EXPERIMENTAL AND NUMERICAL STUDIES ON TUNED LIQUID DAMPER

A Thesis

Submitted by

VENKATESWARA RAO K

In partial fulfilment ofthe requirements for

the award of Degree of

MASTER OF TECHNOLOGY

In

STRUCTURAL ENGINEERING

DEPARTMENT OF CIVIL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY

ROURKELA, ORISSA-769008

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DR. K. C. BISWAL

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CERTIFICATE

This is to certify that the thesis entitled **"EXPERIMENTAL AND NUMERICAL STUDIES ON TUNED LIQUID DAMPER"** submitted by **Mr. VENKATESWARA RAO K** in partial fulfillment of the requirements for the award of Master of Technology Degree in Civil Engineering with specialization in Structural Engineering at the National Institute of Technology Rourkela is an authentic work carried out by him under my supervision.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any Other University/Institute for the award of any degree or diploma.

Date: May 29, 2013

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ABSTRACT

Current trends in the construction industry demands taller and lighter structures, which are also more flexible and having quite a low damping value. This increases failure possibilities and also, problems from the serviceability point of view. Several techniques are available today to minimize the vibration of the structure, out of which concept of using of TLD is a newer one. The tuned liquid damper (TLD) is a liquid filled tank which uses liquid sloshing action to dampen the oscillations of a structure. They are cost effective and low maintenance dynamic vibration absorbers that are being used in flexible and lightly damped structures. A numerical algorithm was developed to investigate the response of the frame model, fitted with a TLD. A nonlinear TLD model was considered. A total of five loading conditions was applied at the base of the structure. First one was a sinusoidal loading corresponding to the resonance condition with the fundamental frequency of the structure, second one was corresponding to compatible time history as per spectra of IS-1893 (Part -1): 2002 for 5% damping at rocky soil and rest three were corresponding to time histories of past earthquake such as El Centro Earthquake record , Sanfranscisco Earthquake and Colianga Earthquake. A series of experimental tests are conducted on a SDOF structure-tuned liquid damper systems to evaluate their performance under harmonic excitation.The effect of the different parameters such as frequency ratio, depth ratio and mass ratio on the behavior has been studied. The effectiveness of the TLD was calculated in terms of percentage of reduction of amplitude of displacements of the structure.

Keywords: Framed structure, Sloshing, Tuned liquid damper, Harmonic excitation, Earthquake, Energy dissipation, Response control.

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Nomenclature

h= undisturbed water depth.

L= Length of the tank.

a = half length of the tank.

b = Tank width.

u = liquid velocity in the x direction

w = liquid velocity in the z direction.

g = gravity acceleration

ρ = liquid density

v= kinematic viscosity of the liquid

Φ = potential function

k = wave number

η = free surface elevation

η_n= free surface elevation at the right tank wall

η_o = free surface elevation of the left tank wall

λ = damping coefficient

ω_l = fundamental frequency of the liquid

S: surface contaminating factor

m = mass of the structure

c = structural damping coefficient

k = structural stiffness

ξ = structural damping ratio

$\ddot{x}_s$=ground acceleration`

F: TLD base shear

λ = Damping coefficient

k= stiffness of a single DOF system

m= mass of a single DOF system.

ω = sinusoidal forcing frequency

μ = mass ratio

Δ = Depth ratio

β =Frequency ratio

CHAPTER-1

INTRODUCTION

The current trend toward the buildings of ever increasing heights and the use of light-weight, high strength materials, and advanced construction techniques have led to increasingly flexible and lightly damped structures. Understandably, these structures are 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. Hence it has become important to search for practical and effective devices for suppression of these vibrations.

1.1 Seismic Protection Systems

Three categories of seismic protection systems have been implemented, as shown in Table 1.1

Table 1.1: Seismic Protection Systems

Conventional Systems	Isolation Systems	Supplemental Damping Systems	
		Passive Damper	Active/Semi-Active Dampers
Flexural Plastic Hinges Shear Plastic Hinges Yielding Braces	Elastomeric Lead Rubber High-Damping Rubber Metallic Lead-Extrusion Friction Pendulum	Metallic Friction Viscoelastic Viscous Tuned-Mass Damper Tuned-Liquid Damper Self-centering	Braces Tuned-Mass Tuned-Liquid Variable Damping Variable Stiffness Piezoelectric Rheological

1.1.1 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.

1.1.2 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.

1.1.3 Supplemental Damping Systems

The supplemental damping system can be categorized in three groups as passive, active and semi-active systems. These dampers are activated by the movement of the structure and decrease the structural displacements by dissipating energy via different mechanisms.

1.1.3.1 Active Systems.

Active systems monitor the structural behavior, and after processingthe 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.

1.1.3.2 Semi-Active Systems.

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.

1.1.3.3 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. The main categories of the passive energy dissipation systems are as follows.

Table 1.2: Types of Passive Dampers

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

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.

1.2 Tuned Liquid Damper

1.2.1 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 [3], who proposed the use of a rectangular container completely filled with two immiscible liquids to reduce the structural response to a dynamic loading. Modi& Welt [4], Fujii et al. [5], Kareem [6], Sun et al. [7], and Wakahara et al. [8] We're also among the first to suggest the use of dampers utilizing liquid motion for civil engineering structures. 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).

1.3 CLASSIFICATION:

Fig 1.1 bellow shows a schematic diagram of the Tuned Liquid Damper family.

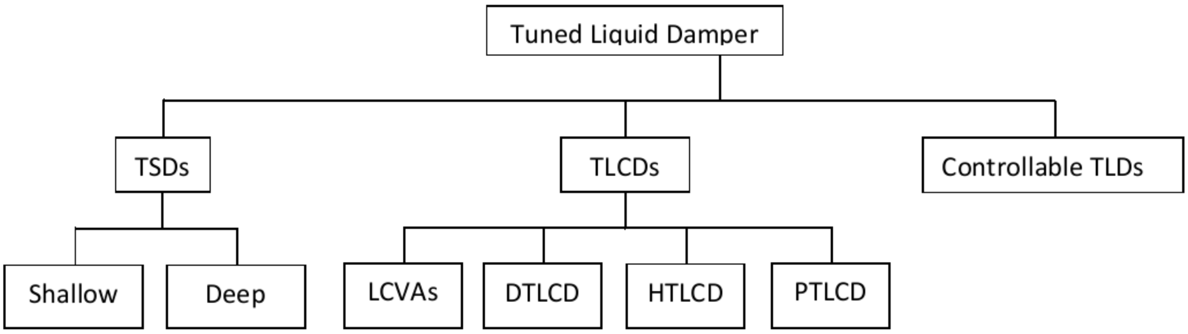


Fig. 1.1 (Schematic of Tuned Liquid Damper family)

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, ER: Electro Rheological, & MR: Magneto Rheological

1.3.1 Tuned Sloshing Damper:

Tuned Sloshing Dampers (TSDs) [4-8] 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. Fig. 1.2 shows the schematic of a TSD. The depth of the liquid in a container could be deep or shallow, depending on the natural frequencies of the structure under control.

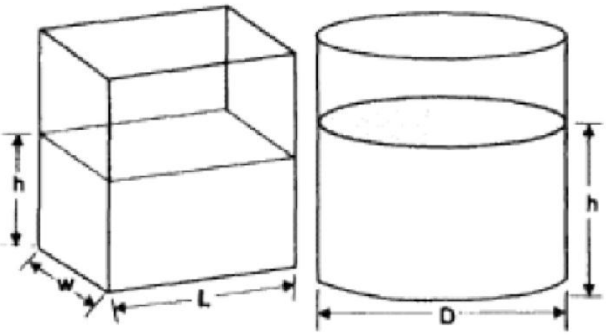


Fig. 1.2 (*Tuned Liquid Damper Dimensions*)

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.

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 [13].

As a passive energy dissipation device TLD presents several advantages over other damping systems such as (i) Low installation and RMO (Running, Maintenance and Operation) cost, (ii) Fewer mechanical problem as no moving part is present, (iii) Easy to install in new as well as in existing buildings as it does not depends on installed place and location, (iv) It can be applied to control a different vibration type of multi-degree of freedom system which has a different frequency for each other (v) Applicable to temporary use (vi) Non restriction to unidirectional vibration (vii) Natural frequency of TLD can be controlled by adjusting the depth of liquid and container dimensions, and (vii) 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.

In order to overcome the drawbacks and to achieve the optimal damping ratio, several methods are proposed such as (i) Installing the TLD at proper position [15] (ii) Wave breaking in shallow water TLDs [7], (iii) Addition of floating beads as surface contaminants [16], (iv) Using submerged nets and screens [17-20], (v) Using Slopped bottoms for TLD [21-23], (vi) Enhancement of bottom roughness by using wedge shaped bottom with steps and with holes [23], (vii) Using a conical TLD [24], and (viii) Inserting poles [25].

1.3.2 Tuned Liquid Column Dampers

Tuned liquid column dampers (TLCD) combine the effect of liquid motion in a tube, which results in a restoring force using the gravity effect of the liquid, and the damping effect caused by loss of hydraulic pressure. Due to the orifice (s) installed inside the container [9]. Fig 1.3 shows the schematic of a TLCD.

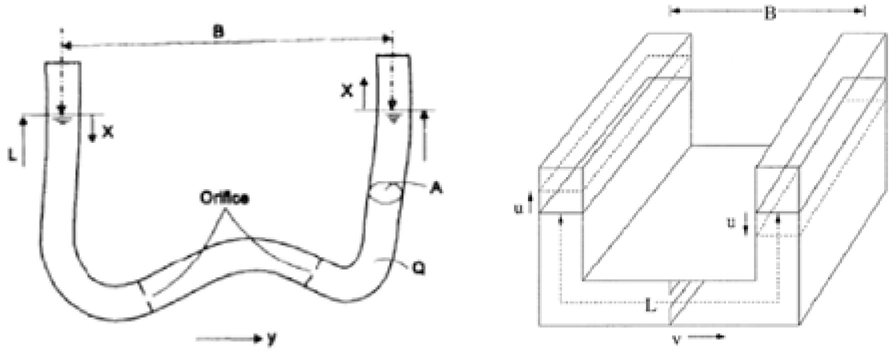


Fig. 1.3 (Tuned Liquid Column Damper Dimensions)

Some advantages of TLCD are: (i) it can have any arbitrary shape which helps it to be fitted in an existing structure; (ii) its behaviour is quite well understood; (iii) the TLCD damping can be controlled by adjusting the orifice opening; (iv) the TLCD frequency can be modified by adjusting the liquid column in the tube. A Double Tuned Liquid Column Damper (DTLCD) is made of two TLCDs in two directions of motion (Kim et al. 2006).Thereby DTLCD is effective in more than one direction eliminating the limitation of regular unidirectional TLDC.

1.3.3 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.

Fig 1.4 provides a schematic diagram for a structural control problem. 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.

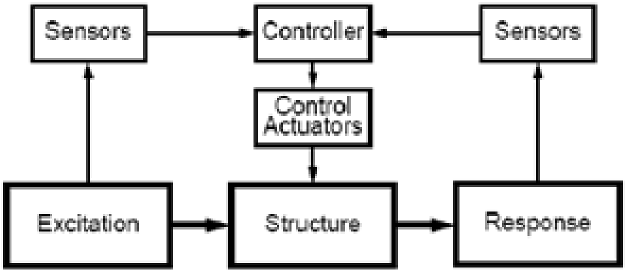


Fig 1.4 (schematic diagram for a structural control problem)

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, 34]. (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 [35]. (iv) Balendra et al. [36] proposed an actively controlled TLCD (Fig 1.8) which is fixed on a movable platform at the top of the tower. The movement of the platform is controlled by a controlled force. A servo-actuator is used to generate the control force based on the feedback from the sensor attached to the top of the tower.

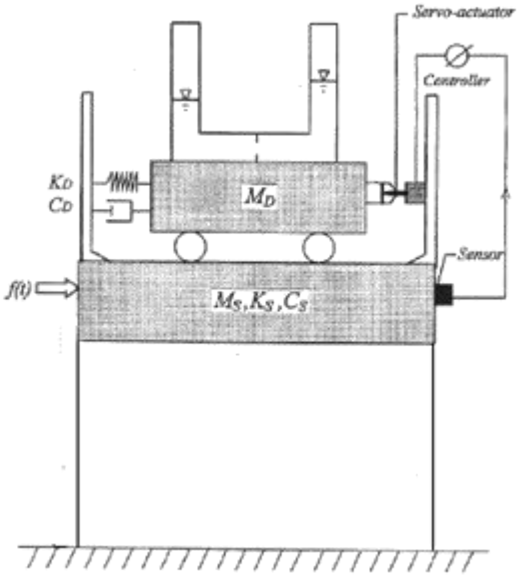


Fig 1.5 (*schematic diagram of the Active TLCD proposed by Balendra et al.*)

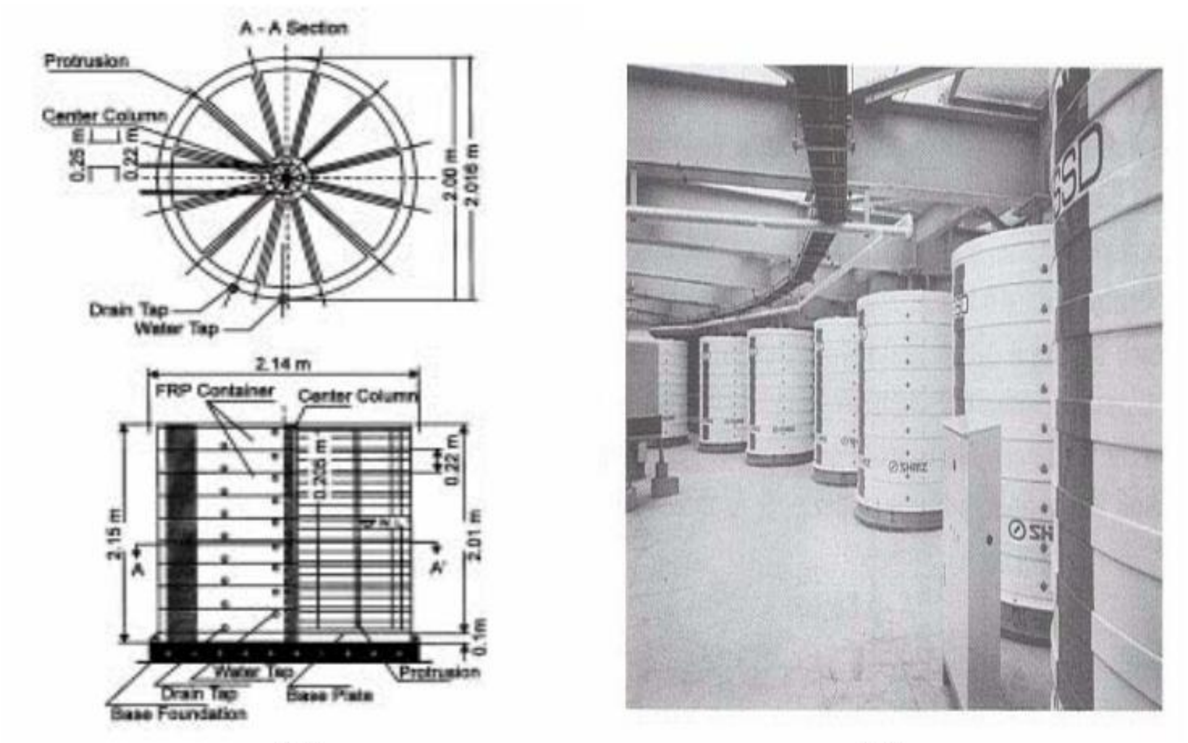
1.4 PRACTICAL IMPLEMENTATION:

Till date, 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%.

Similarly, another experiment unveiled that, the maximum acceleration response of an uncontrolled Yokohama Marine Tower in Japan [15] 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 0.1 m/s^2 or below, and the damping ratio was increased to 4.5%.

A series of TLDs were installed in the Shin Yokohama Prince Hotel (SYPH) in Yokohama, Japan (Fig. 1.6).The TLD system prescribed was a multi-layer stack of 9 circular containers each 2 m in diameter and 22 cm high, yielding a total height of 2 m. It was found that the RMS accelerations in each direction were reduced to 70% by the TLD at wind speeds at 20 m/s. The RMS acceleration without the TLD for the building was over 0.01 m/s, which was reduced to less than 0.006 m/s^2 , defined by the ISO as the minimum perception level at 0.31 Hz. Similar installations are reported for Nagasaki airport tower, Tokyo international airport tower and Yokohama marine tower [15].

The TLD devices installed in the 77.6 m high structure of the Tokyo Airport Tower [15,42] 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/Sec, the reduction in RMS acceleration was about 60% of its value without control.



(a) **(b)**

Fig- 1.6 a) Schematic of TLDs installed in SYPH b) Actual installation in the Building [16]

Tuned Liquid Dampers has, successfully, been applied to some Bridge structures including Ikuchi Bridge, Japan, BaiChay Bridge, Vietnam and Sakitama Bridge, Japan.

CHAPTER-2

LITERATURE REVIEW

2.1 Literature review

Till date TLD has been studied by several researchers. Soong &Dargush [43] provide a comprehensive review of theoretical and experimental studies conducted on TLDs and structure-TLD system. Bauer [3] is the first to propose a damping device consisting of a liquid container filled with two immiscible liquids, in which the motion of the interface is able to dampen the structure effectively. Modi& Welt [4] were also among the first to suggest the use of a TLD in buildings to reduce overall response during strong wind or earthquakes. Due to geometrical similarity they referred these devices to Nutation dampers.

Fujii et al. [5,15] have found by installing wind-induced vibrations of two actual tall towers, at Nagasaki Airport Tower (height 42 m) and Yokohama Marine Tower (height 101 m), were reduced to about half . Sun, et al. [7] Successfully developed an analytical model for TLD, based on shallow water wave theory, which proved to be very effective. They extended this model to account for effect of breaking waves by introducing two empirical coefficients identified experimentally. Wakahara, et al. [8] Carried out theoretical and experimental studies to design an optimum TLD and verified the TLD with an actual application to a high-rise hotel the "Shin Yokohama Prince (SYP) Hotel" in Yokohama. The interaction model considered by them was based on the Boundary Element Method (BEM) for simulating liquid motion in a TLD container. The TLD installation on the building could reduce the wind-induced response to half of the original value.

Sun, et al. [43] measured liquid motion in shallow TLDs, including rectangular, circular, and annular tanks subjected to harmonic base excitation. Using TMD analogy they calibrated the TLD parameters from experimental results. Chen et al. [44]

conducted on a pendulum-like testing model in order to simulate the long period motion of a high rise building. Experimentally, they conclude that the effeteness of the TLD system is significant compared with the optimal TMD system or improved distributed TMD system. Also the dynamic behavior of a TLD system is more similar to the distributed TMD system.

Koh et al. [14] conducted numerical studies to investigate the effect of combined use of liquid dampers which are tuned to different frequencies of a multi-degree-of-freedom structure. The results show that it is beneficial to use the dampers tuned to several vibration modes of the structure. Tamura, et al. [15,41] have found that the damping ratio of 77.6m high Tokyo international Airport Tower have increased to 7.6% from 1.0% by using Tuned liquid Damper. Modi&Seto [45] conducted a numerical study on rectangular TLDs, accounting for nonlinear effects. They included the effects of wave dispersion as well as boundary-layers at the walls, floating particle interactions at the free surface, and wave-breaking. Modi&Munsi [46] conducted an experimental study to improve the TLD efficiency by introducing a two-dimensional obstacle. They conducted a parametric study to decide optimum size and location of the obstacle. Results suggested a significant increase in the energy dissipation, up to 60%, in the presence of the obstacle.

Reed et al. [47, 48] had conducted researches to investigate the effectiveness and robustness of a TLD over a large range of excitation amplitude. From the experiment it is concluded that the response frequency of TLDs increases as excitation amplitude increases. Also the experiment revealed that, the maximum response occurs at a frequency higher than that estimated by the linear water-wave theory. One consequence of this characteristic is that the TLD is robust in dissipating energy over a wide range of frequencies.

Yu et al. [49] proposed a solid mass damper model which they referred as Non-linear-Stiffness-Damping (NSD) model, for the Tuned Liquid Damper with non-linear stiffness and damping. This model was an expansion of Tuned Mass Damper. They calibrated the non-linear characteristics of the NSD model from shaking table experiment tests. Yamamoto &Kawahar [50] considered a fluid model using Navier-Stokes equation in the form of the arbitrary Lagrangian-Eulerian (ALE) Formulation. For the discretization of the incompressible Navier-Stokes equation, they used the improved-balancing-tensor-diffusivity method and the fractional-step method for computational stability.

Chang &Gu [51] studied experimentally the control effects of rectangular TLDs installed on a tall building that vibrates due to vortex excitation. They found that the rectangular TLD is quite effective in reducing the vortex-excited vibration of a building, especially when its frequency is tuned to within the optimal range. The top displacement RMS value reduces to only one-sixth of that of the original building model without a TLD when the generalized mass ratio equals to 2.3%. The optimal frequency of the TLD ranged between 0.9 and 1.0 of that of the building model which was consistent with the analytical derivation.

Kaneko & Ishikawa [52] conducted analytical study on TLD with submerged nets. They employed a liquid model based on nonlinear shallow water wave theory. Effect of the hydraulic resistance produced by the nets was examined. They verified the results of dissipation energy theoretically that obtained by experiment. They found that the optimal damping factor as in the case for TMDs, can be produced by nets, and the TLDs with submerged nets are more effective in reducing structural vibration than TLDs without nets.

Kaneko S. &Mizota Y. [53] expanded previously developed rectangular deep water TLD model [53] to Cylindrical deep water TLD model with a submerged net installed in the middle of the cylindrical liquid container. In the analysis, employing finite amplitude wave theory and Galerkin method in the case of cylindrical tank, they obtained hydrodynamic forces and the free surface elevations. Then, combining the hydrodynamic forces with the equation of motion of the structure, damped transient responses were calculated. The calculated results thus obtained were compared with the experimental results, by which the validity of the modeling methodology was confirmed.

Banarji et al. [54] used the formulation suggested by Sun et al. [7] in order to study the effectiveness of a rectangular TLD in reducing the earthquake response of structures for various values of natural time periods and structural damping ratios. Furthermore, an attempt is made to define appropriate design parameters of the TLD that is effective in controlling the earthquake response of a structure. These parameters include the ratio of the linear sloshing and structure natural frequencies, henceforth called the tuning ratio, the ratio of the masses of water and structure, henceforth called the mass ratio, and the water depth to the TLD tank-length ratio, henceforth called the depth ratio.

Gardarsson et al. [20] extended the idea of dramatically dissipation of tsunami wave energy, by the shores of an ocean coastline, to a TLD, by adding a slopped bottom tank. They experimentally calculated the sloshing characteristics associated with a slopped-bottom TLD and compared with a box-shaped TLD. The 30^0 Sloped bottom TLD considered for the study found to behave like a softening spring, unlike to a box shaped TLD which behaves like a hardening spring. They found the sloped-bottom TLD is especially effective when it is tuned slightly higher than the structure's fundamental response frequency. However, they found some problem associated with slopped bottom TLD, as there will be a greater magnitude of the moment exerted at the TLD base. Olson & Reed [56] analytically studied a slopped bottom TLD proposed by Gardarsson et al. [21] using the non-linear stiffness and damping model developed by Yu et al [50].

Pal et al. [56] investigated the slosh dynamics of liquid-filled containers experimentally using a three-dimensional finite element analysis. The effects of sloshing were computed in the time domain using Newmark's time integration scheme. A simple experimental setup was designed to conduct experiments for measuring some of the basic parameters of sloshing. A sensor device was especially developed to record the free-surface wave heights. Modi et al. [22] investigated on enhancing the energy dissipation efficiency of a rectangular liquid damper through introduction of two dimensional wedge shaped obstacles. From the experiment he concluded that wedging increases damping factor and damping factor further increases for a roughened wedge.

Li et al. [57] proposed a numerical model for the implementation of shallow rectangular TLD where the dynamic properties of shallow liquid in rectangular containers subjected to forced horizontal oscillations are analized directly from the continuity and momentum equations of fluid. Following some practical assumptions, they established the nonlinear partial differential equations describing the wave movement of shallow liquid in rectangular containers and proposed a numerical procedure for the solutions of these equations based on the finite element method.

Ikeda [58] investigated the nonlinear vibrations of a system, in which a rigid rectangular tank partially filled with liquid is attached to an elastic structure subjected to a vertical sinusoidal excitation. First, by taking into account the nonlinearity of fluid force, modal equations involving sloshing modes up to the third mode were derived when the natural frequency of the structure was equal to twice the frequency of sloshing of the liquid surface. Second, resonance curves for this system had been determined from the modal equations by using the harmonic balance method. Finally, the influences of the depth of the liquid and the detuning parameter on the resonance curves had been mainly investigated by showing the resonance curves. It was found that the shapes of the resonance curves markedly change depending on the liquid's depth, and that periodically and chaotically amplitude-modulated motions occur at certain intervals of the excitation frequency. Furthermore, it was also found that coupled vibrations can occur at two ranges of the excitation frequency when the deviation of the tuning condition is comparatively large. Finally he validated the numerical results with experimental results.

Casciati et al. [23] proposed a frustum-conical shaped TLD to an alternative to the traditional cylindrical tank. This allows calibrating the natural frequency through varying liquid depth, making it suitable for semi-active implementation and attains the same level of performance with a little mess. They presented a linear model which is only suitable for small excitations as for larger amplitudes. They validated the linear model only for the case of harmonic excitations.

Biswal et al. [59] studied a two-dimensional finite element analysis for the dynamic analysis of liquid filled rectangular tank with baffles using the velocity potential formulation and the linear water wave theory. The slosh frequencies of liquid in a rectangular tank without and with baffles (thin rectangular plates) were evaluated. The tank-baffle system was considered to be rigid. The slosh response of liquid was studied under steady state sinusoidal base excitation. The slosh frequencies of liquid were computed for different dimensions and positions of baffle(s).

Biswal et al. [60] presented a free vibration analysis of liquid filled rigid cylindrical tank with annular baffles and compared the natural frequencies of liquid with that of the tank without baffles. The slosh frequency parameters of liquid were computed for various locations of baffle in the tank. They observed that the baffle had an appreciable effect on the slosh frequency parameters of liquid when placed very close to liquid-free surface for all R/R ratios. Further, the flexibility of baffle had an effect on the liquid slosh frequency parameters up to a certain thickness of the baffle.

Ikeda & Ibrahim [61] analyzed an elastic structure carrying a cylindrical tank partially filled with liquid where the structure is vertically subjected to a narrow-band random excitation. They derived the modal equations taking into account the liquid nonlinear inertia forces. Nonlinear coupling between liquid modes and structure modes results in 2:1 internal resonance, i.e., when the natural frequencies of the structure and the first anti-symmetric sloshing mode were commensurable. They solved the modal equations numerically using Monte Carlo simulation, and estimated the system response statistics.

Tait et al. [18] discussed the numerical flow model of TLD behavior including the free surface motion, the resulting base shear forces and the energy dissipated by TLD with slat screens. Both linear and nonlinear analytical models for TLD are examined and compared with experimental data. It was found that the linear model is capable of providing a first estimate of the energy dissipating characteristics of a TLD. However, the linear model could not provide realistic estimates of the free surface response for amplitudes experimentally investigated. The nonlinear model could accurately describe the free surface motion, the resulting base shear forces and the energy dissipated over a range of excitation amplitudes. The nonlinear model was capable of modeling a TLD equipped with multiple screens at various screen locations inside the tank. The nonlinear model was also verified over a range of practical fluid depth to tank length ratio values. They outlined a procedure for proper location and size of the slat screens according to the linear model result.

Frandsen [62] adopted a fully nonlinear 2-D tank which is allowed to move both horizontally and vertically by using σ-coordinate transformation for fluid model. He analyzed the model for various liquid heights corresponding to deep water TLD and shallow water TLD. However, the above model is subjected to a limitation that, because of the use of potential flow assumption, both viscous sloshing and rotational motion of the liquid can't be captured by the models introduced above. Kim et al. [11] conducted shaking table experiments to investigate the characteristics of water sloshing motion in the TLD (rectangular and circular) and TLCD. They found the parameters such as wave height, base shear force, and energy dissipation etc. from the experiment. It was found that the TLCD was more effective in controlling vibration than TLD.

Tait et al. [63] studied the ability of a TLD to operate in two directions. They conducted experimental test on bidirectional (2D) structure-TLD model and estimated the free-surface motion, the resulting base shear forces, and the work done by bidirectional tuned liquid dampers (2D TLD) attached to simple structure. The response of a 2D structure-TLD system excited bi-directionally was found to correspond to the linear superposition of the responses of two 1D structure-TLD systems. Findings from this study indicate that by choosing the appropriate aspect ratio for the TLD it can be used to reduce structural responses in two modes of vibration simultaneously with no penalty on its performance.

Jin et al. [64] studied the effectiveness of a cylinder TLD in controlling earthquake response of jacket platform. They applied TLDs to a CB32A oil tank to prove the feasibility. They found that the ratio of the fundamental sloshing frequency of liquid to the natural frequency of platform is the key factor to control earthquake response. The larger ratio of water-mass to platform-mass is also useful to reduce vibration as well.

Lee et al. [65] proposed a real-time hybrid shaking table testing method (RHSTTM) to study the performance of a Tuned Liquid Damper (TLD) controlling seismically excited building structure. The RHSTTM model consists of an analytical building model and physical liquid model placed on a shaking table. The structural responses of the system, to a given earthquake load, were calculated numerically in real time from the analytical building model.he TLD. They validated the structural responses obtained by the RHSTTM and the conventional shaking table test of a single storey steel frame with TLD, and found that the performance of the TLD can be accurately evaluated using the RHSTTM without the physical structural model.

M.J. Tait [19] successfully developed an equivalent linear mechanical model that accounts for the energy dissipated by the damping screens. He developed expressions for equivalent damping ratio expressions for both sinusoidal and random excitation. He further extended to outline a rapid preliminary design procedure initial TLD sizing and initial damping screen design for a TLD equipped with damping screens.

Attari&Rofooei [66] studied the nonlinear interaction between a SDOF structural system, assumed to be an idealization of the MDOF structural system, carrying a circular cylindrical liquid tank. The sloshing mode of the liquid is investigated. The system was considered nonlinear due to the convective term of liquid acceleration and the nonlinear surface boundary conditions, both caused by the inertial nonlinearity. The response of this model under horizontal harmonic and earthquake excitations was studied using 1 and 3 sloshing modes in the neighborhood of 1:2 and 1:1 internal resonances. They also studied the energy transfer from the structural mode to the first unsymmetrical sloshing mode of liquid.

Shang & Zhao [12] numerically studied the effect of two angles-adjustable baffles, in a rectangular TLD. The fundamental natural periods of the damper can be changed in a wide range by adjusting the baffle angles, thus making it more effective in controlling the vibration of structures in a wide frequency range. The amount of eddies could be influenced by the angles of the baffles. They found that the TLD tank is much more effective in reducing the earthquake responses of structure than the same size general rectangular TLD tank.

Marivani, et al. [67] developed an integrated fluid-structure numerical model to simulate the response of an SDOF system outfitted with a TLD. The fluid flow model was a two-dimensional nonlinear model. He successfully validated his model using three fluid flow problems. Further the fluid-structure model was tested; whose results show that the model was capable of capturing the right expected damping effect of the TLD on the structure response.

Samanta and Banerj [69] theoretically modified TLD configuration for SDOF where the TLD rests on an elevated platform that is connected to the top of the building through a rigid rod with a flexible rotational spring at its bottom. For particular values of rotational spring flexibility the rotational acceleration of the rod is in phase with the top structural acceleration. The TLD was subjected to larger amplitude acceleration than the traditional fixed bottom one and its efficiency was increased. Seyed Mehdi Zahrai, SaeedAbbasi and BijanSamali [68] Studied TLD with some installed rotatable bafflesexperimentally. The response of a five story benchmark building was utilized to investigate the contributions of baffles on the efficiency of tunes liquid damper under dynamic excitations. TLD with some installed rotatable baffles is studied experimentally. The main idea behind installing such baffles is to compensate the effects of probable mistuning of the TLD.

2.2 objective

The objective of this work is to study the application of TLD to control the vibration of buildings under various dynamic actions.

2.3 Scope of the present work:

This study focuses on the sloshing type of tune liquid dampers. Water is considered as liquid inside the TLD.A nonlinear model of TLD subjected to horizontal motion is proposed on the basis of shallow water wave theory taking wave breaking into consideration and the structural behavior is assumed to be linear. The TLD properties under horizontal excitation are investigated through developed numerical code. The experimental investigations on liquid damping, a most significant parameter of the TLD, are presented. The properties of TLD are discussed on the basis of the experimental results and numerical simulation.

CHAPTER-3

MATHEMATICAL FORMULAIONS

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, whereas 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).

3.1 Fluid Model based on the Shallow Water Wave Theory

The shallow water wave theory has also been widely used in developing numerical models for TLDs [Shimizu and Hayama (3 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 (31) 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% [Tait et al. [22]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% [Tait (22)]. A numerical model based on the shallow water wave theory was later developed by accounting for the effect of wave-breaking using asemi-empirical parameter added to the governing equations Sun and Fujino (20). Even with such development, the numerical models based on the shallow water wave theory are sti11limited to low fluid heights, and relatively low values of excitation amplitudes [Tait (20)]. Reed et al. (8) 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. [55] 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%. However Yalla and Kareem (19) later published astudy refuting results obtained by Banerji et al. (13), and showing that, with non-harmonic excitation, utilizing the shallow water theory without proper empirical add-ons results in a consistent underestimation of the sloshing force due to improper predictions of sloshing/slamming characteristics of the wave motion.

3.2 Assumptions:

- The liquid is considered homogeneous, irrotational and incompressible.
- The walls of the damper are treated rigid.
- The structure is considered as linear.
- Wave breaking effect is considered by means of two empirical constants.
- Structure, behavior is considered as linear.
- The pressure on the free surface is considered as constant.

The rigid Rectangular tank shown in fig-3.1 with the length 2a, width b and the undisturbed water level h is subjected to a lateral displacement x_s. The liquid motion is assumed to develop only in x-z plane.

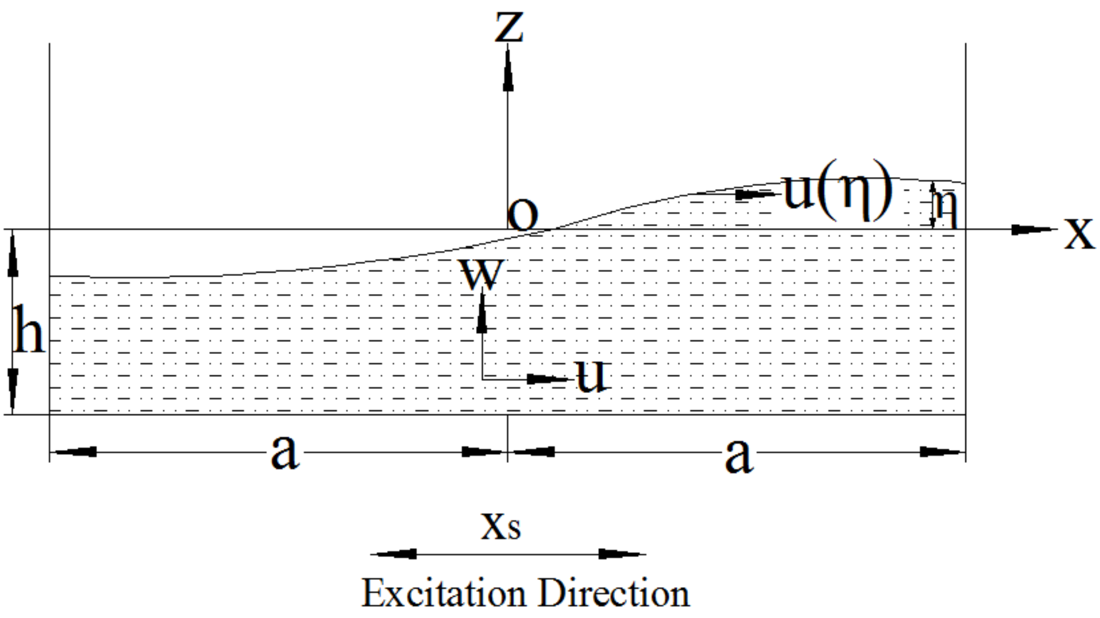


Fig-3.1 Schematic sketch of TLD for Horizontal motion

3.3 Governing Equations:

Continuity Equation:

$$\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}=0 \tag{3.1}$$

Equation of motion:

Two dimensional Navier's strokes Equations

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

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

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 ν 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)

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

K is the wave number

H is defined by [70]

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

Based on the shallow water wave theory potential function is assumed as [70]

$$\phi(x,z,t) = \dot{\phi}(x,t).\cosh\big(k(h+z)\big) \qquad (3.5)$$

3.4 **Boundary conditions:**

u=0 on the end wall x=±a (3.6)

w=o on the bottom z=-h (3.7)

Free surface Boundary conditions

a) Kinematic Boundary condition

$w = \frac{\partial\eta}{\partial t} + u\frac{\partial\eta}{\partial x}$ On the free surface $z = \eta$ (3.8)

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

b) Dynamic Boundary condition

P=p_0= constant on the free surface $z = \eta$ (3.9)

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

$$\frac{\partial \eta}{\partial t} + h\sigma \frac{\partial(\phi u(\eta))}{\partial x} = 0 \tag{3.10}$$

Where $\sigma = \frac{\tanh(kh)}{kh}$

$$\phi = \frac{\tanh\big(k(h+\eta)\big)}{\tanh(kh)}$$

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[75]

$$\frac{\partial u(\eta)}{\partial t} + (1 - T_H^2)u(\eta)\frac{\partial u(\eta)}{\partial x} + C_{fr^2}g\frac{\partial n}{\partial x} + gh\sigma\phi\frac{\partial^2 \eta}{\partial x^2}\frac{\partial \eta}{\partial x} = -C_{da}\lambda u(\eta) - \ddot{x}_s \tag{3.11}$$

Where

$$T_H = \tanh\big(k(h+\eta)\big)$$

$u(\eta) = u(x, \eta, t)$ Horizontal velocity of surface liquid particle

u and$u(\eta)$ are the independent variables of the Basic equations

Damping of liquid sloshing

λ in equation (3.11) is a Damping coefficient

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

$$\lambda = \frac{1}{\eta + h} \frac{8}{3\pi} \sqrt{\omega_l \nu} \left(1 + \left(\frac{2h}{b}\right) + S\right) \tag{3.12}$$

Where

S is the surface contamination factor and a value of 1 corresponding to fully contaminated surface.

$\omega_l =$ Fundamental linear sloshing frequency of the liquid

υ = kinematic viscosity

b= width of the tank

The coefficients C_{fr} and C_{da}Arethey 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

$$C_{da} = 0.57 \sqrt{\frac{h^2 \omega_l}{2a} x_{smax}} \tag{3.13}$$

Where

x_{smax}= Maximum displacement experienced by the structure at the location of the TLD when there is in no TLD attached

3.5 Fundamental sloshing frequency of the TLD

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

$$\omega_l = \frac{1}{2\pi}\sqrt{\frac{\pi g}{2a}\tanh\left(\frac{\pi h}{2a}\right)} \tag{3.14}$$

Where g= acceleration due to gravity.

h= still water level.

L= length of the tank in the direction of sloshing motion.

The equations (3.10) and (3.11) are discretized in space by finite difference method and solved simultaneously using Runge-Kutta-Gill method to find the values of u and η.

3.6 Base shear force due to liquid sloshing

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

$$F = \frac{\rho g b}{2}\left[(\eta_n + h)^2 - (\eta_0 + h)^2\right] \tag{3.15}$$

Where η_n= free surface elevation of the right wall of the tank

η_0 = free surface elevation of the left wall of the tank

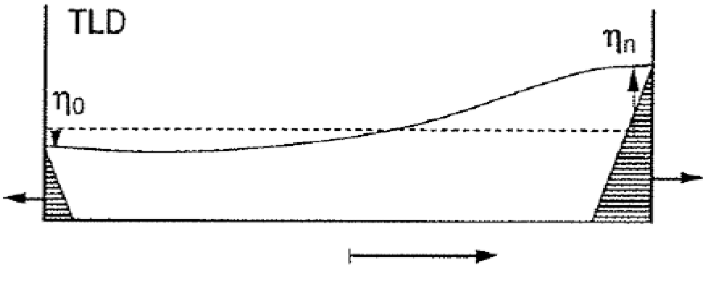


Fig -3.2 Base shear force due to liquid motion

3.7 Structure Model

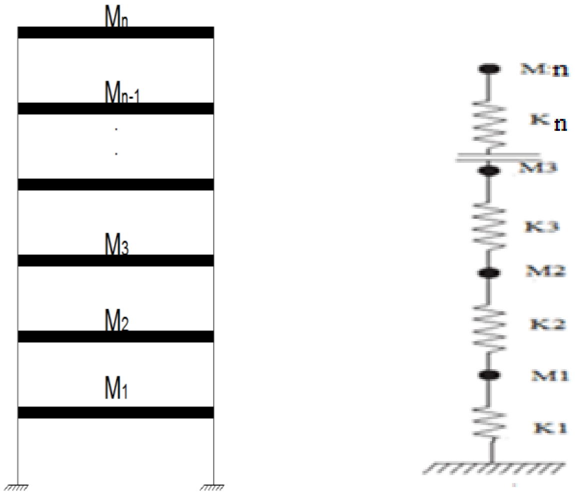


Figure 3.3 Lumped mass model of n-storey shear building

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. The dynamic equation of the structure is

$$m\ddot{x}_s + c\dot{x}_s + kx_s = -a_g m \qquad (3.16)$$

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

$$[\mathrm{M}] = \begin{bmatrix} m_1 & & & & \\ & m_2 & & & \\ & & . & & \\ & & & m_{n-1} & \\ & & & & m_n \end{bmatrix}$$

$$[\mathrm{K}] = \begin{bmatrix} k_1 + k_2 & -k_2 & & & \\ -k_2 & k_2 + k_3 & - & & \\ & & - & - & \\ & & - & k_{n-1} + k_n & -k_n \\ & & & -k_n & kn \end{bmatrix}$$

3.8 The fluid-structure interaction model

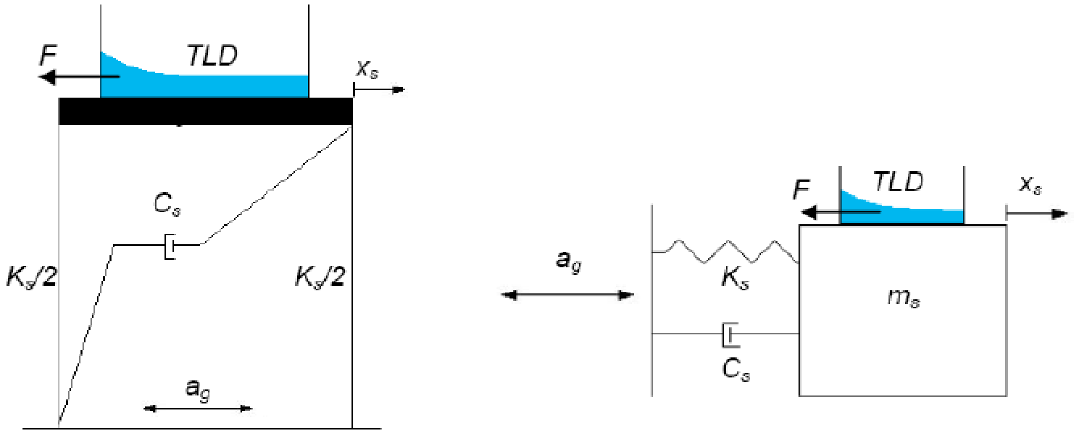


Fig-3.4 SDOF system with a TLD

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

$$m_s \ddot{x}_s + c_s \dot{x}_s + k_s x_s \; = \; -a_g m_s + F \qquad (3.17)$$

Or

$$\ddot{x}_s + 2\omega_s \xi \dot{x}_s + {\omega_s}^2 x_s \; = \; -a_g + \frac{F}{m_s} \qquad (3.18)$$

Where

m_s = mass of the structure.

c_s = damping coefficient.

k_s = stiffness of the structure.

a_g= ground acceleration.

ω_s = natural frequency of the structure.

x_s= structural relative displacement to the ground motion which is the displacement of the TLD.

a_g= ground acceleration.

F = TLD Base shear due to sloshing force on the TLD wall.

The equations (3.10) , (3.11) and (3.18) 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 SDOF Response is calculated using Newmark Beta Methodfrom ethe equation(3.17) the acceleration is found is used in the next step calculation.

CHAPTER-4

NUMERICAL RESULTS

The dynamic response of a SDOF structure equipped with a rectangular shallow tuned liquid damper subjected to different ground motions dealswith the present study. The ground motions considered here are harmonic and recorded earthquake motions.

4.1 Problem statement

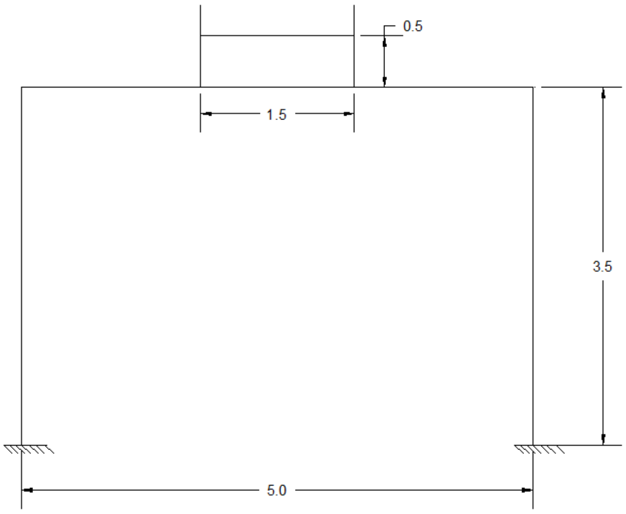


Figure 4.1 Elevation of the 2D plane frame

a) Type of the structure single-storey rigid jointed plane frame.

b) Floor Heights & Bay widths As Shown in figure 4.1

c) Imposed Load	3.5 kN/m^2
d) Materials properties	(M$_{25}$) & Steel (Fe415)
e) Size of columns	250mm x 450 mm
f) Size of beams	250 mm x 400 mm
g) Depth of slab	100 mm
h) Specific weight of R.C.C.	25 kN/m^3

4.2 Preliminary calculations:

1. Modulus of Elasticity of Concrete:

$$E = 5000\sqrt{(fck)} = 25{,}000\ \text{N/mm}^2$$

$$= 2.5\text{x}10^{10}\text{N/mm}^2$$

2. MOI of Column Ic = $bd^3/12$ $=0.25\text{x}0.45^3/12$

$=1.9\text{x}10^{-3}\text{m}^4$

3. MOI of Beam I_b= $bd^3/12$ $=0.25\text{x}0.4^3/12$

$=1.33\text{x}10^{-3}\text{m}^4$

Mass of the structure = 19887 kg

4.3 Dynamic analysis of the structural model:

4.3.1 Response of the structure to Harmonic Ground motion

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

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

Where, x_o and ω are the amplitude and frequency of the forced horizontal acceleration respectively. The excitation amplitude is chosen as 0.005 m and the frequency of the excitation is selected 5.157 rad/sec corresponding to resonance condition. The response of the structure is measured in terms of displacement and accelerations are shown below

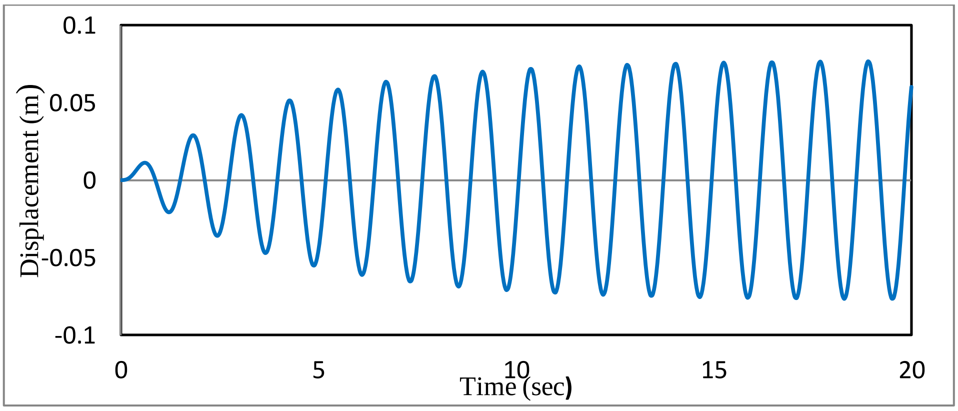


Figure 4.2 Displacement time history of structural response without TLD

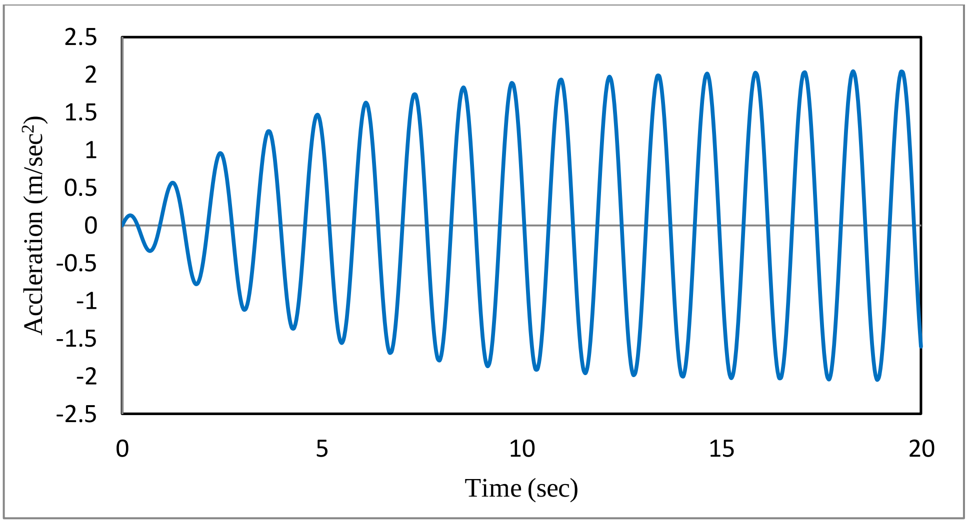


Figure 4.3 Acceleration time history of structural response without TLD

4.4. Response of the structure with TLD to harmonic excitation:

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

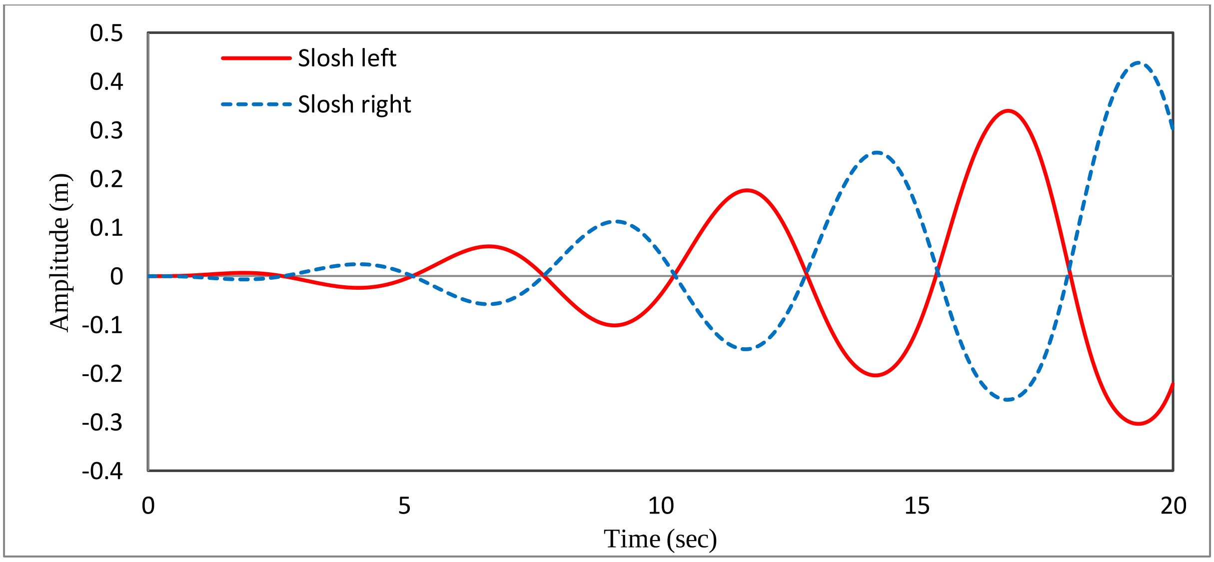


Figure 4.4 Time histories of slosh amplitude at left and right end of the tank

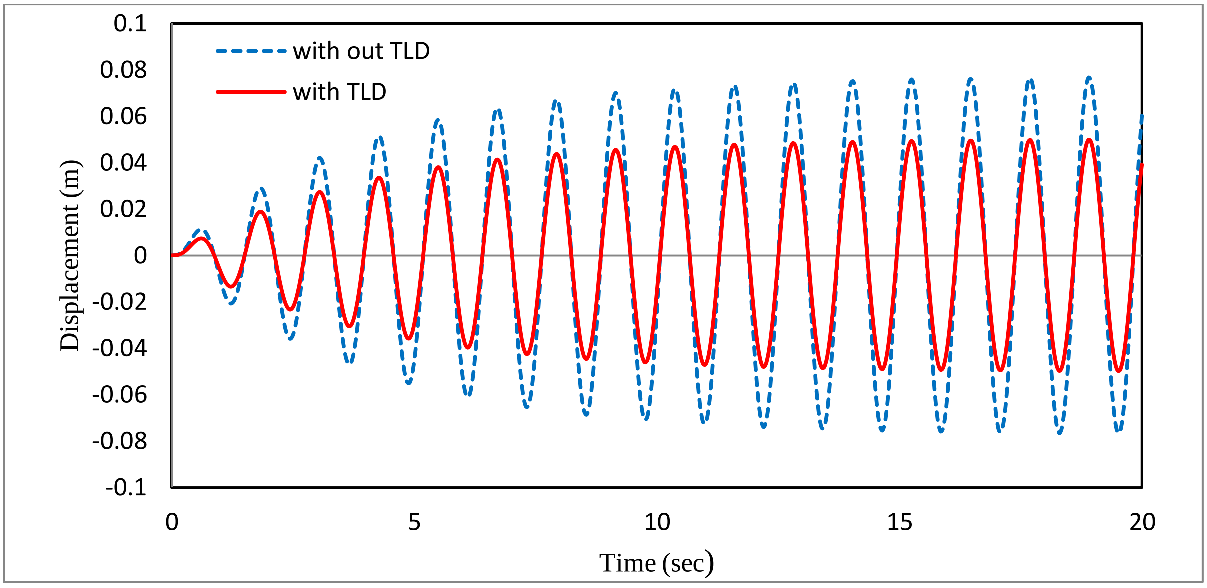


Figure 4.5 Displacement Time histories of structural response with and without TLD

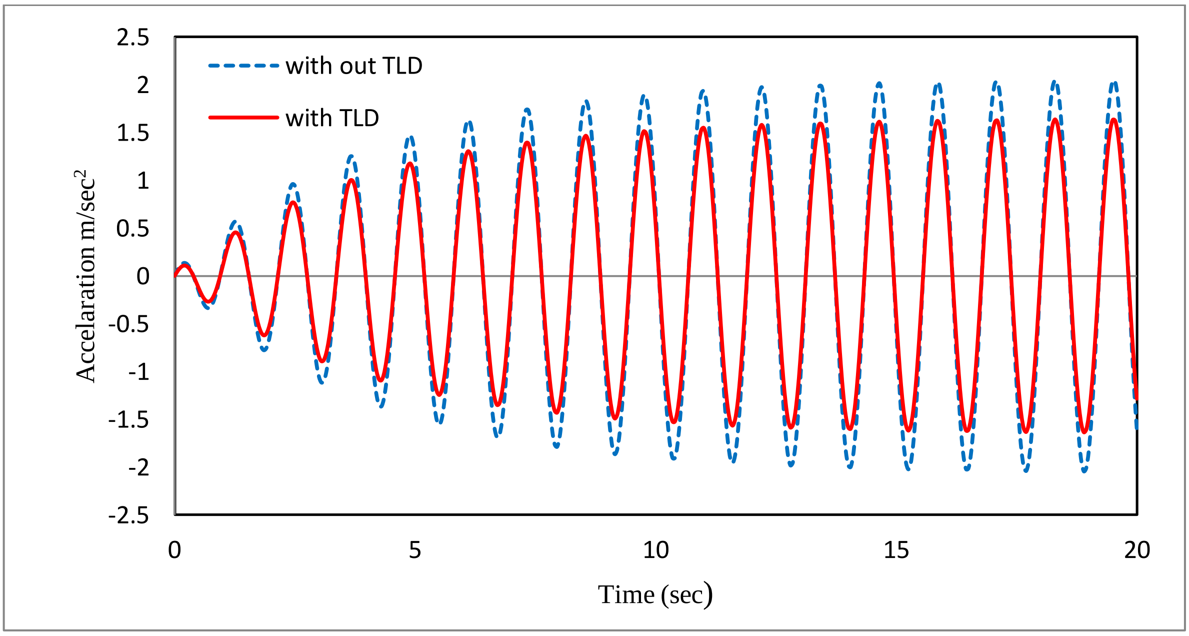


Figure 4.6 Acceleration Time histories of structural response with and without TLD

4.5 Response of the structure to recorded random ground motions.

The random motions are distinguished by their different frequency contents and intensity levels. A total of four recorded ground acceleration time histories are selected for the present analysis.

4.5.1 Compatible time history as per spectra of IS-1893 (Part -1):2002 for 5% damping At rocky soil (PGA=1. 0g)

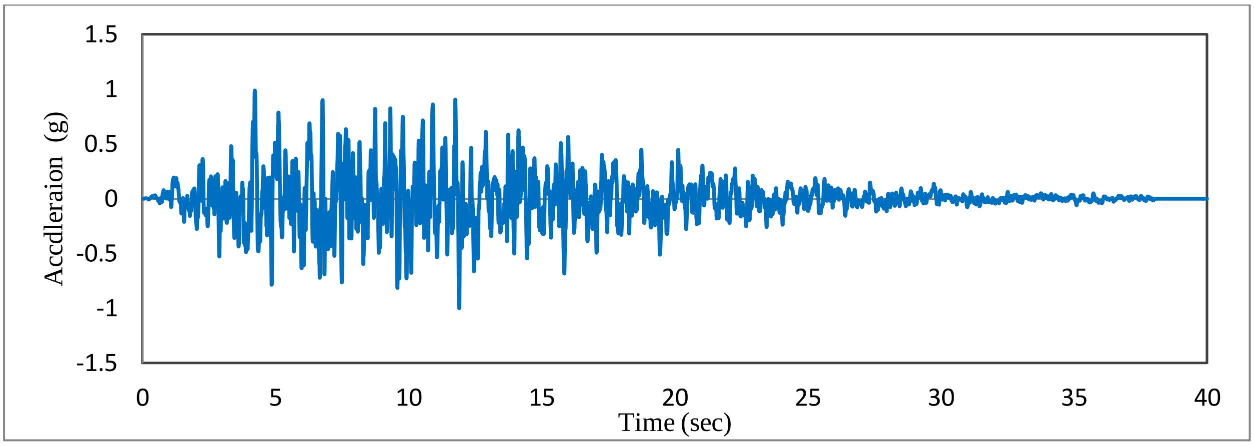


Figure 4.7 Acceleration time history Compatible time history as per spectra of IS-1893 (Part -1): 2002 for 5% damping at rocky site

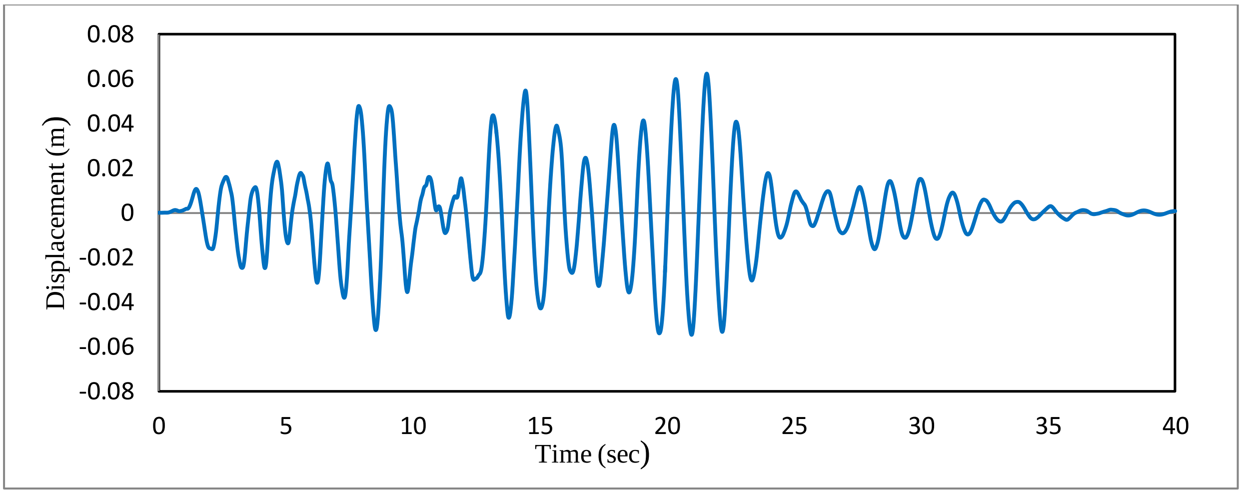


Figure 4.8 Displacement time history of structural response without TLD Compatible time history as per spectra of IS-1893 (Part -1): 2002 for 5% damping at rocky site

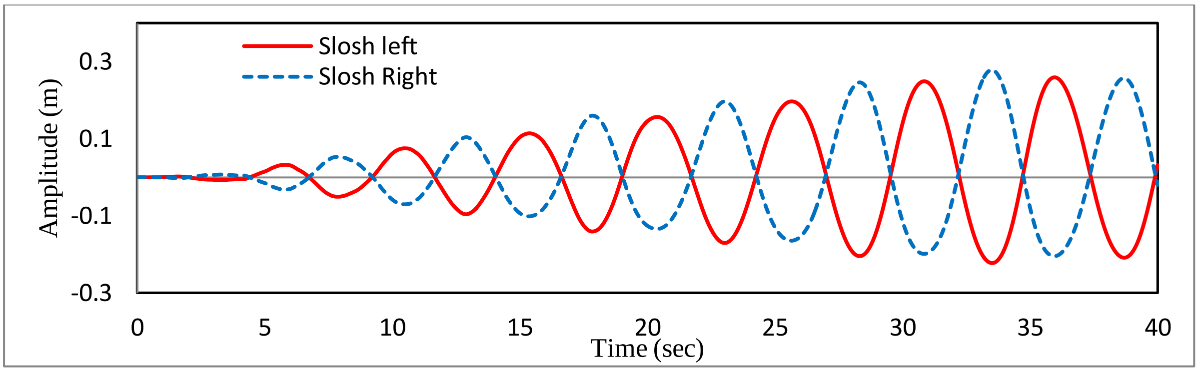


Figure 4.9 Time histories of slosh amplitude at left and right end of the tank corresponds to Compatible time history as per spectra of IS-1893 (Part -1): 2002 for 5% damping at rocky site

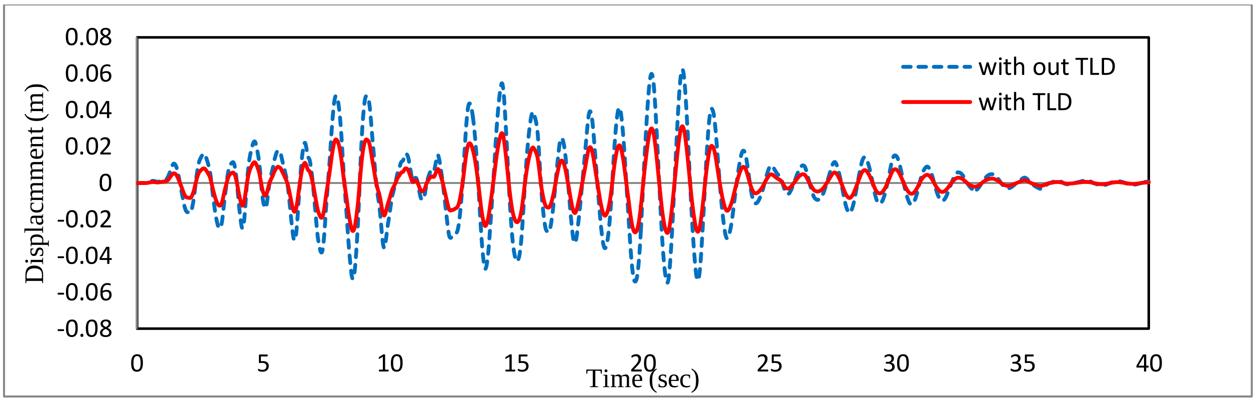


Figure 4.10 Displacement time history of structural response with and without TLD Compatible time history as per spectra of IS-1893 (Part -1): 2002 for 5% damping at rocky site

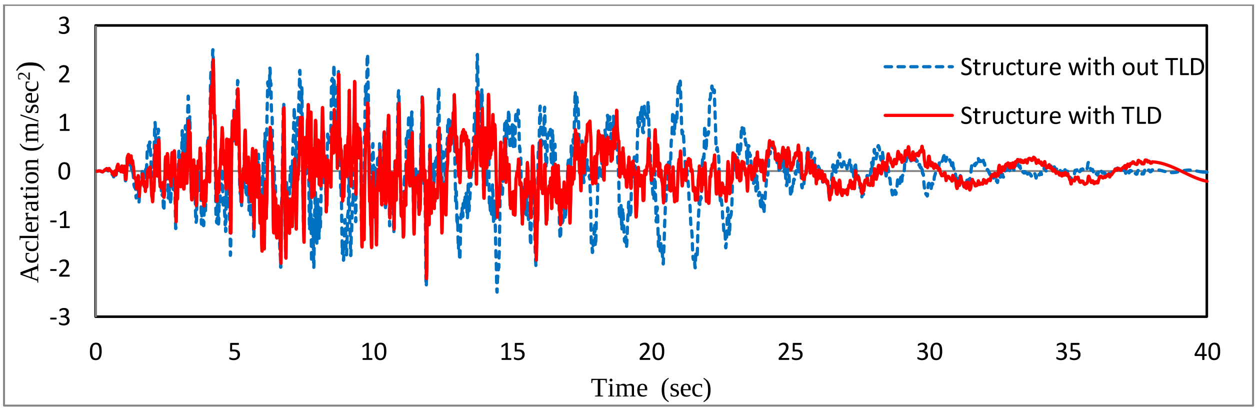


Figure 4.11 Acceleration time history of structural responses with and without TLDCompatible time history as per spectra of IS-1893 (Part -1): 2002 for 5% damping at rocky site

4.5.2 El Centro Ground motion

The EW component of El Centro ground motion is considered which has a peak acceleration of 0.214g.

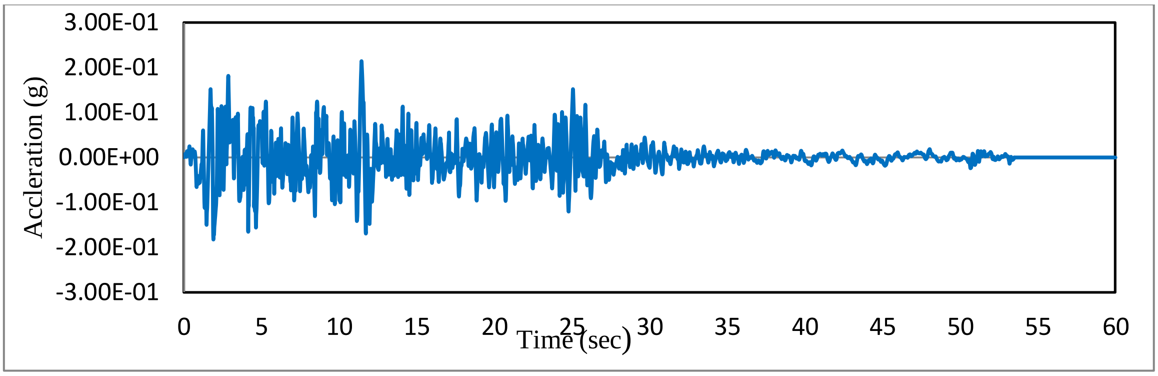


Figure 4.12Acceleration Time history of El Centro EQ Time History

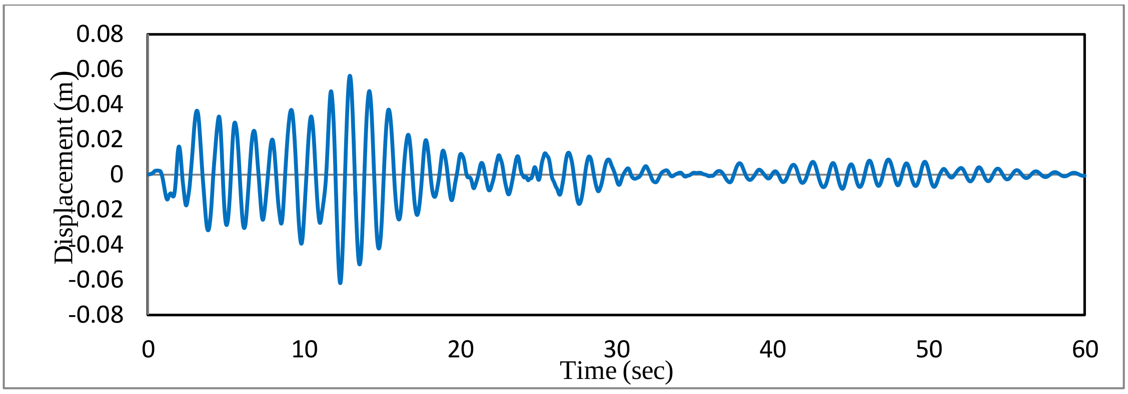


Figure 4 .13 Displacement time history of structural response without TLD corresponds to El Centro ground motion

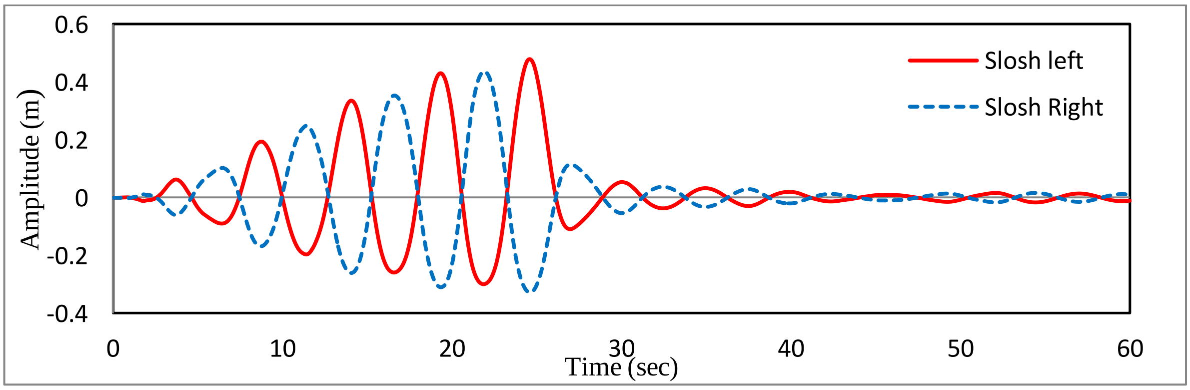


Figure 4.14 Time histories of slosh amplitude at left and right end of the tank corresponds to El Centro ground motion

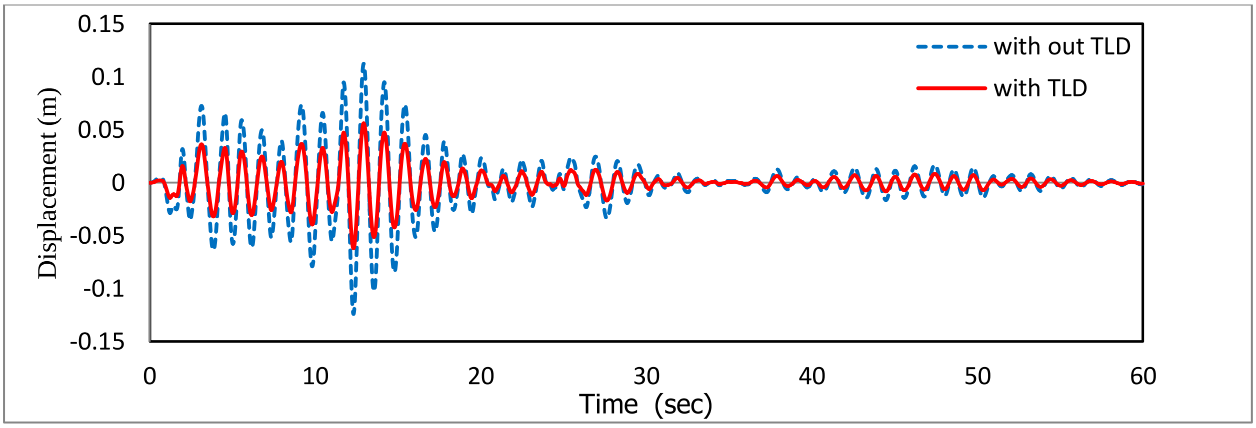


Figure 4.15 Displacement time histories of structural response with and without TLDcorresponds to El Centro Ground motion

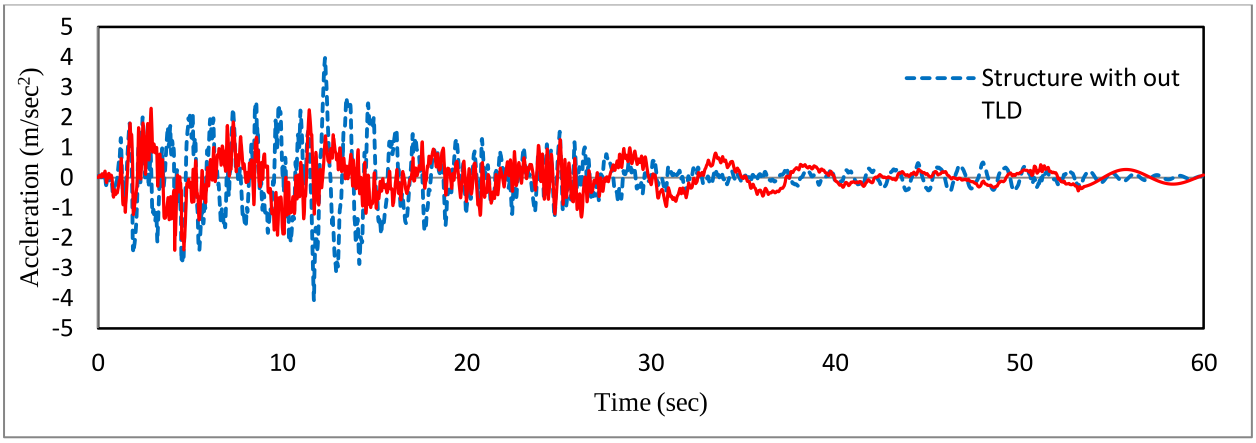


Figure 4.16 Acceleration time histories of structural response with and without TLD corresponds to El Centro Ground motion

4.5.3 Sanfranscisco ground motion

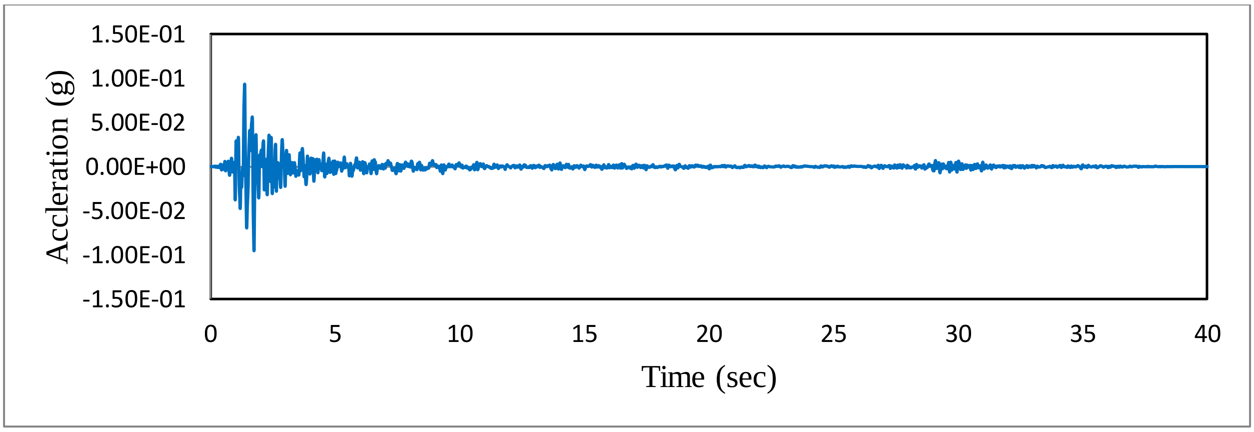


Figure 4.17 Acceleration time historey Sanfranscisco Earthquake

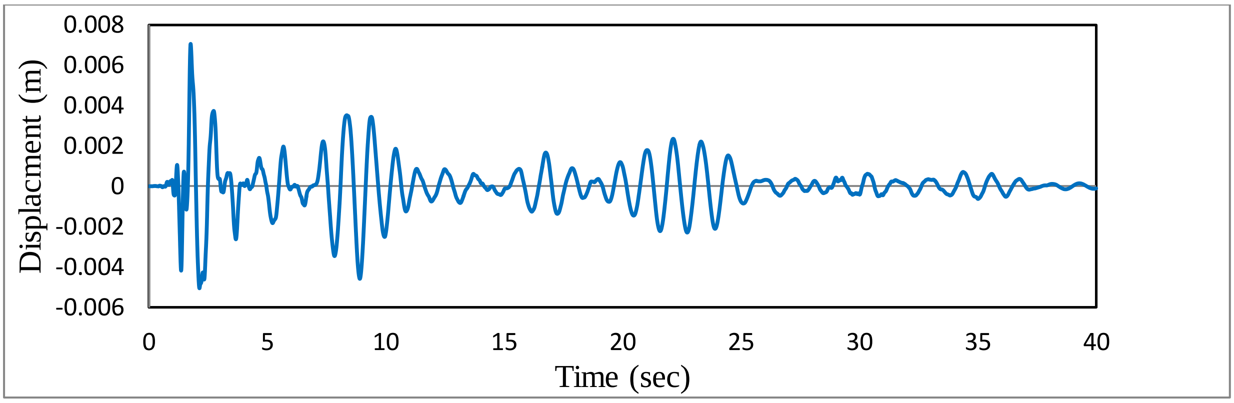


Figure 4.18 Displacement time history of structural response without TLD corresponds to Sanfranscisco ground motion

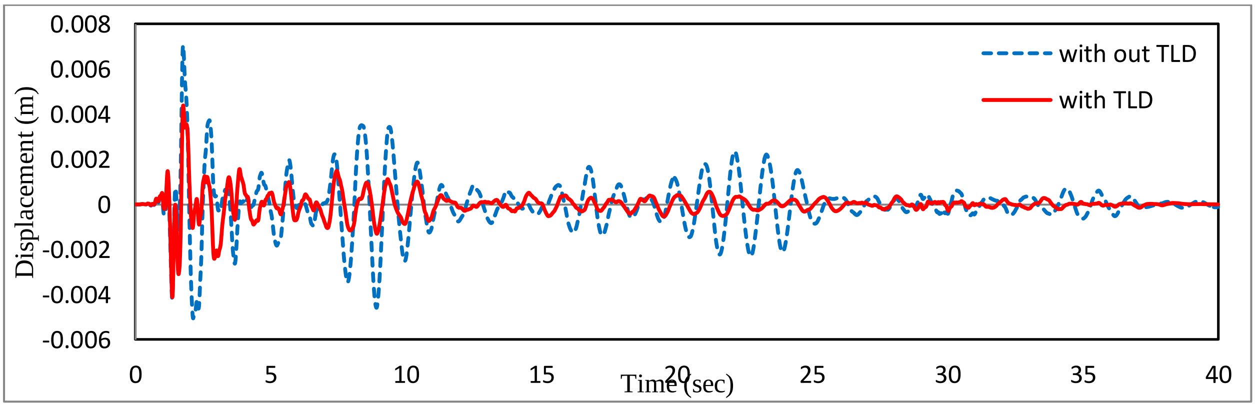


Figure 4.19 Displacement time histories of structural response with and without TLD corresponds to Sanfranscisco ground motion

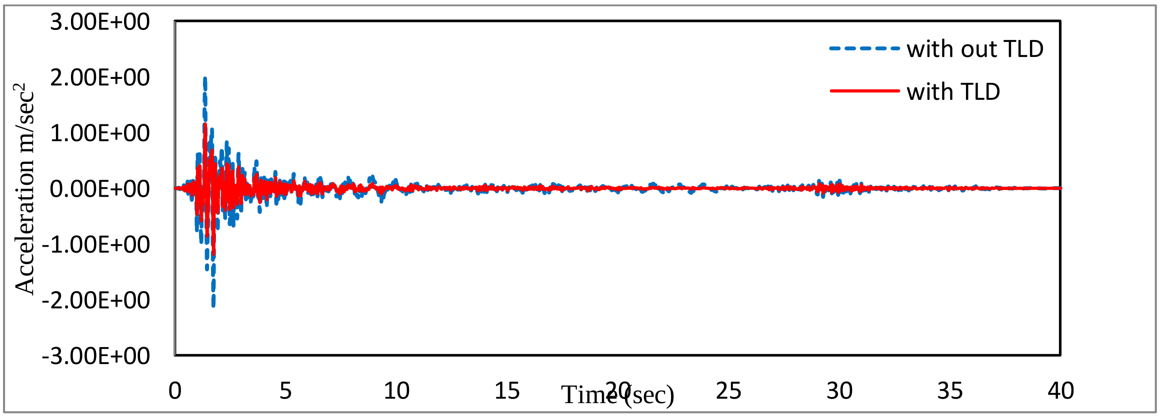


Figure 4.20 Acceleration time history of structural response with and without TLD corresponds to Sanfranscisco ground motion

4.5.4 Colienga ground motion

Colienga ground motion which is has a peak acceleration (PGA=0.14g)

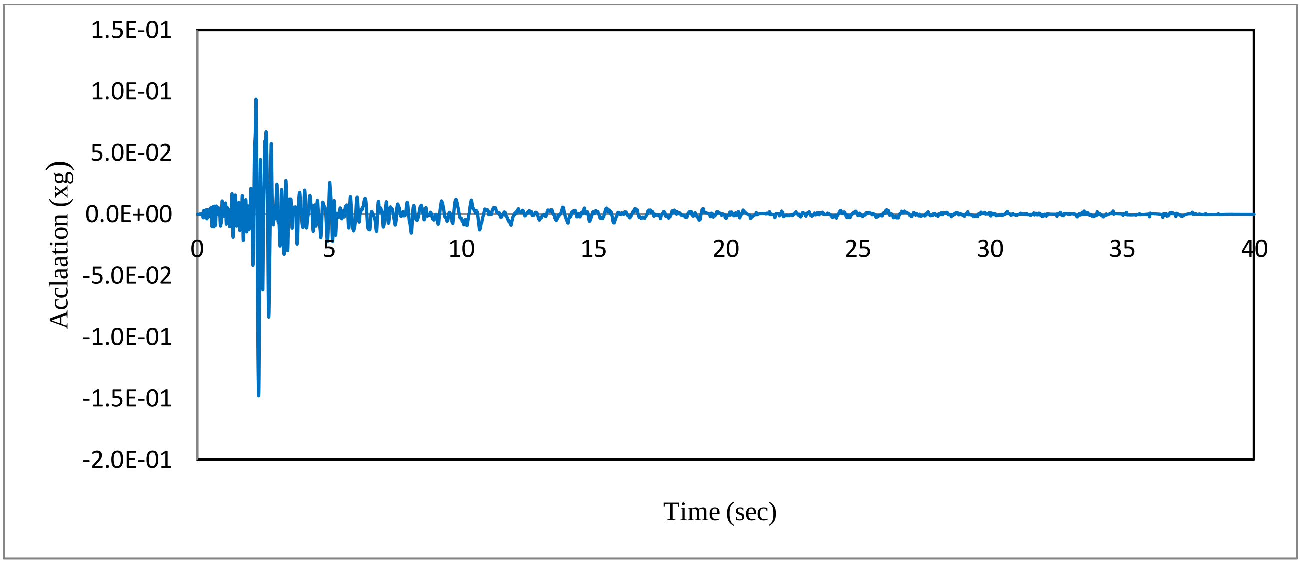


Figure 4.21 Acceleration time history of Colianga Earthquake

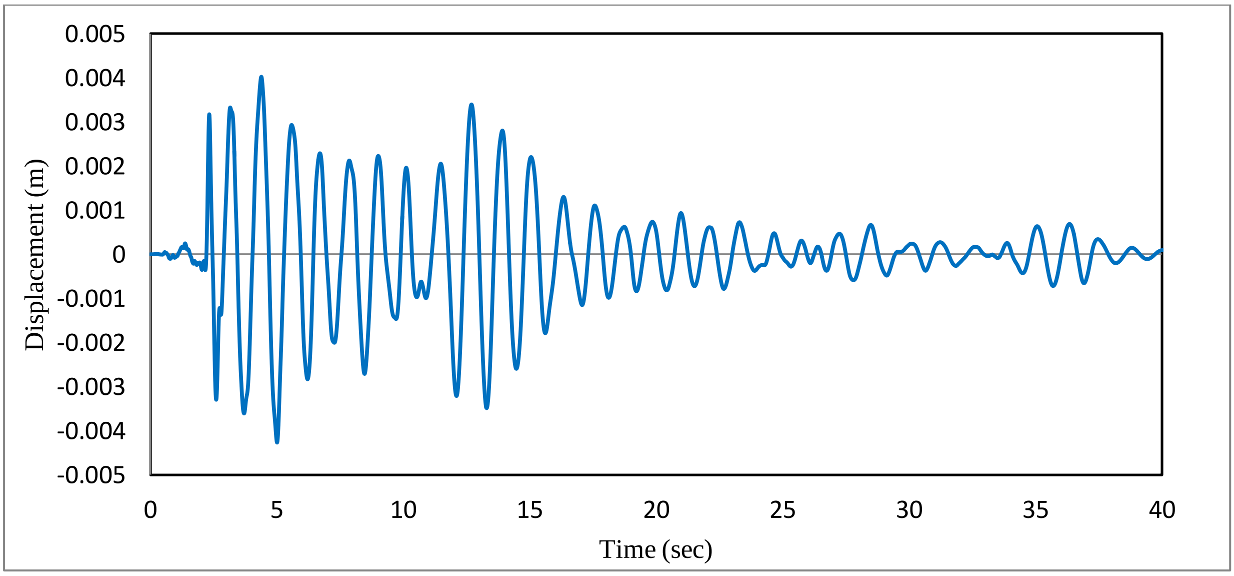


Figure 4.22 Displacement time history of structural response without TLD corresponds to Colienga ground motion

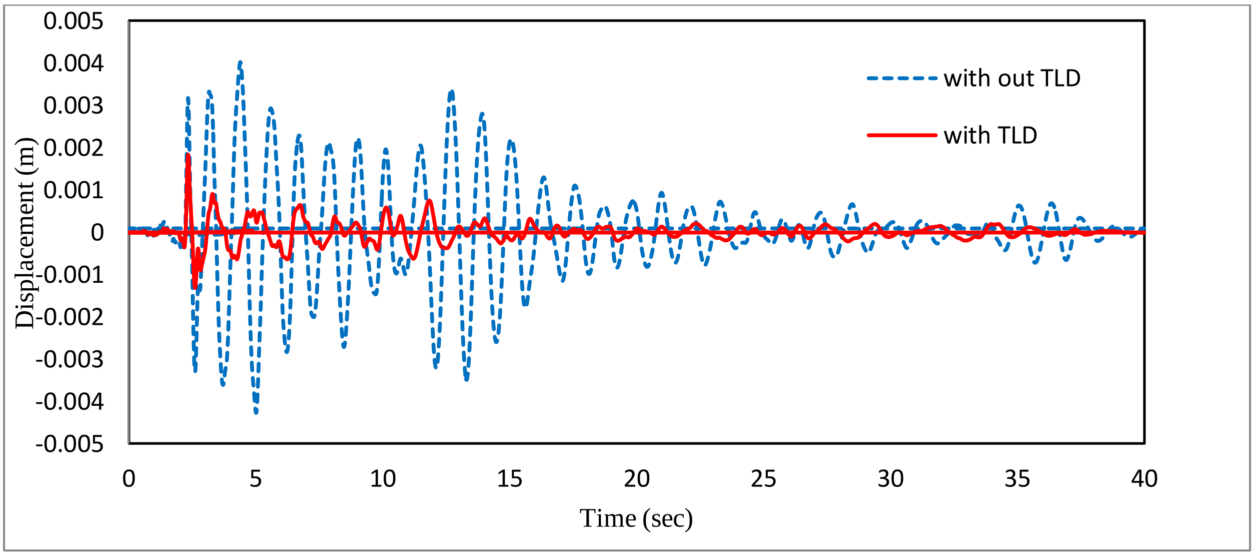


Figure 4.21 Displacement time historiesof structural response with and without TLD corresponds to Colienga ground motion

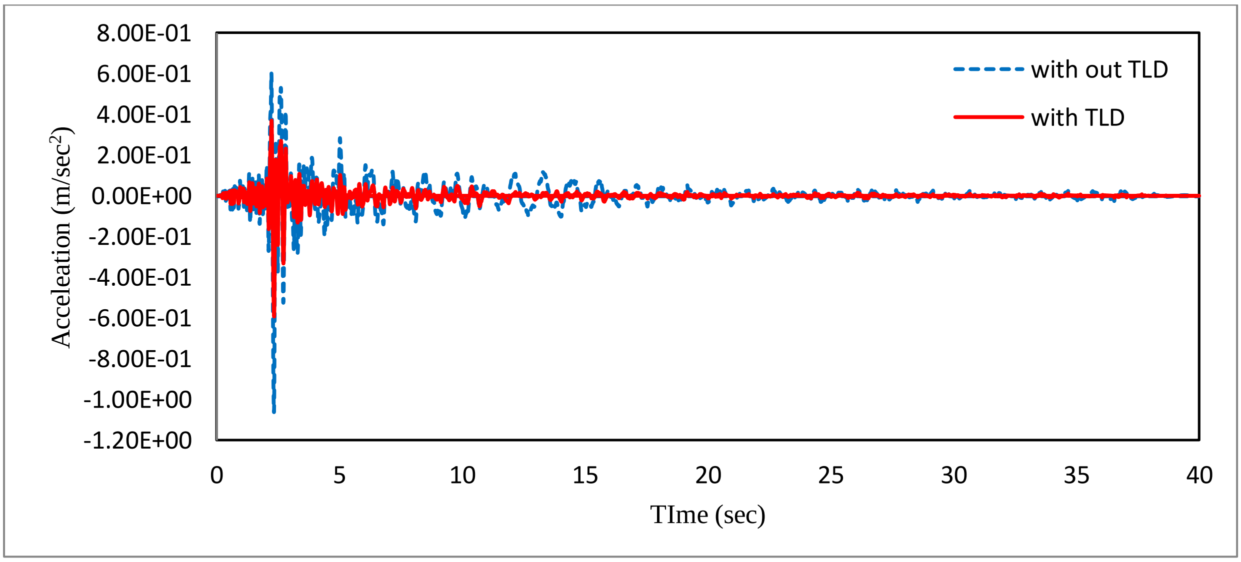


Figure 4.22 Acceleration time histories of structural response with and without TLD corresponds to Colienga ground motion

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	0.076	0.035	53.94
Spectra of IS 1893 (part-1) 2001 for 5% damping at rocky site	0.055	0.031	43.63
Elcentro earthquake ground motion	0.112	0.0562	49.82
Sanfranscisco Earthquake ground motion	0.007	0.004	42.85
Colianga Earthquake Ground motion	0.004	0.0021	47.5

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

Type of loading	Without TLD (m)	With TLD (m)	Percentage reduction (%)
Sinusoidal loading	2.04	1.02	50.98
Spectra of IS 1893 (part-1) 2001 for 5% damping at rocky site	2.503	2.29	8.51
Elcentro earthquake ground motion	3.96	2.29	42.17
Sanfranscisco Earthquake ground motion	2.01	1.15	42.78
Colianga Earthquake Ground motion	6.1	3.69	39.50

From the above tables 4.1 and 4.2 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 and 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. The maximum percentage of reduction in displacement for the TLD under earthquake loading is found in the El Centro earthquake.In case of Sanfransico 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. This leads to the conclusion, that 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 is reached in the first couple of cycles of vibration , when the water motion does not get a chance to dissipate enough energy.

CHAPTER-5

EXPERIMENTAL INVESTIGATION

5.1. Introduction

Due to rapid urbanization and industrialization, there is an increasing demand of high-rise buildings. These buildings inspired the use of high-strength, light-weight materials and the increase in the use of welded connections and light facades that serve as exterior walls without contributing to the structural strength. These developments have led to the construction of flexible buildings with reduced structural damping. As a result, the sensitivity of these buildings to dynamic excitations such as earthquake and wind has increased. Thus, it is essential to search for vibration-suppressing devices to counteract undesirable vibration in the structures. These devices may be passive, active, semi-active or hybrid types. The passive device, tuned liquid damper (TLD), is a type of tuned mass damper (TMD) where the mass is replaced by liquid (generally water). A conventional TMD needs frictionless rubber bearings, special floor for installation, springs, dashpots and other mechanical components which increase the cost of this device. However, the dead weight of the mass has no other functional use.

Although the TLD is usually a rigid tank with shallow water in it, it promises to be most suitable, since existing water tanks in buildings may be used as a TLD without adversely affecting its functional use and also include low cost and maintenance. The working principle of TLD is based on sloshing of the liquid to absorb a portion of the dynamic energy of the structure subjected to seismic motion and thus controlling the structural vibration.

Several research works have been carried out to find the applications of a TLD in reducing the seismic vibration of the structure (Banerji et al. [55]; Banerji et al. [69]; Bauer[3]; Fujino et al.[4]; Tamura et al. [15]. Sun et al. [7]Successfully developed an analytical model for TLD based on shallow-water wave theory. Based on this theory, Banerji et al. [55] have conducted numerical studies on TLD and concluded that TLD can be very effective in reducing vibration of the structure if the design parameters are approximately set. Koh et al. [15] studied the behavior of rectangular liquid dampers under the horizontal acceleration of arbitrary time history.

The objectives of this study are to reduce structural response by installing a model of TLD attached to the structure subjected to sinusoidal external excitation and to study the effects of various parameters, which affect the structural response. These parameters include the ratio of water depth to tank length, called water depth ratio, the ratio of sloshing frequency to structural natural frequency, called tuning ratio, and the ratio of excitation frequency ofthe natural frequency of the structure, called excitation frequency ratio.

5.2 Experimental studies

A series of experiments are conducted to study the dynamic behavior of a structure with TLD when subjected to harmonic base motion given by the shaking table. The harmonic ground motion is defined by its excitation frequency and amplitude of ground motion. As the harmonic motionconsists of a single frequency, the study of the structure with TLD will provide an understanding of the behavior of the TLD - structure system for this kind of motion. The displacement of the structure with and without TLDs is measured by means of Dynamic LVDT and data acquisition system, considering various excitation frequencies.

5.3 Description of laboratory equipment

- Unidirectional Shake Table.
- Power Supply (Universal Power Module).
- Data Acquisition System (Multi-channel Data Acquisition system).

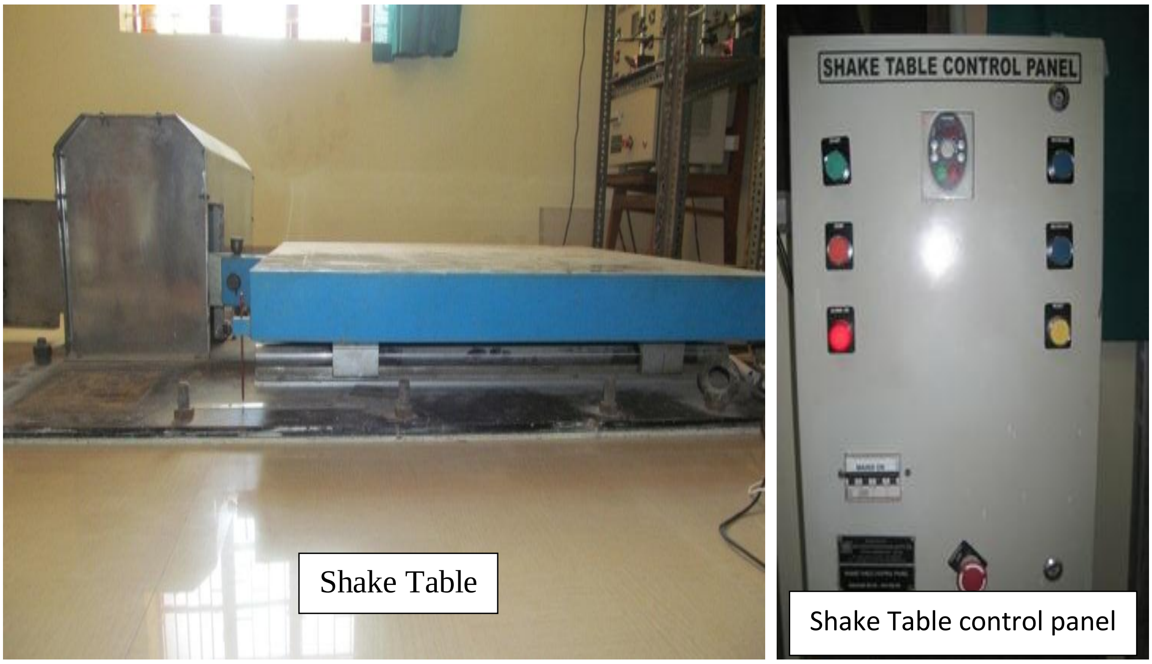
- Measurement Sensors (LVDT’s).

- Test Structure (One-Story Building Model).

5.3.1 Unidirectional Shake Table

The shake table consists of an1m x 1m sliding platform which is driven by an Electric induction motor. The induction motor drives a lead screw which, in turn, drives a circulating ball nut which is coupled to the sliding platform. The servo motor is driven by an amplifier which is embedded within the Universal Power Module (power supply). The sliding platform slides on low friction linear ball bearings which are mounted on two grounds-hardened shafts. The platform surface has 81 tie-down points located on a 100x100mm grid.

The operating frequencies of the shake table range from 0 to 20 Hz. The maximum Displacement of the table is ±50mm with an amplitude resolution of 5mm. The maximum payload is 100 Kg. The table is capable of producing simple Harmonic motion. The excitation frequency of the shaker can be controlled by means of a control panel.



Shake Table

Shake Table control panel

Figure 5.1 unidirectional shake table

5.3.2 Power Supply

The Universal Power Module (power supply) includes a power amplifier for driving the shake table servo motor (figure 5.2) In addition it includes an independent ± 24 volt DC power supply to provide power to the sensors.

5.3.3 Data Acquisition and Control System

NI PCI 6255 multi-function data acquisition (DAQ) system manufactured by National Instruments is used to obtain measurements of physical quantities using sensors and transducers. These measurements may be temperature, pressure, wind, distance, acceleration, etc. In civil engineering applications the most common types of sensors measure displacement, acceleration, force and strain. In this experiment, we are going to use LVDT sensors. Dynamic LVDT is used to measure the displacement of the structure. And also a static LVDT to measure the displacement amplitude of the shake table. The computer system used to perform the tests described herein consisted of an Intel (R) Core (TM) i5 processor with 4GB RAM, 32-bit operating system and running Windows 7 professional. In addition to plug-in data acquisition DAQ devices, most computer-based measurement systems include some form of signal condition. This is because the signals from various sensors and transducers need to be filtered to prepare them for digitizing. The processing of signals to prepare them for digitizing is called signal conditioning. Signal conditioning is required for sensor measurements or voltage inputs greater than 10 V. The present DAQ system has a front-end signal conditioning and switching system, NI SCXI. NI SCXI is a versatile, high-performance signal conditioning platform optimized for high-channel-count applications. The softwares used for data acquisition are NI-DAQmx driver software and NI LabVIEW SignalExpress LE interactive data-logging software. Figure 5.2 Photos of components of data acquisition system,which includes sensors, transducers, signal conditioning devices, cables that connect the various devices to the accessories, programming software, and PC.

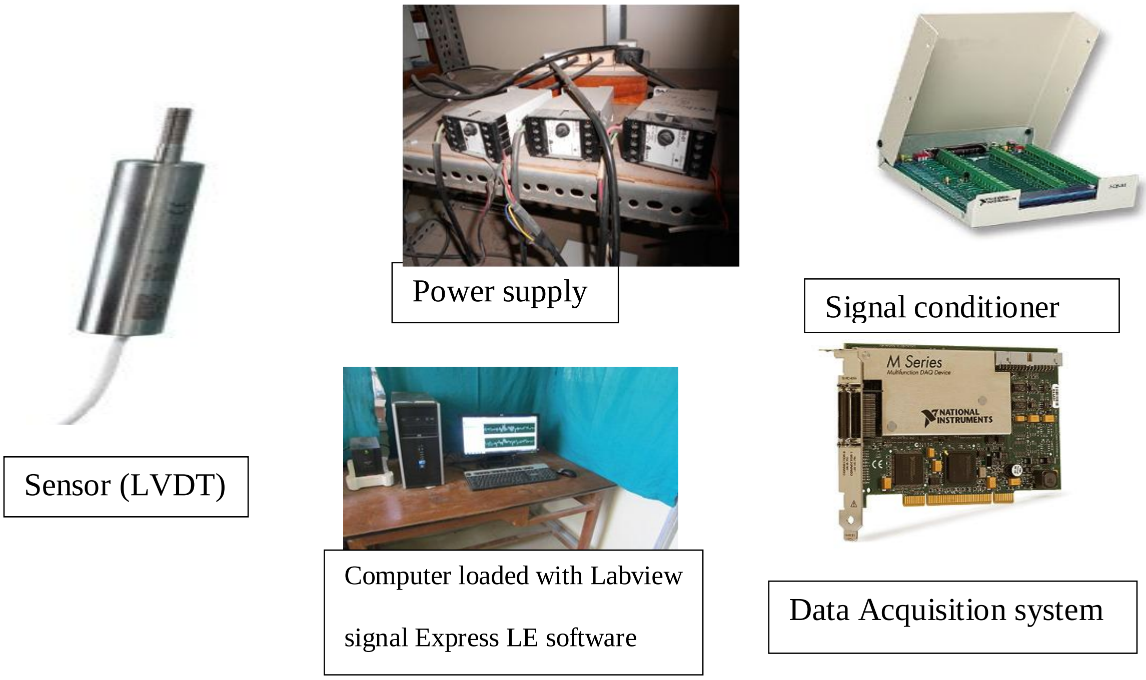


Figure 5.2 Schematic Diagram of Data acquisition system.

5.3.4 Measurement sensors

Unguided armature with threaded tip LVDT (Sensorex Model-SX20MER300) with a stroke range of 300 mm (+/- 150mm), input voltage 24v Dc , and output voltage 0/10 V Dc is used for Displacement measurement of structure. Spring extended armature with standard ball tip LVDT (Honeywell) is used for measuring the excitation amplitude of the shake table. A photograph of the LVDT's is shown in fig—5.3

Figure 5.3 Displacement LVDT’s

5.3.5 TLD-structure model

The test structure developed for this experiment is a one-story building frame. The four columns consist of an Aluminum rectangular section of size 25x3mm and the height of the column is 0.55m. While the roof and the base plates are constructed the roof consists of mild steel and a wooden plate . The The top and bottom of each column is attached to the roof and base plate. The columns are oriented such that bending occurs about the weak axis. An LVDT is attached to the roof level to record the lateral Displacement. The TLD is placed on the structure. The TLD tanks are made up of acrylic sheet, having 12-mm thick sidewalls and base plate.

Figure 5.4 Test structure

5.4 Experimental setup

Figure 5.5 shows an arrangement of the structure over a unidirectional shaking table. The shaking table is arranged to impose horizontal motions on the structure. The required excitation frequency is applied to the structure by means of a control panel.

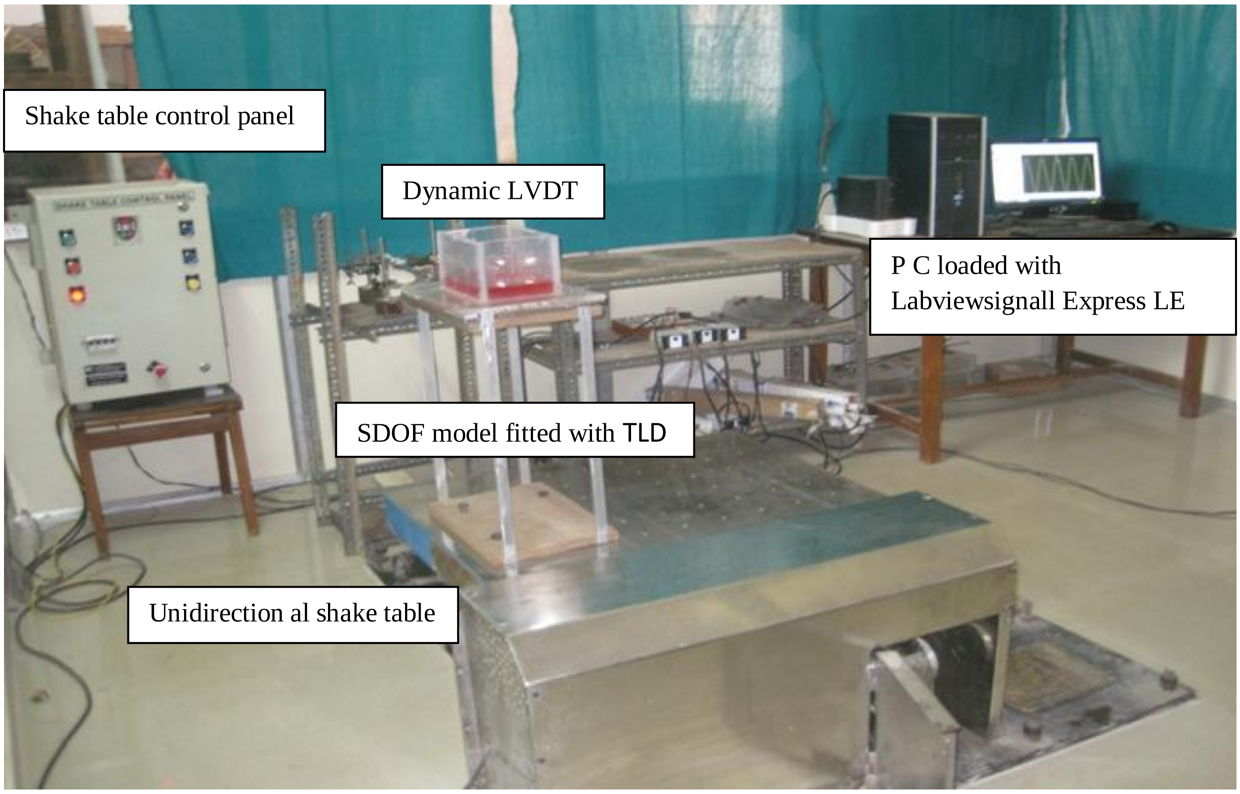


Figure 5.5 Schematic Diagram of Experimental setup

The TLD is placed on the structure. The motion imposed on the structure is Harmonic, with control over the amplitude and the frequency of the oscillations.

The measured response parameter is the Displacement of the structure along the direction of excitation. The displacement response is measured by attaching Sensorex SX20MER300 Dynamic LVDT at the top of the structure. NI-PCI 6255 computerized multi-channel Data acquisition system with Lab view Signal Express LE software for post analysis of data used to acquire and analyze the experimental data.

In each set of experiments, the TLD-structure system is subjected to harmonic sinusoidal base motion with different excitation frequencies. The external sinusoidal excitation is applied to the structure by means of an induction motor.

5.5. 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.

5.5.1. 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 and significant parameter for defining the effectiveness of a rectangular TLD

5.5.2 Excitation Frequency ratio $(\beta = \frac{f}{f_s})$

The frequency ratio $(\beta)$of a rectangular TLDis the ratio of the fundamentallinear sloshing frequencyω_l, which is given by equation (3.14), to the natural vibration frequency of the structure,ω_s.

5.5.3 Mass ratio $(\mu = \frac{m_w}{m_s})$

The mass ratio, μ, is the ratio of the mass of water to the structure mass is also and important pparameter to be considered in the TLD design.

5.6 Experimental results and Discussion

5.6.1 Comparison of Numerical and experimental results

The displacement response time history of the SDOF structure, when it is subjected to a sinusoidal base excitation, is measured from the experiments. And also determined using the numerical simulation. Typical plots of these comparative time histories for the three different frequency ratios 0.9, 1.0 and 1.1 are shown in figure 5.6, 5.7 and 5.8

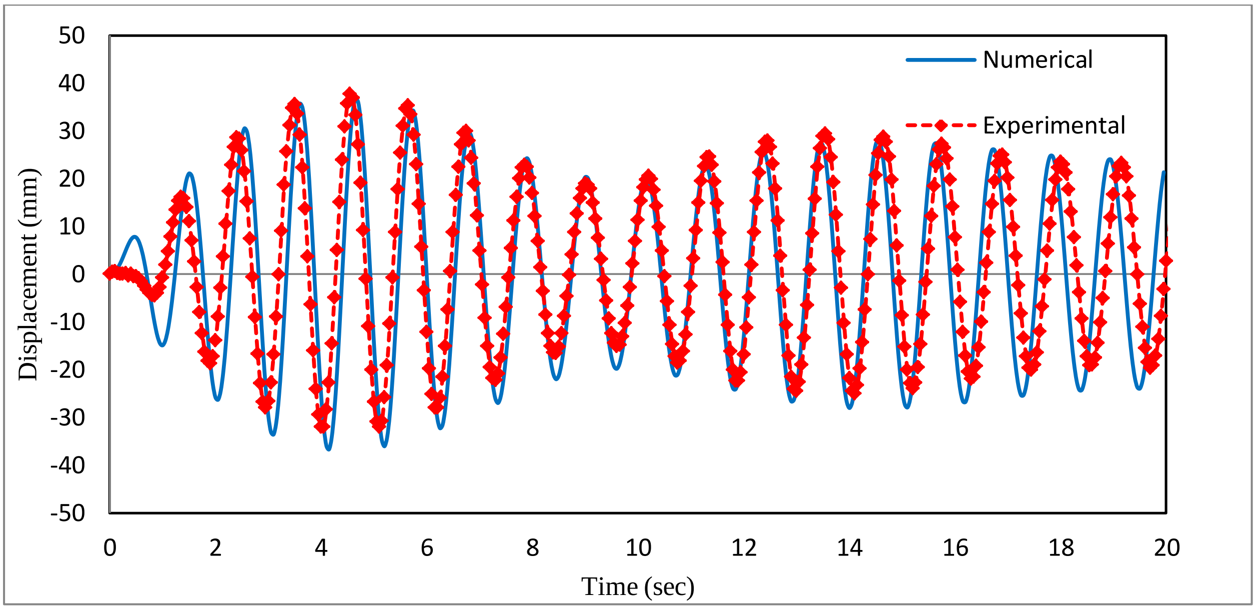


Figure.5.6 comparison of typical numerical and measured structure displacement response histories for frequency ratio=0. 9

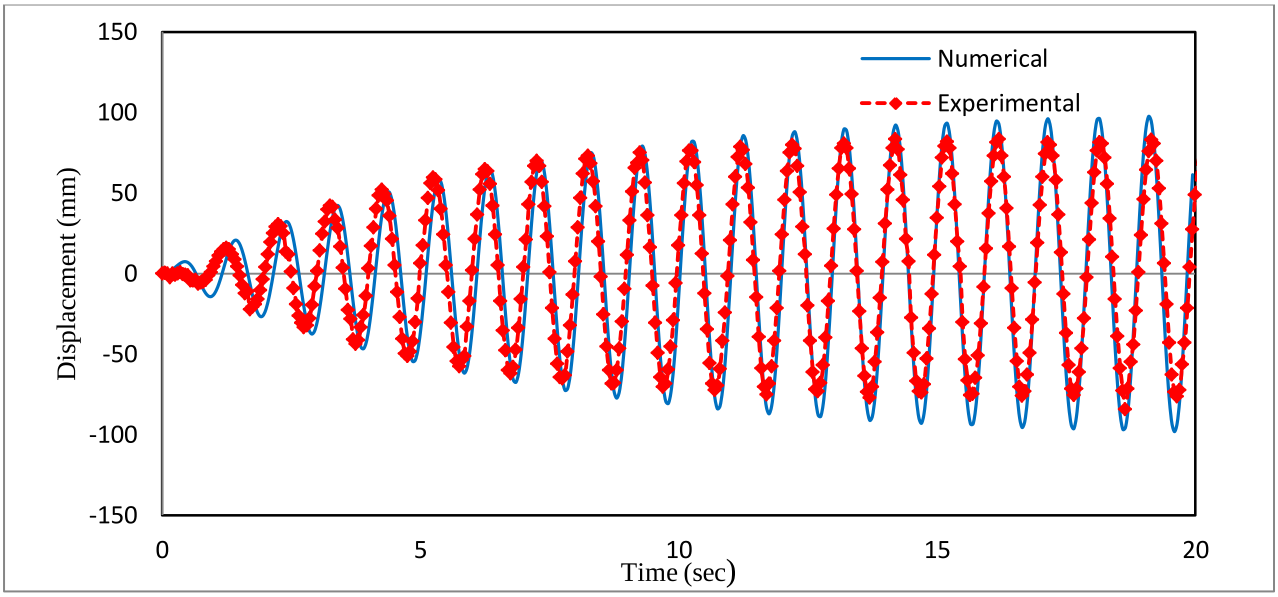


Figure 5.7 Comparison of typical numerical and measured structure displacement response histories for frequency ratio=1.0

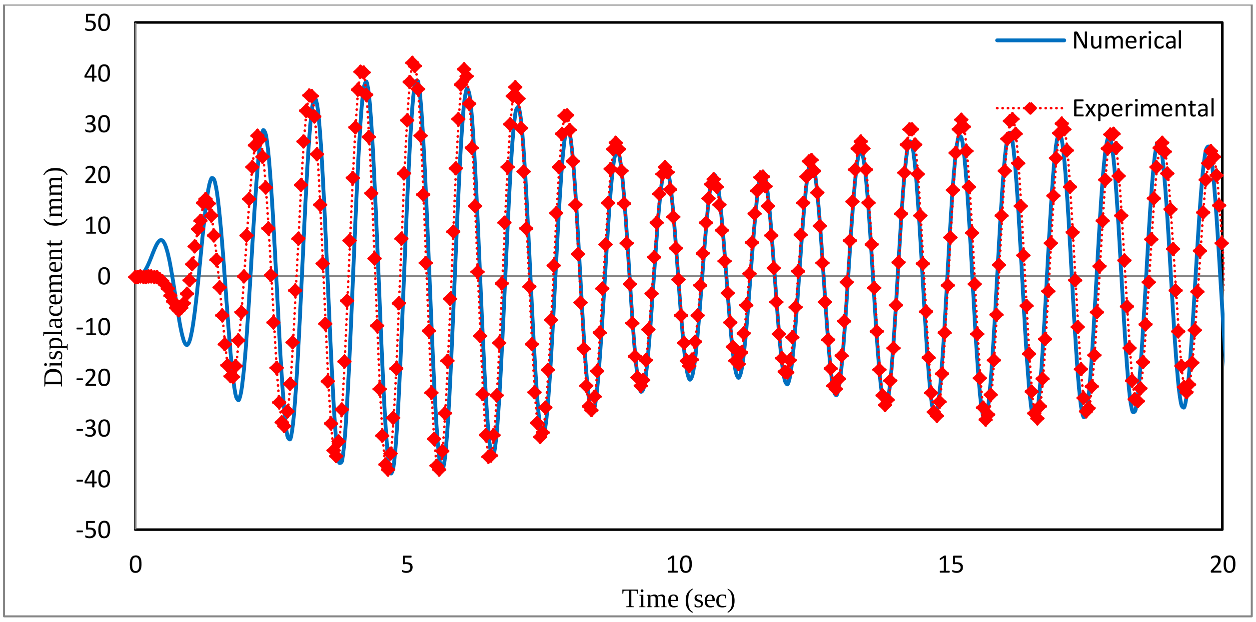


Figure 5.8 Comparison of Typical numerical and measured structure displacement response time histories for frequency ratio =1.10

5.6.2 Effect of Depth ratio on the structural response

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. Different water depth ratios varying from 0.05 to 0.3.The corresponding max response of the structure has been shown in figure-5.9. The figure shows the relationship between the structural response amplitude in resonance condition and the corresponding water depth ratios. From the figure 5. 9, it can be clearly observed that exists an optimum depth ratio0.125 corresponds to the minimum response amplitude.

The reason for this trend can be traced out to the behavior of a TLD. The energy absorbed and dissipated by the TLD depends mostly on the sloshing and wave breaking. The water in the TLD having a larger water depth, i.e. higher v values, does not slosh as much as that for low water depth, because the energy transmitted to the TLD is relatively low.

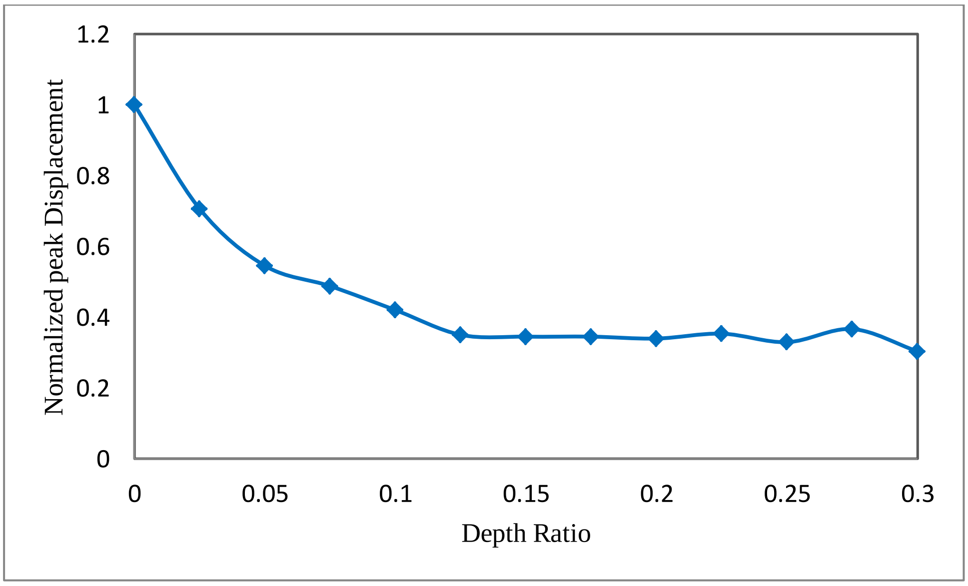


Figure 5.9 Structural response amplitude versus TLD water depth ratio in resonance condition

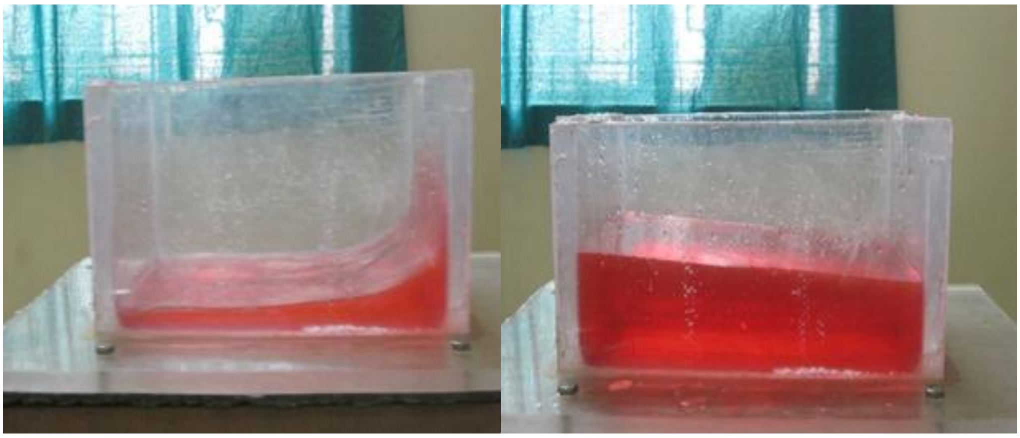


Figure 5.10 Comparison of sloshing response in the TLD for lower and higher water depth ratios

5.6.3 Effect of excitation frequency ratio on structural response

The tuning of a rectangular TLD is the ratio of external excitation frequency to the natural frequency of the structure. For a certain TLD structure system, with fixed system parameters, excitation frequency has a significant effect on the amplitude of structures.In this regard, the frequency response study of the displacement of the structure is carried out with and without TLD.

Lateral sine sweep tests were conducted for structure without and with TLD to identify the natural frequencies of the system. Each of the TLD structure systems were excited with sinusoidal harmonic loading defined by expression $x = x_0 \sin(2\pi \mathrm{f} t)$ (where x_0 is the amplitude of excitation and f is the excitation frequency in cycles/sec) over a range of excitation frequencies with several excitation frequency ratios from 0.5 to 1.5. The displacement amplitude of the excitation was kept constant at 5 mm. The shaking was allowed over a significantly long period so as to allow the structure reach steady state. The time domain amplitude response of the system data for each excitation frequency was recorded with the help of Dynamic LVDT which is attached to the structure in the direction parallel to the direction of excitation, via NI 6225 data acquisition system (DAQ) and

LabView SignalExpress LE software. The peak amplitude of displacement was then recorded and all the Displacement peaks were plotted against their respective excitation frequencies to obtain the frequency response curve of a particular TLD structure system. The excitation frequencies corresponding to the Displacement peaks of frequency response plots gave the respective natural frequencies of the structure. One such frequency response plot for the structure with and without TLD demonstrated in Figure 5.11 From figure 5.11 it is observed that the at the initial stage, when the excitation frequency is lower than the resonant frequency, the peak structural response increased. However, at the region of resonance (f/f's), the response amplitude reduces drastically upon attachment of TLD. Thus, maximum control response is obtained when the structure is subjected to resonance frequency, For other frequency ratios inertial and sloshing components of the TLD interface force interferes with each other, the TLD was observed to be ineffective in dissipating the energy.The reduction of response, considering the resonance condition is obtained as 56.64%.

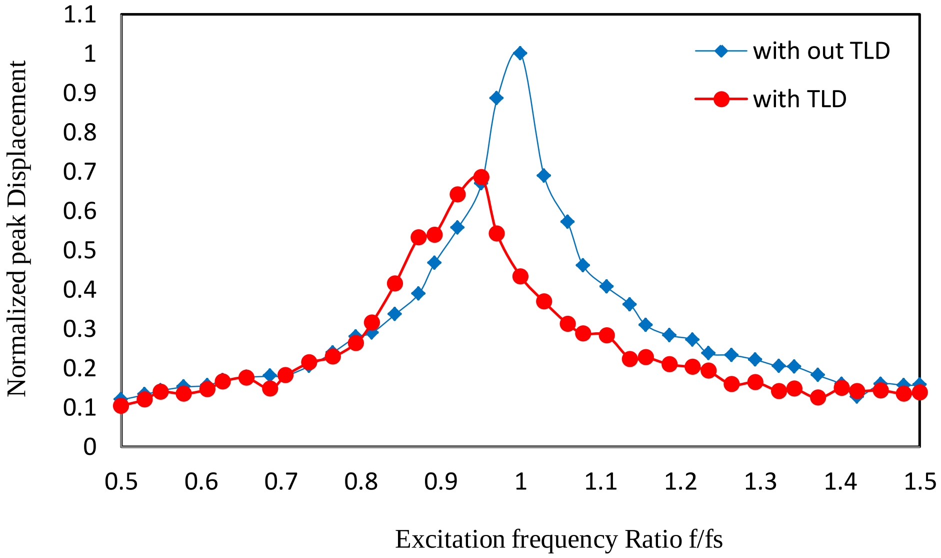


Figure 5.11 Frequency Response of the structure with and without TLD

5.6.4 Experimental determination of damping

The damping of the structure has been found experimentally the method of logarithmic decay of amplitude of free vibrating structure is employed. In this method, the structure was harmonically excited at its resonance frequency. The displacement amplitude of excitation was kept constant 5mm. Sufficient time was allowed for the structure to attend steady state and then the oscillation was stopped to initiate free. The time history of amplitude of the structure during free vibration phase was recorded. The rate of decay of amplitude was then computed, from which the damping ratio was calculated

$$\delta = In\frac{y_1}{y_2} \qquad (5.1)$$

Where y_1 and y_2 are the amplitudes of the peaks

$$\xi = \frac{1}{2\pi}\, In\left(\frac{y_1}{y_2}\right), \quad \xi \text{ is the damping ratio}$$

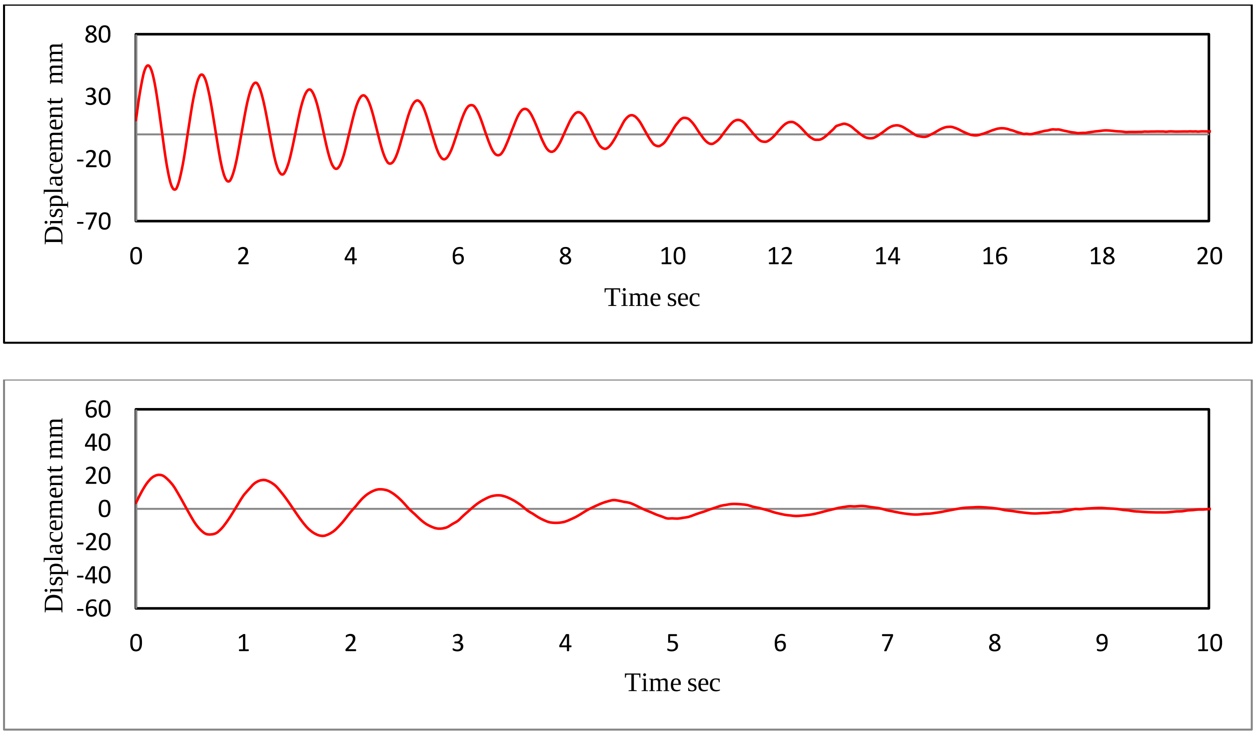


Figure 5.12 Free vibration response of damped system for structure without and with TLD

It is observed that the presence of TLD enhances the structural damping ratio.

5.6.5 Mass Ratio:

The 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 TLD design. 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 6 % has been considered and the excitation frequency is which is equal to the resonance of the structure.

Table – 5.1 percentage reduction in the resonant 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	27.47
1	28.27
1.5	35.85
2	37.71
2.5	38.80
3	45.55
3.5	46.34
4	48.83
4.5	48.13
5	48.24
5.5	47.15
6	47.05

It can be seen from the above table that the efficient reduction in the displacement increased as the mass ratio increased up to 4. %. The increase in mass ratio from 3% to 4% increase the efficiency in the displacement reduction only by 4% while considerably increasing the mass of the water that needs to be employed, from the practical point of view 3% mass ratio can be recommended as the optimum value. For mass ratios larger than 4% beating phenomenon was observed in the TLD behavior and efficiency is reduced.

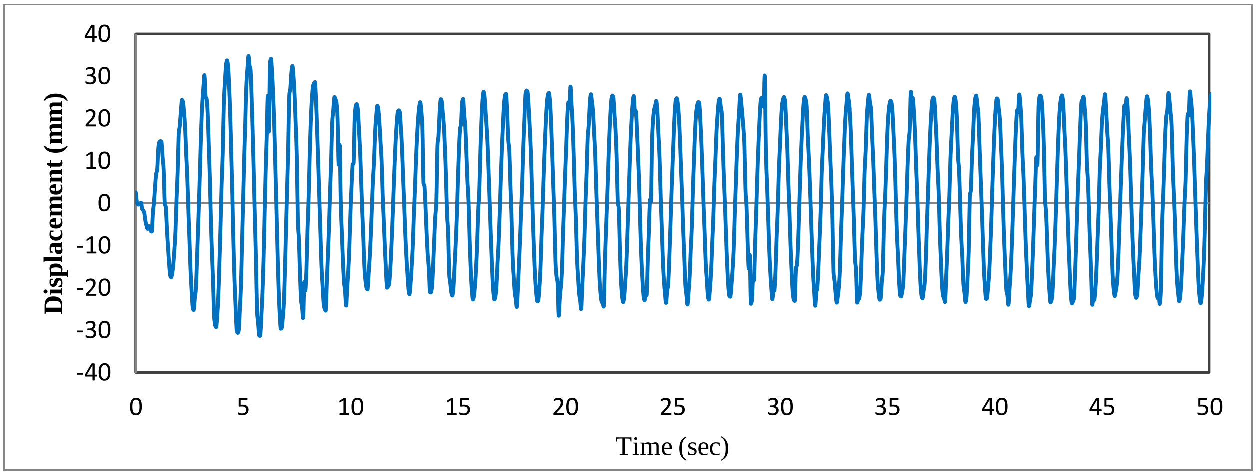


Figure 5.13 Displacement Time History for 5 % Mass ratio

5.7 Response of the TLD-Structure system to Harmonic excitation

Forced vibration analysis is carried out in the TLD-structure system. Investigation The system is subjected to a sinusoidal base motion given in the shaking table. Typical harmonic excitation given to the shake table is recorded by the static LVDT is depicted in Fig. 5.14 The displacement amplitude of the excitation was kept constant at 5 mm. Typical plots of displacement time histories of the structure with and without the TLD for different frequency ratios are shown below

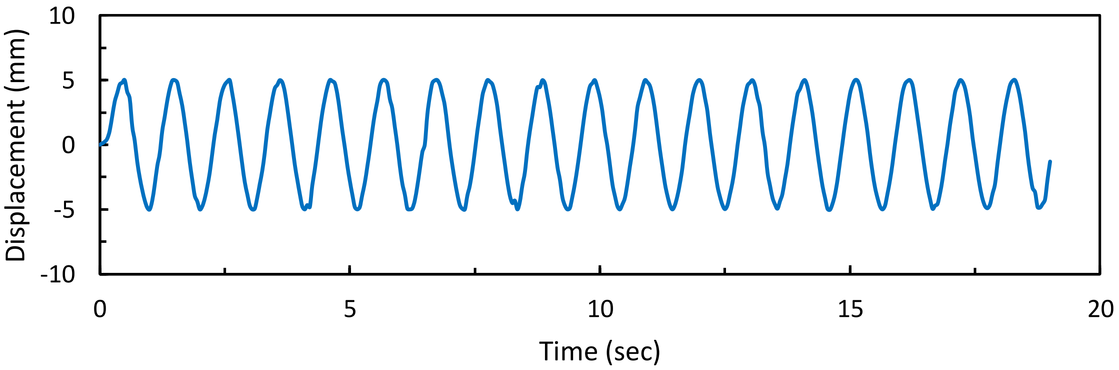


Figure 5.14 Harmonic excitation, displacement amplitude x_0 = 5 mm

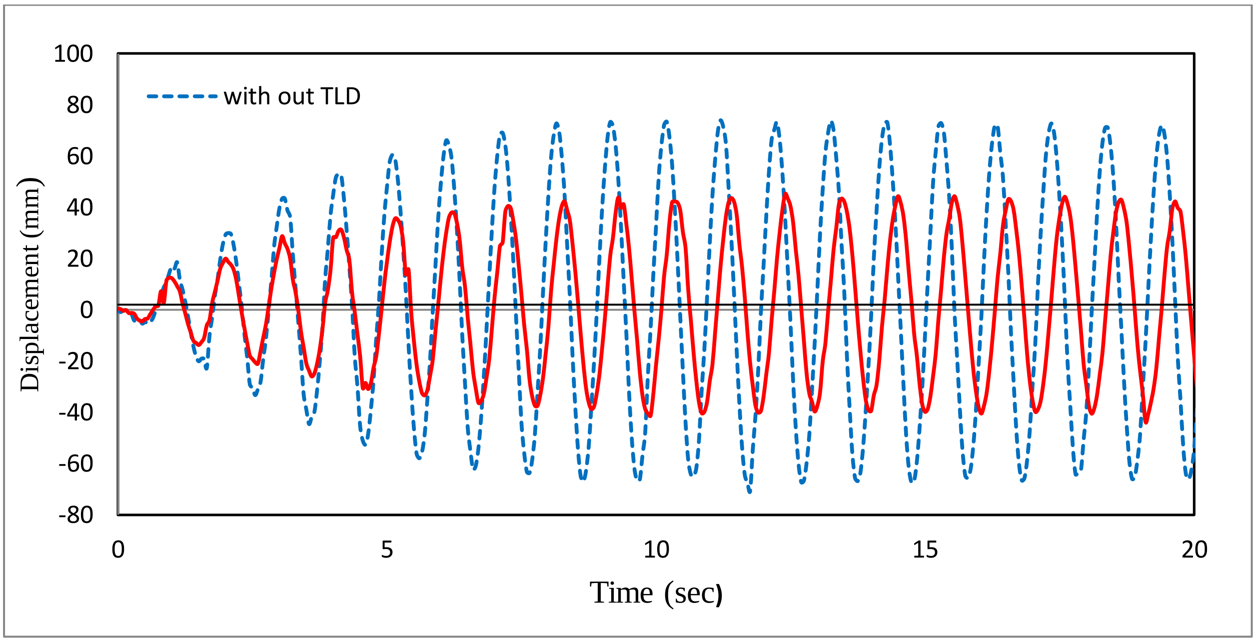


Figure 5.15 Time histories of the structural Displacement with and without TLD (for $\beta = 0..97$)

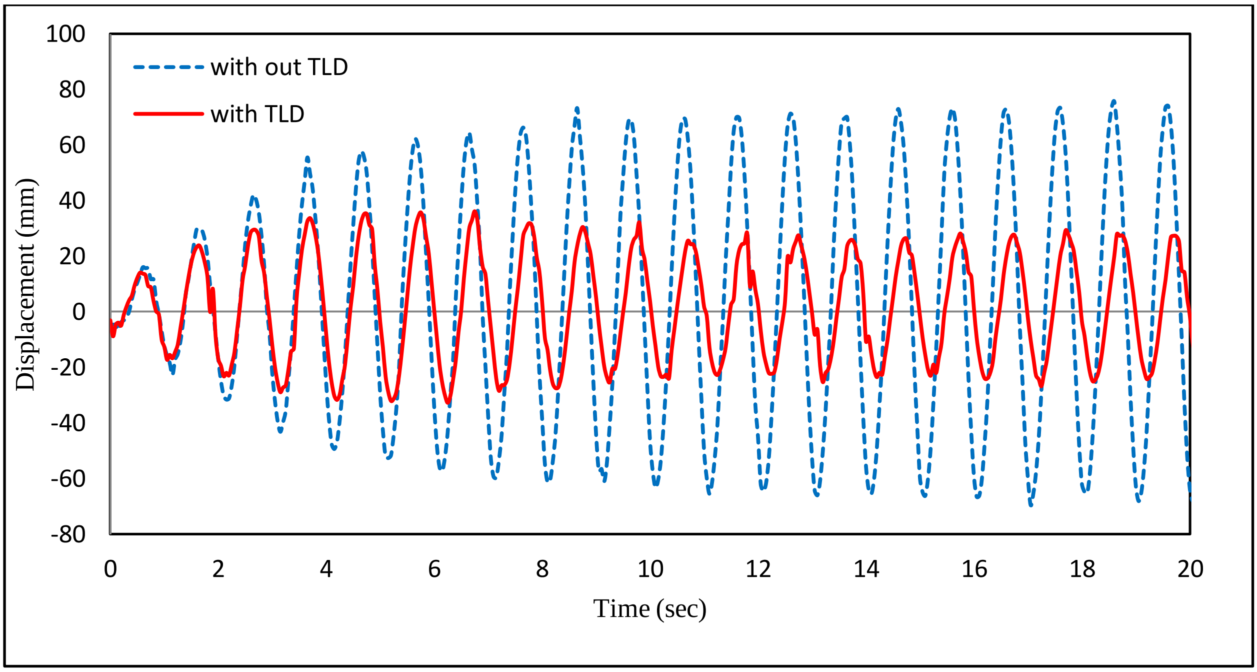


Figure 5.16 Time histories of structural displacement with and without TLD (for $\beta = 1$)

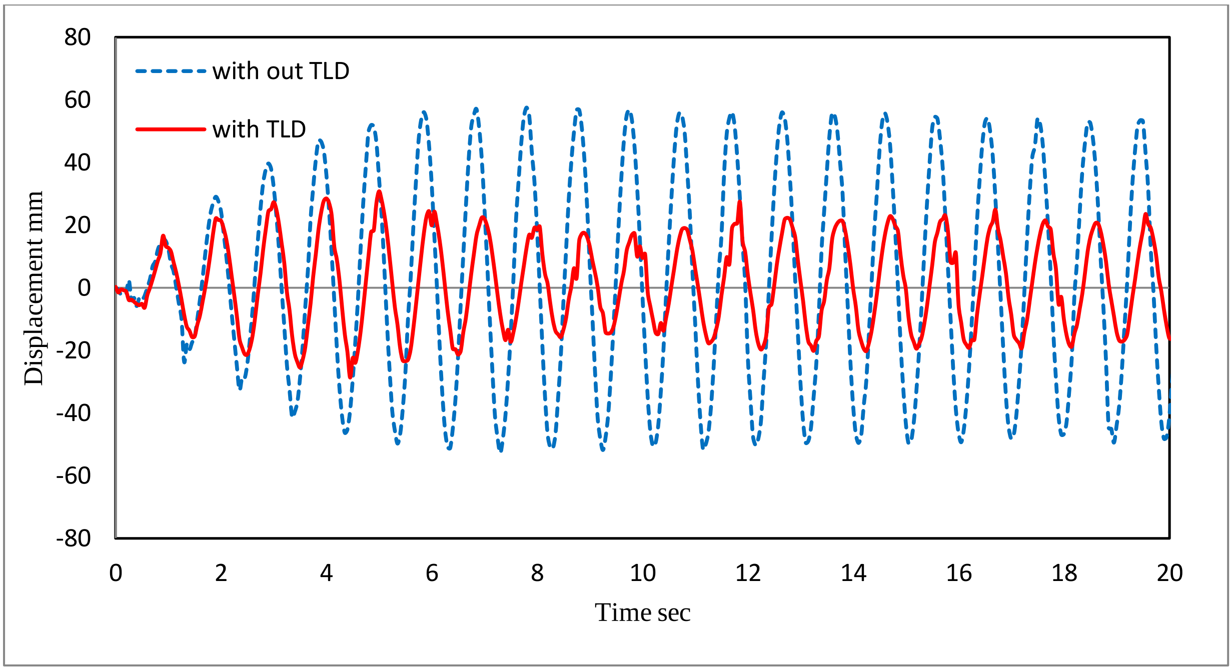


Figure 5.17 Time histories of structural displacement with and without TLD (for $\beta = 1.03$)

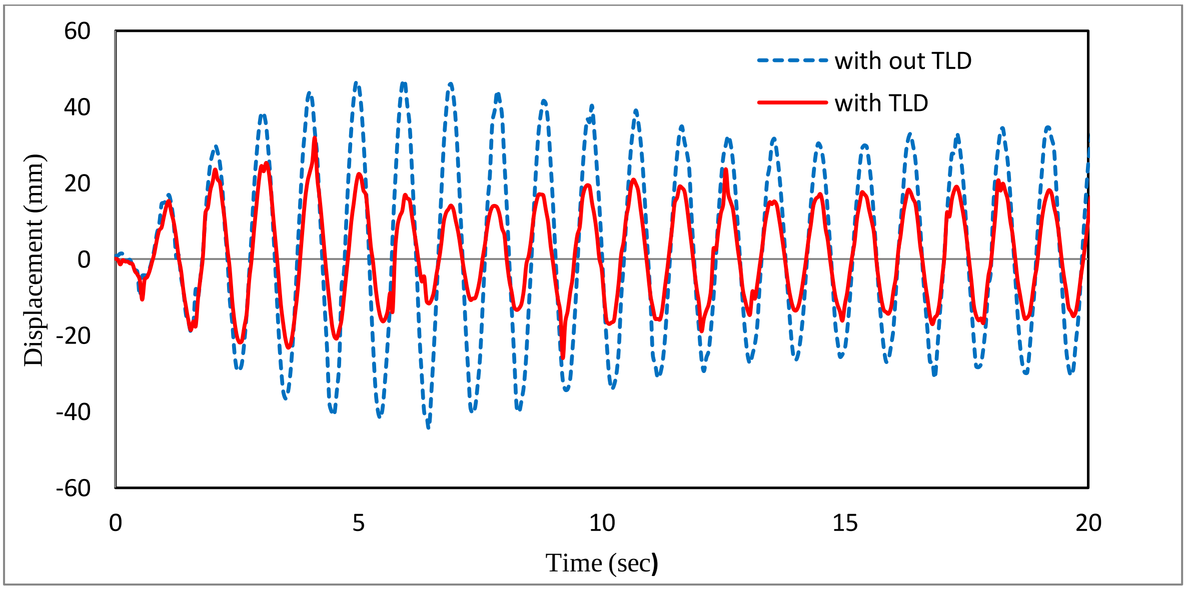


Figure 5.18 Time histories of structural displacement with and without TLD (for $\beta = 1.06$)

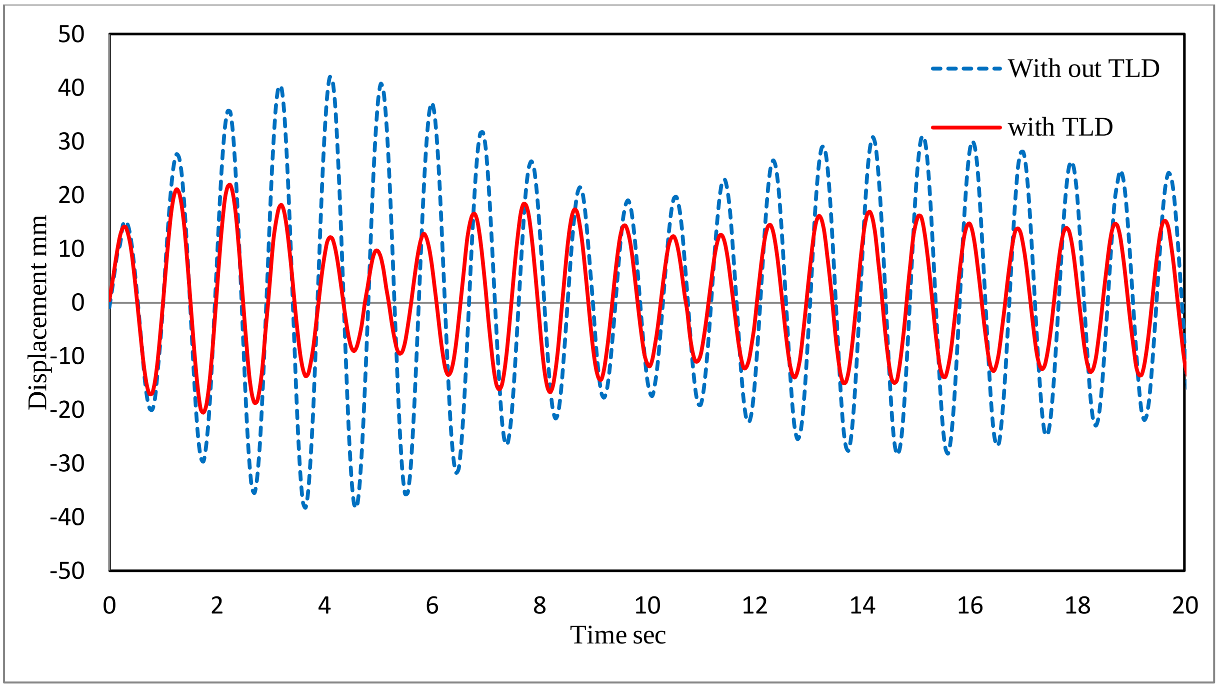


Figure 5.19 Time histories of structural displacement with and without TLD (for $\beta = 1.10$)

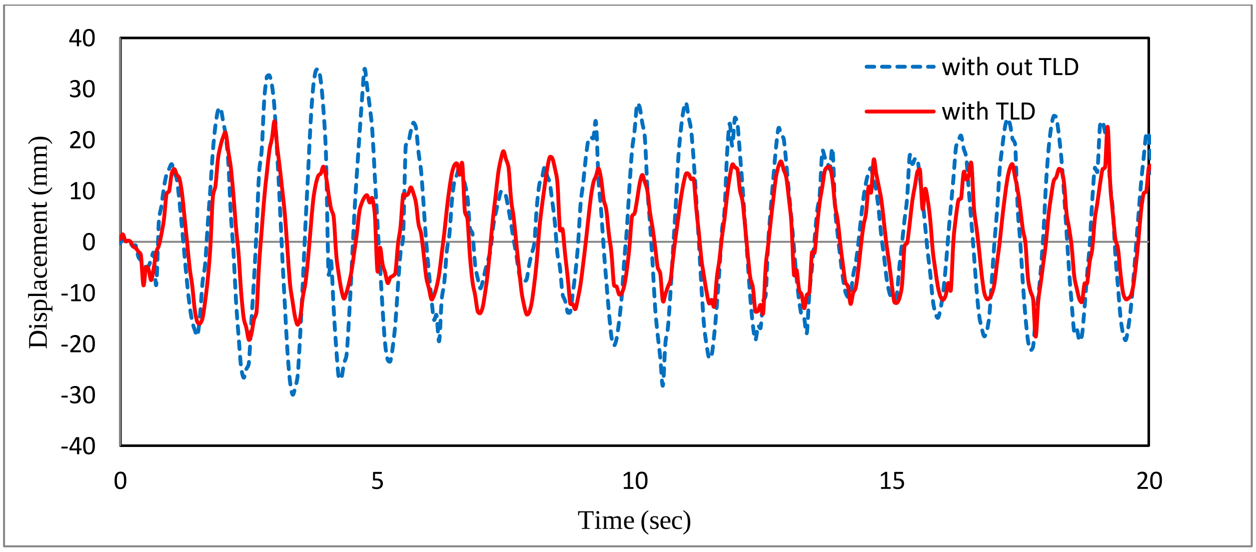


Figure-5.20 Time histories of structural displacement with and without TLD (for $\beta = 1.12$)

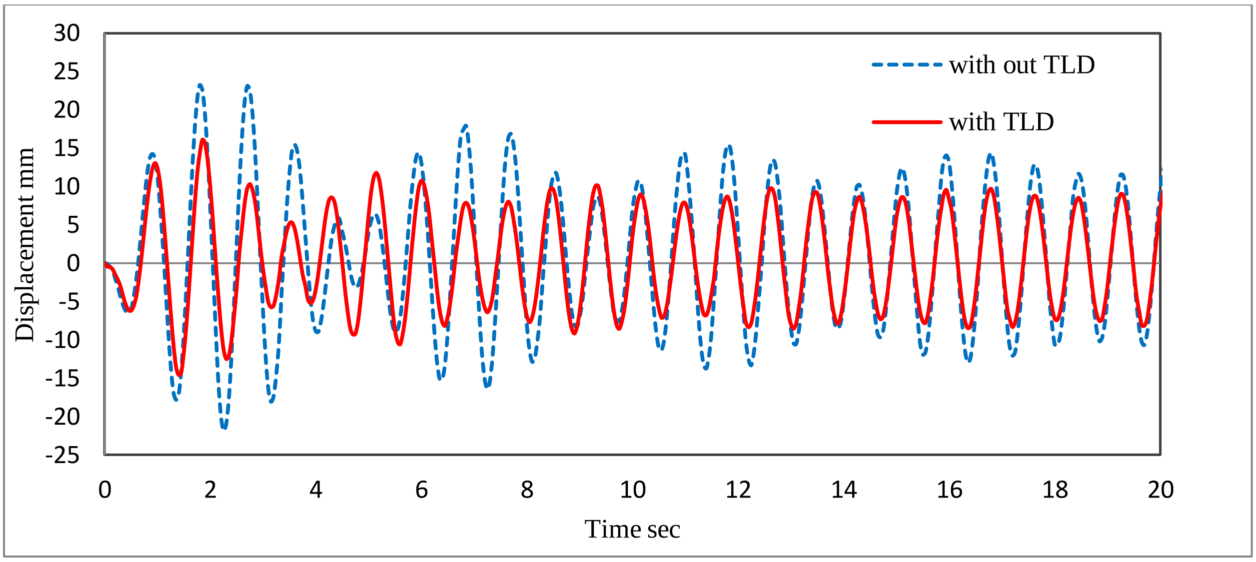


Figure 5.21 Time histories of structural displacement with and without TLD (for $\beta = 1.21$)

Table 5.1 maximum structural displacements with and without TLD and percentage reduction in the displacement for different frequency ratios

Frequency ratio	Max displacement of the structure without TLD (mm)	Max Displacement of the structure with TLD (mm)	Percentage reduction in the displacement
0.97	73.96	45.18	38.86
1	83.45	36.18	56.64
1.03	57.52	30.79	46.470
1.06	47.72	26.11	45.28
1.1	38.43	24.03	37.47
1.12	33.9	23.65	30.24
1.2	23.67	17.49	26.11

A comparison of the peak structural responses of the structure with and without a TLD and percentage reduction for sinusoidal base excitation is presented in the above table.The maximum reduction in the structural responses provided by the TLD corresponds to the cases where the structural frequency is in the vicinity of the significant ground frequency and structural response without TLD is large. In addition the comparison of TLD with different mass rations has been presented. It is observed that for giving structural damping and period increasing the mass ratio from 1 to 4% makes the TLD more effective in reducing structural response. The performance of TLD with different depth rations has been observed at the resonant frequency. It is found that the effectiveness of the TLD in reducing the structural response is eye-catching till 0.125 water depth ratio. For larger values of the water depth ratio the reduction is not significant which indicates the sloshing is not as much as that for a low water depth ratio.

CHAPTER-6

CONCLUSION

CONCLUSION

The present study leads to the conclusion that it is reasonable to implementtuned liquid damper for mitigation of structural response under dynamic action. The numerical and experimental analysis of a SDOF structure subjected to both harmonic and recorded ground motions shows that a properly designed TLD can substantially reduce structural response. The effect of tuned condition on structural response with and without TLD, are evaluated and presented in graphical and tabular forms.

The following conclusions are made from the study:

1. Several excitation frequency ratios varying from 0.5 to 1.5 were considered during the study. The performance of the TLD is observed to be effective in reducing the response of the structure when excitation frequency ratio is near to unity. For other excitation frequency ratios inertial and sloshing components of the TLD interface force interferes with each other, the TLD was observed to be ineffective in dissipating the energy.

2. Different water depth ratios varying from 0.05 to 0.3 are considered for the TLD to evaluate the performance at resonant condition. It is observed there exists an optimum water depth ratio corresponds to the minimum response amplitude. The optimum water depth ratio is found to be 0.125. In case of the higher water depth ratio no significant reduction in response amplitude is observed for higher depth ratios .The energy absorbed and dissipated by TLD depends mostly on the sloshing and wave breaking. The TLD having a higher water depth ratio does not slosh as much as that for low water depth ratios.

3. Different mass ratios ranging from 0.5 to 6 % of the structure has been considered to evaluate the effectiveness of TLD. The reduction in the displacement is significant as the mass ratio increases up to 4 %.The increase in mass ratio from 3% to 4% increase the efficiency in the displacement reduction only by 4%, while the considerable mass of the water that needs to be employed. It is suggested that 3% mass ratio can be recommended as the optimum value. For mass ratios larger than 4% beating phenomenon was observed in the TLD behavior and efficiency is reduced.

4 The damping ratio of the structure is evaluated experimentally with and without TLD corresponds to the resonance condition. It is observed that the presence of TLD enhances the structural damping.

5 From this study, it can be concluded that properly designed TLD with efficient design parameters such as tuning ratio, depth ratio and mass ratio is considered to be a very effective device to reduce the structural response.

FUTURE SCOPE FOR STUDY:

1. The structural model considered in this study is linear one which provides a further scope to study the problem using a nonlinear model for the structure.
2. The study can be further extended by introducing obstacles like baffles, screens and floating particles in the tank to obtain changed control performance.
3. The structure and damper model considered here is two-dimensional, which can be further studied to include 3-dimensional structure model as well as a damper liquid model
4. Application of TLD to control different type of motions other than horizontal motions.
5. The study can be further extended to observe the effect of different tank geometries which include shape of the tank and the nature of the tank bottom.
6. Response ofliquid domain can be studied by Mess Free Methods.

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