JIMMA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

JIMMA INSTITUTE OF TECHNOLOGY

FACULTY OF CIVIL AND ENVIRONMENTAL ENGINEERING

STRUCTURAL ENGINEERING STREAM

OPTIMUM DESIGN OF TUNED LIQUID DAMPER FOR VIBRATION CONTROL OF FRAME STRUCTURES UNDER SEISMIC EXCITATION.

By

BIRUK WOLDEGABREAL

A Thesis Submitted to the School of Graduate Studies of Jimma University in Partial Fulfillment of the Requirements for the Degree of Master of Science in Civil Engineering. (Structural Engineering)

October, 2017

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Advisor: Engr. Elmer C. Agon (Ass. Prof.)

Co-Advisor: Engr. Vinoth Raj Kumar

October, 2017

Jimma, Ethiopia

DECLARATION

I, the under signed, declare that this thesis entitled "**Optimum design of tuned liquid damper for vibration control of frame structures under seismic excitation**" is my original work, and has not been presented by any other person for an award of Degree in this or any other university, and all sources of materials used for the thesis have been duly acknowledged.

Candidate: Biruk Woldegabreal

Signature: _______________

As Master research Advisors, we hereby certify that we have read and evaluated this MSc. research prepared under our guidance, by Biruk Woldegabreal entitled "**Optimum design of tuned liquid damper for vibration control of frame structures under seismic excitation**". We recommend that it can be submitted as fulfilling the MSc thesis requirements.

1. Engr. Elmer C. Agon (Ass. Prof.) __________________ _____________
   Advisor Signature Date
2. Engr. Vinoth Raj Kumar __________________ _____________
   Co-Advisor Signature Date

Place and Date of submission: Faculty of Civil and Environmental Engineering
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ABSTRACT

Current trends in construction industry demands taller and lighter structures, which are also more flexible and having quite low damping value. This increases failure possibilities and also problems from serviceability point of view due to the vibration of structure. There are some effective techniques available to minimize the vibration of structures; Tuned Liquid Damper (TLD) is one of the techniques available to minimize the vibration of the structure. Tuned Liquid Damper is the most economically and environmentally sustainable system, because no power source is required for its operation, free of maintenance, ease of frequency tuning and reduction of motion in two directions simultaneously.

The objective of this research was to prepare optimum design of TLD for vibration control of frame structures under seismic excitation. Analytical analysis was made to investigate the response of the frame structure models fitted with a TLD. Time history analysis was carried out in SAP2000 using the nonlinear transient dynamic analysis. A standard multi-degree of freedom system was investigated to evaluate TLD protection efficiency in case of excitation by using rectangular tanker as liquid damper. To prepare optimum design for TLD it was needed to optimize analytically the passive parameters of the TLD.

A total of five loading conditions were applied at the base of the structure. For optimization design of the damper parametric studies were done using dynamic parameters such as depth ratio and mass ratio. The effectiveness of the TLD was calculated in terms of percentage of reduction of displacements and peak acceleration of the structure.

The results of the study show that TLDs are effective in reducing structural vibrations and the highest structural response reduction has been found from optimum design of the damper which is 48.72% reduction of the structural response. The optimum water depth ratio and mass ratio have found to be 0.122 and 3.5% respectively. From this study, it can be concluded that properly designed TLD with optimum design parameters are considered to be very effective device to reduce the structural response. Further works are required to achieve optimum design of the damper to better protect building structures.

Keywords: Tuned Liquid Damper (TLD), Optimization, Damping

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ACRONYMS

List of Abbreviation

BLD	Bi-Directional Liquid Dampers
DTLCD	Double Tuned Liquid Column Damper
DV	Design Vector
ER	Electro Rheological
HTLCD	Hybrid Tuned Liquid Column Damper
LCVA	Liquid Column Vibration Absorbers
MDOF	Multi Degree of Freedom
MR	Magneto Rheological
MTLCD	Modified Tuned Liquid Column Dampers
OF	Objective Function
PED	Passive Energy Dissipation
PTLCD	Pressurized Tuned Liquid Column Damper
SAP	Structural Analysis Program
SDOF	Single Degree of Freedom
SLD	Sloshing Liquid Damper
TLCD	Tuned Liquid Column Damper
TLD	Tuned Liquid Damper
TMD	Tuned Mass Damper
TSD	Tuned Sloshing Damper

2-D	Two Dimensional
3-D	Three Dimensional

List of Symbols

b	The design vector
f	The natural vibration frequency
f_s	The fundamental linear sloshing frequency
h	Water depth
L	The tank length
m_s	The structure mass
m_w	The mass of water
p_f	The failure probability
R	The admissible domain
T	The vibration duration
X_d	The limitation to displacement
$X_T$max	The admissible TLD displacement
β	The frequency ratio
Δ	The water depth ratio
μ	The mass ratio

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Building structures form a greater part of our society‘s infrastructure system whose proper functioning is essential for sheltering and also it has been used in any type and forms since history of mankind. Similar to other types of infrastructure assets, building structures members can exposed to different type of failures over time due to many reasons, generally due to designing problems and natural disasters like flood, soil sliding and earthquake. With the development of mankind towards designing technologies and construction methods building structures become ever increasing in heights and the use of light-weight, high strength materials, and advanced construction techniques have led to increasingly flexible and lightly damped structures. Causing, these structures to be very sensitive to environmental excitations such as wind, ocean waves and earthquakes. This causes unwanted vibrations inducing possible structural failure, occupant discomfort, and malfunction of equipment. Therefore, it has become important to search ways for practical and effective devices for reducing and if possible, preventing these vibrations which causes structural failures to preserve these capital intensive assets to ensure they perform as expected.

Current building construction trends favor the use of composite and lightweight materials for component and cladding and partitions in order to reduce costs. Advancement in post tensioned technology and use of lightweight concrete composite floor slabs permit reduced thickness and longer spans further reducing costs. Unfortunately the resulting cost reduction also reduces the inherent damping of a structure and consequently, supplemental damping must be used to mitigate wind and seismic oscillations.

The number of tall buildings being built is increasing day by day. Mostly these structures are having low natural damping. So increasing damping capacity of a structural system, or considering the need for other mechanical means to increase the damping capacity of a building, has become increasingly common in the increasing number of tall and super tall buildings. But, it should be made a routine design practice to design the damping capacity into a structural system while designing the structural system.

Regardless of the number of stories and the method of bracing, beyond a certain height, the contribution of the inherent damping characteristics of the structure and the floor dead weight diminish and supplemental damping systems need to be explored as buildings grow taller [36].

The control of structural vibrations produced by earthquake or wind can be done by various means such as modifying rigidities, masses, damping, or shape, and by providing passive or active counter forces. To date, some methods of structural control have been used successfully and newly proposed methods offer the possibility of extending applications and improving efficiency [9].

The selection of a particular type of vibration control device is governed by a number of factors which include efficiency, compactness and weight, capital cost, operating cost, maintenance requirements and safety [36].

Energy dissipating devices (Structural Controls) commonly used structural control to dissipate earthquake-induced forces. Structural controls devices can categorized in different groups depending on their power supply system. These are; Passive, Active, Hybrid and Semi-Active. Passive control devices are systems which do not require an external power source which is common in the case of natural disasters like earthquake. Common examples of passive energy dissipation devices are; base isolation, viscoelastic dampers, tuned mass dampers and tuned liquid dampers.

One of currently used passive control device is Tuned Liquid Damper (TLD), which consists rigid tanks filled with shallow liquid, which is located commonly at the top of the building where the sloshing motion absorbs the energy and dissipates it through viscous action of the liquid wave breaking. Advantages associated with TLDs include low initial cost, virtually free of maintenance and ease of frequency tuning, reduction of motion in two directions simultaneously and can be implemented on existing structures.

1.2 Statement of the Problem

Among the techniques available to minimize vibration of the structure; Passive control devices are systems which do not require external energy supply. Such systems are reliable since they are unaffected by power outages, which are common during natural calamities. And one of passive structural control devices is Tuned Liquid Damper (TLD). Thus far, TLDs are newly used strategies on the implementation for vibration control in many engineering applications. Therefore, there is a need to develop an integrated computational tool to study the effectiveness of TLDs on reducing earthquake induced oscillations in to building structures. This research paper has studied on implementation of TLD for vibration control of frame structure. In doing so due to increasing global competitive market, engineering designs are pushed to the limit of the design constraint boundaries using optimization design. Therefore, it was essential to consider and use economical design approach by using optimization techniques which is the most crucial concept in engineering applications. To achieve an optimized system, parametric studies were done. The parameters studied are mass ratio; ratio of mass of damper to structure and water depth ratio; ratio of stationery liquid height to length of the tank. Therefore, this research paper has studied to develop the optimum design of tuned liquid damper for vibration control of frame structures under seismic excitation.

Catastrophic failures occur in civil engineering structures, such as buildings and bridges, during seismic events. Structures are very sensitive to earthquakes. Earthquakes cause unwanted vibrations inducing possible structural failure, occupant discomfort, and malfunction of equipment. The current trends in construction industry demands taller and lighter structures, which are also more flexible and having quite low damping value. This increases failure possibilities and also problems from serviceability point of view due to vibration of structure caused by earthquake. This causes structural failure, occupant discomfort, malfunctions of equipment and socially as well as economically creates negative influence on the society who are facing earthquake. Therefore, it has become important to search ways for practical and effective devices for reducing these vibrations to preserve and ensure the building structures perform as expected.

The motives behind this research paper was that now a days building structures become flexible and lightly damped because of construction industries start to use materials that are the output of advanced technology which have light-weight, high strength and start constructing very long structures. When these structures exposed to environmental excitation such as earthquakes, they easily affected by earthquake vibrations and it creates structures to causes unwanted vibrations that leads to structural failure, malfunction of equipment, occupant discomfort and even exposing injury and death to human beings which are being inside or around building structures. Having in mind these earthquake doesn’t kill by itself alone but due to lack of having properly damped building structure; creating fear of being inside building structures on society who have using it even though it should help for sheltering in case of natural disasters. Therefore, it has become important to search ways for practical and effective devices for reducing these vibrations; to make the users feel safe, to create safe environment when the users are inside or around it and to preserve these capital intensive assets to perform as expected. And also protecting society from such kind of loses are the duty of the professionals.

1.3 Objectives of the study

1.3.1 General Objective

- The general objective of the study was to optimize the design of tuned liquid damper for vibration control of framed structures under seismic excitation.

1.3.2 Specific Objective

To support the above general objective, the following specific objectives were addressed.

- To investigate the effect of TLD on the dynamic response of multi-storey frame structures under seismic excitations.
- To investigate the effect of depth ratio of TLD for optimum design of the damper.
- To investigate the effect of mass ratio of TLD to structure for optimum design of the damper.
- To evaluate the dynamic parameters of TLD those affect the vibration of structures.

1.4 Research Questions

The research focused towards optimum design of tuned liquid damper for vibration control of framed structures under seismic excitation. And in doing so, it will try to raise and answer the following questions.

1. What is the effect of TLD on the dynamic response of multi-storey frame structures under seismic excitations?
2. What is the effect of depth ratio of TLD for optimum design of the damper?
3. What is the effect of mass ratio of TLD to structure for optimum design of the damper?
4. Which dynamic parameters of TLD can affect the vibration of structures?

1.5 Significance of the Study

Today, catastrophic failures occur in civil engineering structures, such as buildings and bridges, during seismic events like earthquake excitations. One of the main challenges in structural engineering is to develop mitigating design concepts to better protect civil engineering structures, including their material contents and human occupants from these hazards. This study therefore made an attempt to contribute searching for practical, effective and economical devices for structural control of vibrations produced by earthquake excitation by developing the design of TLD based on shallow water wave theory to provide optimum design of tuned liquid damper for vibration control of frame structures under seismic excitation.

Hence, this study is also useful to examine the structural controlling system of seismic excitations specifically for TLD's and their effects on minimizing and controlling seismic events. Analytical formulas and graphical charts were developed to determine the optimal parameters of TLD which helped to show how to choose the optimum length and height of tank, mass of water inside the tanker and methods of optimizing structural controlling devices as a general.

The results of this study can be an input for whom work and study on earthquake disaster mitigation and prevention systems. It will also serve as a reference material to further research in this study area and also for researchers who work to improve and develop TLD's on mitigation and prevention of earthquake excitations.

1.6 Scope and Limitations of the Study

The effectiveness of passive TLD depends on how effectively the parameters are optimized and the frequency of TLD tuned to that of the natural frequency of the structure and upon the issue in implementing the TLD is the additional dead load it imposes on the structure and in turn on the foundation. To address these issues this study arrived at optimizing the dynamic parameters of passive TLD subjected to seismic excitation.

This study was considered the determination of the optimum parameters of TLD to minimize dynamic response of multi-storied building system. To optimize dynamic parameters of the TLD system for minimum top deflection of the structure, optimization analysis were used.

Analytical formulas and graphical charts were developed to determine the optimal parameters of TLD.

TLD has been studied by several researchers. Kareem et al. [58] and Venkateswara [55] have found that TLD have no restriction to unidirectional vibration and reduction of motion in two directions simultaneously can be possible which the advantage of using TLDs is. The analyses which were made for 2-D frame structure can be used for the other direction since there no restriction to unidirectional control of vibration in case of TLDs. Therefore, the researcher has used 2-D frame structure for analysis.

The scope of this work is limited by the analysis and design of TLD and the excitation force applied to building structure and studying the effect of TLD dynamic parameters in structural damping and on the structure at a theoretical level. Laboratory tests were not executed. Mass ratios and water depth ratios were considered for parametric investigation of the damper. Excitation frequency ratios were not used as a parameter for parametric investigation. Because structural oscillation frequencies can be variable in some range due to different factors and it can be hard to perfectly tune damper for specific structure and it is one of the main disadvantages of liquid dampers that only one main oscillation frequency is damped.

Rectangular tanker was used as liquid damper. Two dimensional multi-storey frame structure having 10 storey models were modelled using Structural Analysis Program (SAP2000). Time history analyses were carried out by using the Non Linear transient dynamic analysis to investigate the effect of TLD on the dynamic response of multi-storey frame structures under seismic excitations.

1.7 Operational definition

Damping: is defined as the ability of the structure to dissipate a portion of the energy released during a dynamic loading event and thus one of the most important parameters that limit the response of the structures.

Optimization: is defined as the process of finding the conditions that give the minimum (or maximum) value of a function, where the function represents the effort required (or the desired benefit).

CHAPTER TWO

LITERATURE REVIEW

2.1 General

Today, one of the main challenges in structural engineering is to develop innovative design concepts to better protect civil engineering structures, including their material contents and human occupants from these hazards. Some of the mitigation measures are; the Conventional Approach and Innovative Approach. The Conventional Approach depends upon providing the building with strength, stiffness and inelastic deformation capacity which are great enough to withstand a given level of earthquake-generated force. This is generally accomplished through the selection of an appropriate structural configuration and the carefully detailing of structural members, such as beams and columns, and the connections between them. Innovative Approach in contrast, the basic approach underlying more advanced techniques for earthquake resistance is not to strengthen the building, but to reduce the earthquake-generated forces acting upon it. By de-coupling the structure from seismic ground motion it is possible to reduce the earthquake-induced forces in it and mechanical systems are employed to reduce or control structural responses. This can be done by using base isolation or by using energy dissipating devices (Structural Controls) [1].

Energy dissipating devices (Structural Controls) commonly used structural control to dissipate earthquake-induced forces. Structural controls devices can categorized in different groups depending on their power supply system. These are: Passive structural control devices, Active structural control devices, Hybrid structural control devices and Semi-Active structural control devices. Energy dissipation devices do not involve period elongation or fuse formation. Allows earthquake energy in to the building. Energy dissipation devices are located within the lateral resisting elements to intercept the incoming energy. The intercepted energy will be changed in to heat energy which will be dissipated in to the surrounding [18].

Passive control devices are systems which do not require an external power source which is common in the case of natural disasters like earthquake. These devices impart forces that are developed in response to the motion of the structure. Basic important features of passive energy dissipation devices are; operating without any external energy supply, relatively inexpensive compact and non-invasive to architectural spaces and limits exist on the amount of control attainable. Common examples of passive energy dissipation devices are; base isolation, viscoelastic dampers, tuned mass dampers and tuned liquid dampers [1].

One of currently used passive control device is the Tuned Liquid Damper (TLD), which consists of rigid tanks filled with shallow liquid, which is located commonly at the top of the building where the sloshing motion absorbs the energy and dissipates it through viscous action of the liquid wave breaking and consists auxiliary damping appurtenances such as nets or floating beads. The natural frequency of the fluid is made to match one of the natural frequencies of the vibratory system. Advantages associated with TLDs include low initial cost, virtually free of maintenance and ease of frequency tuning, reduction of motion in two directions simultaneously and can be implemented on existing structures [58].

With the increase of the number and the slenderness of tall buildings, there is need to study structural oscillations of frame structure buildings during a seismic event. In dynamically slender buildings, where the building footprint is much smaller than the building height, inherent damping or core wall stiffness may be insufficient to keep oscillations within acceptable thresholds, as assumptions about the inherent damping of the structure which are in the range of 2% -5% of critical for buildings may not meet the level of damping required. Consequently, supplemental damping must be provided [36].

2.2 Seismic Protection Systems

2.2.1 Conventional Systems

These systems are based on traditional concepts and use of stable inelastic hysteresis to dissipate energy. This mechanism can be reached by plastic hinging of columns, beams or walls, during the axial behavior of brace elements by yielding in tension or buckling in compression or through the shear hinging of steel members [24].

2.2.2 Isolation Systems

Isolation systems are usually employed between the foundation and base elements of the buildings and between the deck and the piers of bridges. These systems are designed to have less amount of lateral stiffness relative to the main structure in order to absorb more of the earthquake energy. A supplemental damping system could be attached to the isolation system to reduce the displacement of the isolated structure as a whole [24].

2.2.3 Supplemental Damping Systems

The control of structures subjected to seismic excitation represents a challenging task for the civil engineering profession. The purpose of vibration control has two fold. One is to improve habitability during strong winds or in moderate earthquakes; the other is to prevent damage to main frame of the structure during severe earthquakes.

The supplemental damping system can be categorized in four groups as: passive, active, semi-active and hybrid control systems. These dampers are activated by the movement of the structure and decrease the structural displacements by dissipating energy via different mechanisms [24]. They are described briefly in the following sections.

2.2.3.1 Active Systems

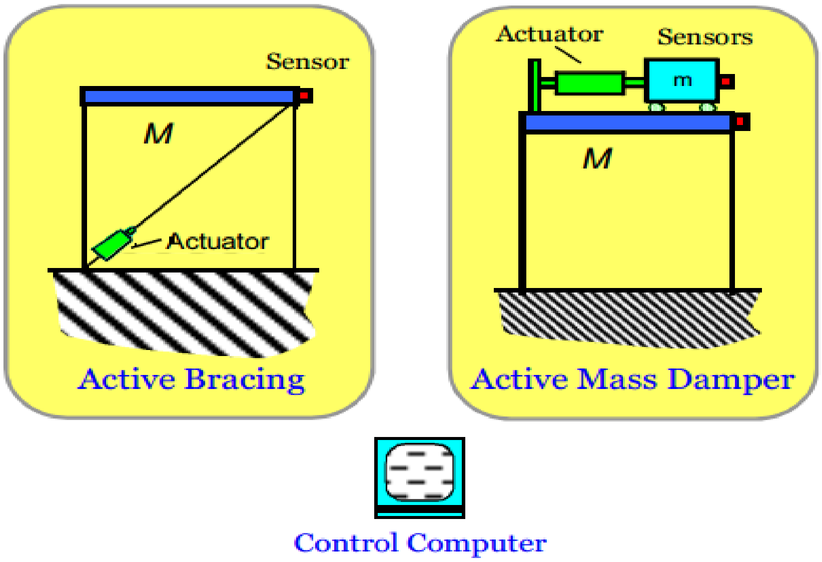

Figure 2.1 Structures with Active Control [21]

Active systems monitor the structural behavior, and after processing the information, in a short time, generate a set of forces to modify the current state of the structure. Generally, an active control system is made of three components: a monitoring system that is able to perceive the state of the structure and record the data using an electronic data acquisition system; a control system that decides the reaction forces to be applied to the structure based on the output data from monitoring system and; an actuating system that applies the physical forces to the structure. To accomplish all this, an active control system needs a continuous external power source. The loss of power that might be experienced during a catastrophic event may render these systems ineffective [20].

2.2.3.2 Semi-Active Systems

A semi-active control system may be defined as a system which typically requires an operation power source, but less than that of active system for its operation and utilizes the motion of the structure to develop the control forces, the magnitude of which can be adjusted by the external power source. It originates from a passive control system in that the control forces are developed as a result of the motion of the structure. The control forces are developed through appropriate (based on predetermined control algorithm) adjustment of the mechanical properties of the semi-active control system. As in an active control system, a controller monitors the feedback measurements and generates an appropriate command signal for semi-active device.

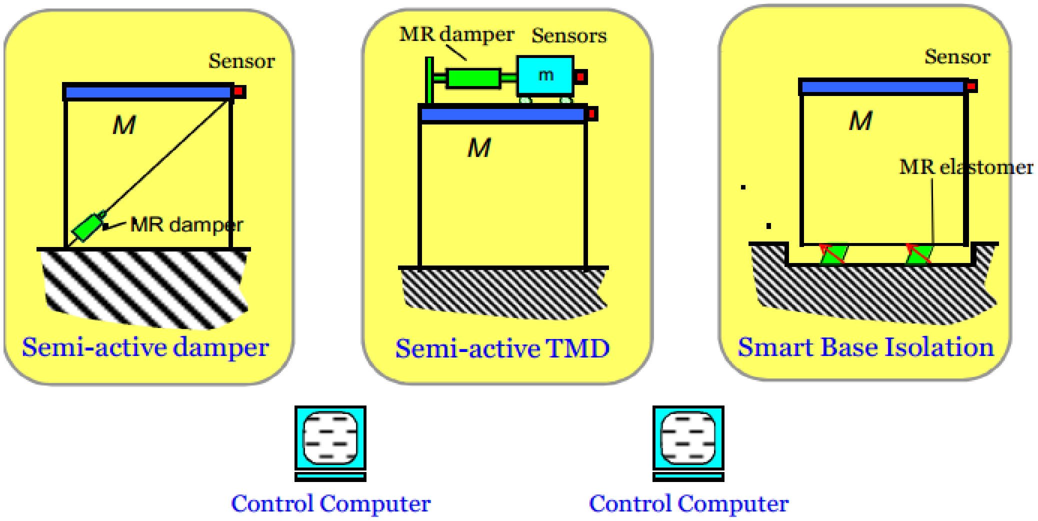

Figure 2.2 Structure with Semi-Active Control [21]

Semi-active systems are similar to active systems except that compared to active ones they need less amount of external power. Instead of exerting additional forces to the structural systems, semi-active systems control the vibrations by modifying structural properties (for example damping modified by controlling the geometry of orifices in a fluid damper). The need for external power source has also limited the application of semi-active systems [18].

The advantage of such system is that it can operate on battery power, which is critical during seismic events when the main power source to the structure may fail. These systems cannot inject mechanical energy into the structure and hence do not have the potential to destabilize the structural system. Examples of such devices are variable-orifice fluid dampers, variable stiffness dampers, controllable friction devices, smart tuned mass dampers and tuned liquid dampers, controllable fluid dampers and controllable impact dampers [49].

2.2.3.3 Hybrid Control System

A Hybrid control system employs the combination of passive and active devices. Because multiple control devices are operating, hybrid control systems can alleviate some of the restriction and limitation that exist when each system is acting alone. Thus higher levels of performance may be achievable. The benefit of this system is that, in the case of power failure, the passive components of the control still offer some degree of protection. Hybrid systems are installed in the form of Hybrid mass damper system and hybrid base isolation [50].

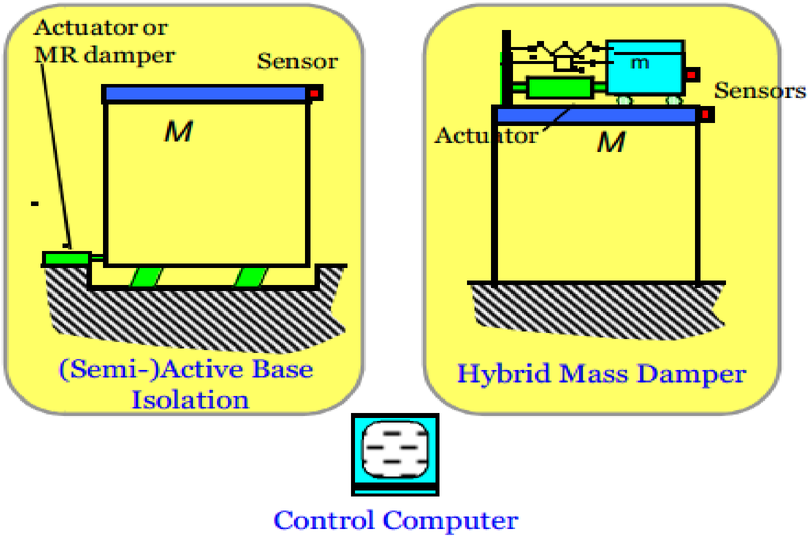

Figure 2.3 Structures with Hybrid Control [21]

2.2.3.4 Passive Systems

Passive systems dissipate part of the structural seismic input energy without any need for external power source. Their properties are constant during the seismic motion of the structure and cannot be modified. Passive control devices have been shown to work efficiently. Those are robust and cost-effective. As such, they are widely used in civil engineering structures [18].

A passive control system may be defined as a system which does not require external power source for operation and utilizes the motion of the structure to develop the control forces. The control forces are developed as a function of the response of the structure at the location of the passive control system. Systems in this category are very reliable since they are unaffected by power outages which are common during earthquakes. Since they do not inject energy into the system, they are unable to destabilize the structure and they have low maintenance requirements. Passive control systems are limited in that; they cannot deal with the change of either external loading conditions or usage pattern.

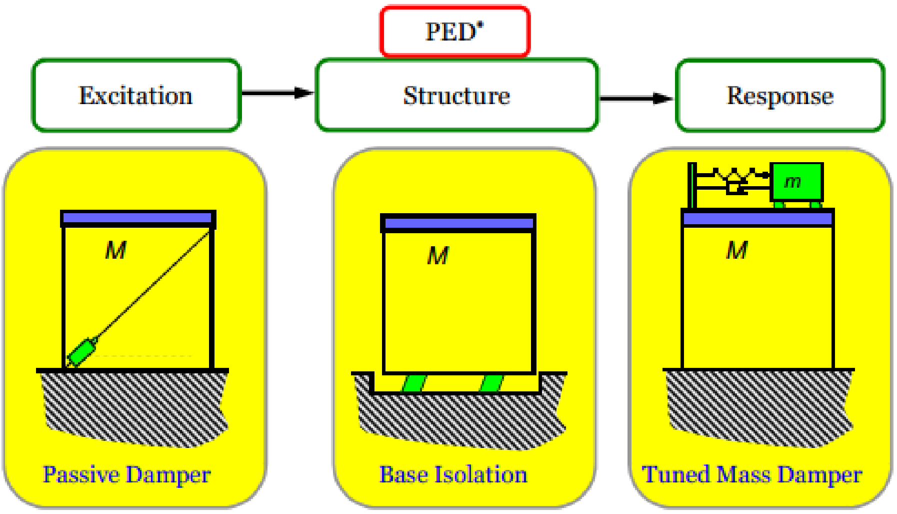

Figure 2.4 Structures with Passive Energy Dissipation (PED) [21]

A large number of passive control systems or PED devices have been developed and installed in structures for performance enhancement under earthquake loads. Commonly, auxiliary damping may be supplied through the incorporation of some secondary system capable of passive energy dissipation, for example, the addition of a secondary mass attached to the structure by a spring and damping element in order to counteract the building motion. Such passive systems were embraced for their simplicity and ability to reduce the structural response [48].

The main categories of the passive energy dissipation systems are shown in the table below.

Table 2.1: Types of Passive Dampers

Displacement-Activated	Velocity Activated	Motion-Activated
Metallic Dampers	Viscous Dampers	Tuned Mass Damper
Friction Dampers		
Self-Centring Dampers	Viscoelastic Dampers	Tuned Liquid Damper
Viscous Dampers		

Displacement-activated devices absorb energy through the relative displacement between the points they connect to the structure. Their behavior is usually independent of the frequency of the motion and is in phase with the maximum internal forces generated at the end of each vibration cycle corresponding to the peak deformations of the structure. Velocity-activated devices absorb energy through the relative velocity between their connection points. The behavior of these dampers is usually dependent on the frequency of the motion and out -of-phase with the maximum internal forces generated at the end of each vibration cycle corresponding to the peak deformations of the structure. Motion-activated dampers are secondary devices that absorb structural energy through their motion. They are tuned to resonate with the main structure, but, out -of-phase from it. These dampers absorb the input energy of the structure and dissipate it by introducing extra forces to the structure; therefore, they let less amount of energy to be experienced by the structure. Tuned mass dampers (TMDs) and tuned liquid dampers (TLDs) are the examples in this category [18].

2.3 Tuned Liquid Damper

2.3.1 General

Design of a tall building is an evolutionary effort between the building owner, the project architect and the structural designer, with the role of the architect and the structural designer to provide a structure that meets the revenue and appearance expectation of the owner without compromising the safety of the occupants or the integrity of the structure. To ensure a seamless and conflict free integration with the structure design supplemental damping systems must be a part of the evolving design process. Therefore, a practical and efficient computational tool can help evaluate the effectiveness of a liquid damper in mitigating the oscillation of a structure subject to a design seismic event during the design process [36].

Damping is defined as the ability of the structure to dissipate a portion of the energy released during a dynamic loading event and thus one of the most important parameters that limit the response of the structures. Attachment of liquid tanks to the structure introduces capability of inducing damping in the system. The sloshing motion of the liquid that results from the vibration of the structure dissipates a portion of the energy release by the dynamic loading and therefore increases the equivalent damping of the structure. These tank devices are referred to as Tuned Sloshing Dampers (TSD). The TSD system relies on the sloshing wave developing at the free surface of the liquid to dissipate a portion of the dynamic energy. The performance of TSD relies mainly on the sloshing of liquid at resonance to absorb and dissipate vibration energy of the structure [22].

Main idea of vibration damper is that damper mass oscillates in counter phase to main structure. As a result amplitudes of main structure oscillations are reduced due to summation with damper oscillations. In the last decades, the idea of tuned liquid dampers (TLD) got an extension and development. Liquid mainly water is used as damping mass in this type of dampers. TLD is a cheap, simple in construction and environmental friendly damper type. Such dampers also can be used as an additional water reserve for the building water supply and the fire-fighting systems [13]. A TLD is a rigid tank partially filled with a liquid, usually water. The TLD sloshing frequency is tuned to the frequency of a specific mode of the structure that requires control. During dynamic excitation, the liquid will slosh against the walls of the tank. This sloshing motion imparts inertial forces approximately anti-phase to the dynamic excitation, thus reducing the structural motion [4].

Tuned Sloshing Dampers (TSDs) are generally rectangular type or circular type and are installed at the highest floor according to building type and the objective for controlling the vibration. A TSD can be classified as shallow water type or deep water type depending on height of water in the tank. This classification of the TSDs is based on shallow water wave theory. If the height of water ‘h’ against the length of the water tank in the direction of excitation ‘L’ (or diameter ‘D’ in case of circular tank) is less than 0.15 it can be classified as shallow water type else as deep water type if is more than 0.15 [2].

Liquid motion is a complex process with many parameters and effects that generally is described with the fluid dynamics laws. TLD properties can be widely changed using different shapes of water tanks with or without additional barriers inside. Usually liquid dampers are strictly connected to the main structure. Liquid motion inside the damper causes oscillations in counter phase to main structure and corresponding damping effect [13].

Sloshing dampers have the simplest construction comparing to the other types of liquid dampers. Generally, it is a rectangular or barrel-shaped container with commensurable all three dimensions that is partly filled with liquid. Liquid impacts sidewalls of container generating damping force. Due to simple construction, sloshing dampers are often meant by the term tuned liquid dampers in literature and papers. However, simple damper construction does not lead to the simple understanding of its mechanic. In SLD happens sloshing - liquid has free surface where waves can arise. Effects of waves, sloshing viscous damping and suppression, sloshing–structure interaction and others occur in this case [13]. Considering that liquid sloshing dynamics is complex developing discipline, precise solution of SLD movement can be hardly obtained in practical case [4].

2.3.2 History

Since 1950s dampers utilizing liquid are being used in anti-rolling tanks for stabilizing marine vessels against rocking and rolling motions. In the 1960s, the same concept was used in Nutation Dampers used to control the wobbling motion of a satellite in space. However, the idea of applying TLDs to reduce structural vibration in civil engineering structures began in the mid1980s by Bauer, who proposed the use of a rectangular container completely filled with two immiscible liquids to reduce the structural response to a dynamic loading. Modi and Welt [35], Fujii et al. [51], Kareem [28] and Sun et al. [52] were also among the first to suggest the use of dampers utilizing liquid motion for civil engineering structures [24].

The first damper utilizing liquid sloshing to dissipate energy was a nutation damper, which is a disc shaped container [14]. Kareem (1990) applied the same energy dissipation concept to a rectangular tank called a tuned sloshing damper (TSD), which is generally much larger than a nutation damper. However, the inherent damping through viscous dissipation in the boundary layers of the liquid in the TSD is an order of magnitude less than optimal [4].

2.3.3 Classification

Tuned liquid dampers (TLDs) can be implemented as: an active or passive device and are divided into two main categories: tuned sloshing dampers (TSD) and Tuned liquid column dampers (TLCDs) [24]. The figure bellow shows a schematic diagram of the Tuned Liquid Damper families.

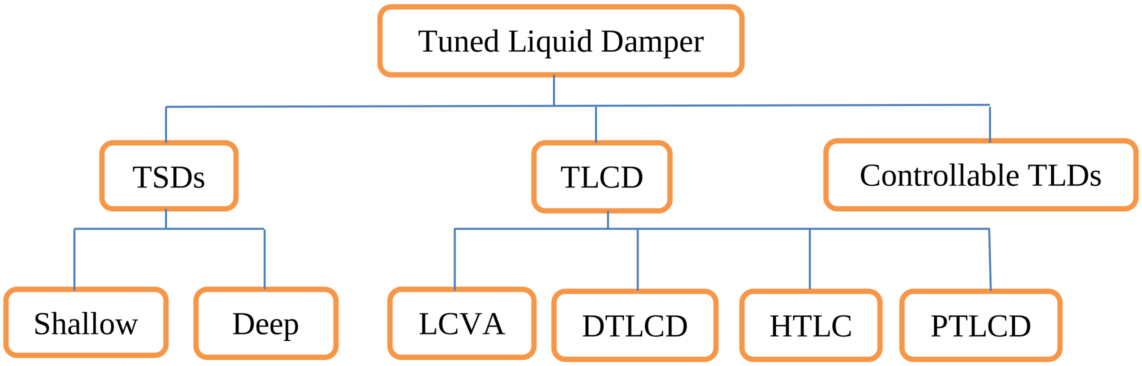

Figure 2.5 Schematic of Tuned Liquid Damper families

TSD: Tuned Sloshing Damper, TLCD: Tuned Liquid Column Damper, LCVA: Liquid Column Vibration Absorbers, DTLCD: Double Tuned Liquid Column Damper, HTLCD: Hybrid Tuned Liquid Column Damper, PTLCD: Pressurized Tuned Liquid Column Damper.

2.3.3.1 Tuned Liquid Column Dampers (TLCD)

One of the most widespread types of liquid dampers is tuned liquid column damper (TLCD). TLCD is U-shaped tube filled with liquid. Liquid flows from one vertical column to the other creating horizontal damping force due to impact on vertical walls and friction between liquid and tube in horizontal part. Liquid motion in TLCD can be well described by hydraulic laws. Due to this TLCD are well investigated and used in engineering practice. For some time similar dampers are used in naval architecture for ship stability and are called antiroll tanks. In this case, special pipes connect two tanks along sides of the ship [23].

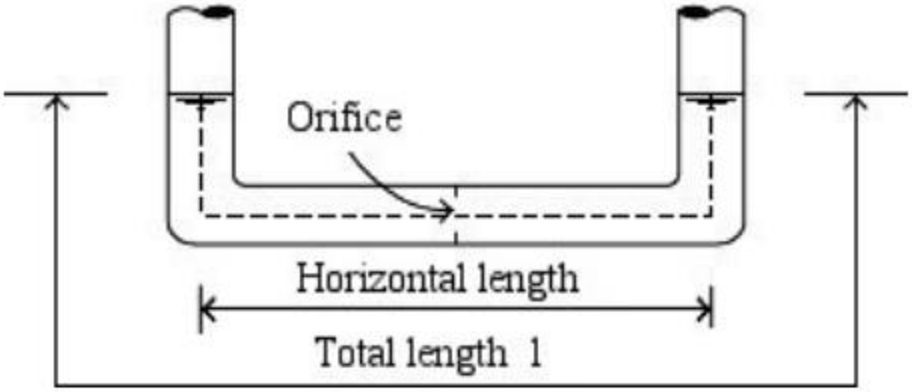

Figure 2.6 Principal structure of TLCD [3]

Natural oscillation frequency of tuned liquid column damper is:

$$\omega = \sqrt{2g / l}$$

Where: l is total length of a water column. Therefore, the adjustment of such dampers to particular structure is simple, by adding or draining some water from it.

However, this simple damper type also has its disadvantages. Firstly, TLCD is planar structure that works only in one direction. Therefore, for real structures that oscillate in all directions improvements should be made. Secondly, TLCD produces relatively small damping force to their own mass comparing to other damper types. Thirdly, TLCD oscillates and creates a significant damping effect in only one frequency. Studies have shown that considerable TLCD damping effect is obtained only if damper and main structure oscillation frequencies ratio does not exceed 0.9-1.1 interval [18].

Therefore, TLCD are suitable for wind turbines, simple geometry towers and other structures with one dominating oscillation frequency. Consequently, researchers propose different modifications of TLCD to improve its effectiveness [23].

2.3.3.2 Modified Tuned Liquid Column Dampers (MTLCD)

Theoretical proposal of TLCD modification is offered by many researchers to raise it effectiveness and range of application. Placing two TLCD in orthogonal directions damping effect in both main vibration directions will be assumed. Such system is called double tuned liquid column damper (DTLCD) [38]. Circular/torsional tuned liquid column dampers (CTLCD/TTLCD) are proposed for the torsional movement of eccentric structures [32]. In this case damper tube is shaped in circle and should be combined with DTLCD to provide damping effect for all types of main construction motion. The problem of unidirectional effectiveness of TLCD also can be solved by placing one TLCD on rotating platform that is controlled by electronics. This electronic control provides right orientation of TLCD to ensure damping in the largest oscillation direction. Such damper is called hybrid tuned liquid column damper (HTLCD) [38].

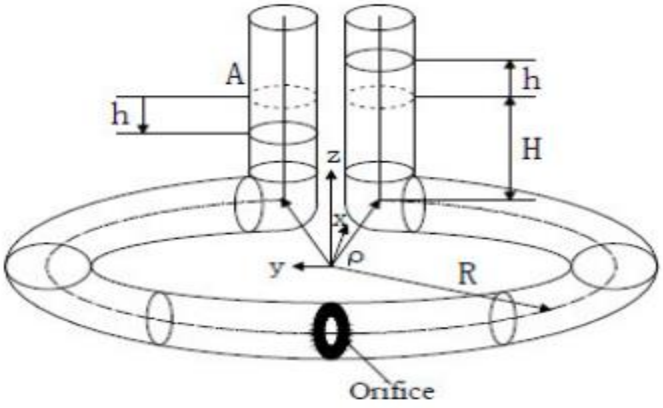

Figure 2.7 Scheme of Circular/Torsional TLCD [24]

More complex shapes of TLCD can be developed and used. Dampers can consist not only from one tube, but from 2 containers connected with different cross section tubes. In this case oscillation frequency depends not only on liquid column length, but on containers and connecting tube geometry. Such dampers sometimes are called liquid column vibration absorbers (LCVA) [23].

To increase the horizontal damping force obtained from liquid motion TLCD can be supplemented with orifices–additional barriers. These barriers can be fulfilled not only as a plate with openings, but also as a steel ball inside damper or in the other ways [4].

Valve that changes free tube cross section can be used instead of an orifice. Such valve allows easy to control damper parameters. The valve can be made with computer control which will change damper parameters according to the dominating structure oscillation mode at the moment [58]. Computer controlled dampers with variable properties are called semi-active dampers, opposite to the passive dampers without real time control [27].

If we hermetically seal both TLCD ends, we will ensure air pressure changes in the end zones during oscillations. Practically additional gas spring to water column in the damper is provided. Such dampers are called pressurized tuned liquid column dampers (PTLCD) or tuned liquid column gas dampers (TLCGD) [12]. This damper type extends frequency range of TLCD.

Some researchers propose to replace tight connection between damper and main structure to elastic. It can be fulfilled by hanging platform with TLCD with ropes to main structure. In this case, pendulum type liquid dampers are obtained [45]. Actually, it is a combination of TLCD and mass damper and it functions according to the more complex motion laws [23].

To provide effective damping at many frequencies multiple tuned liquid column dampers (MTLCD) are proposed a series of liquid column dampers of different sizes simultaneously connected to the main structure. It is an unsophisticated approach to multi-frequency problem and it corresponds with multiple mass damper idea, which is fulfilled in some high-rise buildings. In this case, several different dampers can be located along height of building on different levels. Size of each damper can be consequently reduced and their parameters can be optimized for the particular structure oscillation mode [23].

Some researchers offer to use magneto-rheological fluid or electro-rheological fluids in TLCD. In this case, electromagnetic field generating devices can be placed around TLCD tube. Electromagnetic field can cause changes of rheological properties of fluid and as a result changes of damper mechanical properties. This process under computer control allows adjusting damper properties to most critical structure oscillations at the particular moment. These types of dampers are called magneto-rheological dampers (MR-TLCD) or electro-rheological dampers (ER-TLCD). Similar idea of the damper properties adjustment is used in modern top class vehicle semi-active suspensions [34, 38, 56].

Mentioned examples show that there are many different routes for TLCD development. At the moment it is hard to predict, what approach will be most effective and which will get practical application in construction industry.

2.3.3.3 Sloshing Liquid Dampers (SLD)

Sloshing dampers have the simplest construction comparing to the other types of liquid dampers. Generally, it is a rectangular or barrel-shaped container with commensurable all three dimensions that is partly filled with liquid. Liquid impacts sidewalls of container generating damping force. Due to simple construction, sloshing dampers are often meant by the term tuned liquid dampers in literature and papers [23].

However, simple damper construction does not lead to the simple understanding of its mechanic. In SLD happens sloshing-liquid has free surface where waves can arise. Effects of waves, sloshing viscous damping and suppression, sloshing–structure interaction and others occur in this case. Considering that liquid sloshing dynamics is complex developing discipline, precise solution of SLD movement can be hardly obtained in practical case [41].

As a result, investigations of SLD often are based on experimental studies or simplified calculation models. Widespread SLD simplified calculation model is a tuned mass damper analogy-water in container is represented as solid body suspended on cable (simple pendulum). Such pendulum motion model is well known, but it roughly describes liquid motion [23].

Development of more accurate practical calculation methods of SLD is an actual objective for researchers and civil engineers [47]. SLD can be divided into shallow or deep dampers according to their dimensions. Liquid motion mechanic differs in these cases. Generally damper effectiveness significantly decreases if water depth to tank length ratio is less than 0.10 to 0.15. Natural water oscillation frequency in shallow rectangular SLD without barriers according to the linear water wave theory is [46, 8]

$$\omega = \sqrt{\frac{\pi g}{l}.\tanh\left(\frac{\pi .h}{l}\right)}$$

Where: l is length of damper in the direction of oscillations, h is water depth and g is acceleration of free fall. Any changes of damper geometry accordingly changes oscillations frequency.

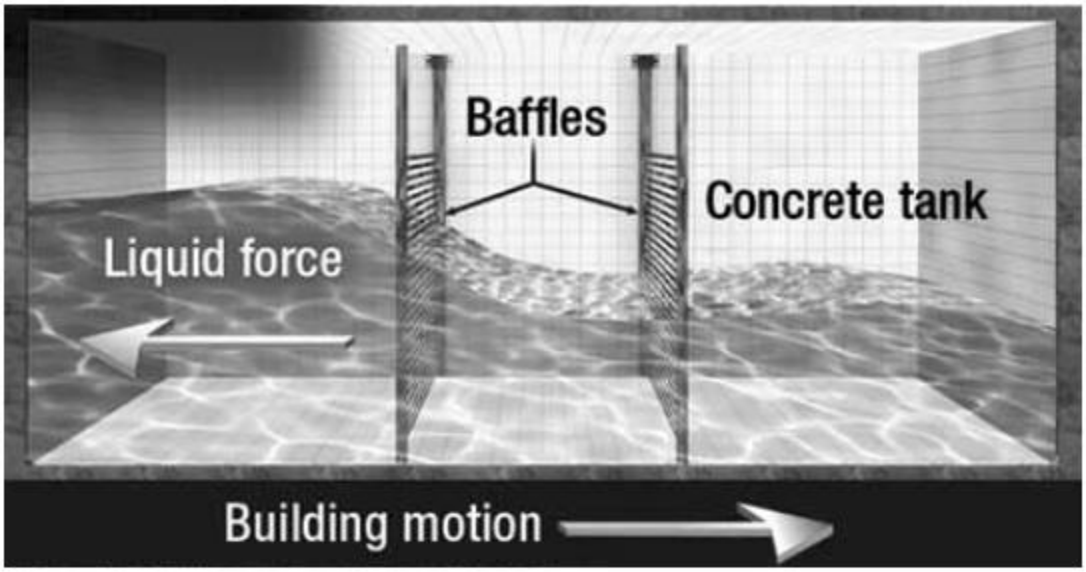

Figure 2.8 SLD with additional slat screens (baffles) [3]

To improve SLD effectiveness and enlarge damping force construction can be supplemented by additional slat screens (baffles)-additional barrier in the container, which receives a part of liquid motion force. Such baffles make liquid motion in damper even more complex, but its effectiveness is generally proved [12,13]. Additional barriers can increase energy dissipation up to 60% [41]. Most suitable structures for SLD practical application are high-rise towers, where damper is also additional water tank for fire-fighting system [27].

As a passive energy dissipation device TLD presents several advantages over other damping systems such as:

- Low installation and RMO (Running, Maintenance and Operation) cost.
- Fewer mechanical problem as no moving part is present.
- Easy to install in new as well as in existing buildings as it does not depends on installed place and location.
- It can be applied to control a different vibration type of multi-degree of freedom system which has a different frequency for each other.
- Applicable to temporary use.
- Non restriction to unidirectional vibration.
- Natural frequency of TLD can be controlled by adjusting the depth of liquid and container dimensions, and
- Water present in the damper can be used for firefighting purpose.

Along with the above mentioned advantages, there are some drawbacks too associated with TLD system. The main drawback of a TLD system that, all the water mass does not participate in counteracting the structural motion. This results the addition of extra weight without getting the any benefit. Again low density of water makes the damper bulky, and hence increases the space required housing it. As is the case for Tuned Mass Damper, there exists an optimal damping factor for TLDs. Since usually plain water is used as the working fluid, it gives a lower damping ratio compared to the optimal value [55].

2.3.3.4 Shallow TLD and Deep TLD

2.3.3.4.1 Types of Tuned Liquid Damper Depending on Dimensions

Tuned Sloshing Dampers (TSDs) are generally of rectangular type or circular type. These are installed on the topmost floor of the building with the objective for controlling the vibration. A TSD can be classified as shallow water type or deep water type depending on height of water in the tank. This classification of the TSDs is based on shallow water wave theory. If the height of water ‘h’ against the length of the water tank in the direction of excitation ‘L’ (or diameter ‘D’ in case of circular tank) is less than 0.15 it can be classified as shallow water type else as a deep water type if is more than 0.15. The figure below shows the schematic representation of TSD types [55].

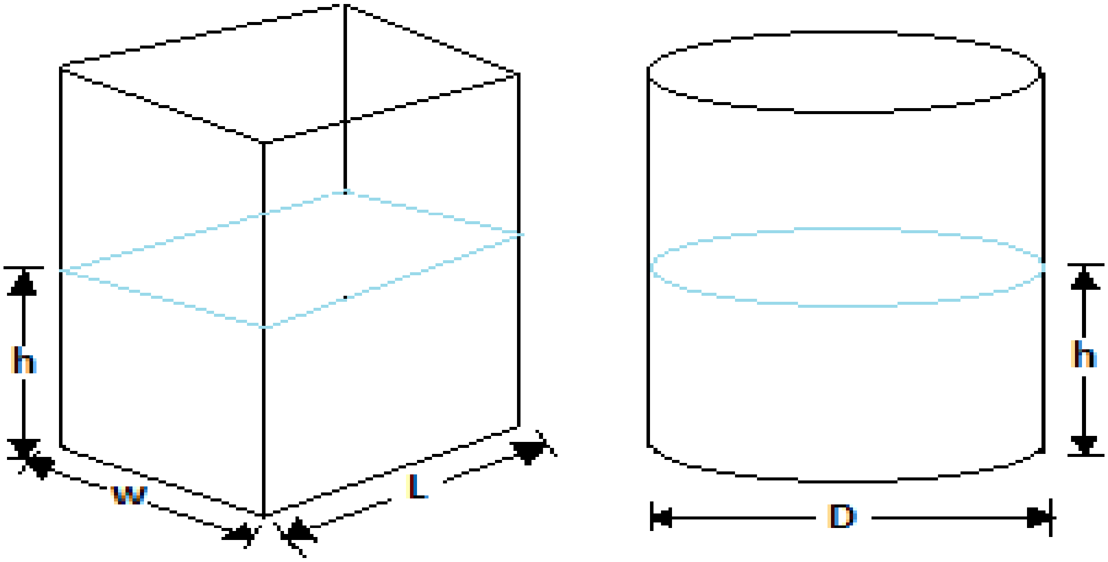

Figure 2.9 Types of Tuned Liquid Damper with respect to dimensions

2.3.3.4.2 Types of Tuned Liquid Damper Depending on Frequencies

The depth of the liquid in a container could be deep or shallow, depending on the natural frequencies of the structure under control. Shallow water type has a large damping effect for a small scale of externally excited vibration, but it is very difficult to analyze the system for a large scale of externally excited vibration as sloshing of water in a tank exhibits nonlinear behavior. In case of deep water type, the sloshing exhibits linear behavior for a large scale of externally excited force [55].

When the frequency of tank motion is close to one of the natural frequencies of tank fluid, large sloshing amplitudes can be expected. If both the frequencies are close to each other, resonance will take place. Generally tuning the fundamental sloshing frequency of the TLD to the natural frequency of the structure causes a large amount of sloshing & wave breaking at the resonant frequency of the combined TLD-Structure system, which dissipates a significant amount of energy [28].

2.3.3.4 Bi-Directional Liquid Dampers (BLD)

For TLCD it is possible to use U-shaped tank with considerable dimension transverse to damper working plane instead of a tube (figure below). In this case in TLCD transversal direction sloshing effect occurs. Such dumper works in one direction as TLCD, but in other as SLD. This construction is called a bi-directional liquid damper (BLD) or combined liquid damper. Main practical advantage of this damper is that one damper ensures practical effect in both directions and effectively uses space [30, 31].

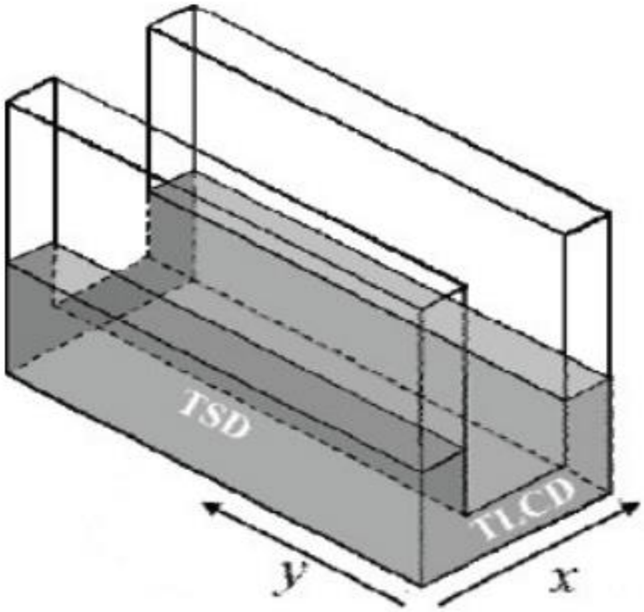

Figure 2.10 Bi-directional liquid dampers (BLD) [30]

To use space even more effectively, in the middle of BLD can be placed one more rectangular liquid container-sloshing damper. Practically it will be one big liquid rectangular container divided by inner walls into separated different type dampers [23].

2.3.3.5 Ways of Improvement of Tuned Liquid Dampers

One of the main disadvantages of tuned liquid dampers is that only one main oscillation frequency is damped. This is not enough for the structures, where simultaneously different vibration modes are essential. Even for structures with one main oscillation mode multi-frequency dampers should be useful, because structure oscillation frequency can be variable in some range due to different factors and it can be hard to perfectly tune damper for specific structure. Therefore, creating an effective multi-frequency liquid damper is a relevant problem. Using multiple liquid dampers-simple incensement of damper amount with different properties. Consequently size of one damper and it effectiveness reduces, but total required space increases. This is a main disadvantage for this approach, especially noting that damper mass and structure mass ratio should reach definite values to provide considerable damping effect 3 to 4% [3, 27]. In addition, it is important to notice that the damper, which has positive effect on one frequency, could create negative oscillations increasing effect on the other frequencies. This feature obliges to choose MTLCD separate damper parameters especially carefully.

Other way to multiply oscillation frequencies damping is semi-active damper creation-damper with computer adjustable properties at any particular moment for the most critical oscillations. Properties adjustment can be done by changing orifices or slat screen dimensions or position, or using magneto-rheological / electro-rheological fluids with variable electromagnetic field. It is complicated to fulfill this elegant idea technically in practice. Semi-active damper should have interconnected oscillation sensors strictly strengthened to main structure in different places, movable or variable details in damper and computer control with corresponding software. Practical realization of such damper would be a serious task in any particular case [23].

Using more complex shapes of water dampers, with special barriers, could be one of the ways to solve the problem and create multi-frequency dampers. Sloshing damper divided with significant slat screens (baffles) into several partitions combine different liquid motions-a part of motion energy causes waves inside each partition, but another part causes waves along whole damper. Choosing relevant shape and amount of barriers inside SLD dampers could help to develop passive multi-frequency damper [14].

Impact of sloshing damper container and barrier shape changes on damping properties is less investigated. Some researcher investigated influence of SLD slope bottom on its properties. It was found that slope bottom decreases waves and makes liquid motion more uniform [20, 8].

Disadvantage of all liquid dampers should be noted water, liquid that is mainly used in dampers, freezes at negative temperatures. This problem is not essential in heated rooms or can be solved using other liquids or antifreeze additives, but this measure reduces practical advantages of liquid dampers. Generally, effectiveness of a damper increases together with damper and structure masse ratio. Some studies show that dampers mass must be at least 3-4% of structure mass to provide significant effect [3, 27].

For heavy reinforced concrete high-rise building large damper, which that requires a lot of space and produces additional load on columns and foundation, is necessary. On the other hand, relatively small damper will be enough for light structures –steel masts and lattice towers, footbridges etc. Damper most effective mass ratio investigation would be a relevant research aim [23].

2.3.3.6 Controllable Tuned Liquid Damper

Being a passive control device, TLDs are generally tuned to a particular frequency (1st natural frequency of structure), and therefore it is effective only if the frequency of forcing function is close to that tuned frequency. But in reality, the forces that act on the structure are often spread over a band of frequencies. This reduces the effectiveness of the damper. In order to improve the effectiveness of damping, against a multi-frequency excitation force, some active or semi-active control devices are proposed by various researchers [55].

In a structural control problem (Active or Semi-active), the excitation force and the response of the structure to the excitation force are measured by the sensors, installed at key locations of the structure. Then the measured force and response are sent to a control computer, which processes them according to a control algorithm, and sends an appropriate signal to the actuators. The actuator then modifies the dynamic characteristics of the damper, to apply the inertial control forces to the structure in the desired manner [55]. The figure below provides a schematic diagram for a structural control problem.

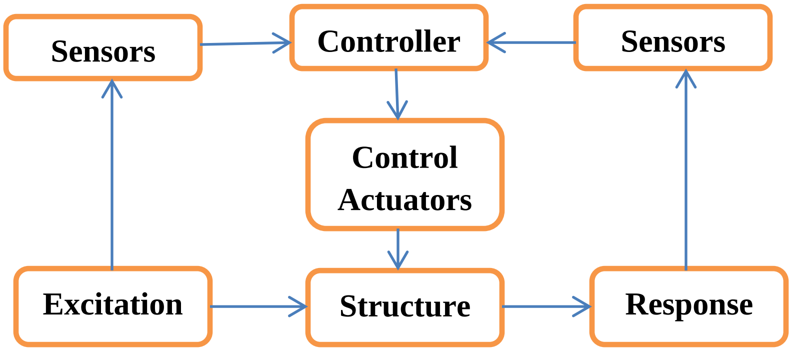

Figure 2.11 Schematic diagrams for a structural control problem

Several means for actively controlled Tuned Liquid Dampers are proposed, such as: (i) controlling the angle of baffles, in case of a TSD, regulates the effective length of the damper, which in turn adjusts the resonance frequency of the TSD [33] (ii) Installing one or more propellers driven by a servo-motor controlled by a computer inside the horizontal section of TLCD. Both the fluid acceleration and the thrust generated by propeller acts simultaneously to increase vibration control ability significantly [6].

2.3.4 Approaches That Have Been Used to Model the Liquid-Tank Behavior

There are two common approaches that have been used to model the liquid-tank behavior. In the first one the dynamic equations of motion are solved by using potential flow theory and shallow water theory. In second approach the properties of the liquid damper are presented by equivalent mass, stiffness and damping ratio essentially modeling the TLD as an equivalent TMD (Tuned mass damper) [24].

2.3.4.1 First Approach: The Shallow Water Wave Theory

- In this approach the dynamic equations of motion are solved by using potential flow theory and shallow water theory.

The shallow water wave theory has also been widely used in developing numerical models for TLDs. Numerical models based on this theory solved the nonlinear Navier Stokes equations under the assumption of relatively low wave height compared to the mean depth of liquid layer. Dean and Dalrymple defined the limit for applying this theory to h/L<0.1, however numerical investigations later verified that it could be used for h/L up to 0.2, with a noted deviation from experimental data up to 14%. This theory also limits the level of excitation amplitude that can be used. Amplitudes greater than 1.6% of the TLD length resulted in deviation from experimental data up to 20% [17].

Below there are graphical representation of shallow water wave theory approach of the fluid-structure interaction model and Schematic sketch of TLD for Horizontal motion.

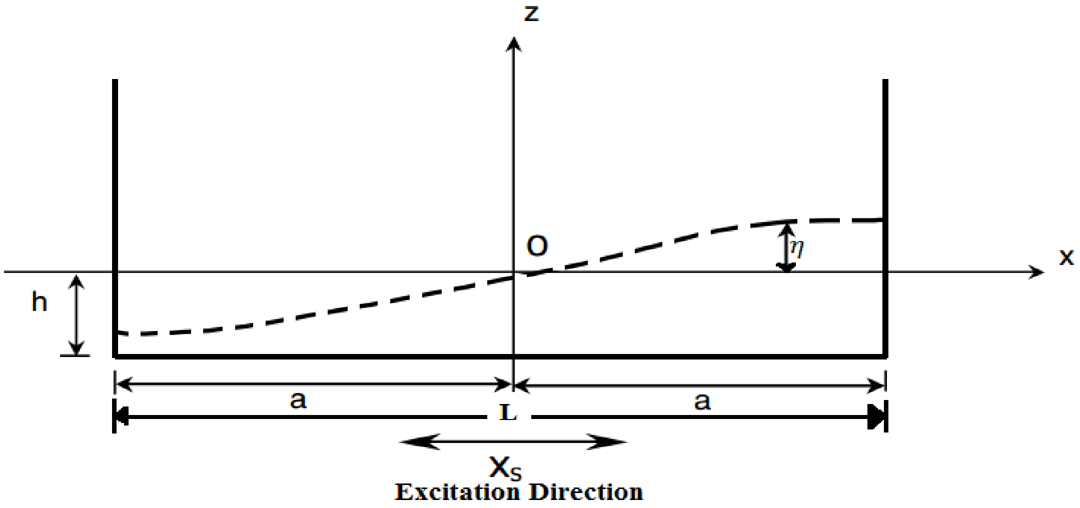

Figure 2.12 Schematic sketch of TLD for horizontal motion of shallow water wave theory

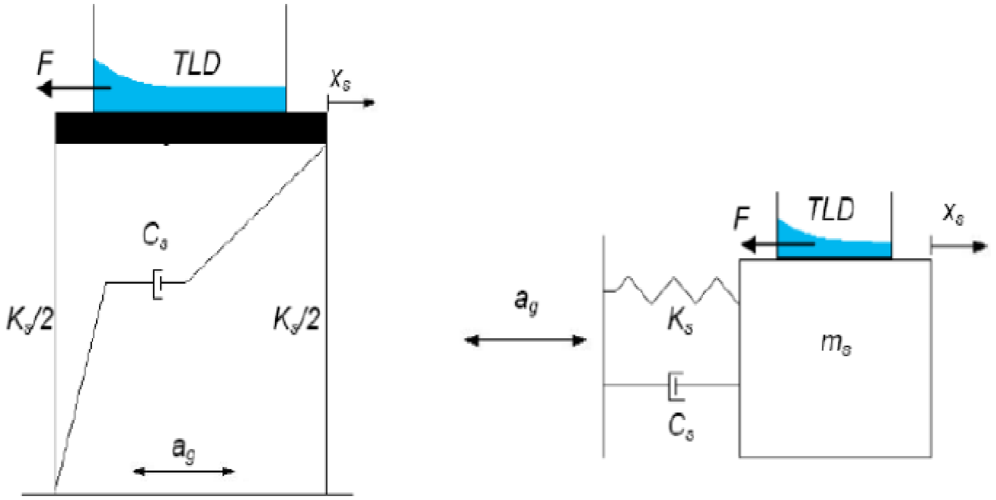

Figure 2.13 Fluid-structure interaction model of SDOF system with a TLD

A numerical model based on the shallow water wave theory was later developed by accounting for the effect of wave-breaking using a semi-empirical parameter added to the governing equations. Even with such development, the numerical models based on the shallow water wave theory are sti11limited to low flu id heights, and relatively low values of excitation amplitudes [8]. Reed et al. developed a numerical algorithm using the shallow wave theory and used it with large amplitude excitation (greater than 1 % of tank length). Although results did not quite match experimental data, the trends were predicted adequately enough to justify the use of the shallow wave theory with some experimental add-on knowledge for adjustment of tuning [3].

The shallow wave theory employed to predict TLD-structure performance under random excitation, modeling an earthquake signal. Their study considered 12 different cases of structure properties with various natural frequencies and damping ratios. They found the TLD to decrease structure sway between 3% and 39% [25]. However Yalla and Kareem later published a study refuting results obtained by Banerji et al. [25], and showing that, with non-harmonic excitation, utilizing the shallow water theory without proper empirical additional results in a consistent underestimation of the sloshing force due to improper predictions of sloshing/slamming characteristics of the wave motion [25].

2.3.4.2 Second Approach: Modelling the TLD as an Equivalent TMD

- In this approach the properties of the liquid damper are presented by equivalent mass, stiffness and damping ratio essentially modelling the TLD as an equivalent TMD (Tuned mass damper) [15].

In this approach, the damping mechanism of the TLD is reviewed. Because the tuned mass damper (TMD) is a well-known passive mechanical damping system that has been used widely for serviceability-based structural vibration control, the damping mechanism of the TMD is continuously referenced in explanation of the TLD [15].

Below there are a graphical representations of, modelling the TLD as an equivalent TMD approach of the fluid-structure interaction model.

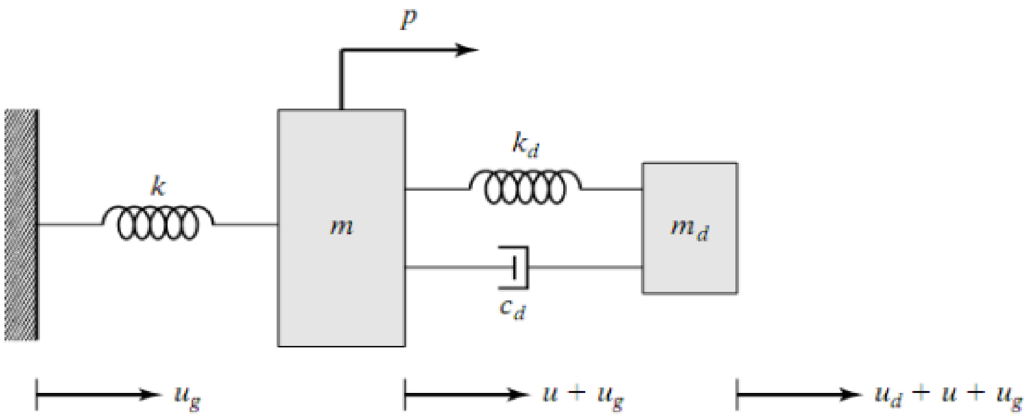

Figure 2.14 SDOF system coupled with a damped TMD system

Schematic sketch of modelling the TLD as an equivalent TMD approach of the fluid-structure interaction model and mechanism of the dampers (TLD & TMD) attached to a structure for Horizontal motion.

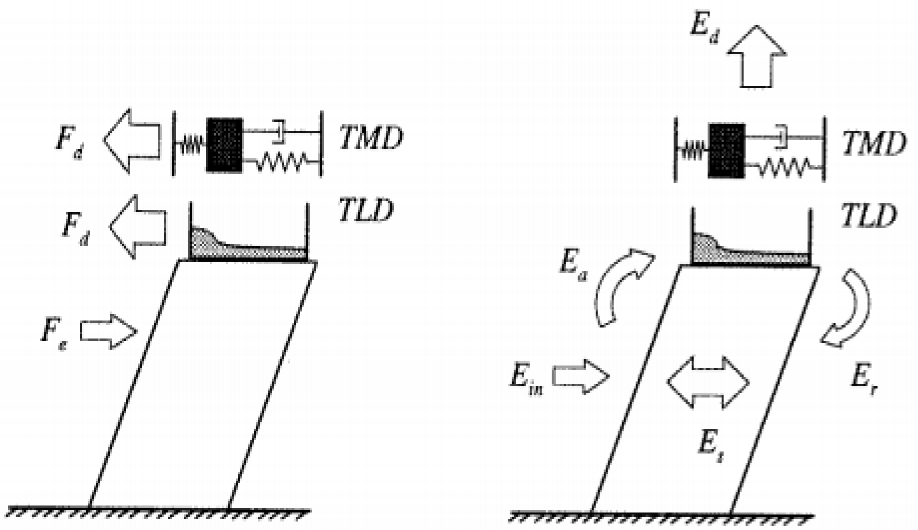

Figure 2.15 Demonstrated schematic Mechanism of the mechanical dampers (TLD & TMD) attached to a structure.

Where: F_e is excitation force, F_d is resisting force by dampers, E_{in} is energy input, E_a is energy absorbed by dampers, E_d is energy dissipated by dampers, E_r is energy returned to structure, E_s is structural vibration energy.

2.3.5 Optimization

2.3.5.1 General

Optimization is the determination of system parameters which maximize the performance based on a performance criterion (also known as an objective function). The desire is to develop closed form expressions relating the damping ratio, mass ratio (ratio of the TLD mass to the structure mass), and water depth ratio; ratio of stationery liquid height to length of the tank. The performance criterion is selected based on a desirable response level for the structure (for example the roof acceleration) when it is excited. Practical considerations must be given with regard to the selection of the mass ratio.

Generally; performing the optimization is characterized by three distinct steps**.** First, the performance of the design is evaluated by analyzing it with the current values of the design variables. Second, the sensitivity of the design to changes in the design variables is evaluated for all design variables; this is called design sensitivity analysis and the sensitivities are the gradients of the objective and constraints. Third, the sensitivity information is used to update the design variables in a way that improves the objective. Therefore, in order to assess the optimization of TLD on the control of vibration of structure, the following scheme were followed.

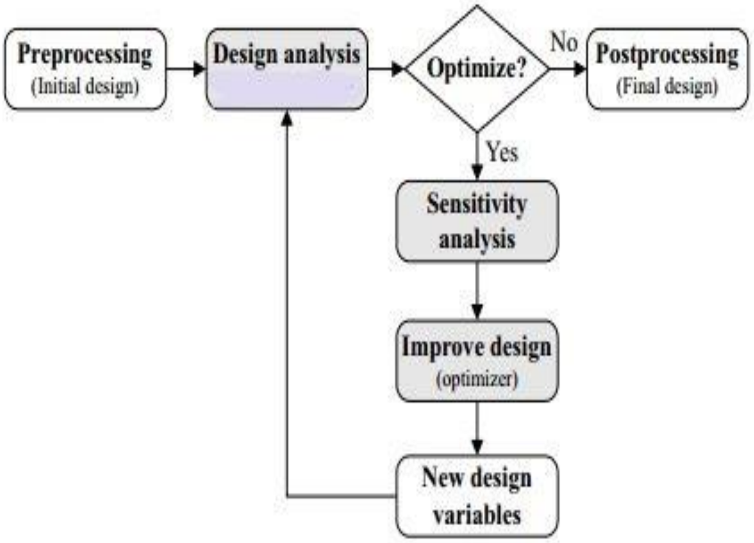

Figure 2.16 Schematic representation of optimization of TLD

In order to improve efficiency of control strategy, it is essential to define the optimum mechanical parameters (i.e. the optimum damping; mass ratio and depth ratios) of TLD. In fact the parameters of TLD system must be obtained through the optimum design procedures to attain a better performance control. For these reasons, the determination of optimum design parameters of TLD to enhance the control effectiveness has become very crucial.

To achieve an optimized system, previous studies have shown that it is advisable to employ dampers that are tuned to the first few dominant modes of the building [29]. The structure-TLD systems are numerically solved to demonstrate the ability of the TLD system to reduce the structural motion. The best system is then chosen for a parametric study. Practical parameters are varied to investigate the robustness of the TLD system. It should be mentioned that the structural modal frequencies are considered in the parametric study because the as-built structural frequencies might deviate from the frequencies estimated from a computer model by over ±15% [4].

Jans V. and Liga G. carried out to observe parameters that affect sloshing damper in the response of the structural system. The parameters studied are mass ratio, ratio of mass of damper to structure, water depth ratio, ratio of stationery liquid height to length of the tank, the tuning ratio, ratio of sloshing frequency to modal frequency of structure, the tuning ratio, ratio of sloshing frequency to modal frequency of structure, etc. For the parametric investigation to determine the optimal TSD parameters the building is subjected to harmonic ground excitation. A parametric study was undertaken to study the effect of mass proportioning on the displacement of the building structure. Accordingly the mass was distributed between two floors instead of lumping at one floor [23]. The structural modal frequencies can be variable in some range due to different factors and it can be hard to perfectly tune damper for specific structure and it is one of the main disadvantages of liquid dampers is that only one main oscillation frequency is damped [52].

2.3.5.2 TLD Parameters

The response of the structure with a TLD attached and subjected to a base excitation will depend on the characteristics of the structural-TLD system. Depth ratio ($\Delta = \frac{h}{L}$): The water depth ratio (Δ), which is the ratio of water depth (h) to the tank length L is significant parameter for defining the effectiveness of a rectangular TLD [16]. Mass ratio: ($\mu = \frac{mw}{ms}$) The mass ratio, (μ), is the ratio of the mass of water to the structure mass is also an important parameter to be considered in the TLD design [22]. Excitation Frequency ratio ($\beta = \frac{f}{fs}$): The frequency ratio (β), of a rectangular TLD is the ratio of the fundamental linear sloshing frequency, which is given by the above equation, to the natural vibration frequency of the structure [13]. It should be mentioned that the structural modal frequencies are considered in the parametric study because the as-built structural frequencies might deviate from the frequencies estimated from a computer model by over ±15-20% [4].

2.3.6 Practical Implementation

The TSDs are extremely practical, currently being proposed for existing water tanks on the building by configuring internal partitions into multiple dampers without adversely affecting the functional use of the water supply tanks. Considering only a small additional mass, if any, is added to the building, these systems and their counterpart TMDs can reduce acceleration responses to 1/2 to 1/3 of the original response, depending on the amount of liquid mass. The first implementation of water tank to resist natures force like wind was the 304m high Sydney tower at Centrepoint, Australia figure below. This building is considered as one of the safest buildings in the world. The tower has a 162,000 liter water tank at the top that acts as a stabilizer on windy days [6].

Figure 2.17 Sydney Center point Tower

TLDs have been used to mitigate wind induced oscillations of airport control towers and a number of bridges. Application of liquid dampers for mitigating wind induced oscillation in buildings is a new concept and has been applied to a few buildings around the world including two in the United States. Even though there are no known instances of TLDs providing supplemental damping to reduce seismic induce oscillations in buildings, the success of TLDs in damping wind induced oscillations creates the possibility of application of TLDs in mitigating building oscillations during seismic events [36].

Tuned liquid dampers have been employed in several civil Engineering structures around the globe, from its first installation in 42 meters high Nagasaki Airport Tower, Nagasaki, Japan in 1987 which was a purely temporary installation, intended to verify the effectiveness of the TLD in reducing structural vibration. The actual measurements were exhaustive one. It was found that, with the installation of 25 vessels of TLD, the decrease in amplitude of vibration is 44 % (i.e. from 0.79 mm without TLD to 0.44 mm) while reduction in RMS displacement was around 35%.

Experiment unveiled that, the maximum acceleration response of an uncontrolled Yokohama Marine Tower in Japan under wind action was 0.27 m/s^2, when the velocity of the wind was in the range of 15-21 m/s, the damping ratio was measured as 0.6%. But after using TLD as a vibration control device, the maximum acceleration response was reduced to 0.1m/s^2 or below, and the damping ratio was increased to 4.5% [54].

The nutation damper has been used in airport towers at the Haneda and Narita International airport to suppress wind-induced vibration. Tamura et al. (1992) experimentally tested the nutation damper combined with building model by small amplitude excitation. And also they investigated the effectiveness of nutation damper applied to 18 degree-of-freedom analytical model of Haneta Airport tower and 21 degree-of-freedom analytical model of Narita airport tower, where the nutation damper was represented as Tuned Mass Damper (TMD). The results showed the 55% reduction of acceleration response of the tower using the nutation damper with 1% mass ratio and floating particles [59].

The TLDs were also applied on the Shin Yokohama Prince Hotel (SYPH) in Yokohama, Japan [54]. The container has the diameter of 2m and the height of 0.22m, and was located in multi-layer stack. Each stack has 9 circular containers and the total height is 2m. It has been noticed that the TLD can reduce 30% of RMS accelerations (from 0.01m/s2 to 0.006m/s2) in each direction under wind load with the speed of 20m/s, which satisfied the ISO minimum perception level at 0.31Hz [59].

The TLD devices installed in the 77.6 m high structure of the Tokyo Airport Tower consists of 1400 tanks filled with water and floating polyethylene particles, which are added to enhance the energy dissipation. The cylindrical containers of diameters 0.6 and 0.125 m are stored in six layers on steel consoles. The total mass of the TLDs is approximately 3.5% of the first modal mass of the tower and its frequency is optimized to 0.74 Hz. The behavior of the TLD has been observed at various wind speeds. In one of these observations, it was found that, with a maximum speed of 25 m/s, the reduction in RMS acceleration was about 60% of its value without control [48].

Tuned Liquid Dampers has, successfully, been applied to some Bridge structures including Ikuchi Bridge, Japan, BaiChay Bridge, Vietnam and Sakitama Bridge, Japan [6]. Similar installations are reported for Nagasaki airport tower, Tokyo international airport tower and Yokohama marine tower [54].

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Study Setting

To assess optimum design of tuned liquid damper for vibration control of frame structures under seismic excitation, the following scheme were followed. Analysis of a TLD positioned on a multi-storey frame structure was made for the usual case of analysis which neglects the influence of TLD and for the case which incorporates the TLD. A different loading condition had been applied at the base of the structure to study the effectiveness of using TLD.

Both shallow water wave theory and modeling the TLD as an Equivalent TMD approaches can be used to model TLD properties. In shallow water wave theory; the dynamic equations of motion are solved by using potential flow theory and shallow water theory which has been widely used in developing numerical models for TLDs and numerical models based on this theory solved the nonlinear Navier Stokes equations under the assumption of relatively low wave height compared to the mean depth of liquid layer. In modeling the TLD as an Equivalent TMD properties of the liquid damper are presented by equivalent mass, stiffness and damping ratio essentially modeling the TLD as an equivalent TMD. In this study shallow water wave theory was utilized.

Finally optimization of TLD designs were done by parametric investigation of TLD attached to multi-storey frame structure which is subjected to harmonic ground excitation.

3.2 Exploratory Research

This study was design in the way that important and exact information was gathered from study design methodologies. The research study was conducted by analytical method at a theoretical level by using rectangular tanker as liquid damper. The analysis on the findings of the total peak response of frame structure models by using the routine of SAP2000. Therefore, the objective of the research had been achieved in accordance with the methodologies outlined below.

- ➢ The research addressed a more complete design approach by doing TLD design by using shallow water wave theory and also to achieve the optimum design of TLD; the TLD mass ratio (Effect of mass ratio on percentage reductions of top storey displacement) and height of water inside tank (Effect of depth ratio on percentage reductions of top storey displacement) has optimized.
- ➢ A standard multi-degree of freedom system was investigated to evaluate TLD protection efficiency in case of excitation.
- ➢ To optimize dynamic parameters of the TLD system for minimum top deflection of the structure, the dynamic parameters of TLD was investigated.
- ➢ More precisely, this model was used to develop different optimizations criteria which minimize the main system displacement and the inertial acceleration.

3.3 Study Variables

The study variables both dependent and independent were assessed in this research which displays the optimum design of tuned liquid dampers.

- ❖ **Dependent variable**

In other case the dependent variable which was the output and its result depend on the independent variables which directly related to the general objectives.

- ✓ Optimum design of TLD.

- ❖ **Independent variables**

These independent variables were more related with specific objectives but each specific objective was affecting one another. The independent variables which are measured and manipulated to determine its relationship to observed phenomena were selected and listed below.

- ✓ Peak displacement of the structure.
- ✓ Peak acceleration of the structure.
- ✓ Mass Ratio of TLD to structure
- ✓ Height to Depth ratio of Tank

3.4 Study Procedures

The procedures include:

1. Analysis of the structural system without TLD was made.
2. Analysis of the structural system with TLD; the structural system with a rectangular container containing shallow water mass was made in order to survey the role of TLD for vibration control.
3. Then each of the above two cases are again treated by varying the parameters, which are likely to influence the vibration of the structure, including (a) mass ratio and (b) water depth ratio of the tank.
4. A parametric study was undertaken to study the effect of mass proportioning on the displacement of the building structure.

Finally, conclusions and recommendations were drawn following the results of the parametric study.

3.5 Data collecting Procedure

The data collection processes have been done from the output of time history analysis of frame structure with and without TLDs. The time history analysis was carried out in SAP2000 using the Non-Linear transient dynamic analysis for different cases. Then the data which was collected from each case was prepared for analysis stage.

3.6 Data Analysis and Presentation

After the data has been properly collected from each case; it was processed and analyzed those data using data sheet, tables, charts and graphs. And finally presenting and interpreting the outputs was formulated. Analytical formulas and graphical charts were developed to determine the optimal parameters of TLD.

3.7 Ethical Consideration

While doing anything concerned research without any harm and oppressed of the community in the study setting and area, rather with great respects.

3.8 Data Quality Assurance

The quality of data collection was assured without any hesitations because the researcher has been following primary source of data collection (the first witness of a fact) and secondary source of data collection. Therefore; the assurance of those data are highly recognized and those data are true.

3.9 Limitation of the Research

The research has been limited by the following. The analysis and design of TLDs and the excitation forces applied to frame structures and studying the effect of TLD dynamic parameters for optimization design of the damper by considering;

- Two dimensional multi-storey frame structure having 10 storey models were Investigated.
- Rectangular water tanker was used as liquid damper.
- Depth ratio of the damper and mass ratio of the damper to structure are used as dynamic parameters.
- The study was made at a theoretical level.

3.10 Plan for Dissemination of Findings

Dissemination of findings is important so that results can be used to improve engineering and technological industries. After the research paper has been finished, the output is going dissemination in different activities like; conference presentation, internal seminar inside Jimma Institute of Technology and also if it is possible the thesis will publish on journal articles, book chapters and other publications.

3.11 Analysis and Discussions

3.11.1 Mathematical Formulations

In order to design optimum TLD for vibration control of frame structures under seismic excitation, there is a need to develop mathematical formulations as computational tool to account the fluid dynamics and structural analysis to evaluate the effectiveness of TLDs as supplemental dampers.

Both shallow water wave theory and modeling the TLD as an Equivalent TMD approaches can be used to develop mathematical formulations of rectangular TLD. In shallow water wave theory; the dynamic equations of motion are solved by using potential flow theory and shallow water theory which has been widely used in developing numerical models for TLDs and numerical models based on this theory solved the nonlinear Navier Stokes equations under the assumption of relatively low wave height compared to the mean depth of liquid layer. In modeling the TLD as an Equivalent TMD properties of the liquid damper are presented by equivalent mass, stiffness and damping ratio essentially modeling the TLD as an equivalent TMD. In this study shallow water wave theory was utilized for developing mathematical formulations.

3.11.1.1 Fluid Model Based on the Shallow Water Wave Theory

The Fluid Model Based on shallow water wave theory has also been widely used in developing numerical models for TLDs. Numerical models based on this theory solved the nonlinear Navier Stokes equations under the assumption of relatively low wave height compared to the mean depth of liquid layer.

The limit for applying this theory to $h/L<0.1$, however numerical investigations later verified that it could be used for h/L up to 0.2, with a noted deviation from experimental data up to 14%. This theory also limits the level of excitation amplitude that can be used. Amplitudes greater than 1.6% of the TLD length resulted in deviation from experimental data up to 20% [53].

A numerical model based on the shallow water wave theory was later developed by accounting for the effect of wave-breaking using a semi-empirical parameter added to the governing equations Sun and Fujino [51]. Even with such development, the numerical models based on the shallow water wave theory are limited to low fluid heights, and relatively low values of excitation amplitudes [53].

Reed et al. [41] developed a numerical algorithm using the shallow wave theory and used it with large amplitude excitation (greater than 1 % of tank length). Although results did not quite match experimental data, the trends were predicted adequately enough to justify the use of the shallow wave theory with some experimental add-on knowledge for adjustment of tuning.

Banerji et al. [7] employed the shallow wave theory to predict TLD-structure performance under random excitation, modeling an earthquake signal. Their study considered 12 different cases of structure properties with various natural frequencies and damping ratios. They found the TLD to decrease structure sway between 3% and 39%.

The rigid Rectangular tank shown in figure below with the length 2a, width b and the undisturbed water level h was subjected to a lateral displacement x_s. The liquid motion is assumed to develop only in x-z plane. It is also assumed that the liquid is incompressible, irrotational fluid, and the pressure is constant on the liquid free surface.

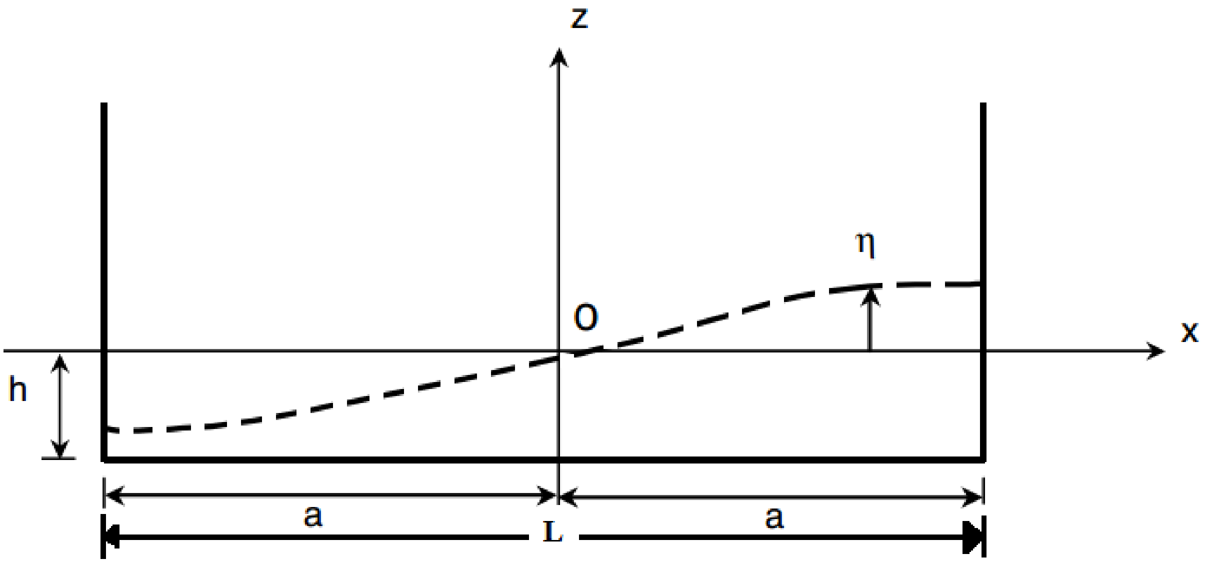

Figure 3.1 Dimensions of the Rectangular TLD

3.11.1.2 Governing Equations

The continuity and two-dimensional Navier-Stokes equations that are employed to describe liquid sloshing are defined as:

3.11.1.2.1 Continuity Equation

$$\frac{\partial \mathrm{u}}{\partial x}+\frac{\partial w}{\partial z}=0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 3.1$$

3.11.1.2.2 Equation of motion

Two dimensional Navier’s strokes Equations:

$$\frac{\partial \mathrm{u}}{\partial t}+u\frac{\partial u}{\partial x}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+v\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial z^2}\right)-\ddot{x}_s \ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 3.2$$

$$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+v\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial z^2}\right)-g \ldots\ldots\ldots\ldots\ldots\ldots \; 3.3$$

Where u(x, t) and w(x, t) are the liquid velocities relative to the tank in the x and z direction, respectively, g is the gravity acceleration, p is the pressure, ρ denotes the density and v represents the kinematic viscosity of the liquid.

The liquid outside the Boundary layer is considered as potential flow and velocity potential is given by Sun (1991):

$$\Phi(x,z,t)=-\frac{gH}{2\omega}\frac{\cosh(k(h+z))}{\cosh kh}+\cos(kx-\omega t) \ldots\ldots\ldots\ldots \; 3.4$$

Where K is the wave number and H is defined as (Sun 1991)

$$H=\frac{2\eta}{\sin(kx-\omega t)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 3.5$$

Based on the shallow water wave theory, potential   is assumed as (Shimisu and Hayama 1986):

$$\Phi(x,z,t)=\Phi(x,t).\cosh(k(h+z)) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 3.6$$

3.11.1.3 Boundary Conditions

u=0 ……………………………………….. On the end wall x = ±a ……..3.7

w=0 ………………………………………. On the bottom z = -h ………3.8

- **Free surface boundary conditions**

a) Kinematic Boundary condition

$$w = \frac{\partial \eta}{\partial t} + u\frac{\partial \eta}{\partial x}$$ On the free surface $z = \eta$ …….… 3.9

Where $\eta(x,t)$ is the free surface elevation.

b) Dynamic Boundary condition

P=p_0= constant on the free surface $z = \eta$ …..... 3.10

Neglecting the thickness of boundary layer integrating the continuity equation (3.1) with respect to z, the continuity equation can be approximately expressed, with the aid of boundary conditions as:

$$\frac{\partial \eta}{\partial t} + h\sigma\frac{\partial(\Phi u(\eta))}{\partial x} = 0$$ ………………………………….……...3.11

Where $\sigma = \frac{\tanh(kh)}{kh}$ and $\Phi = \frac{\tanh(k(h+\eta))}{\tanh(kh)}$

- **The Equation of Motion In Integral Form**

The velocity w and differentials can be expressed in terms of the horizontal velocity u and the equations are integrated with respect to z from bottom to free surface [52].

$$\frac{\partial \mathrm{u}(\eta)}{\partial t} + (1 - T_H^2)u(\eta)\frac{\partial u(\eta)}{\partial x} + C_{fr^2}\, g\frac{\partial n}{\partial x} + gh\sigma\phi\frac{\partial^2 \eta \partial \eta}{\partial x^2 \partial x} = -C_{da}\lambda u(\eta) - \ddot{x}_s$$ ………. 3.12

Where: $T_H = \tanh(k(h+\eta))$; $u(\eta) = u(x,\eta,t)$ Horizontal velocity of surface liquid particle, u and (η) are the independent variables of the Basic equations and λ in equation is a Damping coefficient.

- **Damping of Liquid Sloshing**

Damping co-efficient accounting for the effect of side wall and free surface is:

$$\lambda = \frac{1}{\eta + h}\frac{8}{3\pi}\sqrt{\omega_l v}\left(1 + \left(\frac{2h}{b}\right) + S\right) \quad \text{………………………….………… 3.13}$$

Where S is the surface contamination factor and a value of 1 corresponding to fully contaminated surface, ω_l is fundamental linear sloshing frequency of the liquid, υ is kinematic viscosity, b is width of the tank.

The coefficients C_{fr} and C_{da} are incorporated to modify the water wave phase velocity and damping respectively, when wave are unstable ($\eta > h$) and break.

C_{fr} is found empirically having a constant value 1.05

$$C_{da} = 0.57\sqrt{\frac{h^2\omega_l}{2a}x_{s\max}} \quad \text{……………………………………… 3.14}$$

Where x_{smax} is maximum displacement experienced by the structure at the location of the TLD when there is in no TLD attached.

3.11.1.4 Fundamental Sloshing Frequency of the TLD

The fundamental sloshing frequency of a TLD, can be estimated using the following equation

$$\omega_l = \frac{1}{2\pi}\sqrt{\frac{\pi g}{2a}\tanh\left(\frac{2\pi}{2a}\right)} \quad \text{………………………………. 3.15}$$

Where g is acceleration due to gravity, h is water level and L=2a is length of the tank in the direction of sloshing motion.

Equations (3.11) and (3.12) are discretized in space by finite difference method and solved simultaneously using Runge-Kutta-Gill method to find the values of u and η.

3.11.1.5 Base Shear Force Due To Liquid Sloshing

The force induced in the wall due to liquid sloshing can be found by:

$$F = \frac{\rho g b}{2}\left[(\eta_n + h)^2 - (\eta_0 + h)^2\right] \ldots\ldots\ldots\ldots\ldots .. \; 3.16$$

Where η_n is free surface elevation at the right wall of the tank and η_0 is free surface elevation at the left wall of the tank.

3.11.1.6 Structure Model

Plane concrete building frame can be idealized as shear building, which is modeled as one dimensional multi-degree of freedom system with one degree of freedom at each node. It is assumed that the axial stiffness of the beam at the floor level is very high so there will be no rotation at the floor level between any beam column joints.

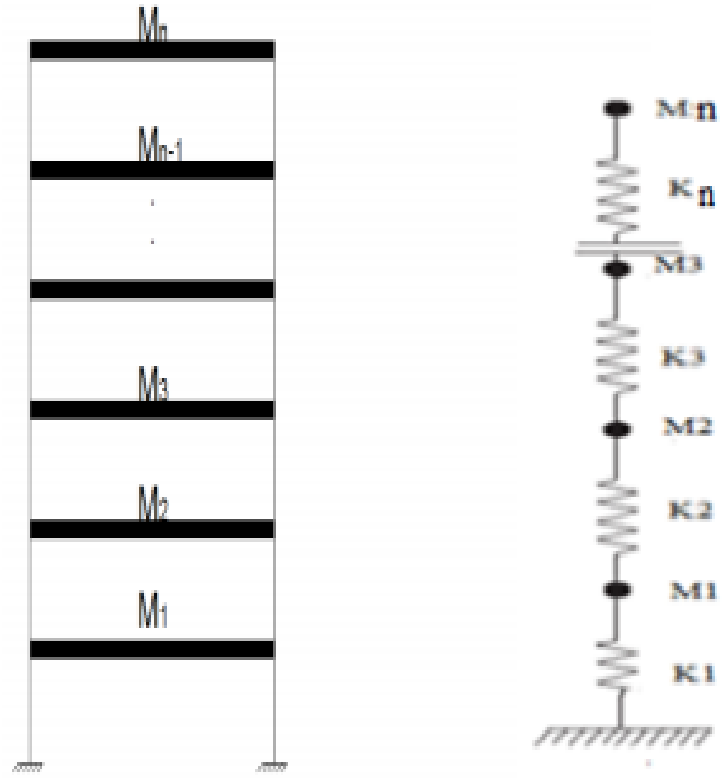

Figure 3.2 Lumped mass model of n-storey shear building

The dynamic equation of the structure is:

$$m\ddot{x}_s + c\dot{x}_s + kx_s = -a_g m \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.17$$

Where m is the mass matrix, c is damping matrix and k is the stiffness matrix is given by:

$$[M]=\begin{bmatrix} m_1 & & & & \\ & m_2 & & & \\ & & . & & \\ & & & m_{n-1} & \\ & & & & m_n \end{bmatrix} \text{ and } [K]=\begin{bmatrix} k_1+k_2 & -k_2 & & & \\ -k_2 & k_2+k_3 & - & & \\ & & - & - & \\ & & - & k_{n-1}+k_n & -k_n \\ & & & -k_n & k_n \end{bmatrix}$$

3.11.1.7 The Fluid-Structure Interaction Model

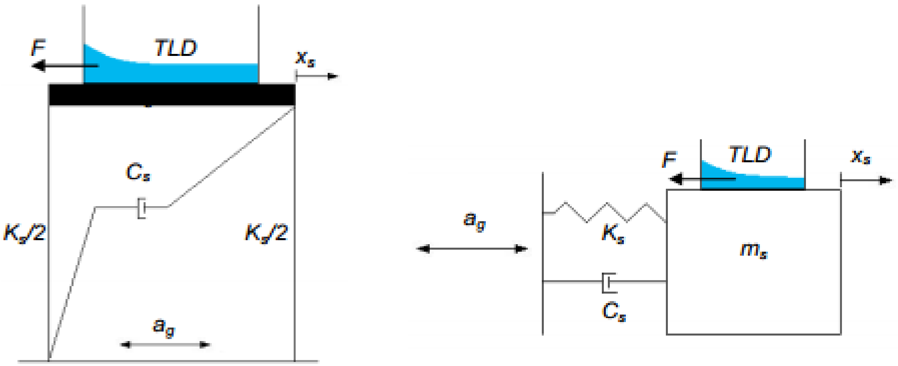

Figure 3.3 Schematic of SDOF System Attached with a TLD [18]

The equation of motion of the TLD structure interaction system subjected to ground acceleration a_g is one of the two:

$$m_s\ddot{x}_s + c_s\dot{x}_s + k_s x_s = -a_g m_s + F \quad \ldots\ldots\ldots\ldots\ldots\ldots 3.18$$

$$\ddot{x}_s + 2\omega_s\xi\dot{x}_s + \omega^2{}_s x_s = -a_g + \frac{F}{m_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots 3.19$$

Where m_s is mass of the structure, c_s is damping coefficient, k_s is stiffness of the structure, a_g is ground acceleration, ω_s is natural frequency of the structure, x_s is structural relative displacement to the ground motion which is the displacement of the TLD and F is TLD Base shear due to sloshing force on the TLD wall.

The equations (3.11), (3.12) and (3.19) must be solved simultaneously in order to find the response of the structure attached with a TLD. By knowing the structural acceleration at each time step, equations (3.10) and (3.11) are solved using Runge-Kutta-Gill method and TLD Base shear F is calculated based on η. Using the value of F, the Response is calculated using Newmark Beta Method from equation (3.18) the acceleration is found is used in the next step calculation. The equations of motion for liquid sloshing inside rectangular tanker were solved and described in Appendix A.

3.11.2 Structure Model Formulation

During an earthquake a structure coupled to a TLD will experience two forces acting on the structure. One is due to the storey forces induced by the earthquake acceleration and the other one is the TLD sloshing force generated by the fluid sloshing in the damper. The resultant of the story and TLD sloshing force determines the structure displacement.

The effectiveness of the TLD in controlling vibration is measured in terms of controlled displacement of top storey of the structure using TLD and uncontrolled displacement of top storey of the structure without using TLD. In the present paper, dynamic characteristics of an idealized multi-storey frame structure in 2-D form are studied when attached with tuned liquid filled tank as passive damper under dynamic excitation. A multi-storied building can be represented as a kinematic system of interconnected mass, springs and dashpots. The mass of each floor of the building provides oscillatory force and building columns provide the lateral stiffness. The material composition of the building frame (beams and columns) provides the inherent damping.

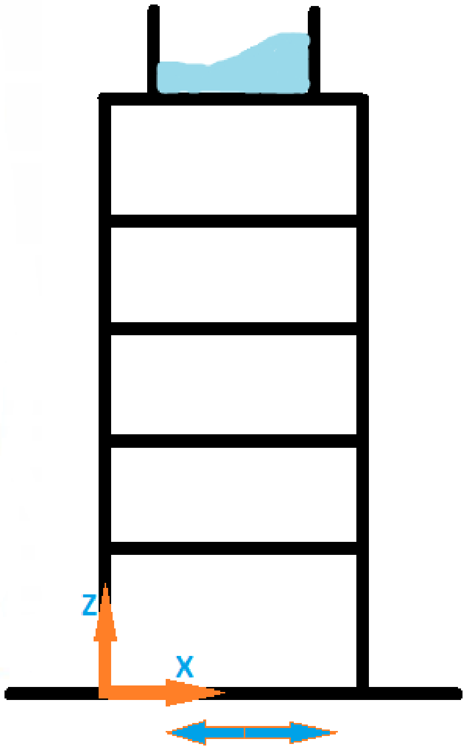

Figure 3.4 Schematic representation of Structure and fluid system

To investigate the effect of TLD protection efficiency on the dynamic response of multi-storey frame structures under seismic excitations, this study was design in the way that dynamic analysis of the structural model has made for response of the frame structure to harmonic ground motion without TLD, response of the frame structure to harmonic excitation with TLD and response of the frame structure to recorded random ground motions so that the effectiveness of TLD was investigated on protection efficiency of frame structures under seismic excitation.

The problem has been studied in three parts; firstly, the responses of the structure to the above mentioned loading conditions are studied. Secondly, the response of the fluid model to the above mentioned loading conditions has been studied; finally, the three frequencies namely structure modal frequency, sloshing frequency and the excitation frequency are kept to operate at the same time and Fluid-Structure interaction model has been studied. Multi-storey framed structure, Namely 10 storey was modeled using the routines of SAP2000. The columns and beams were designed as concrete frame. The details of the model are shown in Table 3.1 and the material properties used are given in Table 3.2.

Table 3.1 Details of the Models

No. of Storey	No. of Bays	Floor Height (m)	Bay size (m)	Column Size (m)	Beam Size (m)
10	2x2	3	5	1.0x1.0	0.4x0.5

Table 3.2 Properties of Materials

Material	Young's Modulus N/m^2	Poisson's ratio	Density Kg/m
Concrete	3.2×10^{10}	0.2	2549.29
Rebar	2.0×10^{11}	0.3	8004.77

3.11.2.1 Modal Analysis

The natural frequencies and mode shapes are important parameters in the design of a structure for dynamic loading conditions. Modal analysis uses the overall mass and stiffness of a structure to find the various periods at which it will naturally resonate. The basic equation solved in a typical undamped modal analysis is the classical Eigen value problem:

$$[K]\{\Phi i\} = \omega i^2 [M]\{\Phi_i\}\ (\omega t)$$

Where: $[K]$ = stiffness matrix

$\{\Phi_i\}$ = mode shape vector (eigenvector) of mode i

ωi = natural circular frequency of mode i (ωi^2 is the eigen value)

$[M]$ = mass matrix

Modal analysis was carried out for the full model and the time period and modal mass participated in the first few dominant modes were found out. For the purpose of calculating the dynamic response, the mass of the structure is calculated directly from the dead load. Based on period and mass of the structure, the stiffness of structure was calculated using equation $K_s = \omega o^2 M$. The values of mass (M) and stiffness (k_s) for the model are given in Table 3.3.

Kareem et al. [58], Koh et al. [29] and Sun et al. [51] have shown that to achieve an optimized system, it is advisable to employ a parametric study of the dampers that are tuned to the first few dominant modes of the building. Generally tuning the fundamental sloshing frequency of the TLD to the natural frequency of the structure causes a large amount of sloshing & wave breaking at the resonant frequency of the combined TLD-Structure system, which dissipates a significant amount of energy. Therefore, in this research the first few dominant modes, from mode-1 up to mode-3 were used for modal time history analysis of frame structure and TLD-Structure systems. Modal frequencies and generalized properties for the first three modes of the building are shown in the table below.

Table 3.3 Modal frequencies and generalized properties for the first three modes of the building

Mode Name	Time Period T in sec	Frequency (Hz)	Circular Frequency (rad/sec)	Effective Mass of the structure M (Kg)	Stiffness of the Structure Ks (N/m)
Mode-1	0.32811	3.0478	19.15	178450.3	65441740.14
Mode-2	0.10504	9.5201	59.817	178450.3	638508287.53
Mode-3	0.06523	15.331	96.325	178450.3	1655752112.33

3.11.3 Dynamic Analysis of the Structural Model

To show the behavior of Tuned Liqued Damper, time history analysis was done using Non Linear transient dynamic analysis for the models with and without TLD using the frame structure which is subjected to Harmonic Ground Motion and Recorded Random Ground Motions; El Centro, New Hall LA Country Fire Station, Santa Monica-City Hall and Oakland-Outer Harbor Wharf ground motion.

The structure is subjected to a sinusoidal forced horizontal base displacement given by:

$$x = x_0 \sin(\omega t)$$

Where, x_0 and ω are amplitude and frequency of the forced horizontal acceleration respectively. The excitation amplitude is chosen as 0.010891m and the frequency of the excitation is selected 19.15 rad/sec corresponding to resonance condition.

For the Non Linear transient dynamic analysis of frame structure incorporated with TLD; wave loads are generated from sloshing motion of the liquid inside tanker which was created due to ground motion applied at the base of the structure that reacted against the motion of the structure.

The definition of the wave load handled through the define load patterns option with the tools that are available for generating wave loading within SAP2000. From the menu bar select Define, and then define a New Load Pattern; wave with a type of Wave and with automated lateral load pattern based on API WSD2000 specifications was made.

Next it was selected the wave case and have gone to Modify Lateral Load Pattern option. Here it was specified the wave load parameters; such as the Wave Characteristics, Current Profile, Marine Growth which affect the width of the member, Drag and Inertial Coefficients which when used with velocities and accelerations generated forces on the member. For wave characteristics; for the wave type it had two options. From Selected Wave Theory and User Defined. For this research it was selected; From Wave Theory and generate a wave loading using Stokes wave theory.

Velocities and accelerations were calculated in the fluid have been resolved in to drag and inertial forces. And they have been automatically applied as varying distributed loads on the members. These distributed loads are applied against the motion of the structure that dissipate a portion of structural responses and resulted in reduction of peak response.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Response of the Structure to Harmonic Ground Motion

The response of the structure is measured in terms of displacement and acceleration are shown in figures below. To show the behavior of Tuned Liqued Damper, time history analysis was done for the models with and without TLD using the frame structure which is subjected to a sinusoidal forced.

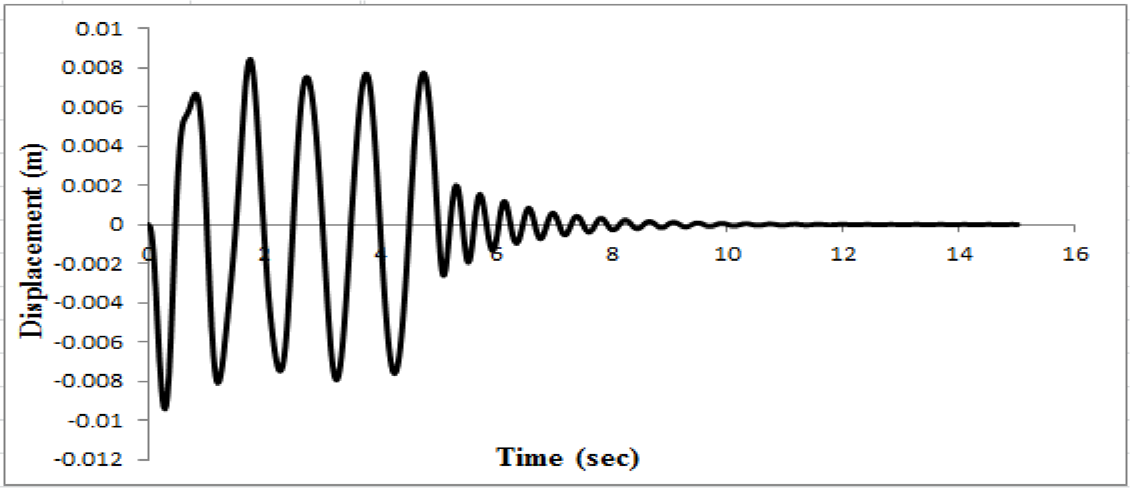

Figure 4.1 Displacement time history of structural response without TLD

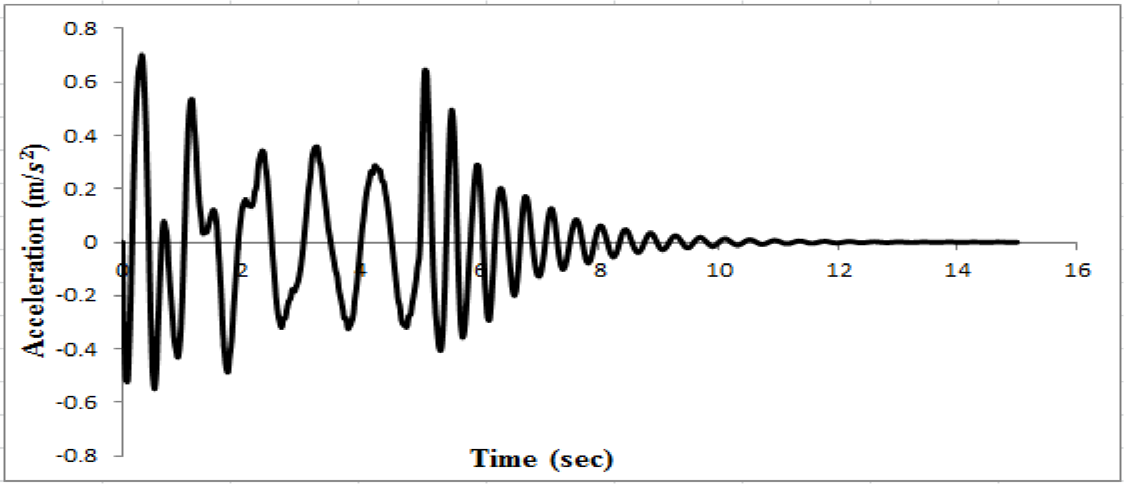

Figure 4.2 Acceleration time history of structural response without TLD

4.1.1 Response of the Structure with TLD to Harmonic Ground Motion

The structure combined with TLD is subjected to the harmonic motion of same amplitude and frequency as in case of structure without TLD. The reduced dynamic response of the structure is found numerically and shown as below

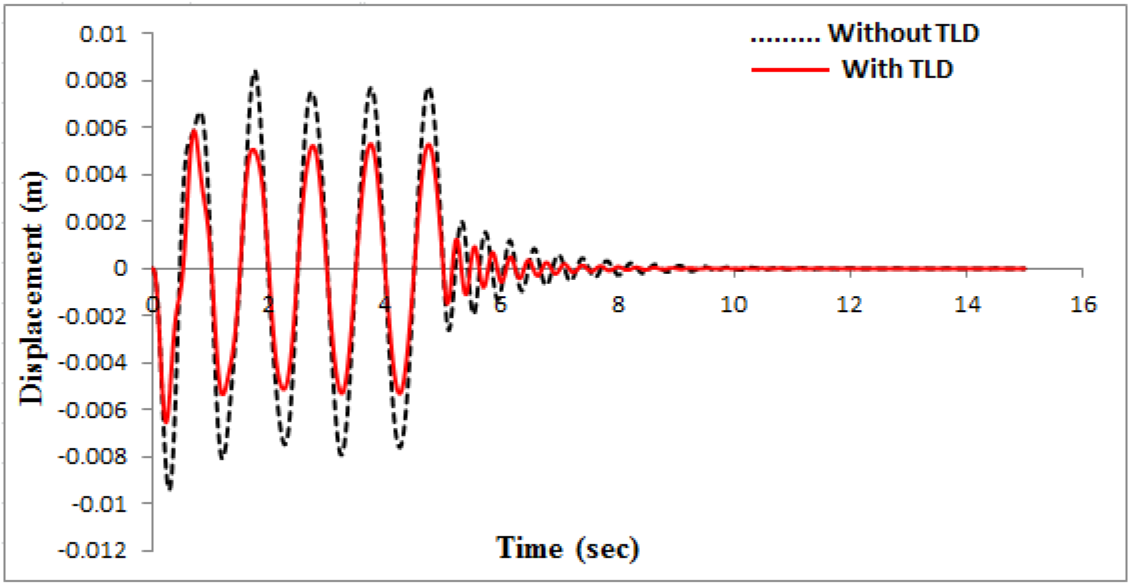

Figure 4.3 Displacement Time histories of structural response with TLD

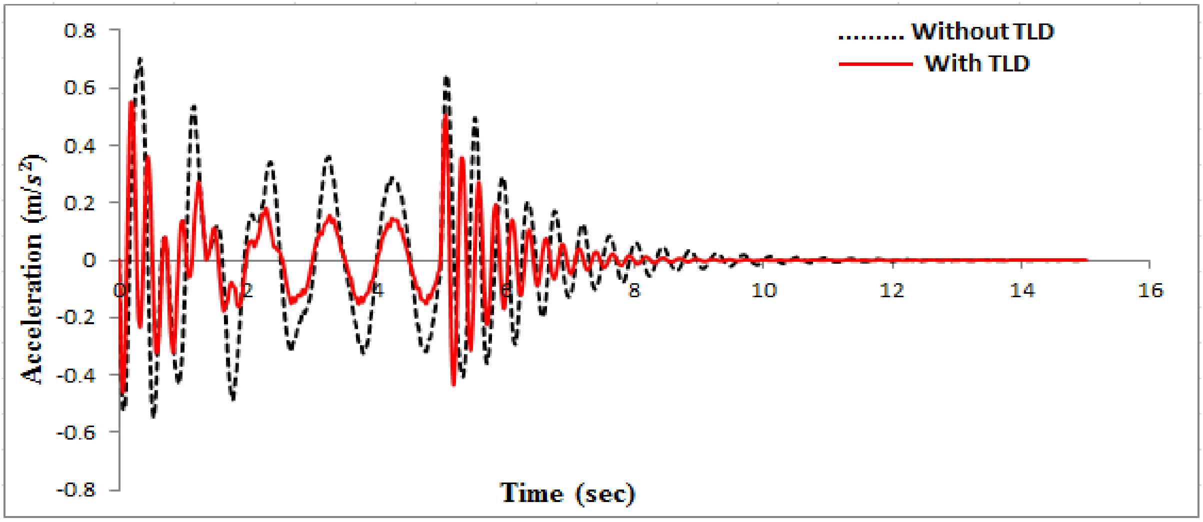

Figure 4.4 Acceleration Time histories of structural response with TLD

4.2 Response of the Structure to Recorded Random Ground Motions

The recorded random motions are distinguished by their different frequency contents and intensity levels. Four recorded ground acceleration time histories are selected for the present analysis. Time history analysis is carried out in SAP2000 using the Non Linear transient dynamic analysis.

4.2.1 El Centro Ground Motion

The component of El Centro ground motion is considered for the frame structure model with and without TLD. The responses are shown in figures below.

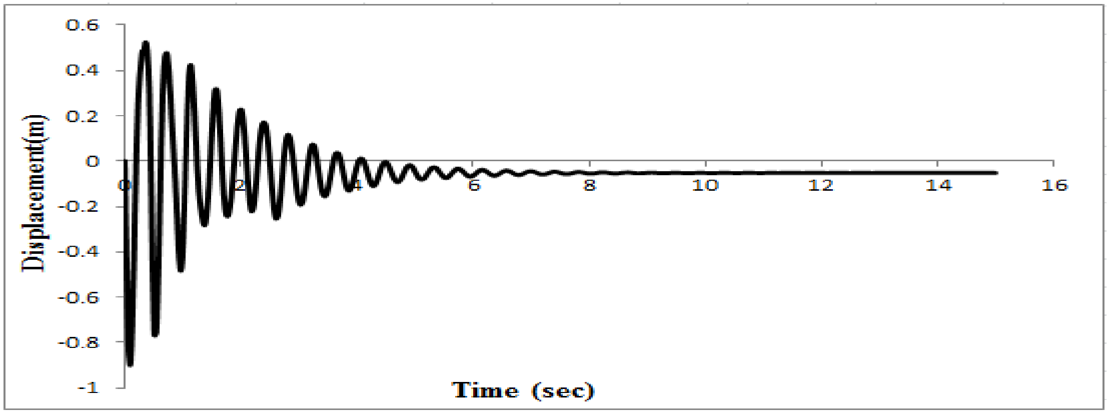

Figure 4.5 Displacement time history of structural response without TLD corresponds to El Centro ground motion

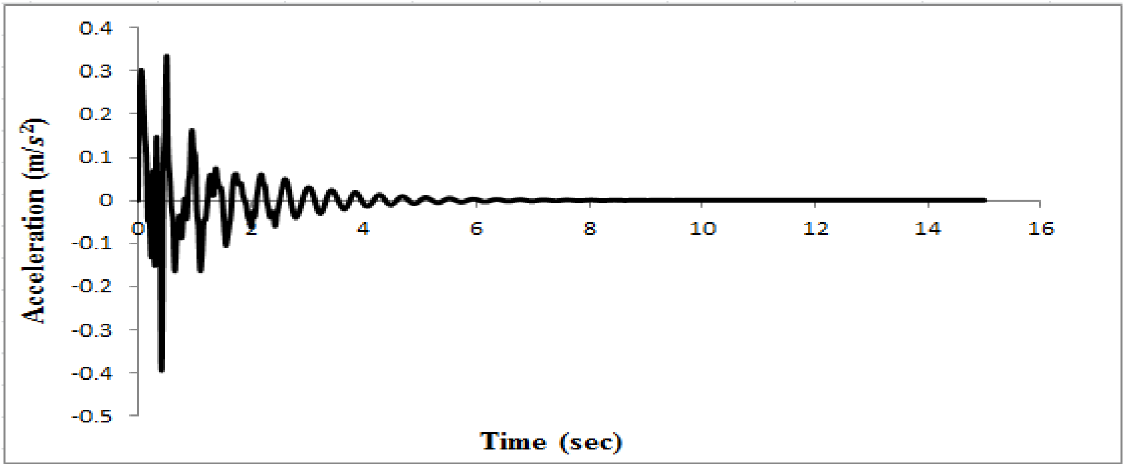

Figure 4.6 Acceleration Time history of structural response without TLD corresponds to El Centro ground motion

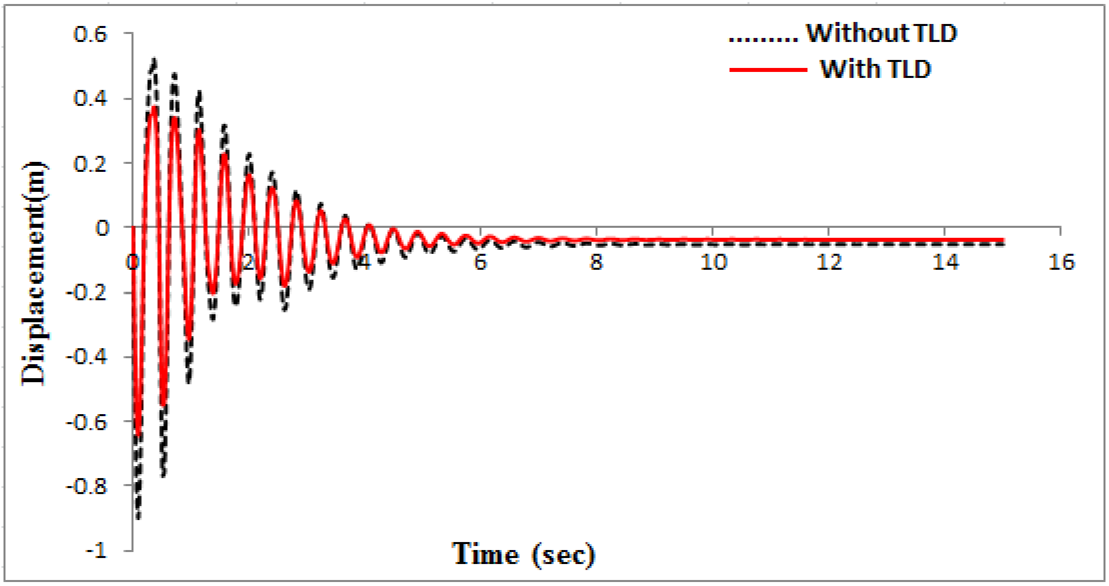

Figure 4.7 Displacement time history of structural response with TLD corresponds to El Centro ground motion

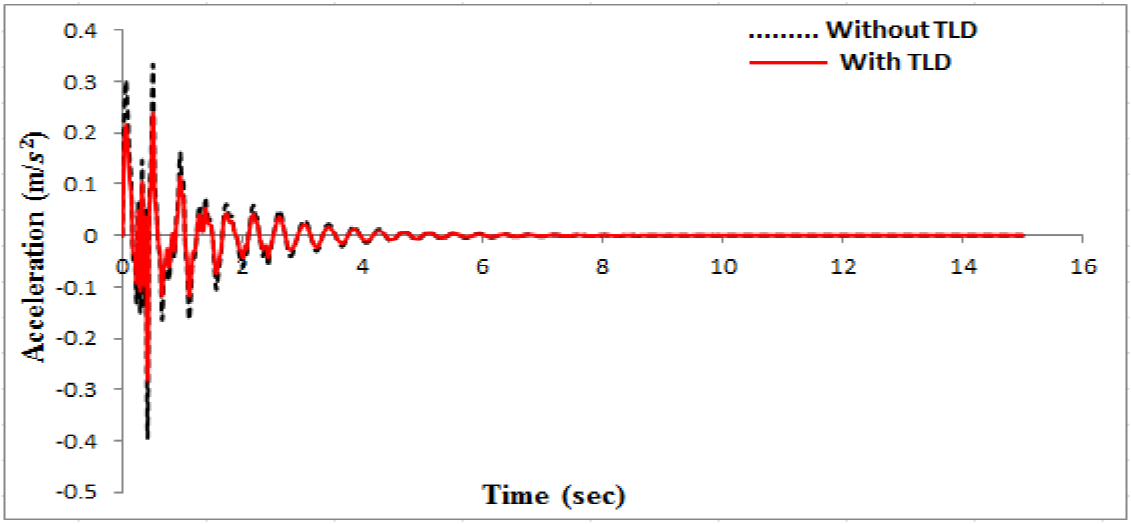

Figure 4.8 Acceleration Time history of structural response with TLD corresponds to El Centro ground motion

4.2.2 New Hall LA Country Fire Station

The component of New Hall LA Country Fire Station ground motion is considered for the frame structure model with and without TLD. The responses are shown in figures below.

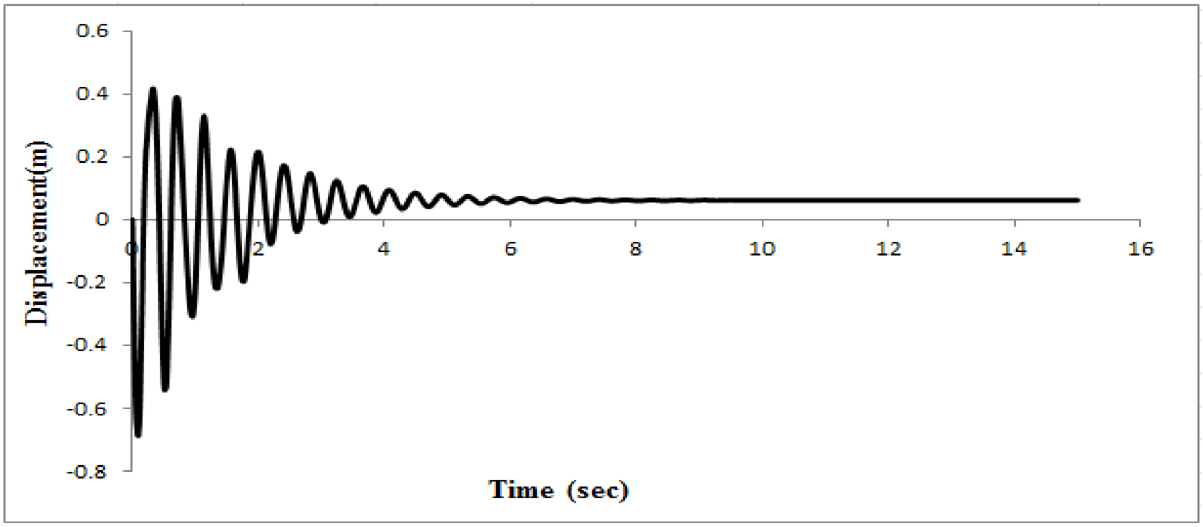

Figure 4.9 Displacement time history of structural response without TLD corresponds to New Hall LA Country Fire Station ground motion

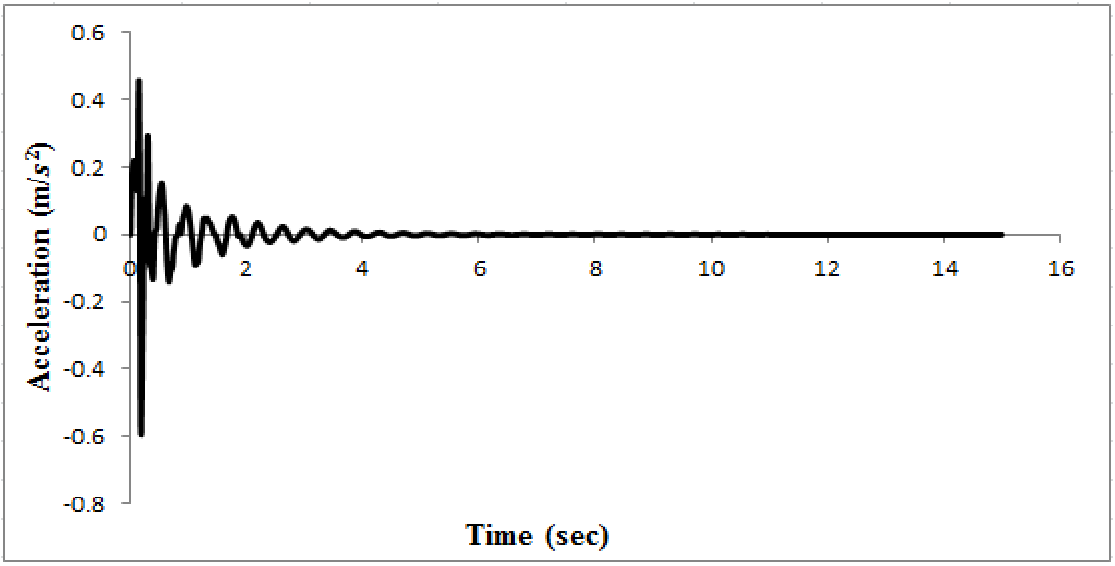

Figure 4.10 Acceleration Time history of structural response without TLD corresponds to New Hall LA Country Fire Station ground motion

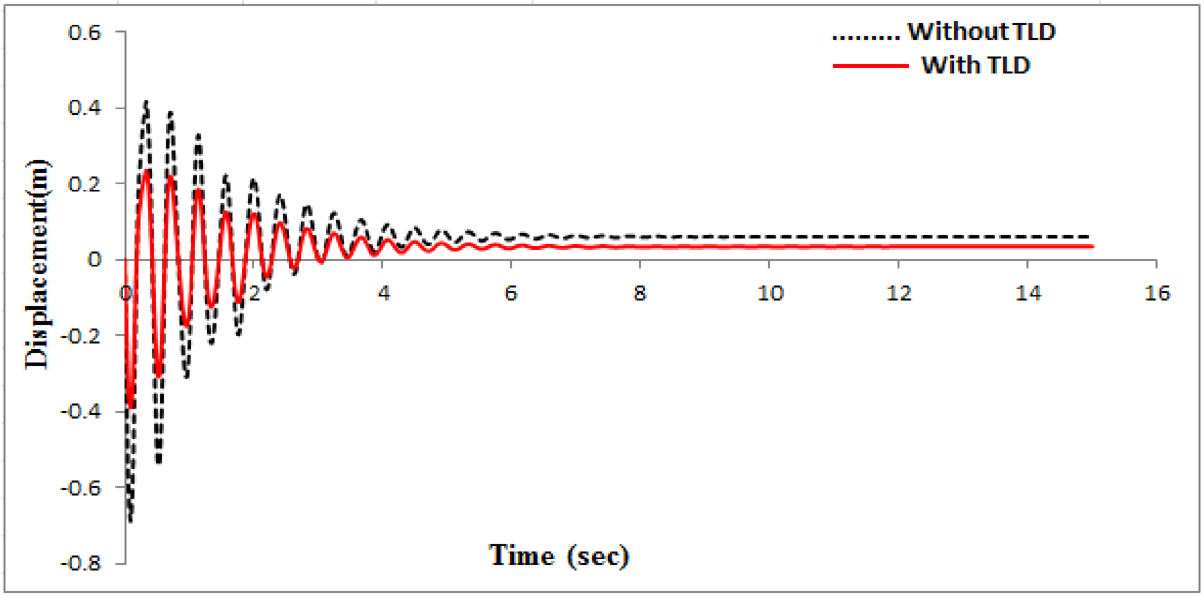

Figure 4.11 Displacement time history of structural response with TLD corresponds to New Hall LA Country Fire Station ground motion

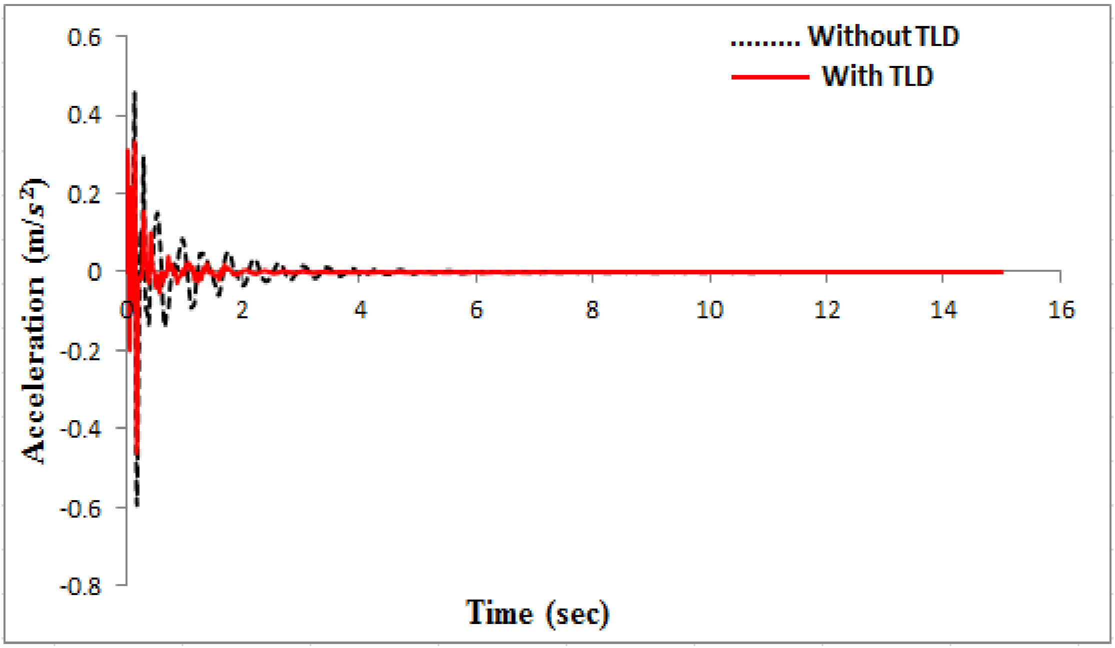

Figure 4.12 Acceleration Time history of structural response with TLD corresponds to New Hall LA Country Fire Station ground motion

4.2.3 Oakland-Outer Harbor Wharf

The component of Oakland-Outer Harbor Wharf ground motion is considered for the frame structure model with and without TLD. The responses are shown in figures below.

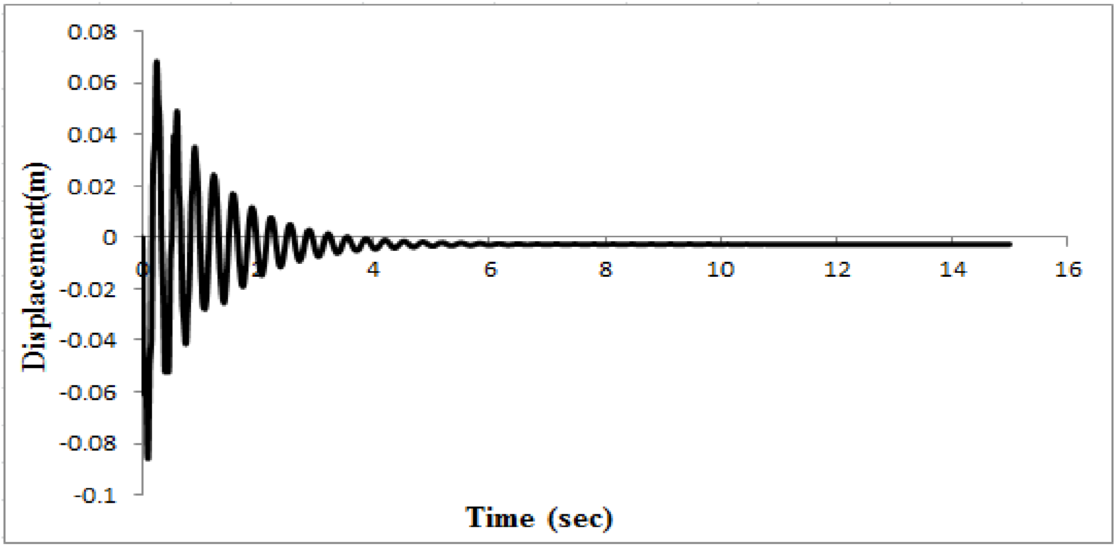

Figure 4.13 Displacement time history of structural response without TLD corresponds to Oakland-Outer Harbor Wharf ground motion

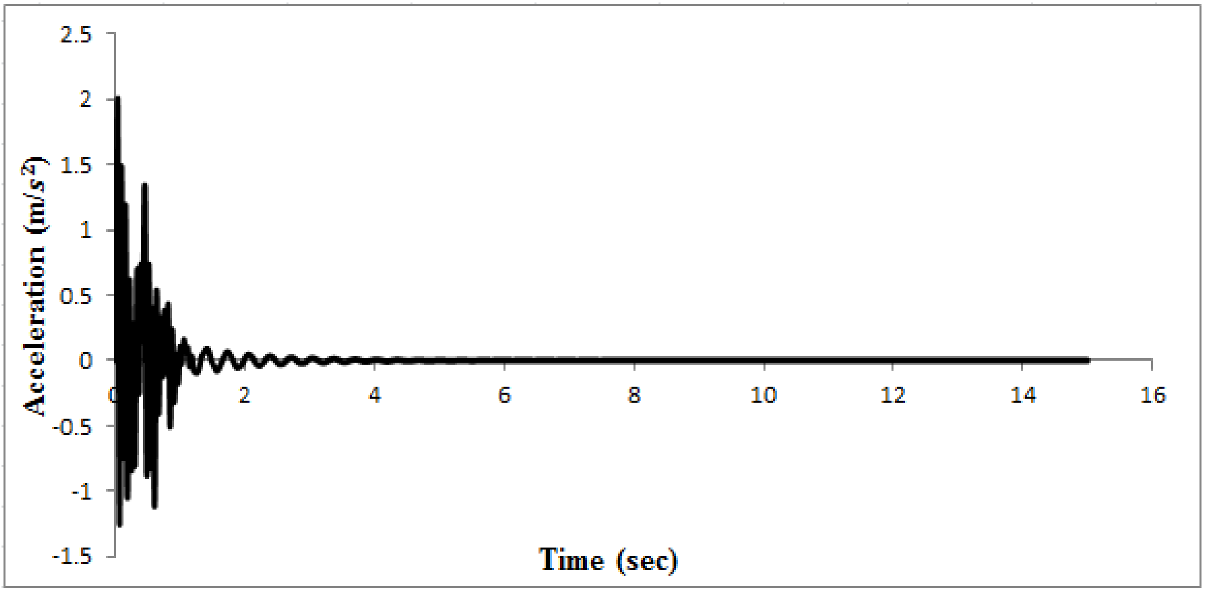

Figure 4.14 Acceleration Time history of structural response without TLD corresponds to Oakland-Outer Harbor Wharf ground motion

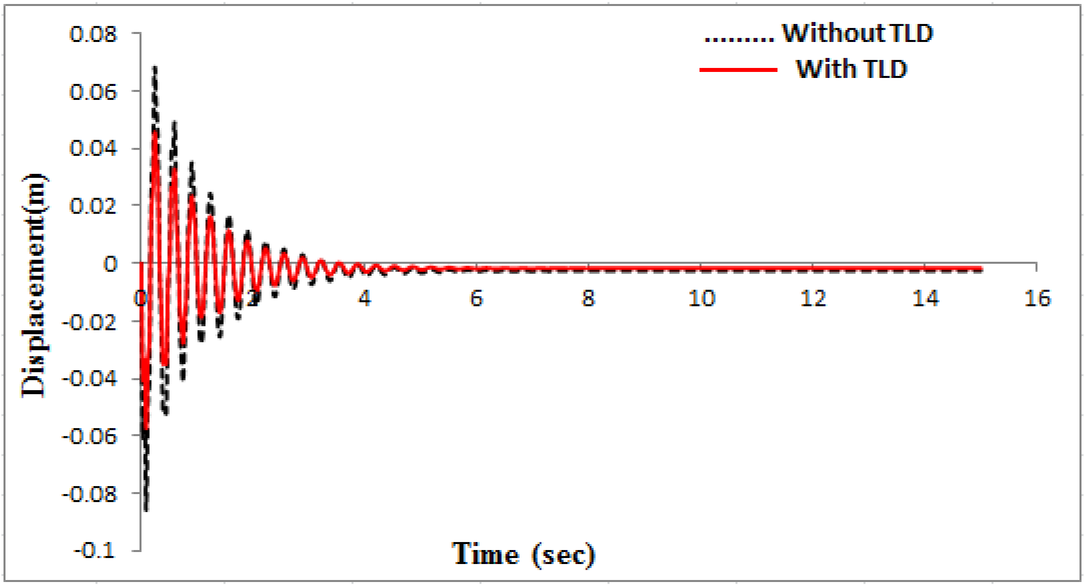

Figure 4.15 Displacement time history of structural response with TLD corresponds to Oakland-Outer Harbor Wharf ground motion

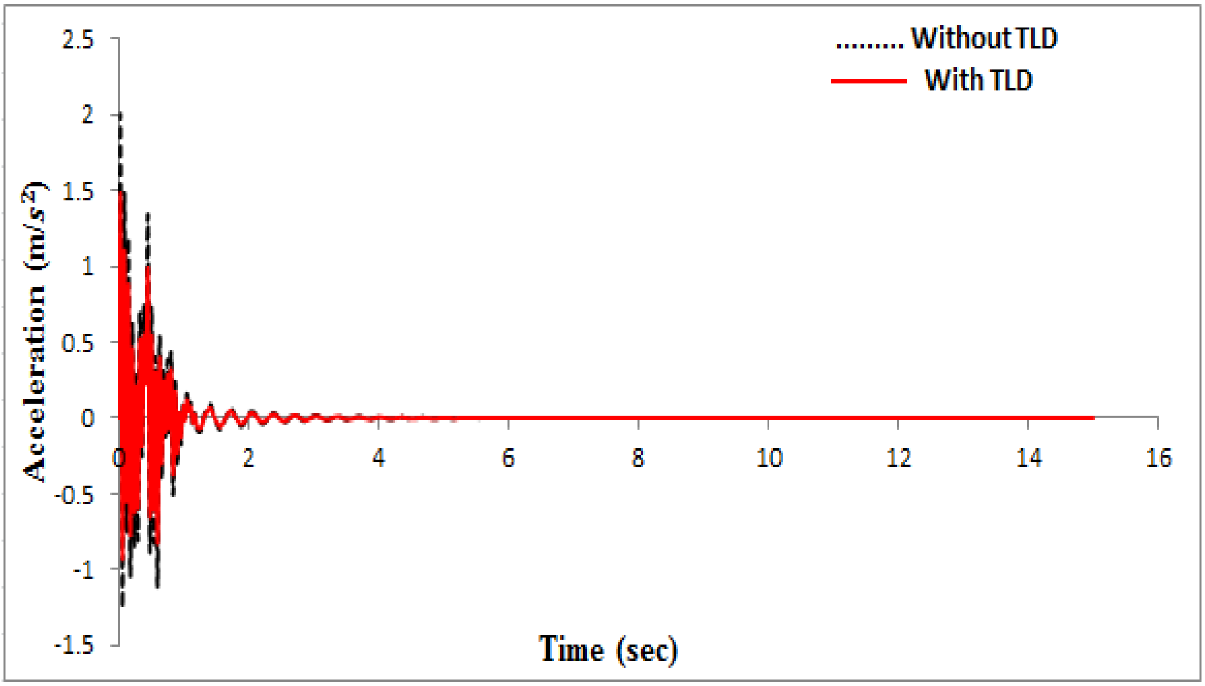

Figure 4.16 Acceleration Time history of structural response with TLD corresponds to Oakland-Outer Harbor Wharf ground motion

4.2.4 Santa Monica-City Hall

The component of Santa Monica-City Hall ground motion is considered for the frame structure model with and without TLD. The responses are shown in figures below.

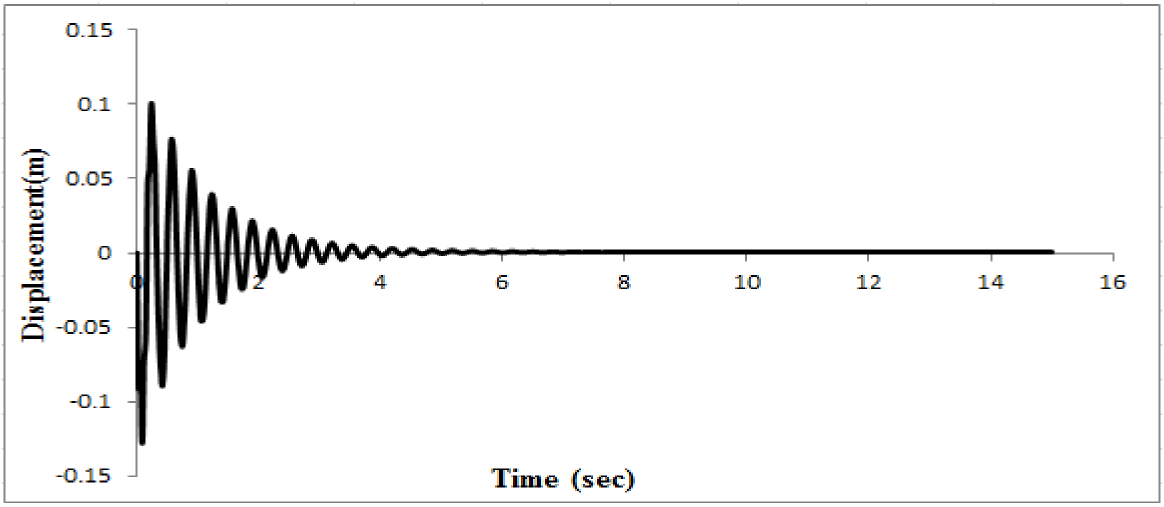

Figure 4.17 Displacement time history of structural response without TLD corresponds to Santa Monica-City Hall ground motion

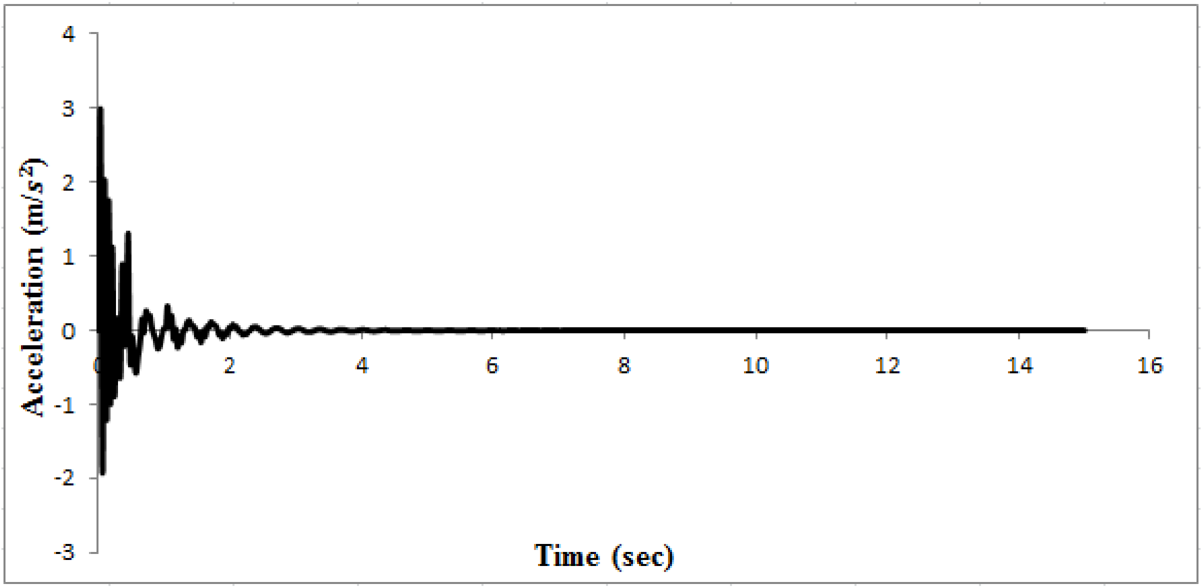

Figure 4.18 Acceleration Time history of structural response without TLD corresponds to Santa Monica-City Hall ground motion

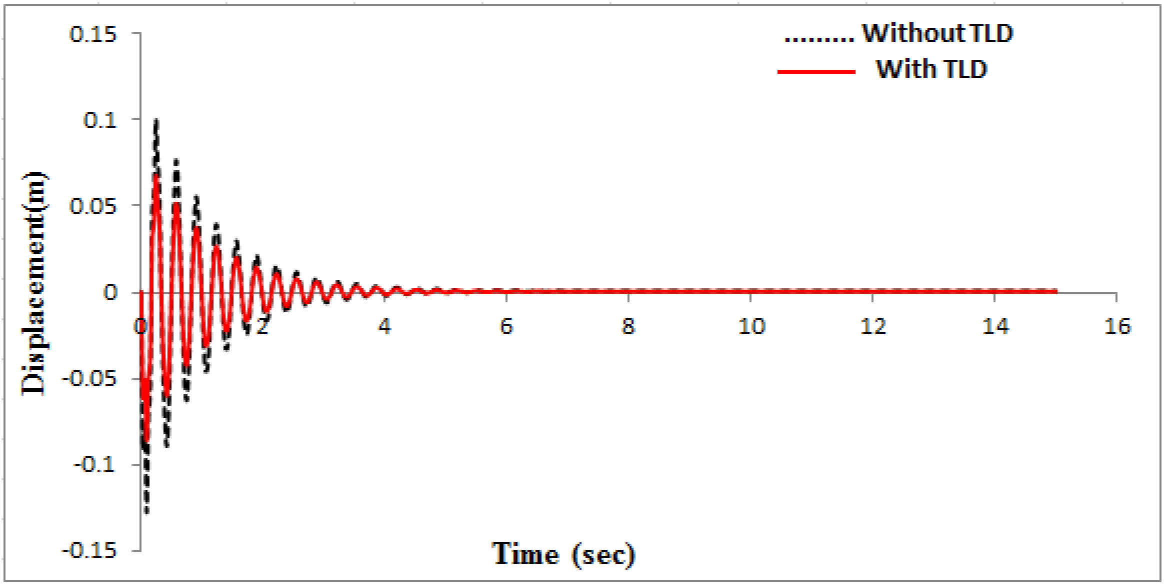

Figure 4.19 Displacement time history of structural response with TLD corresponds to Santa Monica-City Hall ground motion

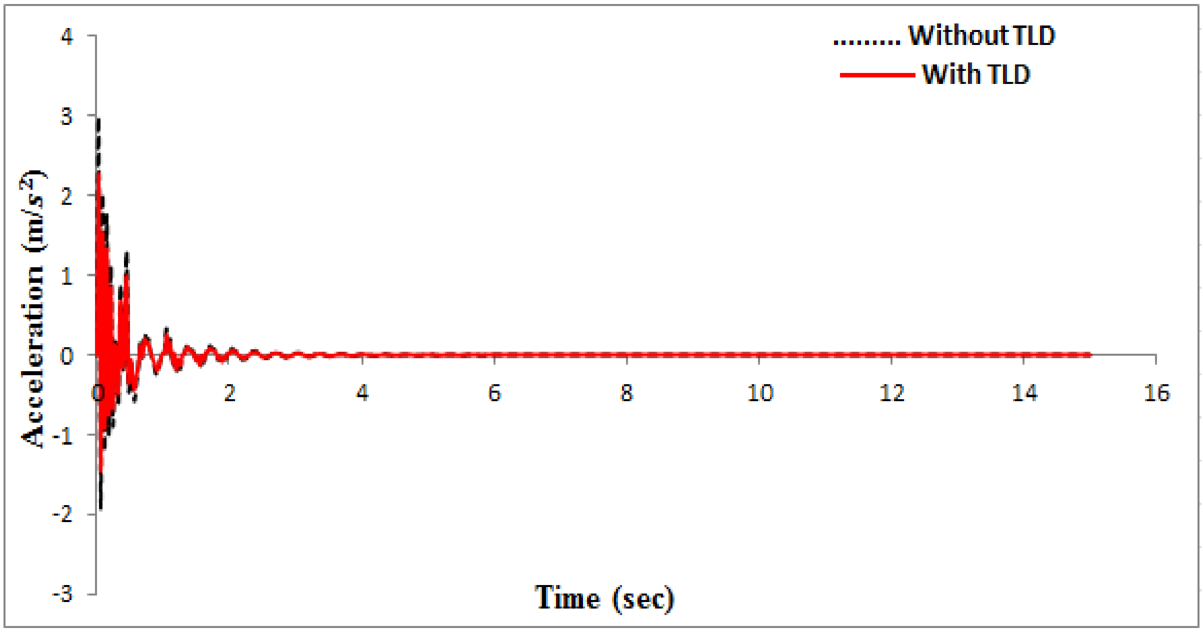

Figure 4.20 Acceleration Time history of structural response with TLD corresponds to Santa Monica-City Hall Grounds ground motion

The percentage reduction of the peak structural responses of the frame structure with and without a TLD for sinusoidal base excitation and percentage reduction for random ground motion are presented and summarized in the tables below.

Table 4.1 Peak relative displacements of the structure and the percentage reduction by TLD

Type of loading	Without TLD (m)	With TLD (m)	Percentage Reduction (%)
Sinusoidal loading	0.00842	0.00588	30.22
El Centro earthquake ground motion	0.523373	0.37338	28.66
New Hall-LA Country Fire Station	0.417252	0.23637	43.35
Oakland-Outer Harbor Wharf	0.067961	0.04540	33.20
Santa Monica-City Hall Grounds	0.100258	0.06751	32.68

Table 4.2 Peak acceleration of the structure and the percentage reduction by the TLD

Type of loading	without TLD (m/s^2)	with TLD (m/s^2)	Percentage Reduction (%)
Sinusoidal loading	0.69935	0.549	28.50
Elcentro earthquake ground motion	0.85148	0.6553	23.04
New Hall-LA Country Fire Station	0.434727	0.3256	25.10
Oakland-Outer Harbor Wharf	1.985892	1.4688	26.04
Santa Monica-City Hall Grounds	2.962725	2.2419	24.33

4.3 Discussions

From the above results which are summarized in Tables 4.4 and 4.5 it can be seen that a TLD provides a comparable reduction in both the peak total acceleration and relative displacement of the structure. The percentage of reduction in the displacement is more in case of New Hall-LA Country Fire Station ground motion 43.35% and acceleration is more in case of sinusoidal loading 28.50%.

The percentage of reduction in the acceleration is more in case of sinusoidal loading as the considered sinusoidal load contains single frequency it is very easy to tune the TLD with the same frequency. In case of earthquake event the peak ground acceleration is in the initial part of the time history. It can be seen that TLD is not effective in the initial phase of the structure’s vibration, because the water motion is then weak. Once the strong motion starts, the TLD becomes increasingly effective in reducing the response, as water sloshing increasingly dissipates more energy.

4.4 Optimization of Design Parameters

4.4.1 General

In all engineering fields, designers try to find solutions showing good performance, which satisfy several requirements. Using optimization techniques, designers can obtain the optimum within the imposed conditions. Structures designed in this way are safe, more reliable and less expensive than the traditional ones. Generally speaking, the structural optimization problem can be formulated as the selection of a set of decision variables that are the parameters of the design which characterize structural configuration, collected in the so called design vector (DV) b, over a possible admissible domain R. The optimum DV must be able to minimize a given Objective Function (O.F.) and to satisfy some constraint conditions.

In deterministic based optimization problems, the aim is to minimize a suitable objective function under certain deterministic behavioural constraints, usually on stresses and/or displacements. In reliability-based optimum design, probabilistic constraints are utilized in order to take into account randomness in some involved parameters. In general, probabilistic constraints define the feasible region of the design space by restricting the probability that a deterministic constraint is violated within the allowable probability of violation.

The defined optimization problem has been stated first by Nigam (1972) and transformed into a standard nonlinear programming one. It could be stated as:

$$\begin{aligned} &\text{Minimize O.F. } (b, t) \\ &\text{Subject to } p_f\,(b, t) \le \overline{p}_f \\ &\qquad\qquad b \in R \end{aligned}$$

The objective function could be defined either by a standard deterministic way like the total structural weight or the elements volume or in a stochastic one. In a stochastic case, response statistics could be used, as covariance or spectral moments of variables of interest like displacement, acceleration or structural stress in relevant elements. The reliability constraint imposes that possible DVs must guarantee a failure probability p_f (b, t) smaller than a given maximum acceptable one, defined as $\overline{p}_f$.

4.4.2 Optimization of TLD

To achieve an optimized system, previous studies have shown that it is advisable to employ a parametric study of the dampers that are tuned to the first few dominant modes of the building [29]. The structure-TLD systems are numerically solved to demonstrate the ability of the TLD system to reduce the structural motion. The best system is then chosen for a parametric study.

In this study, the mechanical parameters of TLD are collected in the two element design vectors which are water depth ratio and mass ratio of TLD:

$$b = (\Delta, \mu)T$$

The criterion selected for the optimization is the minimization of the peak displacement of the structure. As usually done in many real practical engineering applications, the global system failure is associated to an excessive TLD displacement, and for this reason a limitation to displacement X_d is imposed.

Thus, the TLD optimum design is finally posed in a complete framework as follows:

Minimize   O.F. = peak displacement of the structure.

$$\text{Subject to } X_{T(T)} \leq X_T\text{max} \mid_T \in [0, T]$$

Where $X_T$max is the admissible TLD displacement and T is the vibration duration.

4.4.2.1 Parametric Studies

In order to improve efficiency of control strategy, it is essential to define the optimum mechanical parameters water depth ratio; ratio of stationery liquid height to length of the tank and mass ratio; ratio of mass of damper to structure of TLD. In fact the parameters of TLD system must be obtained through the optimum design procedures to attain a better performance control. For these reasons, the determination of optimum design parameters of TLD to enhance the control effectiveness has become very crucial. For the parametric investigation to determine the optimal TLD parameters the frame structure was subjected to harmonic ground excitation.

4.4.2.1.1 Depth Ratio

The depth ratio, which is the ratio of depth of the water h to the tank length L, is a significant parameter for defining the effectiveness of the rectangular TLD. Numerical models based on shallow water wave theory limits the depth ratio up to 0.2 (h/L<0.2).

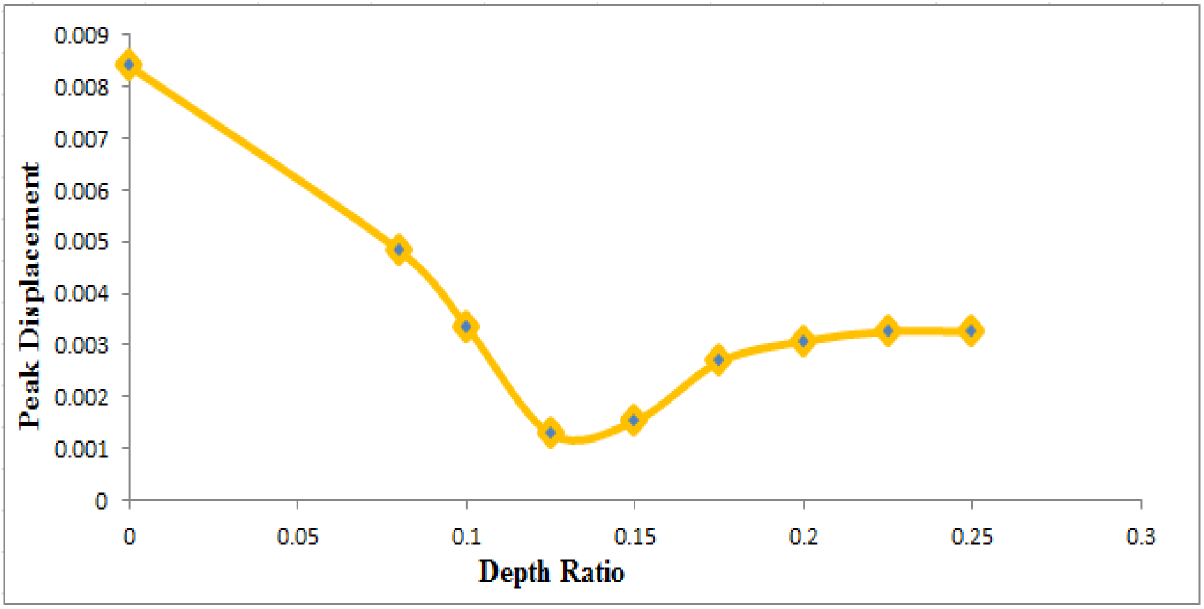

Figure 4.21 Frame Structure response peak displacements versus TLD water depth ratio in resonance condition

Different water depth ratios varying from 0.8 to 2.2 has been considered and the corresponding maximum response of the structure has been shown in figure above. The figure shows the relationship between the structural response amplitude in resonance condition and the corresponding water depth ratios. From this figure, it can be clearly observed that an optimum depth ratio was 0.122 corresponds to the minimum response amplitude.

From above result it can be seen that TLDs with higher water depth ratio have no significant reduction in structural response when compared with lower depth ratio of TLDs. And this leads to conclude that the energy absorbed and dissipated by TLDs depends mostly on the sloshing and wave breaking.

4.4.2.1.2 Mass Ratio

The TLD efficiency under a range of mass ratio which is the ratio of the mass of water to the structure mass is also an important parameter to be considered in the optimum design of TLD. The TLD efficiency under different ranges of mass ratio's has been investigated in terms of structural displacement reduction. The different mass ratios varying from 0.5 % to 5.5 % has been considered and the corresponding percentage reduction in displacement of the structure has been shown in figures below.

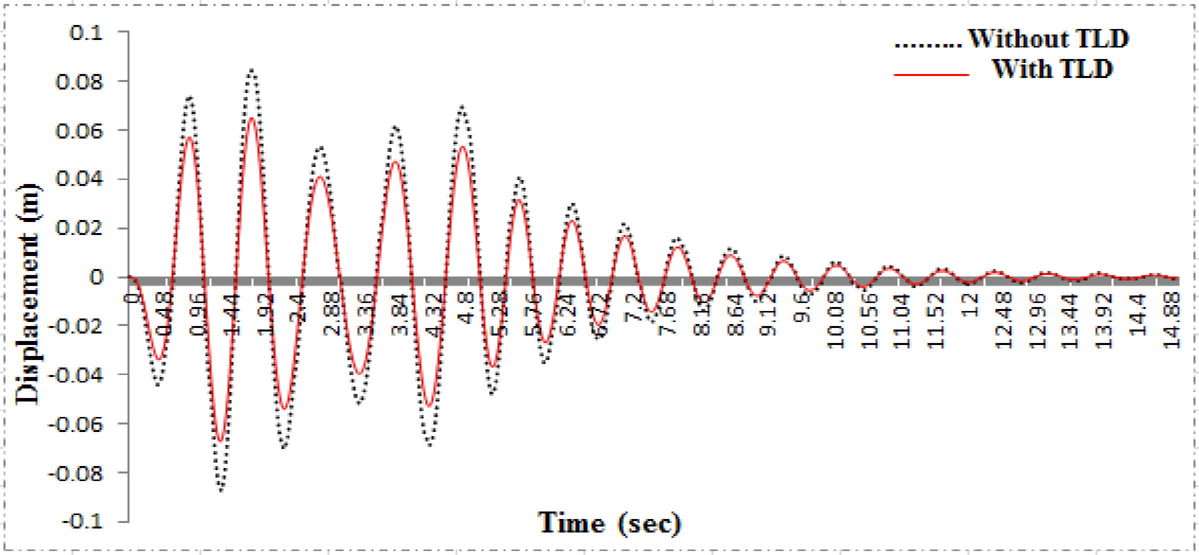

Figure 4.22 Displacement time histories of structural response with and without TLD corresponds to 0.5% mass ratio.

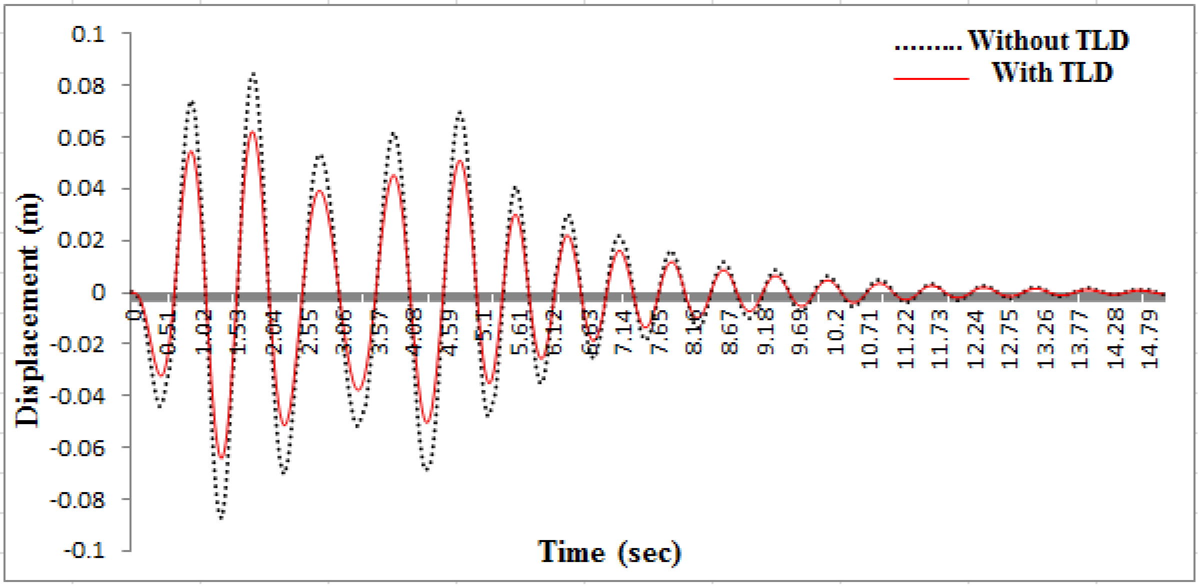

Figure 4.23 Displacement time histories of structural response with and without TLD corresponds to 1% mass ratio.

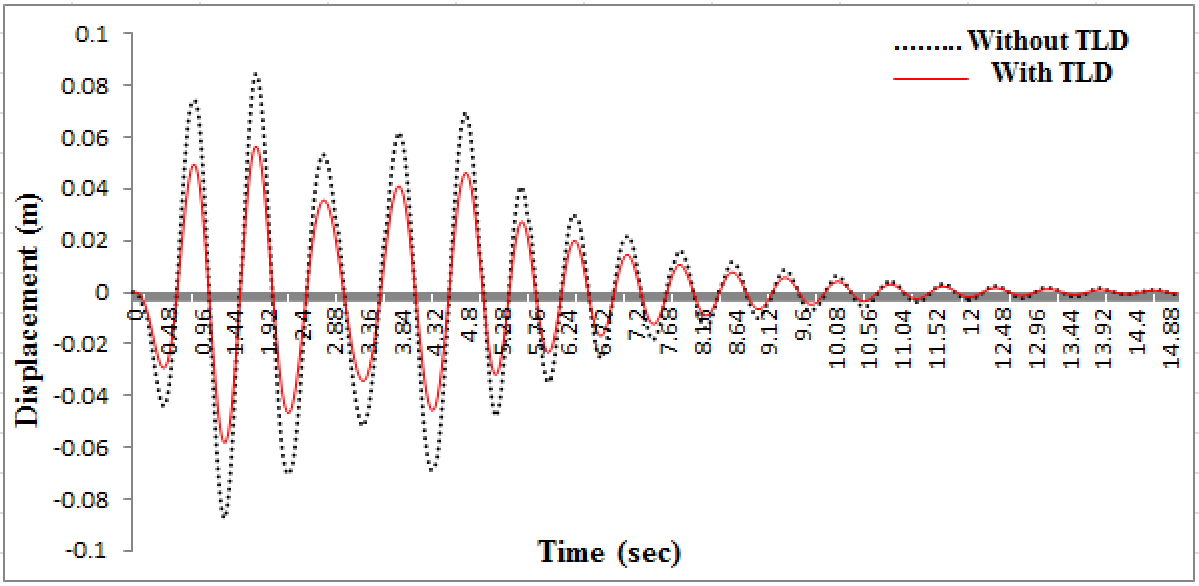

Figure 4.24 Displacement time histories of structural response with and without TLD corresponds to 1.5% mass ratio.

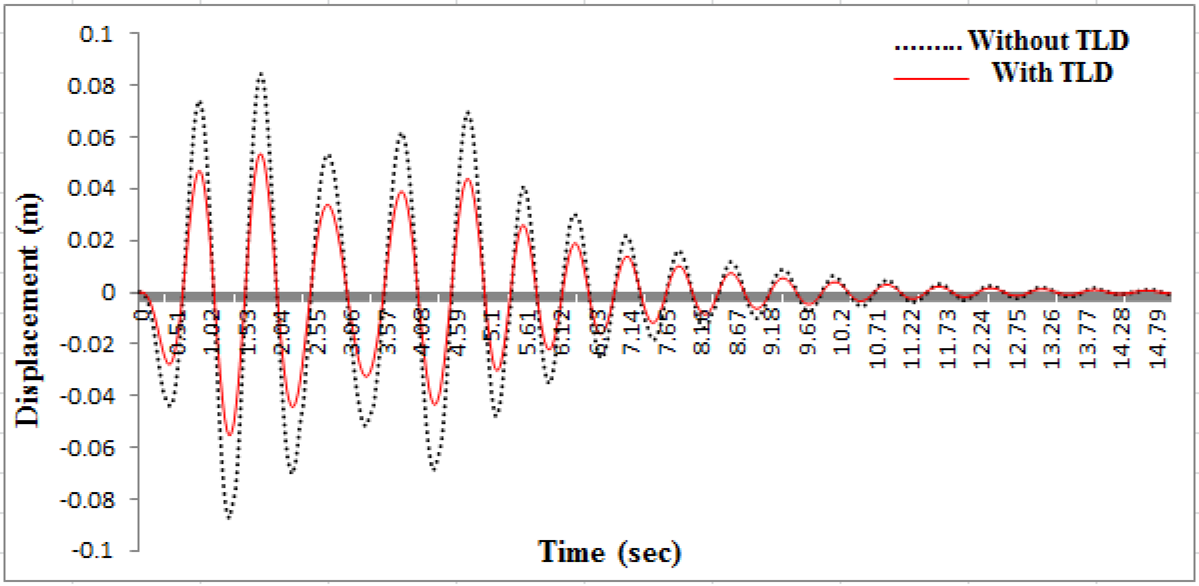

Figure 4.25 Displacement time histories of structural response with and without TLD corresponds to 2% mass ratio.

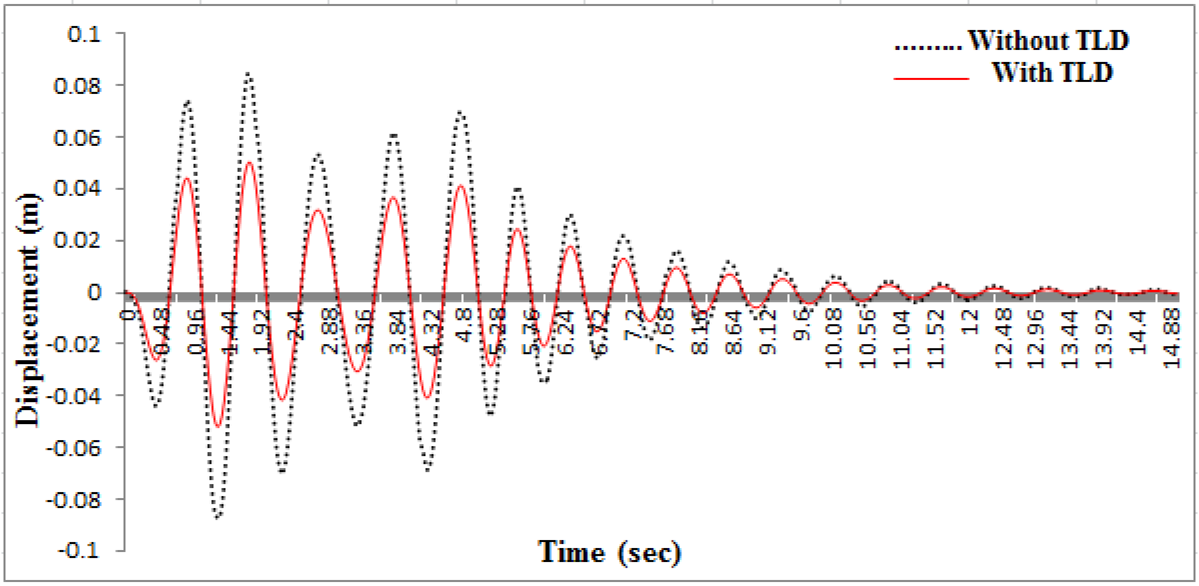

Figure 4.26 Displacement time histories of structural response with and without TLD corresponds to 2.5% mass ratio.

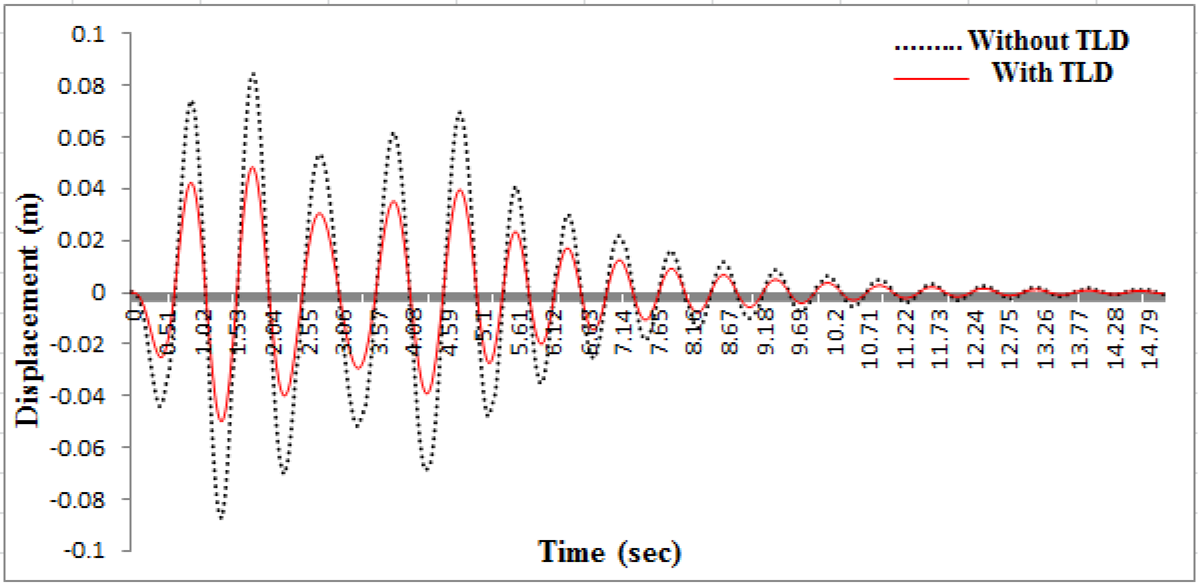

Figure 4.27 Displacement time histories of structural response with and without TLD corresponds to 3% mass ratio.

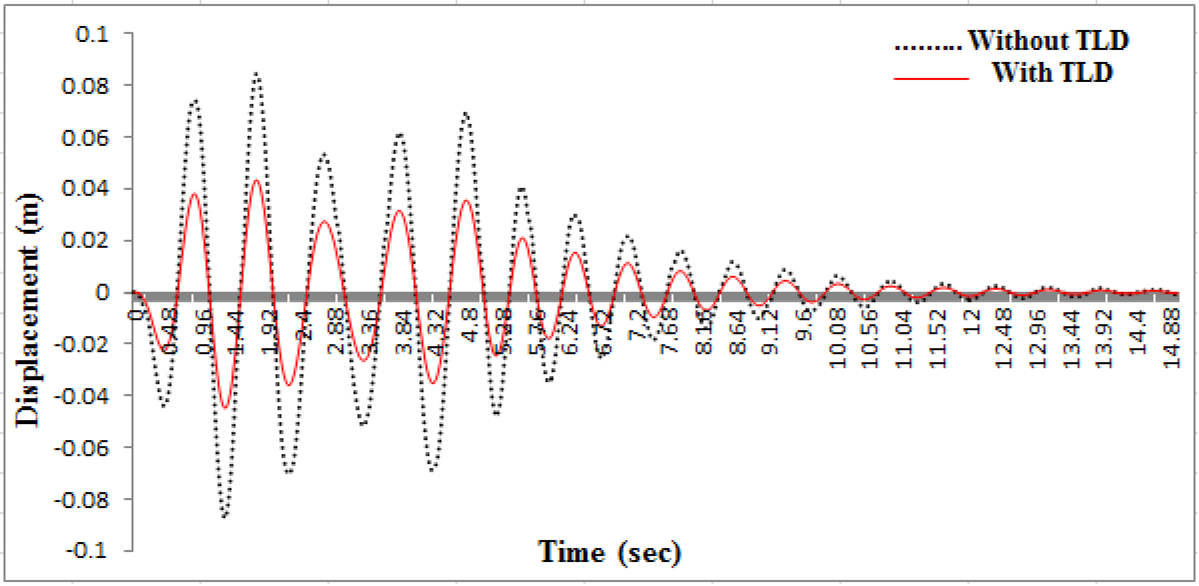

Figure 4.28 Displacement time histories of structural response with and without TLD corresponds to 3.5% mass ratio.

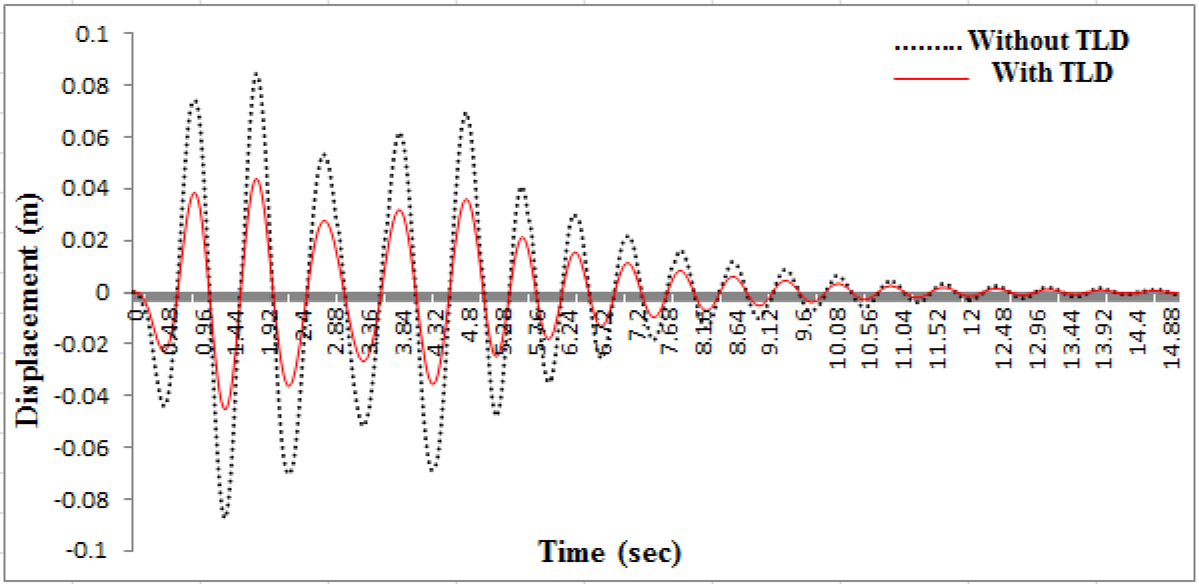

Figure 4.29 Displacement time histories of structural response with and without TLD corresponds to 4% mass ratio.

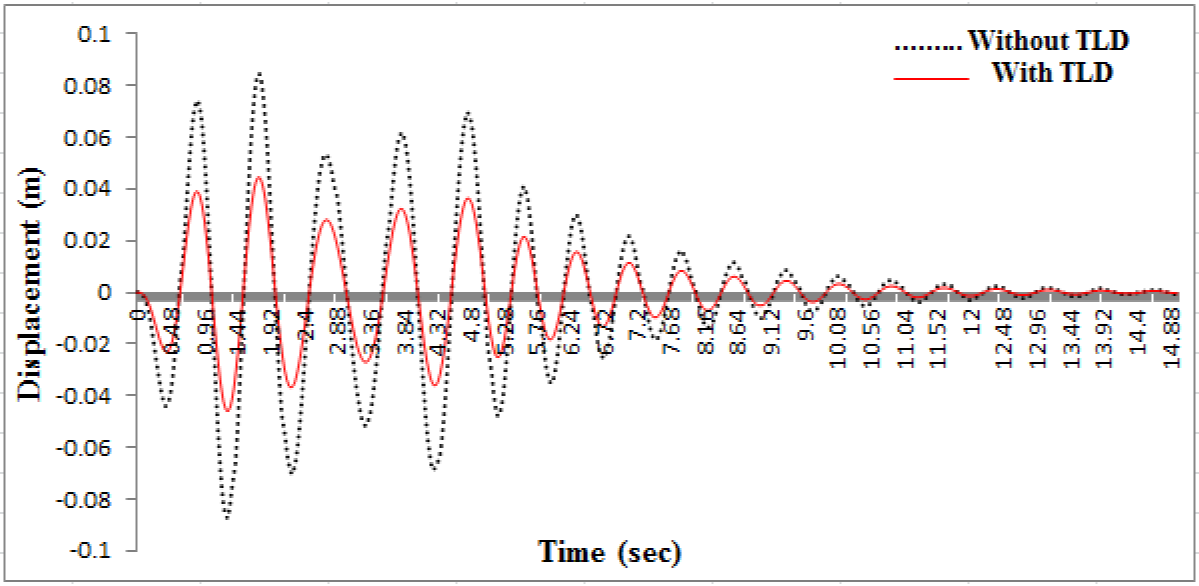

Figure 4.30 Displacement time histories of structural response with and without TLD corresponds to 4.5% mass ratio.

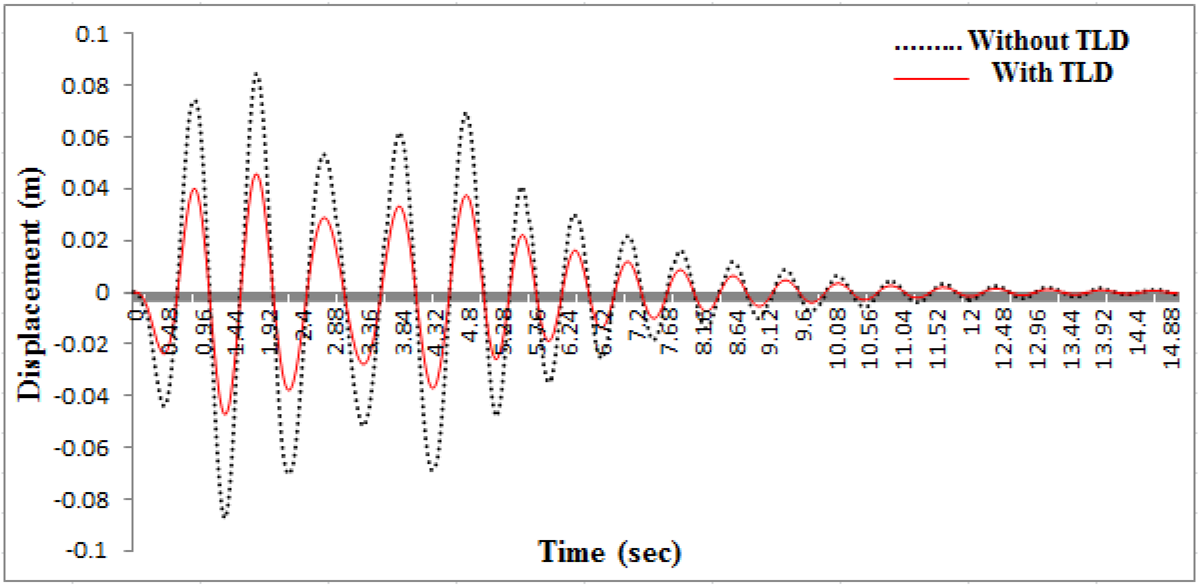

Figure 4.31 Displacement time histories of structural response with and without TLD corresponds to 5% mass ratio.

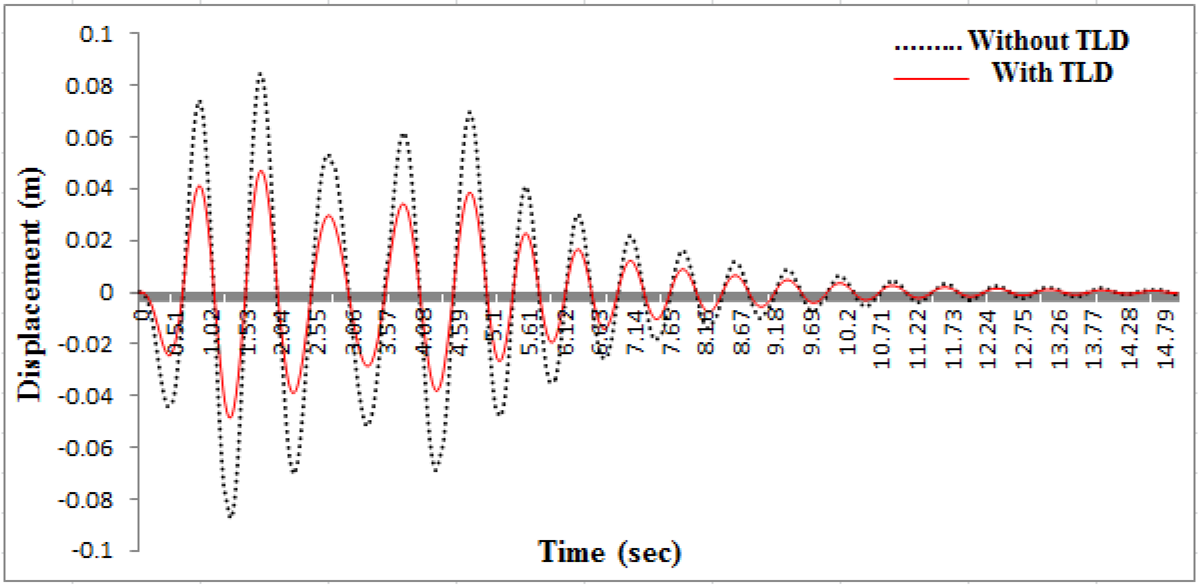

Figure 4.32 Displacement time histories of structural response with and without TLD corresponds to 5.5% mass ratio.

The percentage reduction of the peak structural responses of the frame structure with and without a TLD using different mass ratios for optimum design of TLD are presented and summarized in the tables below.

Table 4.3 Percentage reduction in the peak structural responses by TLD with different mass ratios

Mass Ratio (μ) $\mu = \frac{mass\ of\ water}{mass\ of\ structure} x100$	Percentage Reduction in Displacement (%)
0.5	23.07
1	26.47
1.5	33.33
2	36.7
2.5	40.47
3	42.85
3.5	48.72
4	48.18
4.5	47.37
5	45.94
5.5	44.61

It can be seen from the above figures and summarized table that the efficiency of reduction in the displacement increased as the mass ratio increased up to 3.5 %. For mass ratios larger than 3.5% it was observed that although it is practical in reducing peak structural responses, the efficiency of reduction in the displacement is reduced. Therefore 3.5% mass ratio can be recommended as the optimum value. It was also observed that the optimum design of TLDs using mass ratios had given the highest reduction in structural response which is 48.72% of structural response.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The overall objective of this paper was to determine the optimum design of tuned liquid damper for vibration control of frame structure under seismic excitation that result in utmost a properly designed TLD can substantially reduce structural response to earthquake loading. And also the study leads to the conclusion that it is reasonable to implement tuned liquid damper for mitigation of structural response under dynamic action. The effect of tuned condition on structural response with and without TLD, are evaluated and presented in graphical and tabular forms.

Based on the above discussion, the following conclusion can be made:

- It has been found that the TLDs can be successfully used to reduce vibration of the structure and the optimum design of TLDs had given the highest reduction in the structural response to earthquake loading.
- TLDs have little effect on the structural response during the first few seconds of earthquake excitation. This leads to the conclusion, a TLD may not be effective in reducing the peak response of a structure subjected to a pulse-type of ground motion. This is because for this type of motion the peak values are reached in the first couple of cycles of vibration, when the water motion does not get a chance to dissipate enough energy.
- Different water depth ratios varying from 0.8 to 2.2 are considered for the TLD to investigate the optimum value at resonant condition. It is observed that there exists an optimum water depth ratio corresponds to the minimum response amplitude. The optimum water depth ratio is found to be 0.122.
- It is observed that TLDs with higher water depth ratio have no significant reduction in structural response when compared with lower depth ratio of TLDs. And this leads to conclude that the energy absorbed and dissipated by TLDs depends mostly on the

sloshing and wave breaking. Because the TLD having a higher water depth ratio does not slosh as much as that for low water depth ratios.

- Different mass ratios ranging from 0.5 % to 5.5 % of the structure are considered for the TLD to investigate the optimum value at resonant condition. The efficiency of reduction in the displacement increased as the mass ratio increased up to 3.5 %. For mass ratios larger than 3.5% it was observed that; even if it is practical in reducing peak structural responses, the efficiency of reduction in the displacement is reduced. Therefore it is concluded that 3.5% mass ratio is the optimum value.
- From this study, it can be concluded that properly designed TLD with optimum design parameters such as depth ratio and mass ratio is considered to be a very effective device to reduce the structural response.

5.2 Recommendation

- Implementation of multiple tuned liquid dampers (MTLD) to suppress multiple modes of vibration can be studied.
- Implementing other type of TLDs like cylindrical TLDs, rectangular TLDs with different shapes added within the bottom, TLCDs can be studied to search protection efficiency of the dampers.
- Further works are required to achieve optimum design of the damper such as: using submerged nets and screens, using slopped bottoms for TLD, enhancement of bottom roughness by using wedge shaped bottom with steps and with holes and etc.

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APPENDIX A: Solution of the Equations for Shallow Water Theory Model

A.1 Non-dimensionalization of Basic Equations

To solve equations (3.11) and (3.12) they are non-dimensionalized using the following dimensionless variables:

$$x' = \frac{x}{a};\ \ z' = \frac{z}{h};\ \ \eta' = \frac{\eta}{h};\ \ \varepsilon = \frac{h}{a};\ \ u' = \frac{u}{c_o};\ t' = \frac{t}{t_o};\ k' = ka;\ \ \ddot{x}'_s = \frac{t^2{}_o}{a}\dot{x}_s;\ \ \omega' = \omega t_o$$

Where: $C_o = \sqrt{gh}$ is the wave velocity and $t_o = \dfrac{a}{C_o}$

Multiplying equation (3.11) by t_o/h and equation (3.12) by t_o/C_o the non-dimenionalized basic equations (without considering wave breaking effects) are obtained as:

$$\frac{\partial \eta'}{\partial t'} + \sigma \frac{\partial (\Phi u')}{\partial x'} = 0 \quad \text{.......................................} \quad \text{A-1}$$

$$\frac{\partial \mathrm{u}'}{\partial t'} + \left(1 - T_H^2\right) u' \frac{\partial u'}{\partial x'} + \frac{\partial \eta'}{\partial x'} + \sigma \phi \varepsilon^2 \frac{\partial^2 \eta' \partial \eta'}{\partial x'^2 \partial x'} = -\lambda' u - \ddot{x}'_s \quad \text{.......................................} \quad \text{A-2}$$

Where: $u' = 0$ at the end walls and

The dimensionless damping is:

$$\lambda' = \frac{1}{(\eta' + 1)} \frac{8}{3\pi\varepsilon C_o} \sqrt{\omega_l v} \left(1 + \left(\frac{2h}{b}\right) + S\right) \quad \text{.......................................} \quad \text{A-3}$$

A.2 Discretization of Basic Equations

Equations (A-1) and (A-2) are discretized with respect to x into n divisions. Then, using finite difference approximation and based on backward Tailor series new equations are obtained. Finally, by employing Runge-Kutta-Gill method the equations are solved in the time domain in order to find dimensionless values of u and η.

Yamamoto K. and Kawahara M. suggested the value of n as:

$$n = \frac{\pi}{[2\arccos\sqrt{\tanh(\pi\varepsilon)} / 2\tanh(\pi\varepsilon / 2)]} \quad \text{.......... A-4}$$

Considering first mode of liquid sloshing, dimensionless wave number is found as $k = \pi / 2$.

Equations (A-1) and (A-2) can be written in the following form:

$$\frac{\partial\eta}{\partial t'}' + \sigma\frac{\partial(\Phi u')}{\partial x'} = 0 \quad \text{.......... A-5}$$

$$\frac{\partial \mathrm{u}'}{\partial t'} + H\frac{\partial K}{\partial x'} + \frac{\partial\eta'}{\partial x'} + C\frac{\partial I}{\partial x'} = -\lambda' u - \ddot{x}'_s \quad \text{.......... A-6}$$

Where: $\mathrm{H}=(1/2)(1-T^2{}_\mathrm{H})$; $K=\mathrm{u}'^2$; $C=\sigma\phi\varepsilon^2$; and $\mathrm{I}=(1/2)(\partial\acute{\eta}/\partial\acute{x})^2$

Then, equations (A-5) and (A-6) are discritized in x using backward Tailor series and obtained as:

$$\frac{\partial\eta'}{\partial t'} = -\sigma\frac{(\phi_{i+1}u'_{i+1} - \phi_i u_i)}{\Delta x'} = \sigma\frac{(\phi_i u'_i - \phi_{i+1}u_{i+1})}{\Delta x'}, \ i = 1 \sim n-1 \quad \text{.......... A-7}$$

$$\frac{\partial\eta'}{\partial t'} = -\sigma\frac{(\phi_1 u'_1 - \phi_o u_o)}{\Delta x' / 2} = -2\sigma\frac{(\phi_1 u'_1)}{\Delta x'}, \ i = 0 \quad \text{.......... A-8}$$

$$\frac{\partial\eta'}{\partial t'} = -\sigma\frac{(\phi_{n+1}u'_{in1} - \phi_n u_n)}{\Delta x' / 2} = 2\sigma\frac{(\phi_n u'_n)}{\Delta x'}, \ i = n \quad \text{.......... A-9}$$

$$\frac{\partial u'}{\partial t'} = \left(\frac{1}{\Delta x'}\right)(\eta'_{i-1} - \eta'_i) + H_i(K_{i-1} - K_i) + C_i(I_{i-1} - I_i) - \lambda' u' - \ddot{x}'_s, \quad \text{.......... A-10}$$

$$i = 1 \sim n$$

Where: $\Delta x' = \Delta x / a = (L/n)\left(1 / \tfrac{L}{2}\right) = 2/n$ A-11

$$\phi_i = \tanh\left(K'\varepsilon\left(1 + \frac{\eta'_{i-1} + \eta'_i}{2}\right)\right) \Big/ \tanh(K'\varepsilon) \quad i = 1 \sim n \quad \text{.......... A-12}$$

$$H_i = \left(1 - (\phi_i \tanh(K'\varepsilon))^2\right) / 2 \qquad i = 1 \sim n-1 \quad \text{.......... A-13}$$

$$K_i = \left(\left(u_i' + u_{i+1}'\right)/2\right)^2 \qquad i = 1 \sim n-1 \quad \text{......................... A-14}$$

$$I_i = (((\eta_{i+1} - \eta'_{i-1})/2\Delta x'))^2)/2 \qquad i = 1 \sim n-1 \quad \text{......................... A-15}$$

$$\lambda_i' = \frac{1}{(1+(\eta'_{i-1}-\eta'_i)/2)}\,\frac{8}{3\pi\varepsilon C_o}\sqrt{w_i v}\left(1+\left(\frac{2h}{b}\right)+S\right) \quad \text{.............................. A-16}$$

With the following boundary condition:

$$K_o = K_n = 0 \quad \text{.. A-17}$$

$$I_o = I_n = 0 \quad \text{.. A-18}$$

Figure A-1 shows the discretized container length.

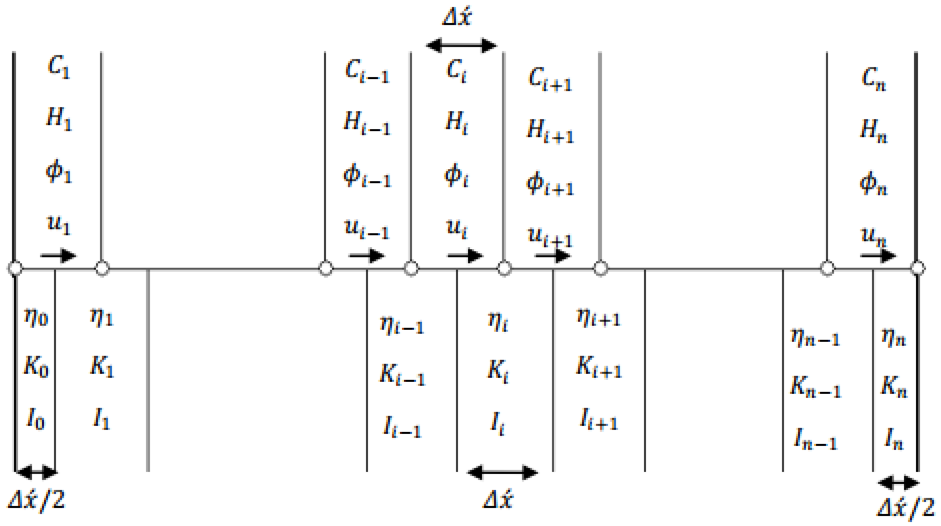

Figure A.1: Schematic of Discretized Tank with Respect to x

Then, the descritized equations are solved with Runge-Kutta-Gill method in time.

A.3 Runge-Kutaa-Gill Method

The equations (A-7) to (A-10) can be defined in the vector form as:

$$\frac{\partial \eta}{\partial t} = f(t,\eta,u) \quad \text{A-19}$$

$$\frac{\partial u}{\partial t} = g(t,\eta,u) \quad \text{A-20}$$

Where: $\eta = (\eta'_o, \eta'_1, ..., \eta'_i, ..., \eta'_n)$ ………… A-21

$$u = (u'_o, u'_1, ..., u'_i, ..., u'_n) \quad \text{A-22}$$

And initial conditions are: $\eta_o = 0$ ………… A-23

$$u_o = 0 \quad \text{A-24}$$

Where the subscript denotes the time step.

The 4th order Runge-Kutta-Gill method is employed as:

$$\eta_{m+1} = \eta_m + \frac{\Delta t}{6}\left(K_1 + \left(2-\sqrt{2}\right)K_2 + \left(2+\sqrt{2}\right)K_3 + K_4\right) \quad \text{A-25}$$

$$u_{m+1} = u_m + \frac{\Delta t}{6}\left(L_1 + \left(2-\sqrt{2}\right)L_2 + \left(2+\sqrt{2}\right)L_3 + L_4\right) \quad \text{A-26}$$

Where: Δt is the time increment and

$$K_1 = f(t_m, \eta_m, u_m) \quad \text{A-27}$$

$$L_1 = g(t_m, \eta_m, u_m) \quad \text{A-28}$$

$$K_2 = f\left(t_m + \frac{\Delta t}{2}, \eta_m + \frac{\Delta t}{2}K_1, u_m + \frac{\Delta t}{2}L_1\right) \quad \text{A-29}$$

$$L_2 = g\left(t_m + \frac{\Delta t}{2}, \eta_m + \frac{\Delta t}{2}K_1, u_m + \frac{\Delta t}{2}L_1\right) \quad \text{A-30}$$

$$K_3 = f\left(t_m + \frac{\Delta t}{2}, \eta_m + \frac{\sqrt{2}-1}{2}\Delta t K_1 + \left(1-\frac{\sqrt{2}}{2}\right)\Delta t K_2, u_m + \frac{\sqrt{2}-1}{2}\Delta t L_1 + \left(1-\frac{\sqrt{2}}{2}\right)\Delta t L_2 \right)$$

…… A-31

$$L_3 = g\left(t_m + \frac{\Delta t}{2}, \eta_m + \frac{\sqrt{2}-1}{2}\Delta t K_1 + \left(1-\frac{\sqrt{2}}{2}\right)\Delta t K_2, u_m + \frac{\sqrt{2}-1}{2}\Delta t L_1 + \left(1-\frac{\sqrt{2}}{2}\right)\Delta t L_2 \right)$$

…… A-32

$$K_4 = f\left(t_m + \frac{\Delta t}{2}, \eta_m + \frac{\sqrt{2}}{2}\Delta t K_2 + \left(1+\frac{\sqrt{2}}{2}\right)\Delta t K_3, u_m - \frac{\sqrt{2}}{2}\Delta t L_2 + \left(1+\frac{\sqrt{2}}{2}\right)\Delta t L_3 \right)$$

…… A-33

$$L_4 = g\left(t_m + \frac{\Delta t}{2}, \eta_m + \frac{\sqrt{2}}{2}\Delta t K_2 + \left(1+\frac{\sqrt{2}}{2}\right)\Delta t K_3, u_m - \frac{\sqrt{2}}{2}\Delta t L_2 + \left(1+\frac{\sqrt{2}}{2}\right)\Delta t L_3 \right)$$

…… A-34

K and L values corresponding to wave height slope and liquid velocity slope are calculated based on equations (A-7) to (A-10) for each division (i.e. for $i = 0 \sim n$) in each time step. Then, using equations (A-25) and (A-26) wave height and velocity are calculated for the next time step. Finally, the interaction force at each time step is calculated using equation (3.16) and used in equation (3.18 or 3.19) to find the structural acceleration for the next time step.

Knowing the initial conditions ((A-23) and (A-24)), the interaction force can be calculated from equation (3.16) as zero. Then, using equation (3.18 or 3.19), the next time step structural acceleration is calculated using Ruge-Kutta-Gill method and used for interaction force calculations.