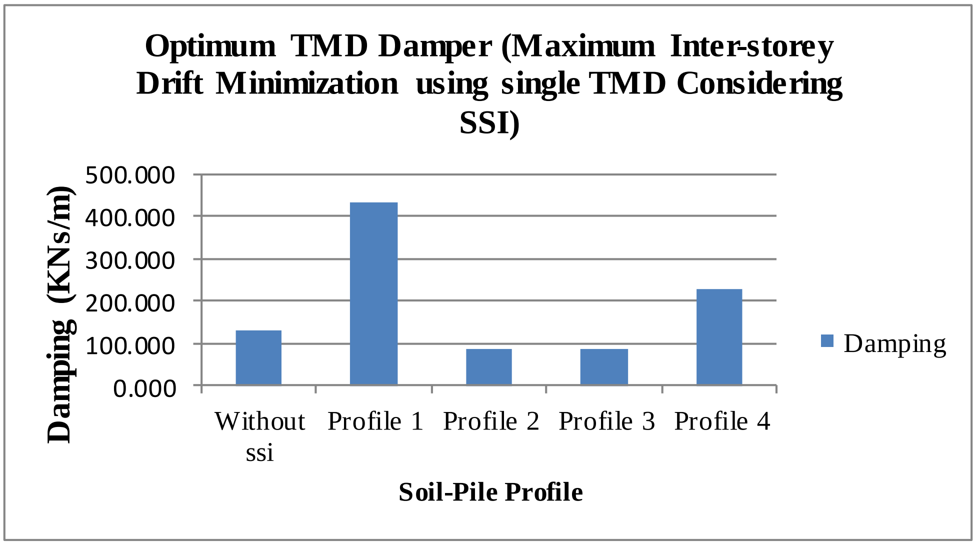


Figure 5.33 Optimum TMD Damping for different soil pile profile for minimization of maximum inter-story drift using single TMD

In the second case four TMDs have been considered to be installed in the structural system to control vibration. Graphical representations of the comparison among the parameters for different frames are shown in Figure 5.34 – Figure 5.36. Soil-Pile systems are classified according to Table 5.12.

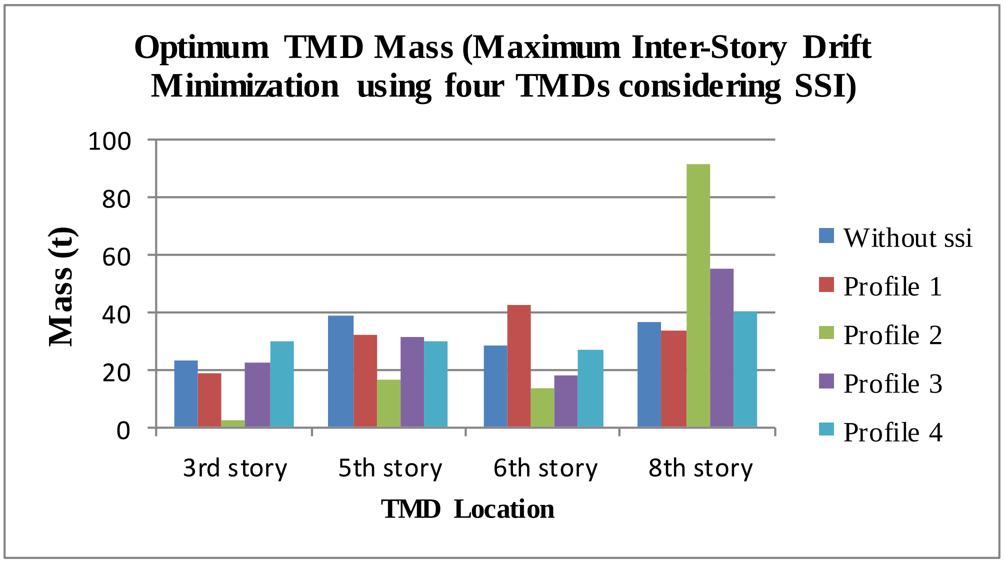


Figure 5.34 Optimum TMD mass at different story level for different soil-pile profile using four TMDs for minimization of maximum inter-story drift

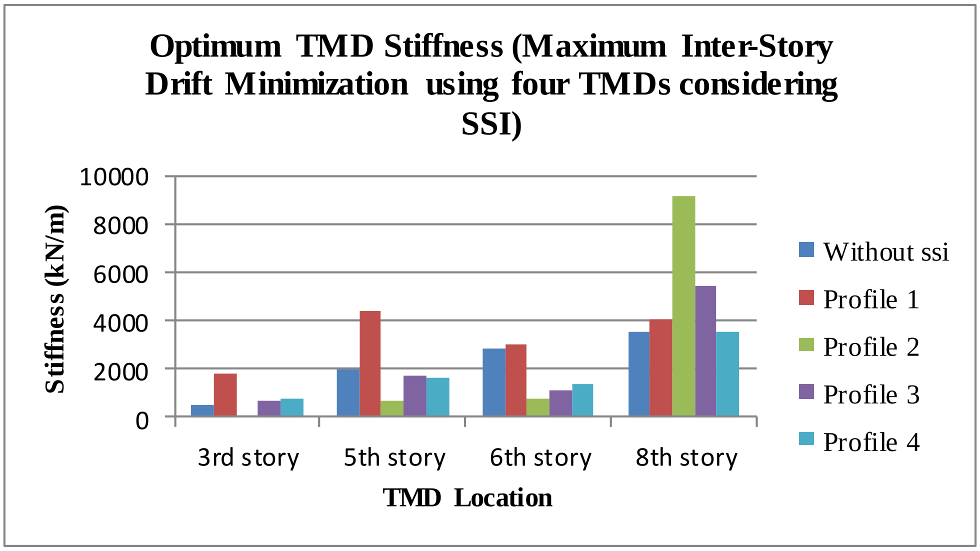


Figure 5.35 Optimum TMD stiffness at different story level for different soil-pile profile using four TMDs for minimization of maximum inter-story drift

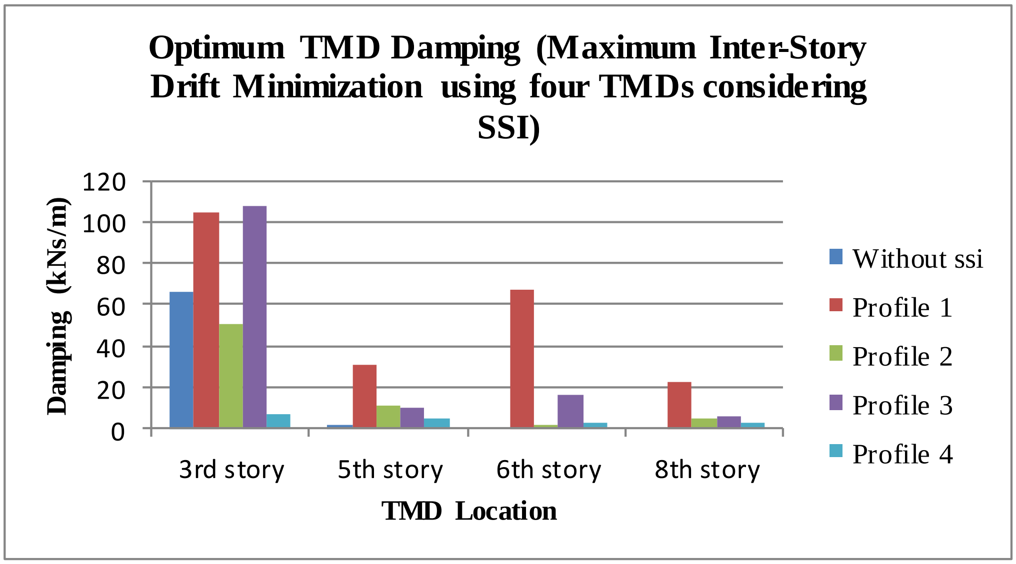


Figure 5.36 Optimum TMD damping at different story level for different soil-pile profile using four TMDs for minimization of maximum inter-story drift

Finally the structural systems were modeled with TMD at each floor considering soil-structure interaction effect to minimize maximum inter-story drift. The comparison among the optimum mass, stiffness and damping values of TMD for structural system with different soil-pile profile are presented in Figure 5.37 – Figure 5.39. The soil-pile profiles are classified according to Table 5.12.

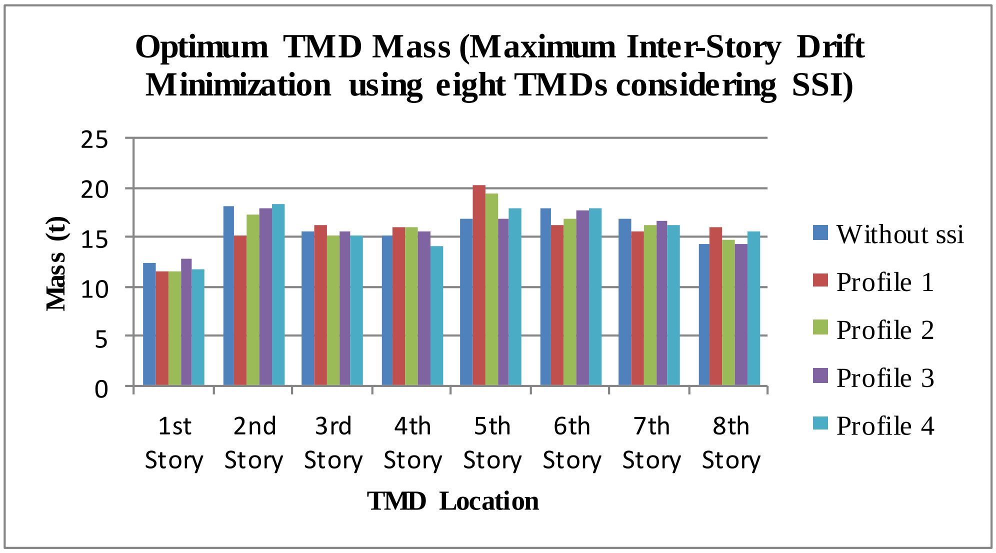


Figure 5.37 Optimum TMD mass at different story level for different soil-pile profile using eight TMDs for minimization of maximum inter-story drift

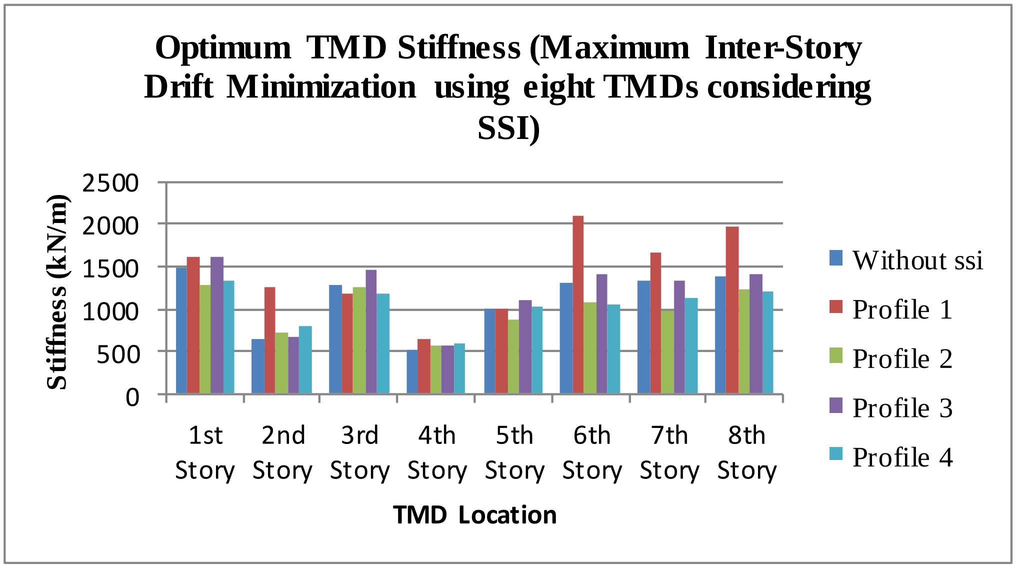


Figure 5.38 Optimum TMD stiffness at different story level for different soil-pile profile using eight TMDs for minimization of maximum inter-story drift

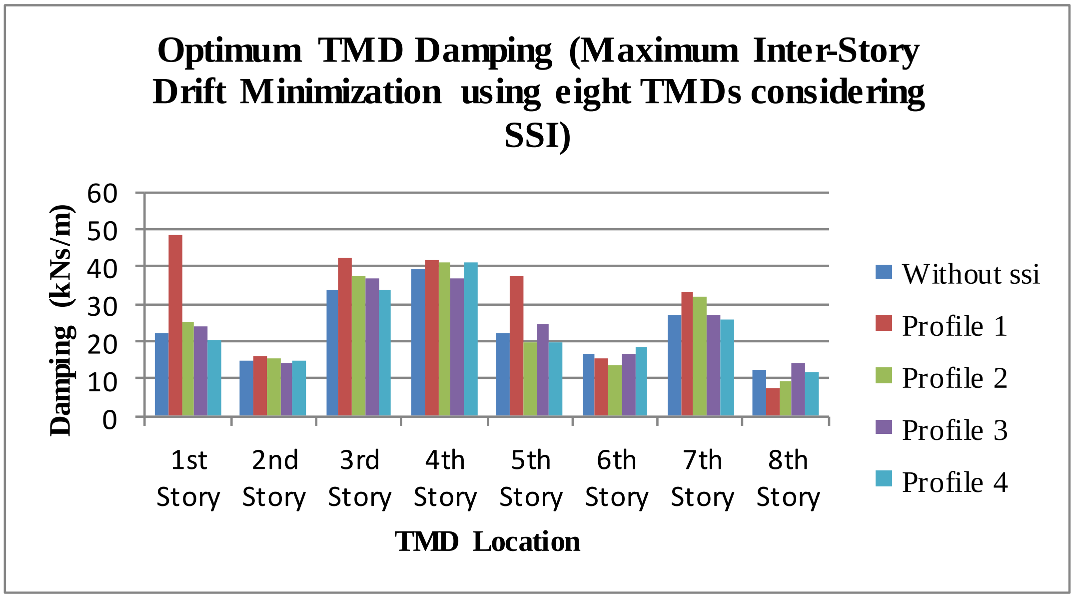


Figure 5.39 Optimum TMD damping at different story level for different soil-pile profile using eight TMDs for minimization of maximum inter-story drift

Minimum inter-story drift obtained at optimum solution for the structural frame with different soil-pile profiles and for different combinations of TMD is shown in Table 5.14. A graphical representation of minimum inter-story drift of structures with optimum Tuned Mass Damper parameters for each case is shown in Figure 5.40.

Table 5.14 Minimized maximum inter-story drift of structural frame obtained at optimum for different soil-pile profile

	Minimized Top Displacement (m)			
Profile	**No TMD**	**1 TMD**	**4 TMD**	**8 TMD**
Without SSI	0.0083	0.0058	0.0061	0.0069
Profile 1	0.0186	0.0077	0.0078	0.0085
Profile 2	0.0119	0.0076	0.0075	0.0090
Profile 3	0.0117	0.0074	0.0076	0.0086
Profile 4	0.0096	0.0061	0.0063	0.0071

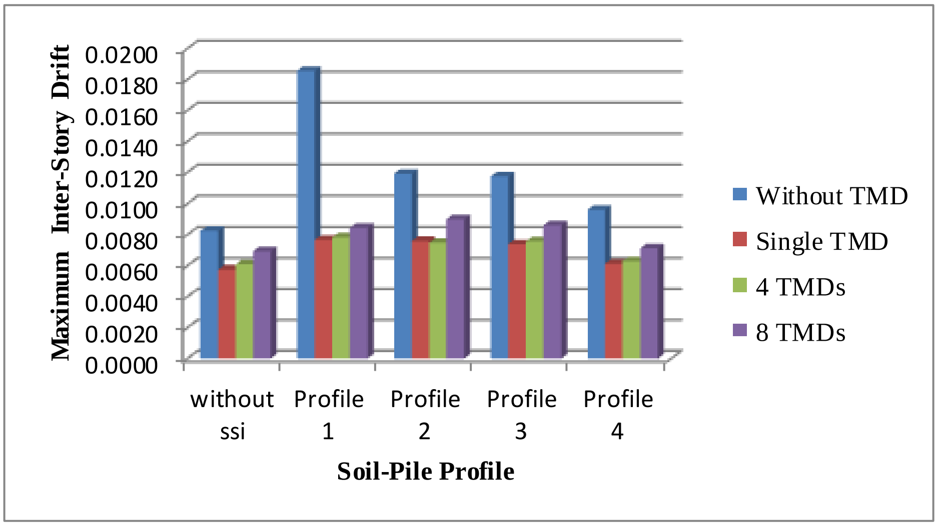


Figure 5.40 Maximum Inter-Story Drift of structural systems with optimum TMD parameters for different soil-pile profiles

It can be observed from the above comparison that the performance of the primary structure considering soil-structure interaction varies from that of the structure which does not take SSI into account. In case of structure without TMD application, maximum inter-story drift is found to be higher when SSI is incorporated into the analysis. Maximum inter-story drift of structure without any TMD decreases with the increase of stiffness of soil-pile system. Application of TMD improves the performance of structure by reducing the maximum inter-story drift of the frame. Minimum inter-story drift of the structure obtained using optimum TMD parameters is higher when soil-structure interaction effect is considered. Performance of the structural system remains almost same with the increase of number of TMD.

Later the performance of the optimum TMD-structure system obtained from the problem formulated without considering soil-structure interaction effect was determined in the presence of soil-structure interaction effect. This study was made to see the performance of the structure installed with optimum TMD parameters, determined in traditional way by avoiding SSI analysis, in real condition. The comparison among the performance of structure under following conditions is shown in Figure 5.41 – Figure 5.44.

(a) Case 1 – Optimum inter-story drift of structure with optimum TMD system obtained without considering SSI effect.

(b) Case 2 – Optimum inter-story drift of TMD-structure system of case 1 in the presence of SSI effect.

(c) Case 3 – Optimum inter-story drift of structure with optimum TMD system obtained considering SSI effect.

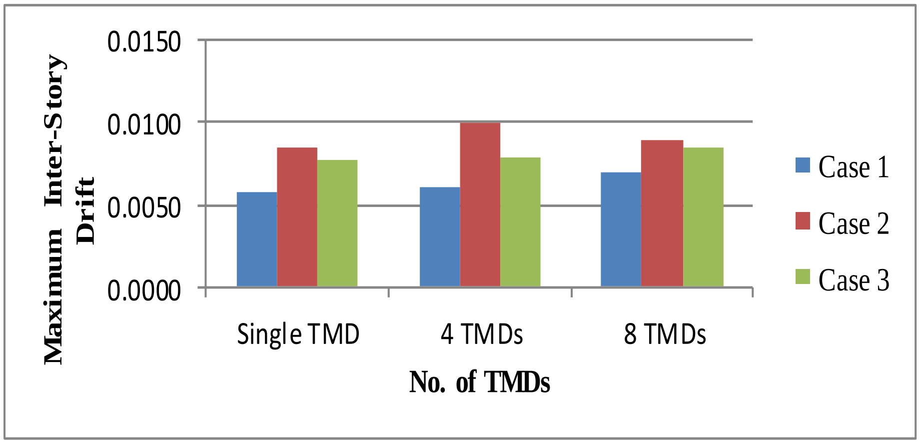


Figure 5.41 Maximum Inter-Story Drift of structure with optimum TMD system for different cases of soil-structure interaction (for Soil-Pile Profile 1)

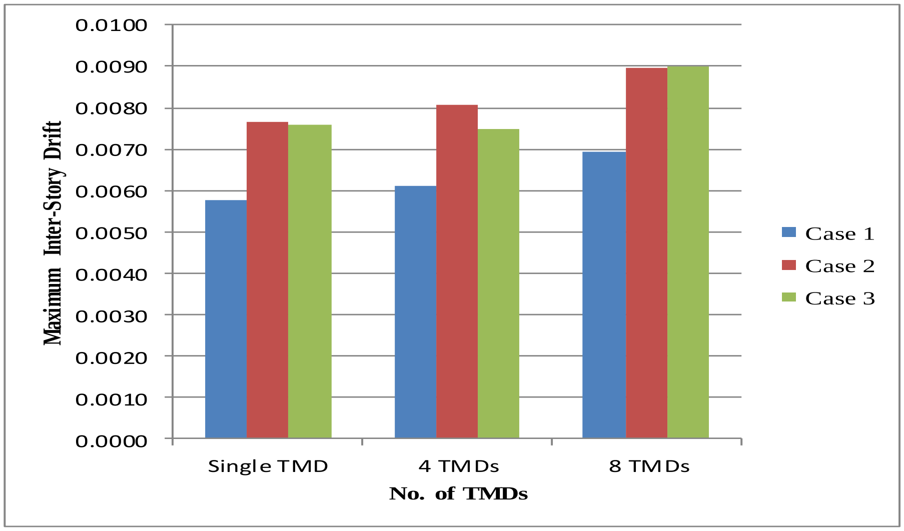


Figure 5.42 Maximum Inter-Story Drift of structure with optimum TMD system for different cases of soil-structure interaction (for Soil-Pile Profile 2)

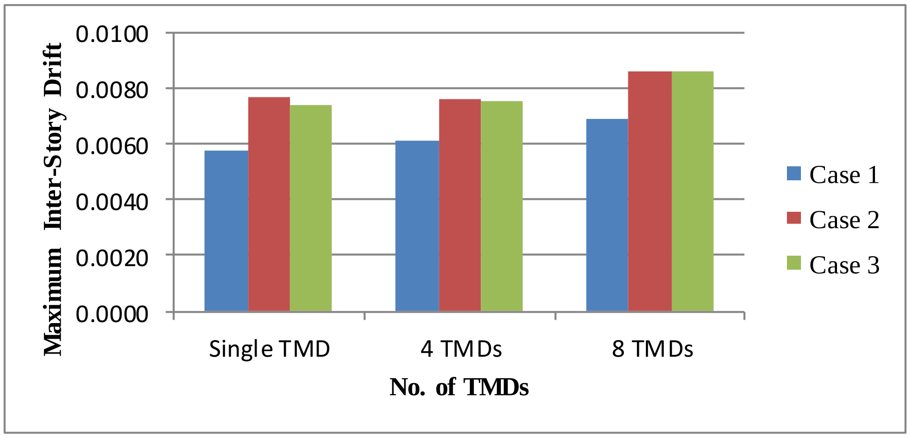


Figure 5.43 Maximum Inter-Story Drift of structure with optimum TMD system for different cases of soil-structure interaction (for Soil-Pile Profile 3)

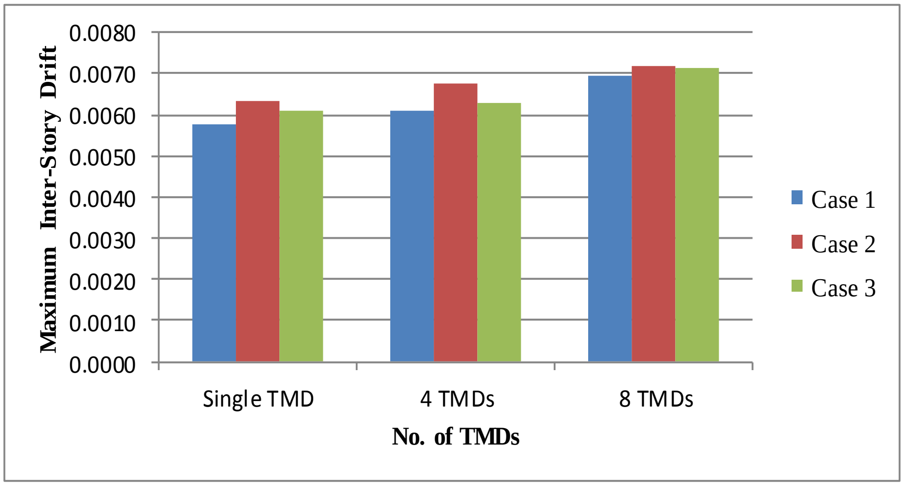


Figure 5.44 Maximum Inter-Story Drift of structure with optimum TMD system for different cases of soil-structure interaction (for Soil-Pile Profile 4)

From the above comparison it can be seen that the performance evaluated for the optimum TMD-structure system without considering SSI effect varies in real condition where SSI exists. Optimum inter-story drift determined without incorporating SSI effect is less than the actual inter-story drift which will occur during earthquake when interaction between the substructure and soil will take place. Incorporation of soil-structure interaction into the optimization process can either improve the performance further than that will occur in real condition if SSI is not considered or remain approximately same.

Chapter 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

In the present study, effort has been made to explore application of a global optimization algorithm called EVOP in vibration control of structures under seismic excitation using Tuned Mass Damper (TMD). A computer program has been developed in C++ to construct the optimization problem and link it with the source code of EVOP. Effectiveness of EVOP in minimizing structural response with optimum TMD parameters is compared with other optimization approaches available in literature. Developed optimization approach is applied to choose optimum Tuned Mass Damper parameters for regular and soft-story frames. Two types of optimization problems were formulated in the present study. First optimization problem was formulated to find out optimum Tuned Mass Damper parameters in order to minimize top displacement of the structural system. Second optimization problem was developed to search optimum Tuned Mass Damper parameters to minimize the maximum inter-story drift of the structure. Application of single Tuned Mass Damper and Multiple Tune Mass Damper were investigated to control the vibration of building frames subjected to El Centro (1940) NS earthquake motion. In case of Multiple Tuned Mass Damper, at first 4 TMDs were installed at 3rd, 5th, 6th and 8th story of the building and later TMD was placed on each story of the building frame. Finally a methodology was developed to optimize Tuned Mass Damper parameters using Evolutionary Operation Algorithm (EVOP) considering soil-structure interaction. A structure-TMD system is studied for different soil-pile condition and a comparative study is made to observe the effect of soil-structure interaction on structural response.

Following conclusions can be made under the scope of the present study:

- EVOP can effectively optimize Tuned Mass Damper (TMD) parameters and minimize top displacement of a structural system with a higher percentage of structural response reduction and a choice of smaller mass, stiffness and damping of TMD. Application of EVOP is effective in minimizing structural response of building frame associated with Multiple Tuned Mass Damper (MTMD) with higher reduction of structural response.

- From the optimum mass, stiffness and damping coefficient of dampers obtained for regular and irregular frames it can be concluded that optimum Tuned Mass Damper parameters can vary depending on the irregularity of the structural system.

- Application of Tuned Mass Damper (TMD) and Multiple Tuned Mass Damper (MTMD) minimizes top displacement approximately in same quantity for both regular and irregular frames subjected to El Centro (1940) NS. From the analysis it can be seen that it is possible to reduce the top deformation even if the bottom story stiffness becomes less. It is also found that TMDs are more efficient in reducing top displacement in irregular frames. In case of regular frames, minimized maximum inter-story drift at optimum solution obtained using TMD and MTMD are approximately same. Analysis reveals that MTMD can reduce maximum inter-story drift MTMD more than TMD for irregular frame with 70% bottom story stiffness while TMD and MTMD show almost same performance in case of frame with 50% stiffness. It can be concluded that location of TMD should be optimized to study performance of MTMD using EVOP.

- Analysis shows that performance of structure using optimum TMD parameters obtained without considering soil-structure interaction (SSI) in the optimization process underestimates the real performance of the structure-TMD system. Incorporation of soil-structure interaction effect into the optimization process can either improve the performance of structure or remain approximately same as the real performance of structural system with optimum TMD parameters obtained without taking SSI into consideration.

- From the study it can be restated that EVOP has the high probability of locating global minimum. Moreover, by observing the potential of EVOP in locating the global minimum effectively and considering the feasibility aspect, it can be concluded that EVOP is effective in optimizing vibration control problems.

6.2 FUTURE RECOMMENDATIONS

The present study can be extended further to include following recommendations.

- Process of finding optimal location and number of Tuned Mass Damper required to obtain minimum structural response can be included in the current methodology and algorithm.

- Optimum Tuned Mass Damper parameters can be determined to minimize torsion of the irregular structure. In this case minimization of torsion of the structure can be set as objective function in the optimization problem.

- In the analysis of soil-structure interaction, vertical and rotational component can be taken into consideration to obtain more accurate response. Also case studies can be performed for heterogeneous soil profile which represents actual condition.

- The study can be extended for other type of foundation except pile foundation.

- EVOP can be explored further for active control of structures.

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APPENDICES

APPENDIX A (COMPUTER PROGRAM WRITTEN IN C++ LANGUAGE)

(a) Minimization of Top Displacement

```
//*************************************************************************************
//__01__01__01__01__01____________Header Files Declaration Zone____________01__01__01__01__
//*************************************************************************************

#include <iostream>
#include <fstream>
#include<math.h>
#define SWAP(a,b){temp=(a);(a)=(b);(b)=temp;}
using namespace std;
#define NR_END 1
#define FREE_ARG char*
#include <cmath>
#include <time.h>

//*************************************************************************************
//__02__02__02__02_______Linking Fortran Language to C/C++ Language______02__02__02__02__02
//*************************************************************************************

extern "C"
{
    void __stdcall EVOP(double*,double*,double*,double*,double*,double*,double*,
                int*,int*,int*,int*,int*,int*,int*,int*,int*,int*,double*,double*,double*,
                double*,double*,double*,double*,double*,double*,double*,double*,double*);
        void __stdcall DINTG2(int*,double*,double*,double*,double*);
        void __stdcall DISCR2(double*,int*,int*,double*,double*,double*,double*);
        void __stdcall EXPCON(int*,int*,int*,int*,double*,double*,double*);
        void __stdcall FUNC(double*,int*,int*,int*,double*);
        double __stdcall RNDOFF(double*);
        void __stdcall IMPCON(int*,int*,double*,double*,double*,double*);
}

//*************************************************************************************
//__03__03__03__03__03___________Function Declaration Zone____________03__03__03__03__03__
//*************************************************************************************

double input_function ();
double matrix_declaration_function ();
double txt_read_form_dynamic_array (char *filename, double *inv);
double mark_tmd_sequence (double *array01, double *array02, int a, int b, double *tf);
double global_mass_matrix (double *a, double b, double **c);
double global_stiffness_damping_matrix (double *a, double *tf, double b, double **c);
double force_matrix (double *a, double *b, double d, double s, double **c);
double central_difference_method (double **globalmass, double **globalstiffness, double
**globaldamping, double **pforce, double **u, double p, double q, double delt);
double matrix_multiplication (double **a, double **b, double **c, double row1, double col1, double row2,
double col2);
void nrerror(char error_text[]);
int *ivector(long nl, long nh);
void free_ivector(int *v, long nl, long nh);
double matrix_solution_function(double **a,double n,double **b,double m, double **resultant);
```

```
double maximum_displacement_function (double **u, double **umax);
double maximum_interstorydrift_function (double *tf, double **u, double **stdisplacement, double
**stdrift, double **stdriftmax, double maxstdrift);
//**************************************************************************************************
//__04__04__04__04__04_________Variable Declaration Zone____________04__04__04__04__04__04
//**************************************************************************************************

double *dof, *tmd, *mcol, *kcol, *ccol, *accel, *tf;
double **globalmass, **globalstiffness, **globaldamping, **pforce;

int d = 12; // total degrees of freedom including tmds
int const tmd_no =4; // number of tmds

int tn, size_accel;
double t, delt; // t=total time of earthquake record, delt=time interval
double **u, **umax;
double **stdisplacement, **stdrift, **stdriftmax, maxstdrift;

// used in central difference method function

double **uint, **vint, **aint, **pforceint;
double **khat, **ahat, **bhat;
double **umin1, **u_0, **u_1;
double **phat;
double **cdotvint, **kdotuint, **mdotaint;
double **ahatdotu_0, **bhatdotu_1;
double **ucol;
double **demokhat, **demoglobalmass;

// for user written subroutine of EVOP

int const nv = 3*tmd_no;
int const icn = 4;

//**************************************************************************************************
//__05__05__05__05__05__________Main Function Zone___________05__05__05__05__05__05__05_
//**************************************************************************************************

int main()
{
        time_t start, stop;
        time(&start);

        int i,j;

        input_function ();
        matrix_declaration_function ();
        txt_read_form_dynamic_array ("dofseq.txt", dof);
        txt_read_form_dynamic_array ("tmdseq.txt", tmd);
        txt_read_form_dynamic_array ("mcol.txt", mcol);
        txt_read_form_dynamic_array ("kcol.txt", kcol);
        txt_read_form_dynamic_array ("ccol.txt", ccol);
        txt_read_form_dynamic_array ("accel.txt", accel);

        //Logical true false vector formed after checking DOF sequence with TMD sequence
        mark_tmd_sequence (dof, tmd, d, tn, tf);
```

```
//****************************************************************************

        DoubleC[nv],FF[nv+1],H[nv*(nv+1)],OLDCC[nv],XDN[nv],XG[nv],XMAX[nv],XMIN[nv],XU
        P[nv],XX[icn],XXMAX[icn],XXMIN[icn],XT[nv];

        double ALPHA,BETA,DEL,GAMA,PHI,PHICPX;
        int ICON,IJK,IMV,IPRINT,K,KNT,LIMIT,N,NRSTRT,NIC;

        // initial value of a feasible point

        int g = 0;
        for (i=0; i<d; i++)
        {
                if (tf[i] == 1)
                {
                        XT [g] = mcol [i];
                        g++;
                        XT [g] = kcol [i];
                        g++;
                        XT [g] = ccol [i];
                        g++;
                }
        }

//*******************************************************************************************
******

//    CONTROL PARAMETERS FOR "EVOP"

         ALPHA = 1.6;
         BETA=0.5;
         GAMA=2.0;
         DEL=1e-12;
         PHI=1e-13;
         PHICPX=1e-17;
         ICON=5;
         LIMIT=100000;
         KNT=25;
         N=nv;
         NIC=icn;
         if (nv <= 5)
         {
                K = 2*nv;
         }
         else
         {
                  K=nv+1;
         }

         IPRINT=2;
         NRSTRT=10;
         IMV=0;
         IJK=1;
```

```
line1:
EVOP(&ALPHA,&BETA,C,&DEL,FF,&GAMA,H,&ICON,&IJK,&IMV,&IPRINT,&K,&KNT,&LIMIT,
&N,&NRSTRT,

&NIC,OLDCC,&PHI,&PHICPX,XDN,XG,XMAX,XMIN,XT,XUP,XX,XXMAX,XXMIN);
          if (IJK < 9) goto line1;

          time(&stop);
          cout<<difftime(stop, start)<<endl;


}

//************************************************************************************
//__06__06__06__06______________Input function Zone________________06__06__06__06__06__06_
//************************************************************************************

double input_function ()
{
        if (tmd_no > 0)
        {
                tn = tmd_no;
        }
        else
        {
                tn = 1; // if no TMD then input tn = 1 & in txt file sequence will be zero.
        }


        // acceleration time input parameters

        t = 53.74; // total earthquake duration
        delt = 0.02; // time step
        size_accel = (t/delt+1);
        return 0;
}



//************************************************************************************
//__07__07__07__07__07____________Matrix/Array Declaration Zone____________07__07__07__07__
//************************************************************************************

double matrix_declaration_function ()
{
        int i, j;

        dof = new double [d];
        tmd = new double [tn];
        tf = new double [d];
        mcol = new double [d];
        kcol = new double [d];
        ccol = new double [d];
        accel = new double [size_accel];
        globalmass = new double *[d];
        globalstiffness = new double *[d];
```

```
globaldamping = new double *[d];
pforce = new double *[d];
u = new double *[d];
umax = new double *[d];
stdisplacement = new double *[d-tmd_no];
stdrift = new double *[d-tmd_no];
stdriftmax = new double *[d-tmd_no];


for (i=0; i<d; i++)
{
        globalmass [i] = new double [d];
        globalstiffness [i] = new double [d];
        globaldamping [i] = new double [d];
        pforce [i] = new double [size_accel];
        u [i] = new double [size_accel];
        umax [i] = new double [1];
}

for (i=0; i<(d-tmd_no); i++)
{

        stdisplacement [i] = new double [size_accel];
        stdrift [i] = new double [size_accel];
        stdriftmax [i] = new double [1];
}

uint = new double *[d]; // initial displacement vector "uint"
vint = new double *[d]; // initial velocity vector "vint"
aint = new double *[d]; // initial acceleration vector "aint"
pforceint = new double *[d]; // initial force vector at time zero
umin1 = new double *[d]; // u_minus_01 matrix
u_0 = new double *[d];
u_1 = new double *[d];
phat = new double *[d];
khat = new double *[d]; // khat declaration
ahat = new double *[d]; // ahat declaration
bhat = new double *[d]; // bhat declaration

for (i=0; i<d; i++)
{
        uint [i] = new double [1];
        vint [i] = new double [1];
        aint [i] = new double [1];
        pforceint [i] = new double [1];
        umin1 [i] = new double [1];
        u_0 [i] = new double [1];
        u_1 [i] = new double [1];
        phat [i] = new double [1];
        khat [i] = new double [d];
        ahat [i] = new double [d];
        bhat [i] = new double [d];
}

cdotvint = new double *[d];
kdotuint = new double *[d];
```

```
          mdotaint = new double *[d]; // "mdotaint" is (pforceint - cdotvint - kdotuint)

          for (i=0; i<d; i++)
          {
                    cdotvint [i] = new double [1];
                    kdotuint [i] = new double [1];
                    mdotaint [i] = new double [1];
          }

          ahatdotu_0 = new double *[d];
          bhatdotu_1 = new double *[d];
          ucol = new double *[d];     // declare ucol - u at different time step
          demokhat = new double *[d];
          demoglobalmass = new double *[d];

          for (i=0; i<d; i++)
          {
                    ahatdotu_0 [i] = new double [1];
                    bhatdotu_1 [i] = new double [1];
                    ucol [i] = new double [1];
                    demokhat [i] = new double [d];
                    demoglobalmass [i] = new double [d];
          }

          return 0;
}

//**************************************************************************************
//__08__08__08__08_____Read Text File & Form Dynamic Array Zone_____08__08__08__08__08__08
//**************************************************************************************

double txt_read_form_dynamic_array (char *filename, double *inv)
{
   double i;
          int j=0;
   char *inname = filename;

          ifstream infile(inname);
   if (!infile)
          {
      cout << "There was a problem opening file "
         << inname
         << " for reading."
         << endl;
      return 0;
   }
          while (infile >> i)
          {
                    inv [j]=i;
                    j++;
   }
   return 0;
}

//**************************************************************************************
//__09__09__09__09______Compare DOF Sequence With TMD Sequence______09__09__09__09__09_
```

```
//********************************************************************************************

double mark_tmd_sequence (double *array01, double *array02, int a, int b, double *tf)

{
    int i, j;
    for (i=0; i<a; i++)
    {
        for (j=0; j<b; j++)
        {
            if ((i+1) == array02 [j])
            {
                tf [i] = 1;

                break;
            }
            else
            {
                tf[i] = 0;
            }
        }
        //cout << tf [i]<<endl;
    }

    return 0;
}



//********************************************************************************************
//__10__10__10__10__10____10___________Global Mass Matrix______________10__10__10__10__10
//********************************************************************************************

double global_mass_matrix (double *a, double b, double **c)
{
    for (int i=0; i<b; i++)
    {
        for (int j=0; j<b; j++)
        {
            if (i==j)
            {
                c[i][j] = a [i];
            }
            else
            {
                c [i][j] = 0;
            }
        }
    }
        return 0;
}

//********************************************************************************************
//__11__11__11__11__11_______Global Stiffness & Damping Matrix______11__11__11__11__11__11_
//********************************************************************************************
```

```
double global_stiffness_damping_matrix (double *a, double *tf, double b, double **c)
{
        int i,j;

        for (j=0; j<b; j++)
        {
                for (i=0; i<b; i++)
                {
                        c [i][j] = 0;
                }
        }

        for (j=0; j<b; j++)
        {
                if (tf [j] == 1)
                        {
                                c [j][j] = a [j];
                                c [j+1][j] = - c [j][j];
                        }
                else
                        {
                                int x=0;
                                for (i=(j-2); i<=(j-1); i++)
                                {
                                        if (i>=0)
                                        {
                                                if (tf [j-1] == 1)

                                                {
                                                        c [i][j] = - a [i];
                                                        x = x + c [i][j];
                                                }
                                                else
                                                {
                                                        c [j-1][j] = - a [j-1];
                                                        x = c [j-1][j];
                                                }
                                        }
                                }
                                int n=0;

                                for (i=(j+1); i<=(j+2); i++)

                                {
                                        if (i<b)
                                        {
                                                if (tf [j+1] == 1)

                                                {
                                                        c [i][j] = n;
                                                        n = - a [j];
                                                }
                                                else

                                                {
                                                        c [i][j] = n - a [j];
```

```
                            n = a [j];
                        }
                    }
                }

                c [j][j] = - (x - a [j]);            }
    }

    return 0;
}

//**************************************************************************************
//__12__12__12__12__12__12___________Global Force Matrix_____________12__12__12__12__12_
//**************************************************************************************

double force_matrix (double *a, double *b, double d, double s, double **c)
{
    int i,j;

    for (j=0; j<s; j++)
    {
        for (i=0; i<d; i++)
        {
            c [i][j] = - a [i] * b [j]* 9.81; // El centro NS ground acceleration data in terms of
“g”         }

    }
    return 0;
}

//**************************************************************************************
//__13__13__13__13__13__13________Central Difference Method__________13__13__13__13__13_
//**************************************************************************************

double central_difference_method (double **globalmass, double **globalstiffness, double
**globaldamping, double **pforce, double **u, double p, double q, double delt)

{

    int i,j;

    for (i=0; i<p; i++)
    {
        uint [i][0] = 0;
    }

    for (i=0; i<p; i++)
    {
        vint [i][0] = 0;
    }

    for (i=0; i<p; i++)
    {
        pforceint [i][0] = pforce [i][0];
    }
```

```
// calculate initial acceleration matrix "aint"

matrix_multiplication (globaldamping, vint, cdotvint, p, p, p, 1);
matrix_multiplication (globalstiffness, uint, kdotuint, p, p, p, 1);

for (i=0; i<p; i++)
{
        mdotaint [i] [0] = pforceint [i] [0] - cdotvint [i] [0] - kdotuint [i] [0];
}


for (i=0; i<p; i++)
{
        for (j=0; j<p; j++)
        {
                demoglobalmass [i][j] = globalmass [i][j];
        }
}

matrix_solution_function(demoglobalmass, p, mdotaint, 1, aint);

// calculate khat, ahat, bhat, umin1

for (j=0; j<p; j++)
{
        for (i=0; i<p; i++)
        {
                khat [i][j] = (globalmass [i][j])/(delt*delt) + (globaldamping [i][j])/(2*delt);
        }
}

for (j=0; j<p; j++)
{
        for (i=0; i<p; i++)
        {
                ahat [i][j] = (globalmass [i][j])/(delt*delt) - (globaldamping [i][j])/(2*delt);
        }
}

for (j=0; j<p; j++)
{
        for (i=0; i<p; i++)
        {
                bhat [i][j] = globalstiffness [i][j] - 2*(globalmass [i][j])/(delt*delt);
        }
}

for (i=0; i<p; i++)
{
        umin1 [i][0] = uint [i][0] - delt * (vint [i][0]) + (delt*delt/2) * aint [i][0];
}

for (i=0; i<p; i++)
{
        u_0 [i][0] = umin1 [i][0];
        u_1 [i][0] = uint [i][0];
```

```
          }


// calculate "ucol" at different time step and combine into "u”

          for (j=0; j<q; j++)

          {
                    // calculate ahatdotu_0 and bhatdotu_1

                    matrix_multiplication (ahat, u_0, ahatdotu_0, p, p, p, 1);
                    matrix_multiplication (bhat, u_1, bhatdotu_1, p, p, p, 1);

                    // renew demokhat to khat

                    int x, y;

                    for (x=0; x<p; x++)
                    {
                              for (y=0; y<p; y++)
                              {
                                        demokhat [x][y] = khat [x][y];
                              }
                    }

                    // calculate phat

                    for (i=0; i<p; i++)

                    {
                              phat [i][0] = pforce [i][j] - ahatdotu_0 [i][0] - bhatdotu_1 [i][0];
                    }


                    int flag_matherror =0;

                    for (i=0; i<p; i++)
                    {
                              if (phat [i] [0]> (6*1E+100))
                              {
                                        flag_matherror = 1;
                              }
                    }

                    // solve using Gauss Jordan Elimination

                    if (flag_matherror == 1)
                    {
                              for (i=0; i<p; i++)
                              {
                                        ucol [i][0] = 10000;
                              }
                    }

                    else
                    {
```

```
                        matrix_solution_function(demokhat, p, phat, 1, ucol);
                }

                for (i=0; i<p; i++)
                {
                        u [i][j] = ucol [i][0];
                        u_0 [i][0] = u_1 [i][0];
                        u_1 [i][0] = ucol [i][0];
                }
        }

        return 0;

}


//**************************************************************************************
//__14__14__14__14__14__14________Matrix Multiplication Zone_________14__14__14__14__14__14
//**************************************************************************************

double matrix_multiplication (double **a, double **b, double **c, double row1, double col1, double row2,
double col2)
{
        int i, j, k;

        if (col1 != row2)
        {
                cout<< "matrix multiplication is not possible"<< endl;
        }
        else

        {

        for (i = 0 ; i < row1 ; i++)

        {
                for (j = 0 ; j < col2 ; j++)

                {
                        c[i][j] = 0;

                        for( k = 0 ;k < col1 ; k++)

                        {
                                c[i][j] += a[i][k]*b[k][j];
                        }
                }
        }

        }

        return 0;
}

//**************************************************************************************
//__15__15__15__15__15__15_________Matrix Solution Function__________15__15__15__15__15__
```

```
//**************************************************************************************

void nrerror(char error_text[])
/* Numerical Recipes standard error handler */
{
        fprintf(stderr,"Numerical Recipes run-time error...\n");
        fprintf(stderr,"%s\n",error_text);
        fprintf(stderr,"...now exiting to system...\n");
        exit(1);
}

int *ivector(long nl, long nh)
/* allocate an int vector with subscript range v[nl..nh] */
{
int *v;
v=(int *)malloc((size_t) ((nh-nl+1+NR_END)*sizeof(int)));
if (!v) nrerror("allocation failure in ivector()");
return v-nl+NR_END;
}

void free_ivector(int *v, long nl, long nh)
/* free an int vector allocated with ivector() */
{
free((FREE_ARG) (v+nl-NR_END));
}

double matrix_solution_function(double **a,double n,double **b,double m, double **resultant)

{
        int *indxc,*indxr,*ipiv;
        int i,icol,irow,j,k,l,ll;
        double big,dum,pivinv,temp; //or float??(in nric)

        indxc=ivector(1,n);   /*the integer arrays ipiv,indxr,and indxc are used for
                                                bookkeeping on the pivoting*/
        indxr=ivector(1,n);
  ipiv=ivector(1,n);

        for(j=0;j<n;j++) ipiv[j]=0;
        for(i=0;i<n;i++)   //this is the main loop over the column to be reduced
        {
                big=0.0;
                for(j=0;j<n;j++)  //this is the outer loop of the search for a pivot element
                        if(ipiv[j]!=1)
                                for(k=0;k<n;k++)
                                {
                                        if(ipiv[k]==0)
                                        {
                                                if(fabs(a[j][k])>=big)
                                                {
                                                        big=fabs(a[j][k]);
                                                        irow=j;
                                                        icol=k;
                                                }
                                        }
                                }
```

```
                                        ++(ipiv[icol]);
                                        if(irow!=icol)
                                        {
                                                  for(l=0;l<n;l++) SWAP(a[irow][l],a[icol][l])
                                                            for(l=0;l<n;l++) SWAP(a[irow][l],a[icol][l])
                                        }

                                        indxr[i]=irow;
                                        indxc[i]=icol;
                                        if(a[icol][icol]==0.0) nrerror("gaussj:Singular Matrix");
                                        pivinv=1.0/a[icol][icol];
                                        a[icol][icol]=1.0;

                                        for(l=0;l<n;l++) a[icol][l]*=pivinv;
                                        for(l=0;l<m;l++) b[icol][l]*=pivinv;

                                        for(ll=0;ll<n;ll++)
                                                  if(ll!=icol)
                                                  {
                                                            dum=a[ll][icol];
                                                            a[ll][icol]=0.0;
                                                            for(l=0;l<n;l++) a[ll][l]-=a[icol][l]*dum;
                                                            for(l=0;l<m;l++) b[ll][l]-=b[icol][l]*dum;
                                                  }
          }

          for(l=n;l>=1;l--)
          {
                    if(indxr[l]!=indxc[l])
                              for(k=0;k<n;k++)
                                        SWAP(a[k][indxr[l]],a[k][indxc[l]]);
          }

          free_ivector(ipiv,1,n);
          free_ivector(indxr,1,n);
          free_ivector(indxc,1,n);

          for(int p=0; p<n; p++)
          {
                    resultant [p][0] = b[p][0];
          }

          return 0;
}


//*************************************************************************************
//__16__16__16__16__16__16______Maximum Displacement(Each Story)_____16__16__16__16__16_
//*************************************************************************************

double maximum_displacement_function (double **u, double **umax)
{

          int i, j;
```

```
    for (i=0; i<d; i++)
    {
        umax [i][0] = fabs (u [i][0]);

        for (j=1; j<size_accel; j++)
        {
            if ( fabs (u [i][j]) > umax [i][0] )
            {
     umax [i][0] = fabs (u [i][j]);
            }
        }
    }

    return 0;
}


//*************************************************************************************
//__17__17__17__17__17__17__________Explicit Constraint Function_________17__17__17__17__17_
//*************************************************************************************

void __stdcall EXPCON(int *IFLG,int *ISKP,int *KKT,int *KOUNT,double XMAX[nv],double
XMIN[nv],double XT[nv])
{

    *KOUNT = *KOUNT+1;
    *KKT = *KKT+1;

    int i;

    for (i=0; i<nv; i=i+3)
    {
        XMIN [i] = 0.000001;
        XMAX [i] = 220.000001;

        XMIN [i+1] = 0.000001;
        XMAX [i+1] = 24000.0001;

        XMIN [i+2] = 0.000001;
        XMAX [i+2] = 600.0001;
    }

}


//*************************************************************************************
//__18__18__18__18__18_______Function Value Generated by EVOP_______18__18__18__18__18__
//*************************************************************************************

void __stdcall FUNC(double *F,int *KOUNT,int *KUT,int *N,double XT[nv])
{

    int i;
    int h = 0;

    for (i=0; i<d; i++)
```

```
		{
			if (tf[i] == 1)
			{
				mcol [i] = XT [h];
				h++;
				kcol [i] = XT [h];
				h++;
				ccol [i] = XT [h];
				h++;
			}
		}

		global_mass_matrix (mcol, d, globalmass);
		global_stiffness_damping_matrix (kcol, tf, d, globalstiffness);
		global_stiffness_damping_matrix (ccol, tf, d, globaldamping);
		force_matrix (mcol, accel, d, size_accel, pforce);
		central_difference_method (globalmass, globalstiffness, globaldamping, pforce, u, d, size_accel,
delt);
		maximum_displacement_function (u, umax);

   *KOUNT = *KOUNT+1;
   *KUT = *KUT+1;

   *F = umax[1][0]; // minimize the top story displacement

}

//**************************************************************************************
//__19__19__19__19__19_________Implicit Constraint Function_________19__19__19__19__19__19__
//**************************************************************************************

void __stdcall IMPCON(int *KOUNT,int *M,double XT[nv],double XX[icn],double XXMAX[icn],double
XXMIN[icn])
{

		int i, j;

		double sum_tmdmass = 0;
		double sum_tmdstiffness = 0;
		double sum_tmddamping = 0;

		*KOUNT = *KOUNT + 1;
		*M = *M + 1;

		int s = 0;


		for (i=0; i<d; i++)
		{
			if (tf[i] == 1)
			{
				mcol [i] = XT [s];
				s++;
				kcol [i] = XT [s];
				s++;
				ccol [i] = XT [s];
```

```
            s++;
        }
    }

    for (i=0; i<d; i++)
    {
        if (tf[i] == 1)
        {
            sum_tmdmass = sum_tmdmass + mcol [i];
            sum_tmdstiffness = sum_tmdstiffness + kcol [i];
            sum_tmddamping = sum_tmddamping + ccol [i];
        }
    }


    global_mass_matrix (mcol, d, globalmass);
    global_stiffness_damping_matrix (kcol, tf, d, globalstiffness);
    global_stiffness_damping_matrix (ccol, tf, d, globaldamping);
    force_matrix (mcol, accel, d, size_accel, pforce);

    central_difference_method (globalmass, globalstiffness, globaldamping, pforce, u, d, size_accel,
delt);

    maximum_displacement_function (u, umax);

    double storyheight = 3.048; // height in meter

    int k = 0;

    // to determine "stdisplacement", which is to pick stroy displacements only, from "u" vector

    for (i=0; i<d; i++)
    {
        if (tf [i] == 0)
        {
            for (j=0; j<size_accel; j++)
            {
                stdisplacement [k] [j] = u [i] [j];
                //k++;
            }

            k++;
        }
    }


    for (j=0; j<size_accel; j++)
    {
        for (i=0; i<(d-tmd_no); i++)
        {
            if (i<(d-tmd_no-1))
            {
                stdrift [i] [j] = (stdisplacement [i] [j] - stdisplacement [i+1]
[j])/storyheight;
            }
            else
```

```
                        {
                                stdrift [i] [j] = (stdisplacement [i] [j] - 0)/storyheight;
                        }
                }
        }

        for (i=0; i<(d-tmd_no); i++)
        {
                stdriftmax [i][0] = fabs (stdrift [i][0]);

                for (j=1; j<size_accel; j++)
                {
                        if ( fabs (stdrift [i][j]) > stdriftmax [i][0] )
                        {
         stdriftmax [i][0] = fabs (stdrift [i][j]);
                        }
                }

                // cout<<stdriftmax [i][0]<<endl;
        }


// to find out maximum interstory drift

        maxstdrift = fabs (stdriftmax [0][0]);

        for (j=1; j<(d-tmd_no); j++)
        {
                if ( fabs (stdriftmax [j][0]) > maxstdrift )
                {
       maxstdrift = fabs (stdriftmax [j][0]);
                }
        }

//      cout<< "Maximum story drift is      "<<maxstdrift<<endl;


//***************************************************************************************
*****

        XX[0]= maxstdrift;
        XXMAX[0]= 0.1;
        XXMIN[0]= 0.000001;

        XX[1]= sum_tmdmass;
        XXMAX[1]= 220.000001;
        XXMIN[1]= 0.000001;

        XX[2]= sum_tmdstiffness;
        XXMAX[2]= 24000.000001;
        XXMIN[2]= 0.000001;

        XX[3]= sum_tmddamping;
        XXMAX[3]= 600.000001;
        XXMIN[3]= 0.000001;
 }
```

(b) Minimization of Maximum Inter-Story Drift

```
//*************************************************************************************
//__18__18__18__18__18_______Function Value Generated by EVOP_______18__18__18__18__18__
//*************************************************************************************

void __stdcall FUNC(double *F,int *KOUNT,int *KUT,int *N,double XT[nv])
{
        int i;
        int h = 0;

        for (i=0; i<d; i++)
        {
                if (tf[i] == 1)
                {
                        mcol [i] = XT [h];
                        h++;
                        kcol [i] = XT [h];
                        h++;
                        ccol [i] = XT [h];
                        h++;
                }
        }

        global_mass_matrix (mcol, d, globalmass);
        global_stiffness_damping_matrix (kcol, tf, d, globalstiffness);
        global_stiffness_damping_matrix (ccol, tf, d, globaldamping);
        force_matrix (mcol, accel, d, size_accel, pforce);

        central_difference_method (globalmass, globalstiffness, globaldamping, pforce, u, d, size_accel,
delt);

        maximum_displacement_function (u, umax);


//*************************************************************************************

        int j;

        double storyheight = 3.048; // height in meter

        int k = 0;

        // to determine "stdisplacement", which is to pick stroy displacements only, from "u" vector

        for (i=0; i<d; i++)
        {
                if (tf [i] == 0)
                {
                        for (j=0; j<size_accel; j++)
                        {
                                stdisplacement [k] [j] = u [i] [j];
                                //k++;
                        }
```

```
                        k++;
                }
        }


        for (j=0; j<size_accel; j++)
        {
                for (i=0; i<(d-tmd_no); i++)
                {
                        if (i<(d-tmd_no-1))
                        {
                                stdrift [i] [j] = (stdisplacement [i] [j] - stdisplacement [i+1]
[j])/storyheight;
                        }
                        else
                        {
                                stdrift [i] [j] = (stdisplacement [i] [j] - 0)/storyheight;
                        }
                }
        }


        // Calculate stdriftmax. It contains maximum drift of each story within the whole time period

        for (i=0; i<(d-tmd_no); i++)
        {
                stdriftmax [i][0] = fabs (stdrift [i][0]);

                for (j=1; j<size_accel; j++)
                {
                        if ( fabs (stdrift [i][j]) > stdriftmax [i][0] )
                        {
         stdriftmax [i][0] = fabs (stdrift [i][j]);
                        }
                }
        }

// to find out maximum interstory drift

        maxstdrift = fabs (stdriftmax [0][0]);

        for (j=1; j<(d-tmd_no); j++)
        {
                if ( fabs (stdriftmax [j][0]) > maxstdrift )
                {
       maxstdrift = fabs (stdriftmax [j][0]);
                }
        }


   *KOUNT = *KOUNT+1;
   *KUT = *KUT+1;

   *F = maxstdrift; // minimize the maximum inter-story drift

}
```

```
//*************************************************************************************
//__19__19__19__19__19_________Implicit Constraint Function_________19__19__19__19__19__19__
//*************************************************************************************

void __stdcall IMPCON(int *KOUNT,int *M,double XT[nv],double XX[icn],double XXMAX[icn],double
XXMIN[icn])
{

        int i, j;

        double sum_tmdmass = 0;
        double sum_tmdstiffness = 0;
        double sum_tmddamping = 0;

        *KOUNT = *KOUNT + 1;
        *M = *M + 1;

        int s = 0;

        for (i=0; i<d; i++)
        {
                if (tf[i] == 1)
                {
                        mcol [i] = XT [s];
                        s++;
                        kcol [i] = XT [s];
                        s++;
                        ccol [i] = XT [s];
                        s++;
                }
        }

        for (i=0; i<d; i++)
        {
                if (tf[i] == 1)
                {
                        sum_tmdmass = sum_tmdmass + mcol [i];
                        sum_tmdstiffness = sum_tmdstiffness + kcol [i];
                        sum_tmddamping = sum_tmddamping + ccol [i];
                }
        }

        global_mass_matrix (mcol, d, globalmass);
        global_stiffness_damping_matrix (kcol, tf, d, globalstiffness);
        global_stiffness_damping_matrix (ccol, tf, d, globaldamping);
        force_matrix (mcol, accel, d, size_accel, pforce);

        central_difference_method (globalmass, globalstiffness, globaldamping, pforce, u, d, size_accel,
delt);

        maximum_displacement_function (u, umax);
```

```
//*************************************************************************************

            XX[0]= umax [1][0];
            XXMAX[0]= 0.4;
            XXMIN[0]= 0.000001;


            XX[1]= sum_tmdmass;
            XXMAX[1]= 220.000001;
            XXMIN[1]= 0.000001;

            XX[2]= sum_tmdstiffness;
            XXMAX[2]= 24000.000001;
            XXMIN[2]= 0.000001;

            XX[3]= sum_tmddamping;
            XXMAX[3]= 600.000001;
            XXMIN[3]= 0.000001;


 }
```

APPENDIX B (AN EXAMPLE of EVOP OUTPUT)

INPUT PARAMETERS FOR OPTIMIZATION SUBROUTINE EVOP

```
REFLECTION COEFFICIENT                                  ALPHA =.16000000E+01
CONTRACTION COEFFICIENT                                 BETA =.50000000E+00
EXPANSION COEFFICIENT                                   GAMA =.20000000E+01
EXPLICIT CONSTRAINT RETENTION COEFFICIENT                DEL =.10000000E-11
ACCURACY PARAMETER FOR CONVERGENCE                       PHI =.10000000E-12
PARAMETER FOR DETERMINING COLLAPSE OF A COMPLEX IN A SUBSPACE
                                                             PHICPX = .10000000E-
                                                        16
GLOBAL LIMIT ON THE NUMBER OF CALLS TO FUNCTION SUBROUTINE
                                                             LIMIT = 100000
NUMBER OF COMPLEX RESTARTS                               NRSTRT = 10
NUMBER OF CALLS TO FUNCTION SUBROUTINE AFTER WHICH CONVERGENCE
TESTS ARE MADE                                               KNT =      25
NUMBER OF CONSECUTIVE CONVERGENCE TEST_1           ICON =      5
NUMBER OF VARIABLES = NUMBER OF EXPLICIT
CONSTRAINTS                                                   N =      12
NUMBER OF IMPLICIT CONSTRAINTS                            NIC =      1
NUMBER OF COMPLEX VERTICES                                 K =      13
UPPER BOUND OF EXPLICIT CONSTRAINTS AT THE STARTING POINT
XMAX( 1) =       .55000001E+02
XMAX( 2) =       .60000001E+04
XMAX( 3) =       .15000010E+03
XMAX( 4) =       .55000001E+02
XMAX( 5) =       .60000001E+04
XMAX( 6) =       .15000010E+03
XMAX( 7) =       .55000001E+02
XMAX( 8) =       .60000001E+04
XMAX( 9) =       .15000010E+03
XMAX(10) =       .55000001E+02
XMAX(11) =       .60000001E+04
XMAX(12) =       .15000010E+03
LOWER BOUND OF EXPLICIT CONSTRAINTS AT THE STARTING POINT
XMIN( 1) =       .10000000E-05
XMIN( 2) =       .10000000E-05
XMIN( 3) =       .10000000E-05
XMIN( 4) =       .10000000E-05
XMIN( 5) =       .10000000E-05
XMIN( 6) =       .10000000E-05
XMIN( 7) =       .10000000E-05
XMIN( 8) =       .10000000E-05
XMIN( 9) =       .10000000E-05
XMIN(10) =       .10000000E-05
XMIN(11) =       .10000000E-05
XMIN(12) =       .10000000E-05
```

```
COORDINATES OF THE STARTING POINT
XT( 1) =     .40000000E+02
XT( 2) =     .13500000E+03
XT( 3) =     .27600000E+02
XT( 4) =     .40000000E+02
XT( 5) =     .57600000E+04
XT( 6) =     .14800000E+03
XT( 7) =     .40000000E+02
XT( 8) =     .31500000E+04
XT( 9) =     .10900000E+03
XT(10) =     .40000000E+02
XT(11) =     .11900000E+04
XT(12) =     .67100000E+02

UPPER BOUND OF IMPLICIT CONSTRAINTS AT THE STARTING POINT
XXMAX( 1) =     .10000000E+00

LOWER BOUND OF IMPLICIT CONSTRAINTS AT THE STARTING POINT
XXMIN( 1) =     .10000000E-05

IMPLICIT CONSTRAINTS AT THE STARTING POINT
XX( 1) =     .24619301E-01

FUNCTION VALUE AT THE STARTING POINT
FF( 1) =     .27866478E+00
```

OUTPUT SUMMARY FROM SUBROUTINE EVOP

```
   MINIMUM OF THE OBJECTIVE FUNCTION HAS BEEN LOCATED TO THE DESIRED
DEGREE OF ACCURACY FOR CONVERGENCE.  IER = 8
   TOTAL NUMBER OF OBJECTIVE FUNCTION EVALUATION.
NFUNC =    452
   NUMBER OF TIMES THE SUBROUTINE FUNCTION IS CALLED DURING THE
PRESENT CONVERGENCE TESTS. KUT =      6
   NUMBER OF TIMES THE EXPLICIT CONSTRAINTS WERE EVALUATED
KKT =    890
   NUMBER OF TIMES THE IMPLICIT CONSTRAINTS WERE EVALUATED
M =    731
   COORDINATES OF THE MINIMUM
                                                XT( 1) =     .54998896E+02
                                                XT( 2) =     .17524928E+04
                                                XT( 3) =     .10535050E-01
                                                XT( 4) =     .40568367E+02
                                                XT( 5) =     .60000001E+04
                                                XT( 6) =     .77072470E-02
                                                XT( 7) =     .41827272E-01
                                                XT( 8) =     .10929154E+01
                                                XT( 9) =     .15000010E+03
                                                XT(10) =     .54999772E+02
                                                XT(11) =     .17385133E+04
```

```
                                                      XT(12) =       .44974803E-02

    OBJECTIVE FUNCTION VALUE AT THE MINIMUM                F =.25375630E+00
    IMPLICIT CONSTRAINT VALUES AT THE MINIMUM             XX( 1) =.28468620E-01
    UPPER BOUNDS OF EXPLICIT CONSTRAINTS AT THE MINIMUM
XMAX( 1) =       .55000001E+02
 XMAX( 2) =       .60000001E+04
 XMAX( 3) =       .15000010E+03
 XMAX( 4) =       .55000001E+02
 XMAX( 5) =       .60000001E+04
 XMAX( 6) =       .15000010E+03
 XMAX( 7) =       .55000001E+02
 XMAX( 8) =       .60000001E+04
 XMAX( 9) =       .15000010E+03
 XMAX(10) =       .55000001E+02
 XMAX(11) =       .60000001E+04
 XMAX(12) =       .15000010E+03
    LOWER BOUNDS OF EXPLICIT CONSTRAINTS AT THE MINIMIM
XMIN( 1) =       .10000000E-05
 XMIN( 2) =       .10000000E-05
 XMIN( 3) =       .10000000E-05
 XMIN( 4) =       .10000000E-05
 XMIN( 5) =       .10000000E-05
 XMIN( 6) =       .10000000E-05
 XMIN( 7) =       .10000000E-05
 XMIN( 8) =       .10000000E-05
 XMIN( 9) =       .10000000E-05
 XMIN(10) =       .10000000E-05
 XMIN(11) =       .10000000E-05
 XMIN(12) =       .10000000E-05
    UPPER BOUNDS OF IMPLICIT CONSTRAINTS AT THE MINIMUM
XXMAX( 1) =       .10000000E+00
    LOWER BOUNDS OF IMPLICIT CONSTRAINTS AT THE MINIMUM
XXMIN( 1) =       .10000000E-05



 FINAL COMPLEX CONFIGURATION
         VERTICE NUMBER         FUNCTION VALUE              COORDINATES

              1              .25377337E+00
                                              XT( 1) =    .54999638E+02
                                              XT( 2) =    .17384014E+04
                                              XT( 3) =    .37204241E-02
                                              XT( 4) =    .40417277E+02
                                              XT( 5) =    .59999336E+04
                                              XT( 6) =    .24738152E-02
                                              XT( 7) =    .15046631E-01
                                              XT( 8) =    .39558217E+00
                                              XT( 9) =    .14999207E+03
                                              XT(10) =    .54999925E+02
```

```
                        XT(11) =    .17560375E+04
                        XT(12) =    .14699576E-02

2           .25376523E+00
                        XT( 1) =    .54999690E+02
                        XT( 2) =    .17427215E+04
                        XT( 3) =    .29657774E-02
                        XT( 4) =    .40459315E+02
                        XT( 5) =    .59999364E+04
                        XT( 6) =    .21714337E-02
                        XT( 7) =    .11782035E-01
                        XT( 8) =    .30763538E+00
                        XT( 9) =    .14999180E+03
                        XT(10) =    .54999937E+02
                        XT(11) =    .17508512E+04
                        XT(12) =    .12645275E-02

3           .25377782E+00
                        XT( 1) =    .54999442E+02
                        XT( 2) =    .17394829E+04
                        XT( 3) =    .53863037E-02
                        XT( 4) =    .40462416E+02
                        XT( 5) =    .59998958E+04
                        XT( 6) =    .39647118E-02
                        XT( 7) =    .21527426E-01
                        XT( 8) =    .55930779E+00
                        XT( 9) =    .14998741E+03
                        XT(10) =    .54999885E+02
                        XT(11) =    .17553564E+04
                        XT(12) =    .22684441E-02

4           .25375630E+00
                        XT( 1) =    .54998896E+02
                        XT( 2) =    .17524928E+04
                        XT( 3) =    .10535050E-01
                        XT( 4) =    .40568367E+02
                        XT( 5) =    .60000001E+04
                        XT( 6) =    .77072470E-02
                        XT( 7) =    .41827272E-01
                        XT( 8) =    .10929154E+01
                        XT( 9) =    .15000010E+03
                        XT(10) =    .54999772E+02
                        XT(11) =    .17385133E+04
                        XT(12) =    .44974803E-02

5           .25377650E+00
                        XT( 1) =    .54999503E+02
                        XT( 2) =    .17460620E+04
                        XT( 3) =    .48386771E-02
                        XT( 4) =    .40461520E+02
                        XT( 5) =    .59999129E+04
```

```
                      XT( 6) =   .35738629E-02
                      XT( 7) =   .19411367E-01
                      XT( 8) =   .50272594E+00
                      XT( 9) =   .14999008E+03
                      XT(10) =   .54999897E+02
                      XT(11) =   .17495611E+04
                      XT(12) =   .20219851E-02

6         .25376079E+00
                      XT( 1) =   .55000001E+02
                      XT( 2) =   .17310617E+04
                      XT( 3) =   .10000000E-05
                      XT( 4) =   .40401692E+02
                      XT( 5) =   .60000001E+04
                      XT( 6) =   .10000000E-05
                      XT( 7) =   .67322897E-02
                      XT( 8) =   .10000000E-05
                      XT( 9) =   .15000010E+03
                      XT(10) =   .55000001E+02
                      XT(11) =   .17640892E+04
                      XT(12) =   .10000000E-05

7         .25376669E+00
                      XT( 1) =   .54999542E+02
                      XT( 2) =   .17429908E+04
                      XT( 3) =   .44594033E-02
                      XT( 4) =   .40525715E+02
                      XT( 5) =   .59999197E+04
                      XT( 6) =   .32937504E-02
                      XT( 7) =   .17889594E-01
                      XT( 8) =   .46331230E+00
                      XT( 9) =   .14999086E+03
                      XT(10) =   .54999905E+02
                      XT(11) =   .17465593E+04
                      XT(12) =   .18635399E-02

8         .25376028E+00
                      XT( 1) =   .55000001E+02
                      XT( 2) =   .17482060E+04
                      XT( 3) =   .10000000E-05
                      XT( 4) =   .40441811E+02
                      XT( 5) =   .60000001E+04
                      XT( 6) =   .10000000E-05
                      XT( 7) =   .10000000E-05
                      XT( 8) =   .10000000E-05
                      XT( 9) =   .15000010E+03
                      XT(10) =   .55000001E+02
                      XT(11) =   .17485713E+04
                      XT(12) =   .10000000E-05

9         .25375790E+00
```

```
                          XT( 1) =    .55000001E+02
                          XT( 2) =    .17512767E+04
                          XT( 3) =    .10000000E-05
                          XT( 4) =    .40502748E+02
                          XT( 5) =    .60000001E+04
                          XT( 6) =    .10000000E-05
                          XT( 7) =    .10000000E-05
                          XT( 8) =    .10000000E-05
                          XT( 9) =    .15000010E+03
                          XT(10) =    .55000001E+02
                          XT(11) =    .17450500E+04
                          XT(12) =    .10000000E-05

10          .25377659E+00
                          XT( 1) =    .54999357E+02
                          XT( 2) =    .17498667E+04
                          XT( 3) =    .63226554E-02
                          XT( 4) =    .40637608E+02
                          XT( 5) =    .59998881E+04
                          XT( 6) =    .44677968E-02
                          XT( 7) =    .24823225E-01
                          XT( 8) =    .66479934E+00
                          XT( 9) =    .14998680E+03
                          XT(10) =    .54999873E+02
                          XT(11) =    .17355613E+04
                          XT(12) =    .24518495E-02

11          .25377924E+00
                          XT( 1) =    .54998181E+02
                          XT( 2) =    .17399738E+04
                          XT( 3) =    .16556883E-01
                          XT( 4) =    .40490477E+02
                          XT( 5) =    .59996911E+04
                          XT( 6) =    .12598166E-01
                          XT( 7) =    .58861200E-01
                          XT( 8) =    .16913699E+01
                          XT( 9) =    .14996717E+03
                          XT(10) =    .54999622E+02
                          XT(11) =    .17533503E+04
                          XT(12) =    .75997143E-02

12          .25377375E+00
                          XT( 1) =    .54999742E+02
                          XT( 2) =    .17445768E+04
                          XT( 3) =    .24656977E-02
                          XT( 4) =    .40454910E+02
                          XT( 5) =    .59999625E+04
                          XT( 6) =    .18040642E-02
                          XT( 7) =    .97872752E-02
                          XT( 8) =    .25571495E+00
                          XT( 9) =    .14999578E+03
```

```
                              XT(10) =    .54999947E+02
                              XT(11) =    .17508618E+04
                              XT(12) =    .10530611E-02

 13           .25376322E+00
                              XT( 1) =   .54999554E+02
                              XT( 2) =   .17409299E+04
                              XT( 3) =   .43765695E-02
                              XT( 4) =   .40450171E+02
                              XT( 5) =   .59999206E+04
                              XT( 6) =   .30317568E-02
                              XT( 7) =   .16979564E-01
                              XT( 8) =   .45949566E+00
                              XT( 9) =   .14999088E+03
                              XT(10) =    .54999908E+02
                              XT(11) =    .17510951E+04
                              XT(12) =    .18209678E-02
```