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Vibration Control of Building with Passive Tuned Liquid Column Damper

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Abstract

The study focuses on the seismic vibration control of a 10 storied building installed with various structural control systems such as passive linear viscous dampers (LVD) and tuned liquid column damper (TLCD). The building is subjected to different earthquakes that occurred in the past. The displacement, velocity, and acceleration responses for the multi-story building are obtained by mathematically solving the governing equations of motion using the state space approach. Optimum parameters for the dampers are derived from the numerical study. To investigate the effectiveness of dampers in the building, a comparative study between the controlled response and the corresponding uncontrolled response is carried out.

Moreover, the study is carried out to determine the optimum placement of damper to be installed in the multi-storey building under consideration, as well as a comparison of LVD and TLCD in terms of its effectiveness in the reduction of seismic responses of the building. Various response quantities such as top storey displacement and acceleration of the structure are obtained. For the present study, it is observed that response quantities such as displacement and acceleration reduce significantly after the installation of LVD and TLCD.

Keywords - *Linear viscous damper, Optimum, Passive, Seismic Response, Tuned liquid column damper*

I. INTRODUCTION

The continuous growth in population and shortage of land in the urban area has resulted in an increasing number of tall buildings. These tall buildings are generally flexible in nature, comparatively light in weight, having a long vibration period, and low inherent damping. They can easily sustain transverse loads, but whenever they are subjected to vibration caused due to dynamic loads (e.g., earthquake or wind), they undergo vital vibration that may persist longer than the event itself, which can become unacceptable from the perspective of serviceability and safety. Several dampers have been proposed to reduce the structural response of the building under dynamic loading. Dampers are installed in the building, which absorbs the energy of dynamic loading and safeguards the structure against excessive vibration.

In the past, many researchers have investigated the performance of Tuned liquid column damper (TLCD) on the structures by considering passive, semi-active and active control systems. Majorly experimental work has been done by researchers by taking the single degree of freedom (SDOF) structure and Tuned liquid column damper. Lee et al. (2012) investigated the influence of excitation amplitude on design parameters of a TLCD by comparing the results from shaking table tests to those numerically derived from transfer functions and found out that the natural frequency, damping ratio, and ratio of total liquid mass to the horizontal liquid mass affect the dynamic behavior of TLCD. Altay et al. (2018) studied semi-active tuned liquid column damper (S-TLCD) for the lateral vibration control of high-rise structures. Wang et al. (2016) performed real-time hybrid simulation (RTHS) to evaluate the reduction efficiencies of tuned liquid dampers (TLDs) installed on the top of multi-story structures. Shum and Xu (2002) performed an experimental investigation on the performance of multiple-tuned liquid column dampers (MTLCD) for reducing the torsional vibration of structures. Kalva and Chaudhuri (2015) compared efficiency in vibration suppression of four different kinds of passive TLCDs. These are U-shaped TLCD, liquid column vibration absorber (LCVA), V-shaped TLCD, and tuned liquid column ball damper (TLCBD). Saha and Debbarma (2017) studied about mitigation of structural responses by implementing multiple tuned liquid damper (MTLD) on a scaled structure and also with a single tuned liquid damper (STLD). It is found that response reduction by the MTLD is more compared with that of STLD. Banerji et al. (2010) studied the effectiveness of a tuned liquid damper (TLD) in controlling the earthquake response of a structure.

It can reduce the response of a structure up to 40%. Tait et al. (2007) investigated the performance of a 2D structure-TLD system. Findings indicate that a 2D TLD can operate at near to 90% efficiency at a target building acceleration. Tait (2008) proposed an equivalent linear mechanical, mathematical model of a TLD equipped with multiple damping screens. Mevada and Jangid (2012) investigated the seismic response of linearly elastic, single-storey, one-way asymmetric building with linear and non-linear viscous dampers. Pandit et al. (2020) studied seismic vibration control of a two-way asymmetric, 20 storied building installed with various structural control systems such as passive linear viscous dampers (LVDs) and non-linear viscous dampers (NLVDs).

A number of devices are currently being studied in the area of structural control, namely controllable fluid dampers, variable-stiffness devices, tuned mass dampers, friction control devices, viscous fluid devices, etc. Tuned liquid column dampers (TLCDs) is a special type of tuned liquid damper (TLD) that rely on the motion of the liquid column in a U-shaped tube to counteract the action of external forces acting on the structure. Energy dissipation takes place due to the sloshing of liquid in the tuned liquid column damper. The inherent damping is introduced in the oscillating liquid column through an orifice. The orifice opening ratio affects the head loss coefficient, which in turn affects the effective damping of the tuned liquid damper. There are many types of tuned liquid column dampers, such as (i) Double TLCD (Two TLCD in orthogonal direction), (ii) circular/torsional TLCD (iii) Hybrid TLCD (Placing one TLCD on a rotating platform). Advantages of TLCD are, it is simple and cheap in construction and environment-friendly damper, it requires less maintenance also it will not impart major weight to the structure such as tuned mass damper.

In this paper, the seismic response of 10 storied buildings is investigated under different real earthquake ground motions. The specific objectives of the study are summarized as (i) to study the behavior of passive tuned liquid column damper (TLCD) in a 10 storied building. (ii) to study the performance of passive tuned liquid column damper as compared to the passive linear viscous damper in a 10 storied building. (iii) to study various response parameters like displacement, acceleration, storey drift.

II. STRUCTURAL MODEL AND SOLUTION OF EQUATIONS OF MOTION

The system considered is an idealized 10-storied building that consists of a rigid deck supported by structural elements. The building is symmetric about both the x and y-axis. The following assumptions are made for the structural system under consideration:

- The floor of the superstructure is considered rigid.
- Columns are axially rigid.
- The force-deformation relationship of the superstructure is considered linear and within the elastic range.
- The stiffness of beams and slabs is neglected.

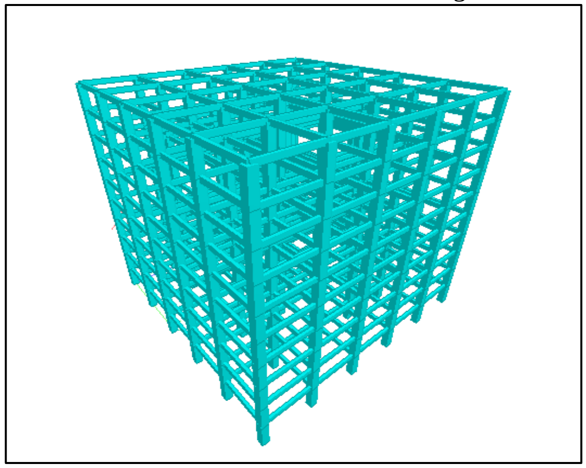


Fig.1 Model of 10 storied building

The model of the building is shown in Fig. 1. The building is symmetric about both the x and y-axis; therefore, one degree-of-freedom is considered for this building, namely, the lateral displacement in the x or y-direction. The governing equations of motion for this structure are expressed by,

$$\mathbf{M\ddot{u} + C\dot{u} + Ku} = -\mathbf{M\Gamma\ddot{u}}_g + \mathbf{\Lambda F} \tag{1}$$

Where **M**, **C**, and **K** are mass, damping and stiffness matrices of the system, respectively; $\mathbf{u}$ is the displacement vector; $\dot{\mathbf{u}}$ is the velocity vector; $\ddot{\mathbf{u}}$ is the acceleration vector; $\mathbf{\Gamma}$ is the influence coefficient vector; $\ddot{\mathbf{u}}_g$ Is the ground acceleration vector; $\mathbf{\Lambda}$ is the matrix that defines the location of the control device, and **F** is the vector of control forces. The mass and stiffness matrix of the 10 storied building can be expressed as,

$$\mathbf{M} = \begin{bmatrix} m_1 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & m_{10} \end{bmatrix},$$

$$\mathbf{K} = \begin{bmatrix} k_1 + k_2 & -k_2 & 0 & 0 & 0 \\ -k_2 & k_2 + k_3 & -k_3 & 0 & 0 \\ 0 & -k_3 & \ddots & 0 & 0 \\ 0 & 0 & 0 & k_9 + k_{10} & -k_{10} \\ 0 & 0 & 0 & -k_{10} & k_{10} \end{bmatrix} \tag{2}$$

Where $m_1, m_2, \ldots, m_{10}$ Represents lumped mass at different floor levels. $k_1, k_2, \ldots, k_{10}$ Represents stiffness of different floor levels. The damping matrix of the system is not known explicitly, and it is constructed from Rayleigh's damping considering mass and stiffness proportional as,

$$\mathbf{C} = a_0\mathbf{M} + a_1\mathbf{K} \tag{3}$$

In which $\mathbf{a_0}$ and $\mathbf{a_1}$ Are the coefficients depend on the damping ratio of two vibration modes? For the present study, 5% damping is considered for both modes of vibration of the system.

The governing equations of motion are solved using the state space method and written as,

$$\dot{\mathbf{z}} = \mathbf{Az} + \mathbf{BF} + \mathbf{E}\ddot{\mathbf{u}}_{\mathbf{g}} \tag{4}$$

Where $\mathbf{z} = \{\, \mathbf{u}\ \dot{\mathbf{u}}\, \}^{T}$ is a state vector. $\mathbf{A}$ is the system matrix; $\mathbf{B}$ is the distribution matrix of control forces, and $\mathbf{E}$ is the distribution matrix of excitations. These matrices are expressed as shown in equation (5), where $\mathbf{I}$ is the identity matrix,

$$\mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix}, \mathbf{B} = \begin{bmatrix} \mathbf{0} \\ -\mathbf{M}^{-1}\mathbf{\Lambda} \end{bmatrix}, \mathbf{E} = -\begin{bmatrix} \mathbf{0} \\ \mathbf{\Gamma} \end{bmatrix} \tag{5}$$

Eq.(4) is discretized in the time domain, and the excitation and control forces are assumed to be constant within any time interval. The solution may be written in an incremental form as,

$$\mathbf{z_{k+1}} = \mathbf{A_d z_k} + \mathbf{B_d F_k} + \mathbf{E_d}\ddot{\mathbf{u}}_{\mathbf{gk}} \tag{6}$$

Where $\mathbf{k}$ denotes the time step and $\mathbf{A_d} = \mathbf{e^{A\Delta t}}$ represents the discrete-time system matrix with $\mathbf{\Delta t}$ as the time interval. The constant-coefficient matrices $\mathbf{B_d}$ and $\mathbf{E_d}$ can be written as

$$\mathbf{B_d} = \mathbf{A^{-1}}(\mathbf{A_d} - \mathbf{I})\mathbf{B}, \quad \mathbf{E_d} = \mathbf{A^{-1}}(\mathbf{A_d} - \mathbf{I})\mathbf{E} \tag{7}$$

III. MODELLING OF TUNED LIQUID COLUMN DAMPER

Tuned liquid column damper operates on the principle of sloshing of liquid in the column to dissipate external energy. Damping is introduced in the tuned liquid column damper by changing the orifice area or valve opening or by providing baffle walls. By changing the orifice area or valve opening, the head loss coefficient can be adjusted. For the passive system, the value of the head loss coefficient is unchanged for the tuned liquid column damper. Fig. 2(a) and Fig. 2(b) show the schematic diagram and mathematical model of a typical TLCD, respectively.

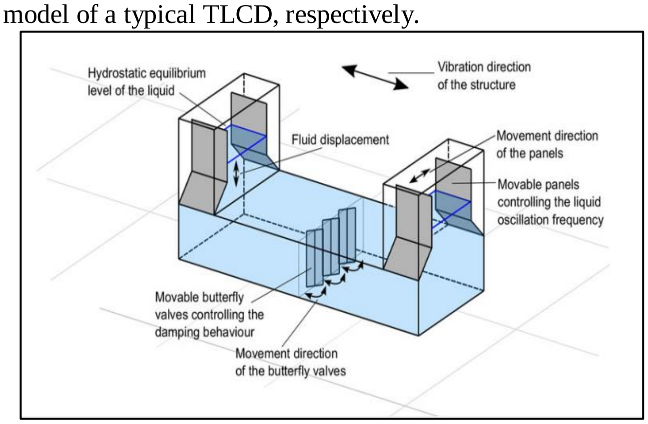


Fig. 2(a)

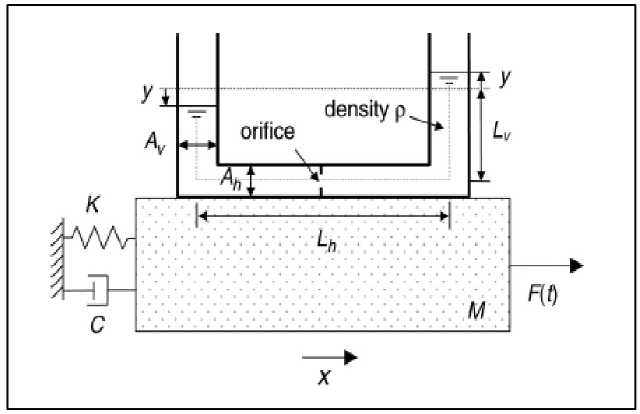


Fig. 2(b)

Fig.2 (a) Schematic diagram of the TLCD (Altay et al.[1]) (b) Mathematical model of TLCD (Wu et al.[12])

The equation of motion for structure-TLCD combined system is derived by Yalla et al. (2001) expressed as,

$$\begin{bmatrix} \mathbf{M} + \mathbf{m_f} & \alpha\mathbf{m_f} \\ \alpha\mathbf{m_f} & \mathbf{m_f} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{u}}_s \\ \ddot{\mathbf{u}}_\mathbf{f} \end{bmatrix} + \begin{bmatrix} \mathbf{C} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \dot{\mathbf{u}}_s \\ \dot{\mathbf{u}}_\mathbf{f} \end{bmatrix} + \begin{bmatrix} \mathbf{K} & \mathbf{0} \\ \mathbf{0} & \mathbf{k_f} \end{bmatrix} \begin{bmatrix} \mathbf{u}_s \\ \mathbf{u_f} \end{bmatrix} = \begin{bmatrix} \mathbf{X(t)} \\ \mathbf{0} \end{bmatrix} + \begin{bmatrix} \mathbf{0} \\ \mathbf{1} \end{bmatrix} \mathbf{F(t)} \tag{8}$$

Where the control force $\mathbf{F(t)}$ is given by,

$$\mathbf{F(t)} = -\frac{\boldsymbol{\rho A \zeta(t)|\dot{u}_f|}}{\mathbf{2}}\dot{\mathbf{u}}_\mathbf{f} \tag{9}$$

Where,

u_s	displacement of the primary system
u_f	displacement of the liquid in the damper
M	mass of the primary system
K	stiffness of the primary system
C	damping coefficient of the primary system
k_f	stiffness of the liquid column (=2ρAg)
m_f	mass of liquid in the tube (=ρAl)
ζ	headloss coefficient
ρ	liquid density
A	cross-sectional area of the tube
α	length ratio (=b/l)
l	length of the liquid column
b	horizontal length of the column
g	gravitational constant
X(t)	external force acting on the primary mass

The headloss coefficient is an important parameter that is controlled by varying the orifice area of the valve. The negative sign in Eq. (9) ensures that the control force is always acting in a direction opposite to the liquid velocity.

IV. MODELLING OF FLUID VISCOUS DAMPER

Fluid viscous dampers operate on the principle of fluid flowing through an orifice which provides the force that resists the motion of the structure during a seismic event. Fig. 3(a) and Fig. 3(b) show the schematic diagram and mathematical model of a typical fluid viscous damper (FVD), respectively.

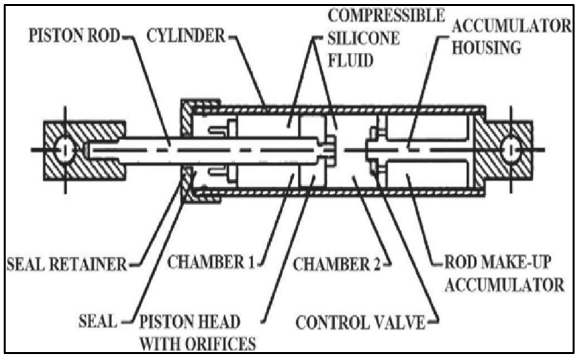


Fig. 3(a)

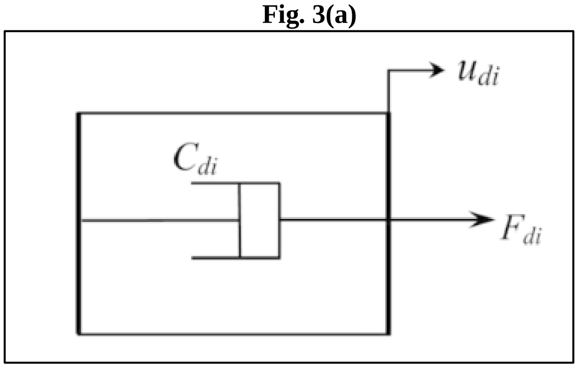


Fig. 3(b)

Fig. 3(a) Schematic diagram of the FVD (b) Mathematical model of FVD (Pandit et al.[6])

FVD consists of a cylindrical body and central piston, which strokes through a fluid-filled chamber. The commonly used fluid is a silicone-based fluid that ensures proper performance and stability. Differential pressure generated across the piston head results in damper force.

$$\boldsymbol{F_i = C_{di}}\ |\dot{\mathbf{u}}_{di}|^{\alpha}\mathbf{sign}(\dot{\mathbf{u}}_{di}) \quad (10)$$

The force in a viscous damper $\boldsymbol{F_i}$ is proportional to the relative velocity between the ends of a damper, and it is given by Eq. (10), where $\boldsymbol{C_{di}}$ is a damper coefficient of the ith damper; $\dot{\mathbf{u}}_{di}$ Is the relative velocity between two ends of a damper which is to be considered; $\boldsymbol{\alpha}$ is the power-law coefficient or damper exponent ranging from 0.1 to 1 for seismic applications, and sign(.) is signum function. The design of piston head orifices primarily controls the value of the exponent. When $\boldsymbol{\alpha}$ = 1, a damper is called a linear viscous damper (LVD), and with the value of $\boldsymbol{\alpha}$ smaller than unity, a damper will behave as a non-linear viscous damper (NLVD).

V. NUMERICAL STUDY

The seismic response of linearly elastic, idealized 10-storied building installed with passive tuned liquid column damper and the linear viscous damper is investigated by numerical simulation using MATLAB. Parameters of the building are considered as per Table I.

TABLE I
BUILDING PARAMETERS

Parameters	Values	Units
Plan dimension	30 x 30	m
Height of the building	30	m
Typical storey height	3	m
Beam	300 x 550	mm
Column	400 x 400	mm
Live load	3	kN/m^2
Floor finish load	1	kN/m^2
Slab thickness	120	mm
Outer wall thickness	230	mm
Inner wall thickness	120	mm
Total lumped mass of the building	8.28 x 10^6	kg
Grade of concrete	M25	-
Grade of steel	Fe 500	-

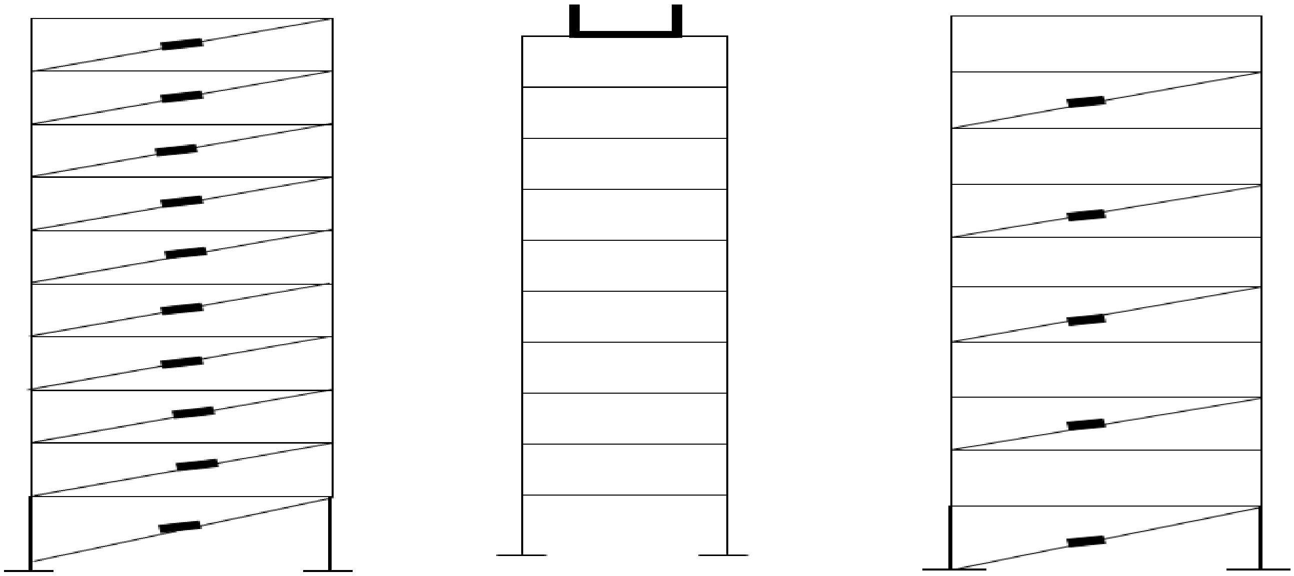


Fig. 4(a) **Fig. 4(b)** **Fig. 4(c)**

Different configurations of building

For this 10-storied building, three different configurations are taken here, (i) Building with viscous dampers placed at all stories (ii) Building with viscous damper placed at alternate storey (iii) Building with tuned liquid column damper placed at roof level only. Figure 4(a), 4(b) and 4(c) shows these configurations. The assumption in all three configurations is that an equivalent damper is placed at the center of the mass of the floor.

The response quantities of interest are; displacement, velocity, and acceleration of the top storey, storey drift, damping force. Based on the parametric study, the optimum value of the damping coefficient of LVD and the headloss coefficient of TLCD are calculated. The different cross-sectional areas of TLCD are also taken for comparison.

The responses are obtained by performing time history analysis under four different earthquake ground motions, namely Imperial Valley (1940), Loma Prieta (1989), Northridge (1994), and Kobe (1995). The details of earthquakes such as peak ground acceleration (PGA), duration, and recording station are summarized in Table II.

TABLE II
DETAILS OF EARTHQUAKE MOTIONS CONSIDERED FOR THE NUMERICAL STUDY

Earthquake	Recording station	Duration (sec)	PGA (g)
Imperial Valley, 1940	El Centro	40	0.31
Loma Prieta, 1989	Los Gatos Presentation Centre	25	0.96
Northridge, 1994	Sylmar Converter Station	40	0.89
Kobe, 1995	Japan Meteorological Agency	48	0.82

In order to study the effectiveness of implemented passive LVD and TLCD system, the response is expressed in terms of indices, R_d and R_a defined as follows,

$$R_d = \frac{\text{Top storey displacement of controlled structure}}{\text{Top storey displacement of the uncontrolled structure}} \tag{11}$$

$$R_a = \frac{\text{Top storey acceleration of the controlled structure}}{\text{Top storey acceleration of the uncontrolled structure}} \tag{12}$$

The value of R_d and R_a less than one indicates that the installed damper is effective in controlling the response in terms of displacement and acceleration.

VI. PARAMETERS FOR LINEAR VISCOUS DAMPER

For fluid viscous damper, a damping coefficient exists, which is shown in Eq. (10) as C_d. Its value varied from 1000 to 3.45 x 10^7 N-s/m. By plotting the graph of R_d (and R_a)

versus damping coefficient, optimum damping coefficient value can be achieved. Figures 5(a) and 5(b) shows the graph of R_d versus damping coefficient and R_a versus damping coefficient for damper placed at all stories, respectively. Here the value of α is taken 1 for the present study, so it is called linear viscous damper (LVD). These graphs consist of data of four earthquakes, namely Imperial Valley, Loma Prieta, Northridge, and Kobe. The graphs also show the average value of all earthquakes considered. From these graphs optimum damping coefficient found out is 1.6 x 10^7 N-s/m for LVD placed at all stories case such as to have a reasonable reduction in displacement and acceleration.

For a building with LVD placed at alternate storey same procedure is carried out to obtain optimum damping coefficient. R_d versus damping coefficient and R_a versus damping coefficient graphs are shown in Fig. 6(a) and Fig. 6(b), respectively. From these graphs optimum damping coefficient found out is 1.5 x 10^7 N-s/m for LVD placed at alternate storey case.

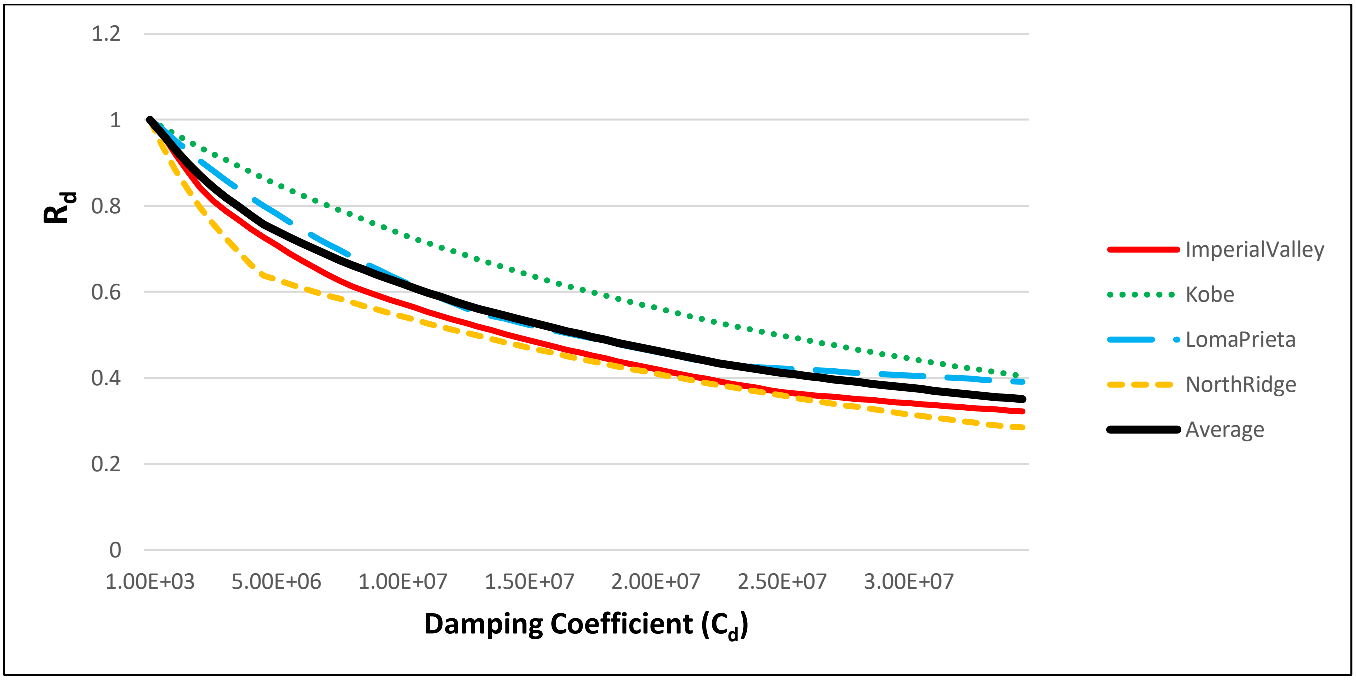


Fig. 5(a) R_d versus damping coefficient for LVD placed at all stories

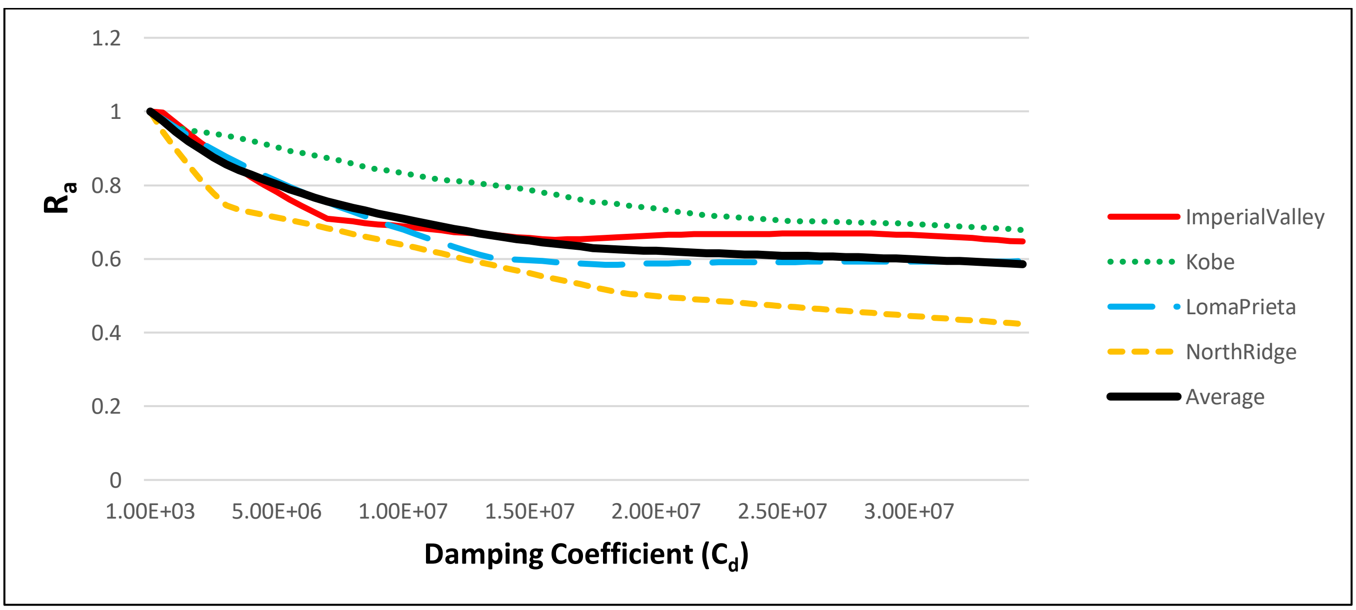


Fig. 5(b) R_a versus damping coefficient for LVD placed at all stories

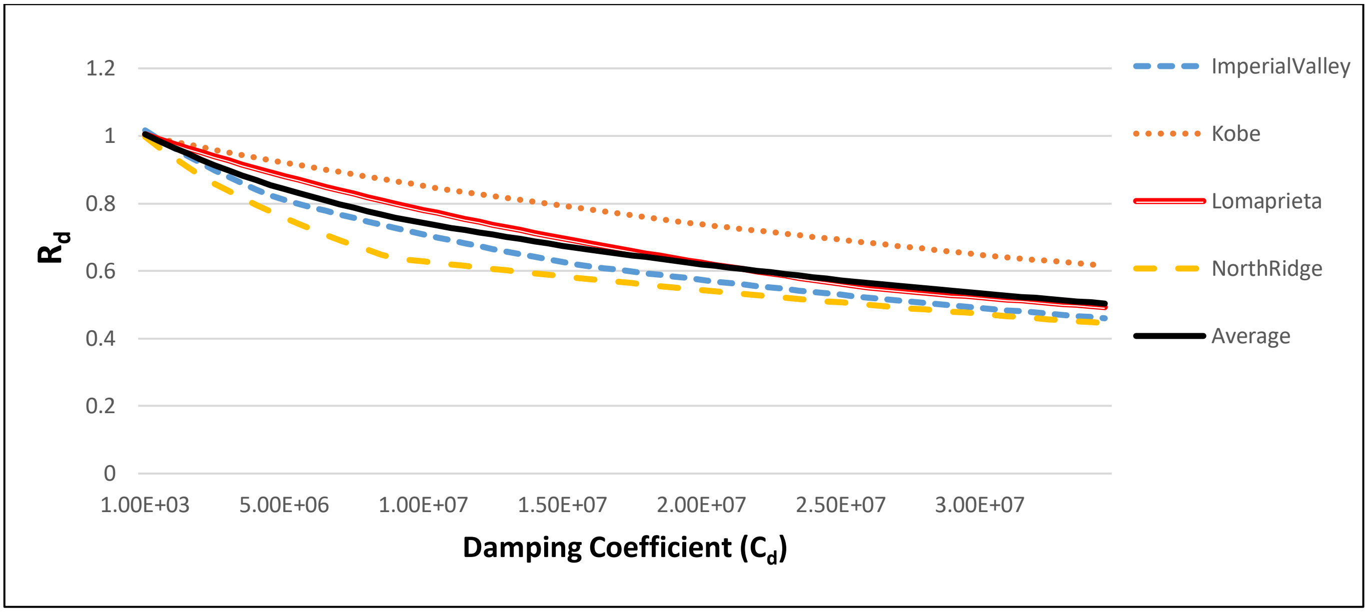


Fig. 6(a) R_d versus damping coefficient for LVD placed at the alternate storey

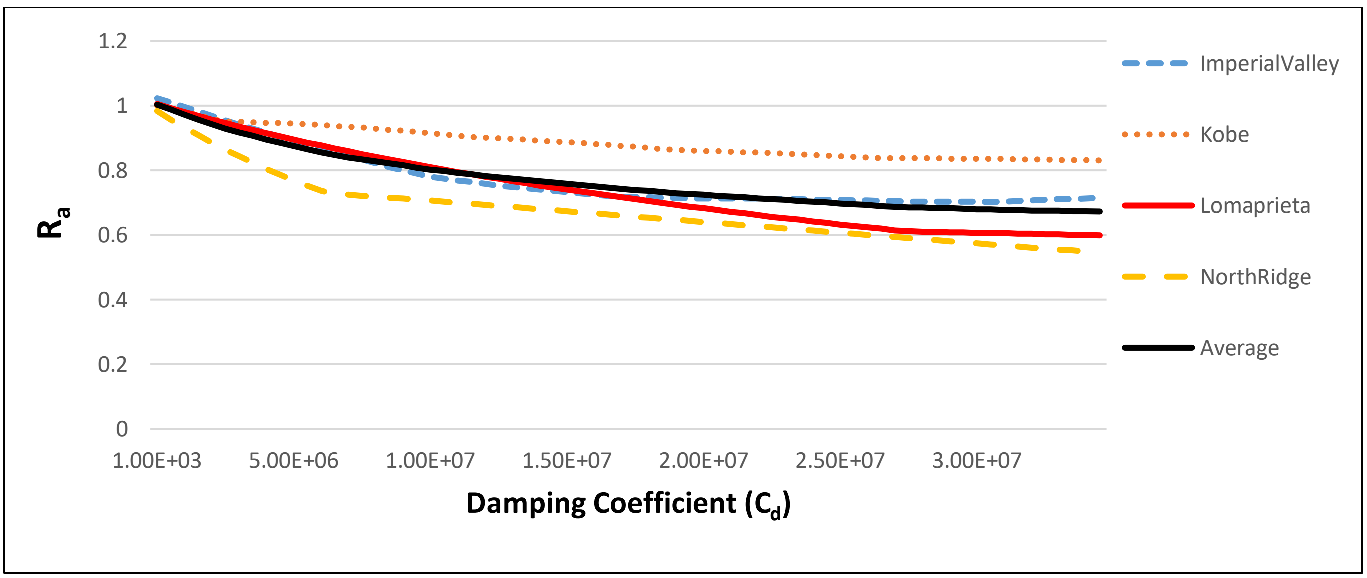


Fig. 6(b) R_a versus damping coefficient for LVD placed at the alternate storey

VII. PARAMETERS FOR TUNED LIQUID COLUMN DAMPER

For tuned liquid column damper (TLCD) provided at the roof level of the building, headloss coefficient and cross-sectional area of the tube are important parameters as shown in Eq.(9). The value of ρ is taken 1000 kg/m^{3,} i.e., the density of water. Here, the different cross-sectional areas of the tubes are taken to study the response of the building, such as 0.25 m^2, 1 m^{2,} and 4 m^2. Optimum headloss coefficient can be found out from the graphs of R_d and R_a versus headloss coefficient shown in figures 7(a) and 7(b), respectively, for 4 m^2 cross-sectional area of TLCD. The range of values taken for the headloss coefficient is 500 to 7400. From these graphs, the optimum headloss coefficient was found to be 4000. The relationship between parameters R_d (and R_a), headloss coefficient, and cross-sectional area of TLCD can be further observed from the graphs shown in Fig. 8(a) and Fig. 8(b). It is observed that by increasing the cross-sectional area of TLCD, the values of R_d and R_a are decreasing, which indicates that by increasing the cross-sectional area of TLCD, reduction in the response of the building in terms of displacement and acceleration is achieved. Figures 8(a) and 8(b) shows the response to the Northridge earthquake.

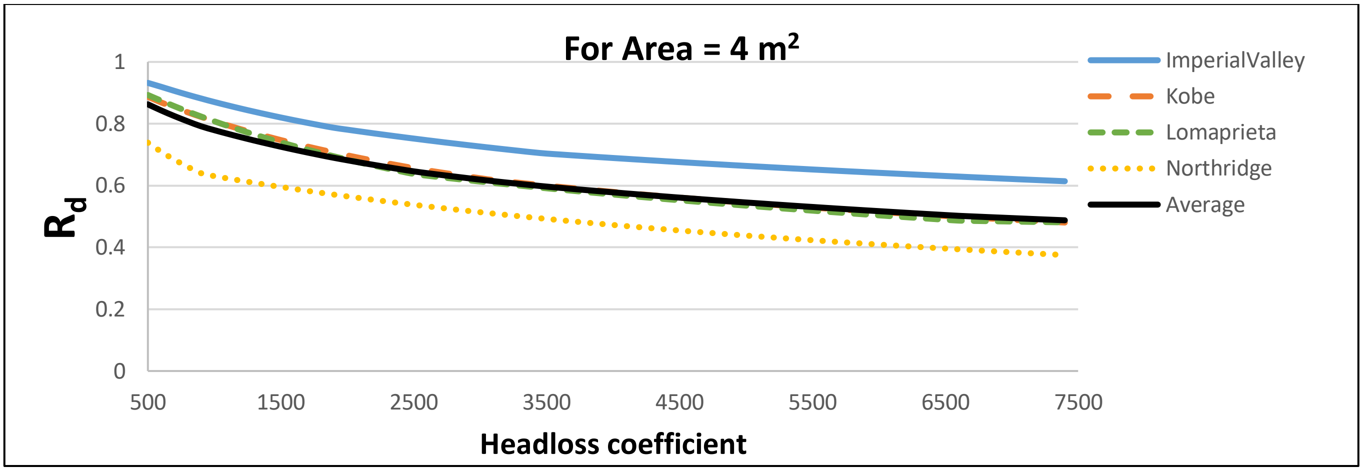


Fig. 7(a) R_d versus Headloss coefficient for TLCD placed at roof level

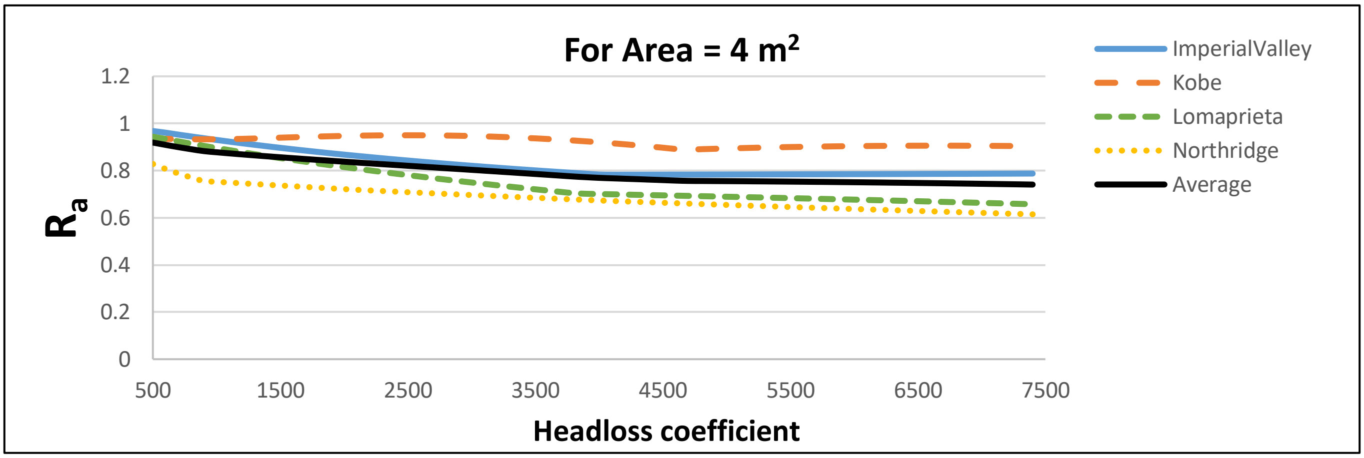
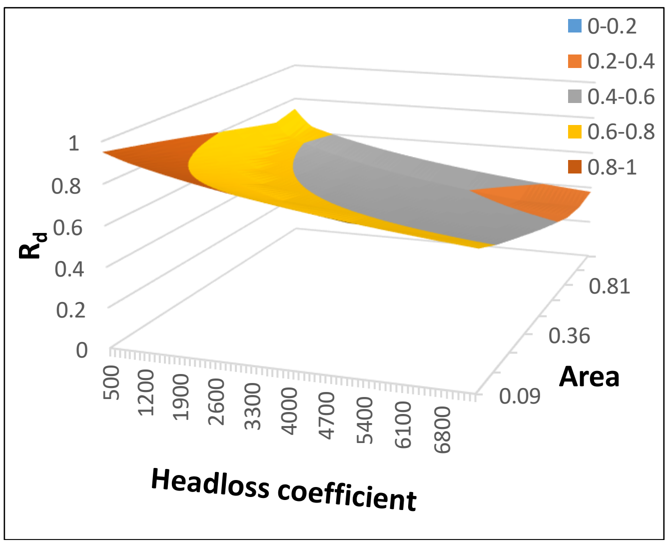


Fig. 7(b) R_a versus Headloss coefficient for TLCD placed at roof level



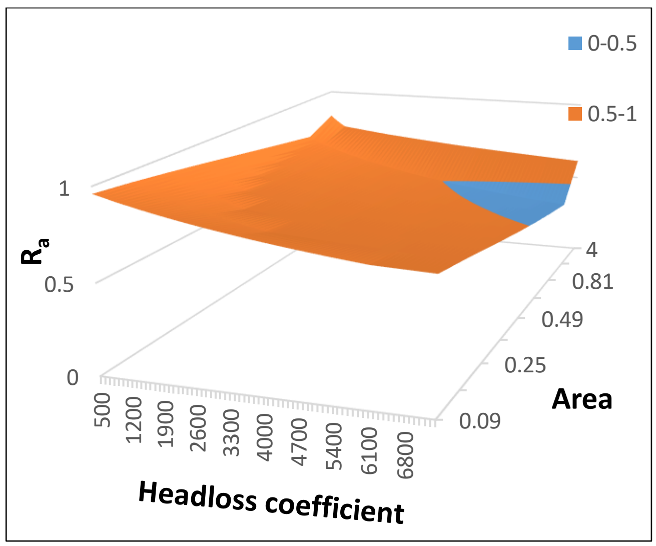


Fig. 8(a) **Fig. 8(b)**

Fig. 8 (a) Relationship between R_d, headloss coefficient, and cross-sectional area of TLCD for Northridge earthquake. (b) Relationship between R_a, headloss coefficient, and cross-sectional area of TLCD for Northridge earthquake.

VIII. RESPONSE WITH LVDs

Based on the optimum parameters derived in an earlier section, the displacement and acceleration responses are obtained for LVD placed at all stories. Displacement and acceleration time histories of the top storey are shown in Fig. 9(a) and Fig. 9(b), respectively, for the Northridge earthquake by taking optimum damping coefficient 1.6 x 10^7 N-s/m. It is clearly seen from Fig. 9(a) that by providing LVD at all stories of the building, a significant reduction is observed in displacement. From Fig. 9(b) reduction in acceleration is also observed. The hysteresis loop for damping force-displacement is shown in Fig. 9(c). The hysteresis loop indicates the dissipation of energy and reflects the behavior of the damper. The energy dissipated by the damper is 1.1448 x 10^6 Joule. Fig. 9(d) shows the damping force-velocity relationship.

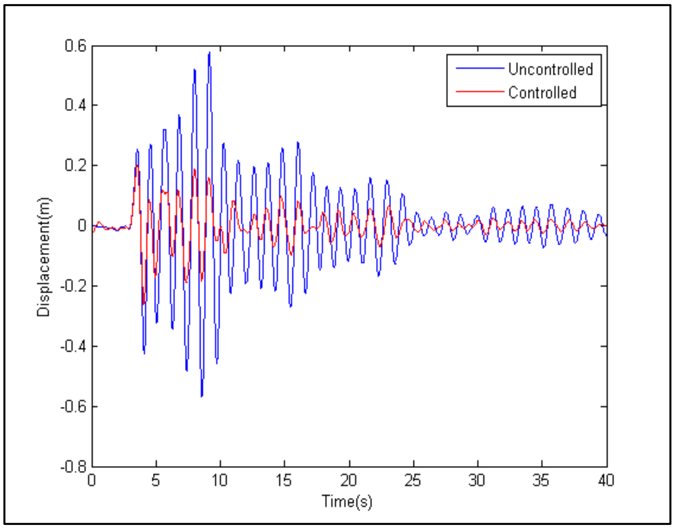


Fig. 9(a)

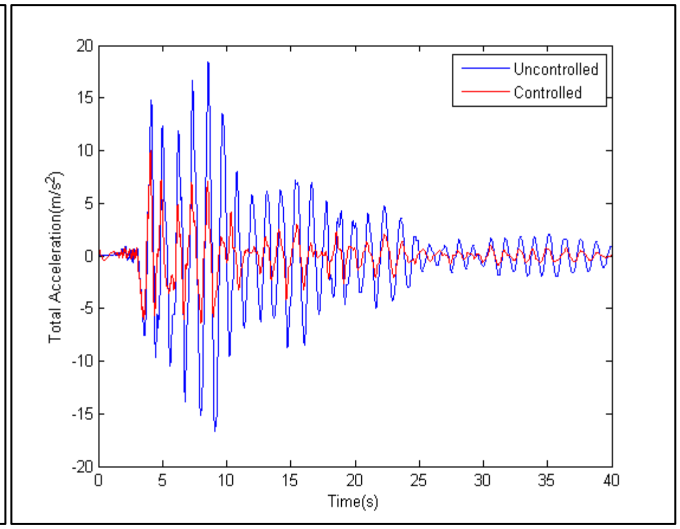


Fig. 9(b)

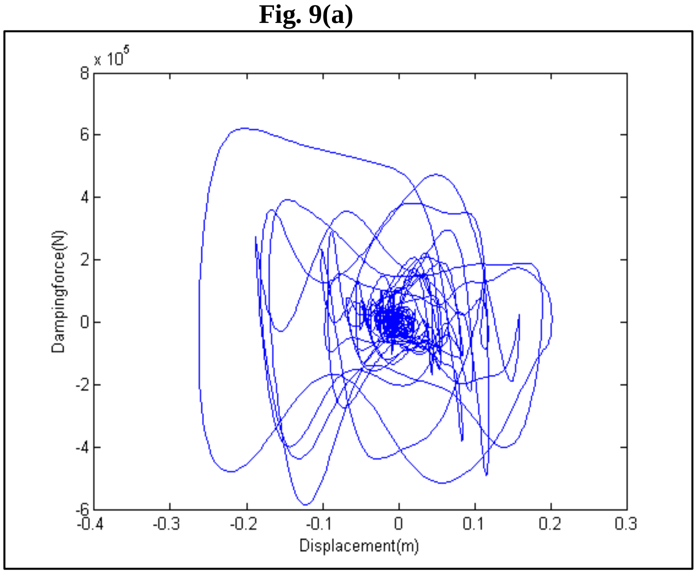


Fig. 9 (c)

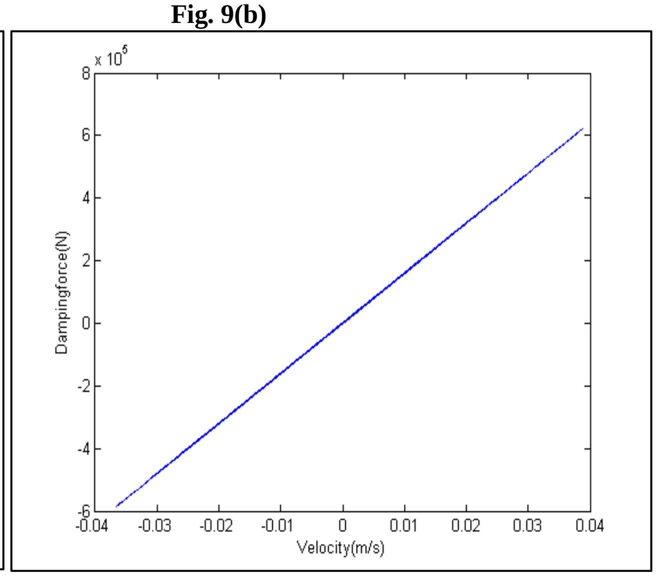


Fig. 9 (d)

Fig. 9 (a) Displacement time history for Northridge earthquake for LVD placed at all stories.
(b) Acceleration time history for Northridge earthquake for LVD placed at all stories.
(c) Damping force-displacement relationship for Northridge earthquake for LVD placed at all stories.
(d) Damping force-velocity relationship for Northridge earthquake for LVD placed at all stories.

For LVD placed at the alternate storey of a building, displacement and acceleration time histories of the top storey are shown in Fig. 10(a) and Fig. 10(b), respectively for the Northridge earthquake by taking optimum damping coefficient 1.5 x 10^7 N-s/m. It is clearly seen from Fig. 10(a) that by providing LVD at the alternate storey of the building, a reduction in displacement is taking place. From Fig. 10(b) reduction in acceleration is also observed. The hysteresis loop for damping force-displacement is shown in Fig. 10(c). The energy dissipated by the damper is 2.1447 x 10^6 Joule. Fig. 10(d) shows the damping force-velocity relationship.

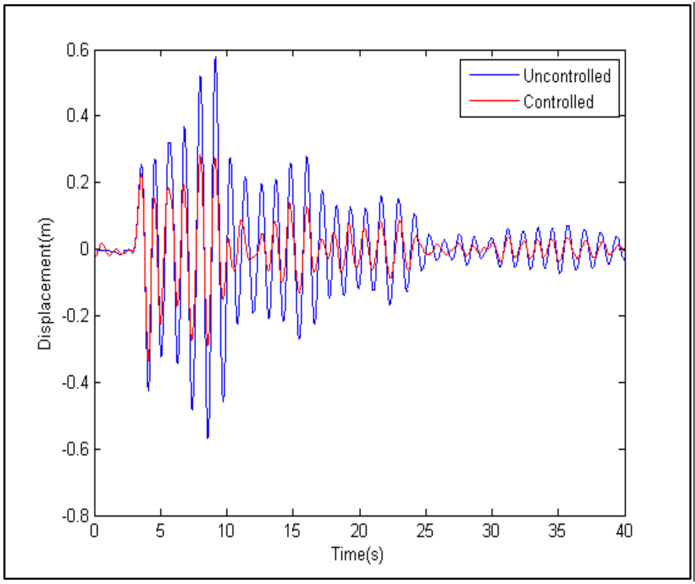


Fig. 10(a)

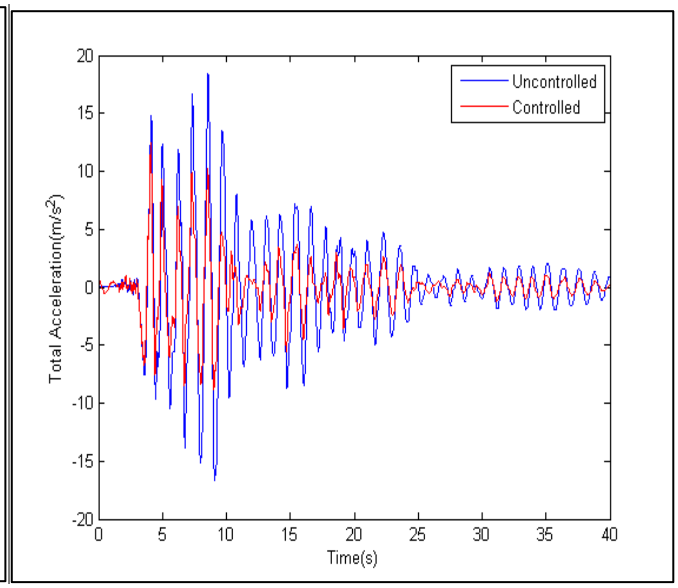


Fig. 10(b)

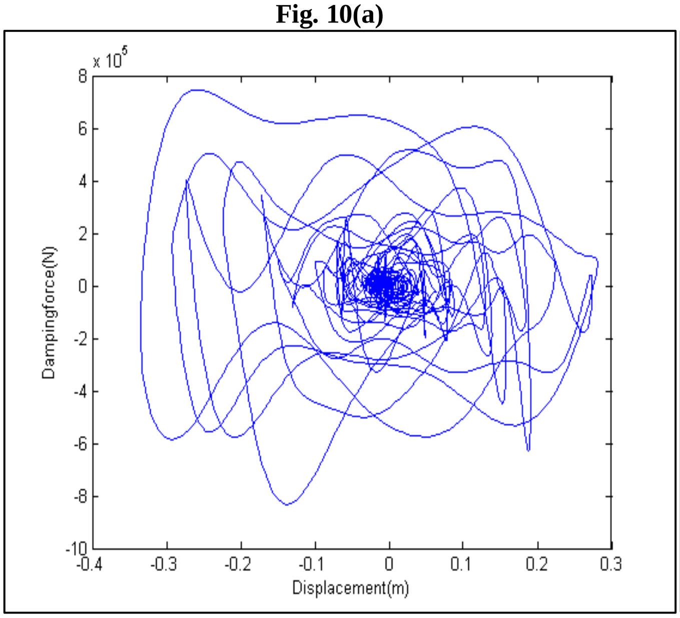


Fig. 10(c)

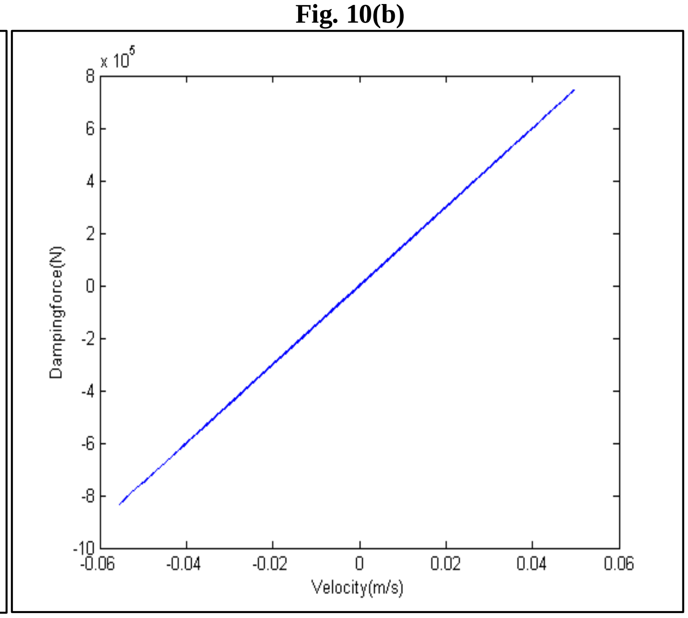


Fig. 10(d)

Fig. 10 (a) Displacement time history for Northridge earthquake for LVD placed at the alternate storey.
(b) Acceleration time history for Northridge earthquake for LVD placed at the alternate storey.
(c) Damping force-displacement relationship for Northridge earthquake for LVD placed at an alternate storey.
(d) Damping force-velocity relationship for Northridge earthquake for LVD placed at the alternate storey.

TABLE III
COMPARISON OF RESULTS OF LVD

Case	Average % Reduction in Displacement	Average % Reduction in Acceleration
Dampers Placed at All Stories	48.43	35.83
Dampers Placed at Alternate Storey	32.42	23.86

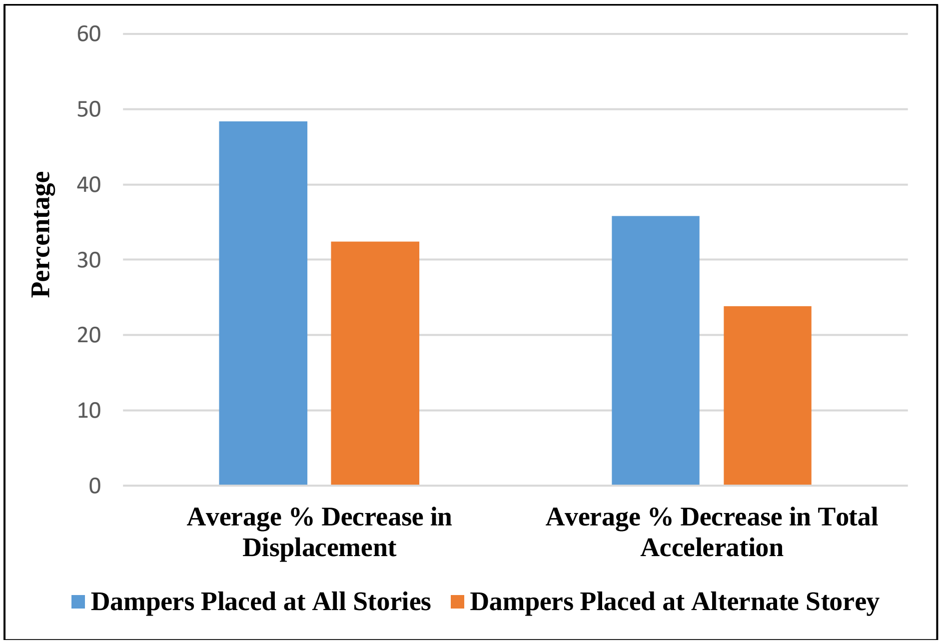


Fig. 11 Comparison of results of LVD

Table III shows the comparison between LVD placed at all stories of the building and LVD placed at the alternate storey of the building in terms of average percentage reduction in displacement and acceleration. Fig. 11 shows the similarities. The average reduction is based on all considered earthquakes.

Based on Table III & Fig.11, it can be noticed that depending on the requirement of quantities to be reduced, and it can be decided to select dampers at all stories or alternative storey because the reduction by dampers placed at the alternate storey is also quite reasonable in comparison to dampers placed at all stories.

IX. RESPONSE WITH SINGLE TLCD

Response of the building is observed by providing TLCD of different cross-sectional areas at the roof level only due to the fact that water tanks placed at roof level only are designed to act as TLCD. Three different cross-sections of the tube, 0.25 m^2, 1 $m^{2,}$ and 4 $m^{2,}$ are taken to observe the response of the building. The optimum headloss coefficient for all TLCD is 4000. Fig. 12(a) shows the displacement time history of the top storey of a building for TLCD of 4 m^2 cross-sectional area for the Northridge earthquake. It can be seen that a significant amount of reduction is taking place in terms of displacement by providing a TLCD of 4 m^2 cross-sectional area. Significant reduction in terms of acceleration is also observed from the acceleration time history of the top storey of building for TLCD of 4 m^2 cross-sectional area for Northridge earthquake in Fig. 12(b). Damping force-displacement relationship is shown in Fig. 12(c). Energy dissipated by the damper is 3.2467 x 10^7 Joule. Damping force-velocity relationship is shown in Fig. 12(d).

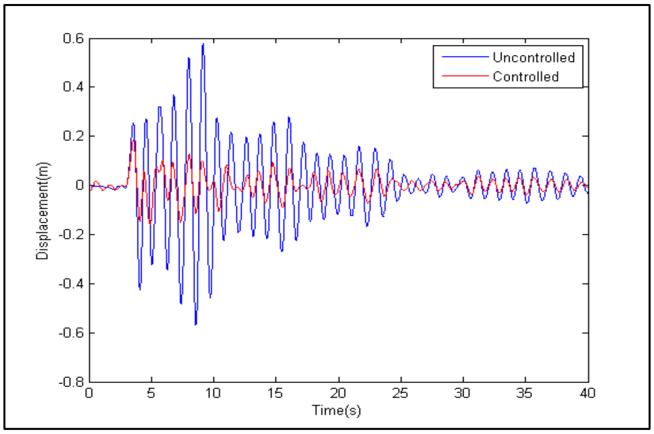


Fig. 12(a)

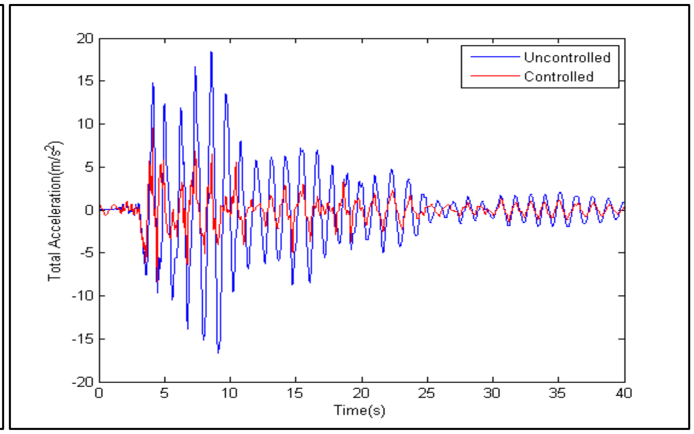


Fig. 12(b)

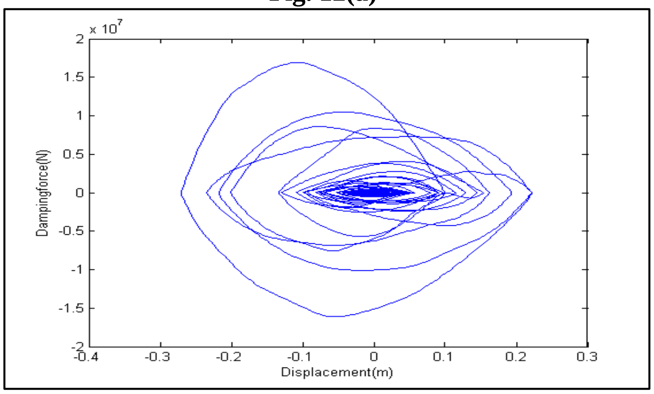


Fig. 12(c)

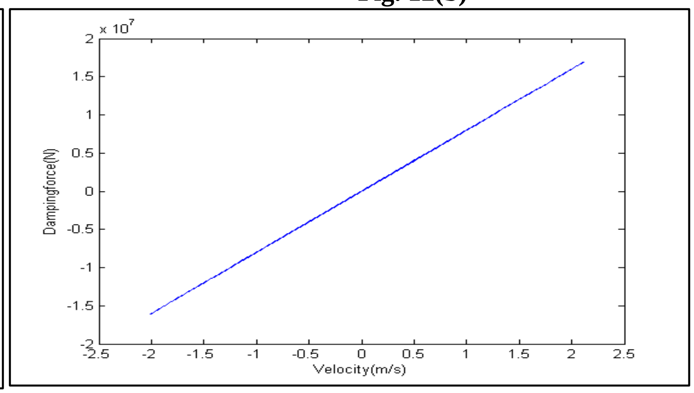


Fig. 12(d)

Fig. 12 (a) Displacement time history for Northridge earthquake for TLCD (4 m^2) placed at roof level.
(b) Acceleration time history for Northridge earthquake for TLCD (4 m^2) placed at roof level.
(c) Damping force-displacement relationship for Northridge earthquake for TLCD (4 m^2) placed at roof level.
(d) Damping force-velocity relationship for Northridge earthquake for TLCD (4 m^2) placed at roof level.

X. RESPONSE WITH MULTIPLE TLCDs

Multiple TLCD of the same cross-sectional area can also be provided to control the response of the building. Three TLCD of the same cross-sectional area of 0.25 m^2 is provided at the roof level of the building to observe the response of the building in terms of displacement and acceleration, the result of which is included in Table IV. Comparison between the different cross-sectional area of TLCD in terms of percentage reduction in displacement and acceleration is shown in Table IV. The cross-sectional area of TLCD is represented as ‘A’ in Table IV. Figure 13 shows a similar comparison.

Based on Table IV & Fig.13, it can be noticed that by increasing the cross-sectional area of TLCD, the average percentage reduction in terms of displacement and acceleration is increased. Significant reduction in terms of displacement and acceleration is observed by providing multiple TLCDs at roof level.

XI. COMPARATIVE PERFORMANCE BETWEEN LVD & TLCD

Comparison can be done between LVD and TLCD of the different cross-sectional areas provided on the same 10-storied building, which is shown in Table V. Figure 14 shows a similar comparison.

Based on Table V & Fig.14, it can be noticed that both LVD and TLCD are effective in reducing the response of building in terms of displacement and acceleration. It can be observed that by providing a single TLCD of the cross-sectional area of 4 m^2, the average percentage reduction in displacement obtained is nearly the same as by providing LVD at all stories. So, based on target reduction requirement, a single TLCD of the required cross-sectional area can be provided.

TABLE IV
COMPARISON OF DIFFERENT CROSS-SECTIONAL AREA OF TLCD

Case	Average % Reduction in Displacement	Average % Reduction in Acceleration
TLCD (A=0.25m^2)	7.76	4.34
TLCD (A=1m^2)	22.09	12.23
TLCD (A=4m^2)	42.13	23.00
Three TLCD (A=0.25m^2)	18.38	10.47

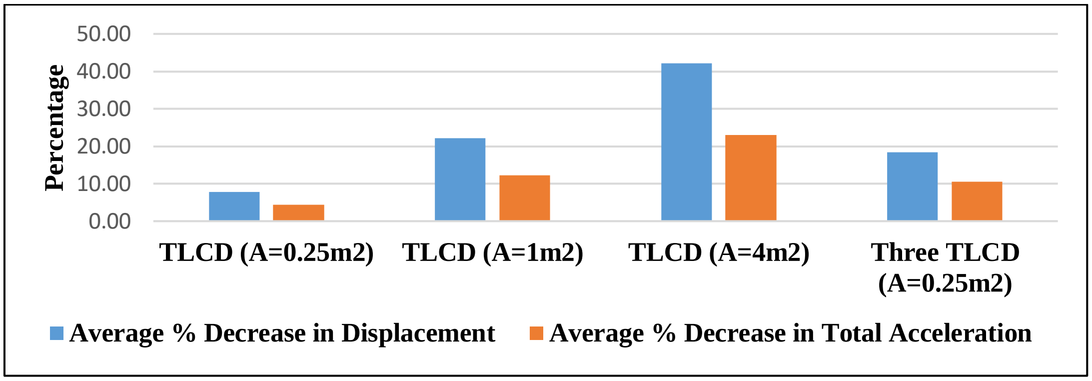


Fig. 13 Comparison of the different cross-sectional area of TLCD

TABLE V
COMPARISON BETWEEN LVD AND TLCD

Case	Average % Reduction in Displacement	Average % Reduction in Acceleration
Viscous Damper Placed at All Stories	48.43	35.83
Viscous Damper Placed at Alternate Storey	32.42	23.86
TLCD (A=0.25m^2)	7.76	4.34
TLCD (A=1m^2)	22.09	12.23
TLCD (A=4m^2)	42.13	23.00
Three TLCD (A=0.25m^2)	18.38	10.47

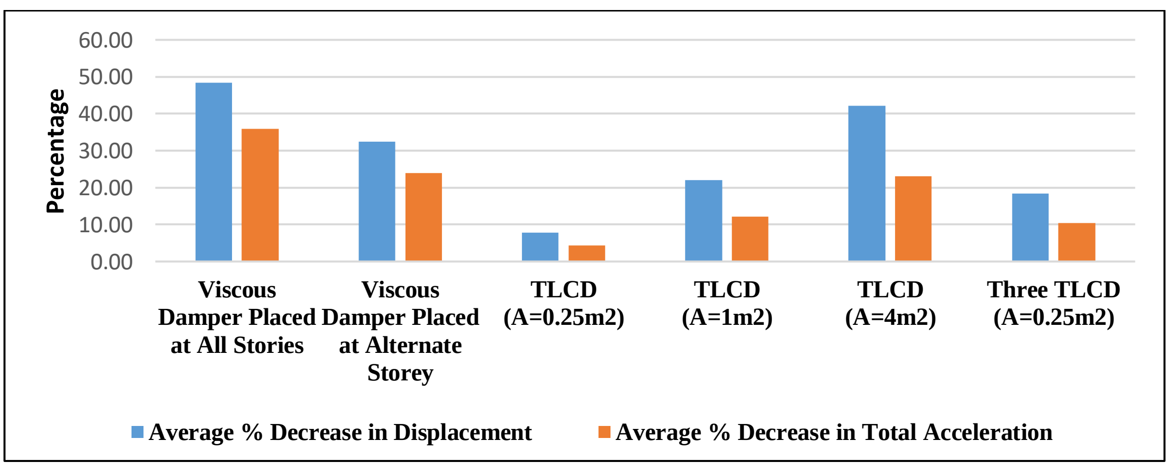


Fig.14 Comparison between LVD and TLCD

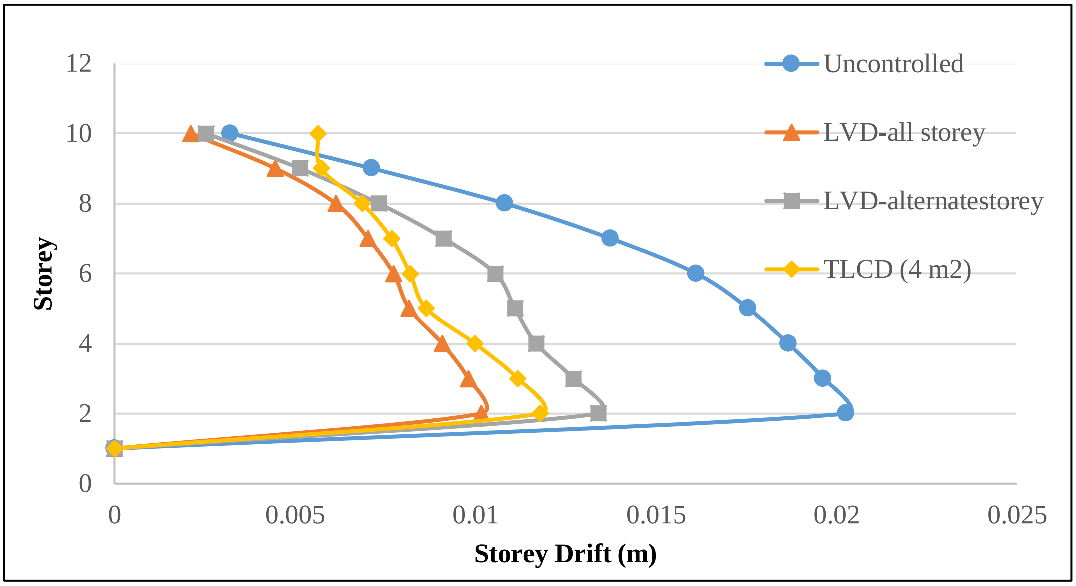


Fig.15 Comparison of storey drift among different systems

XII. STOREY DRIFT

Storey drift is the lateral displacement of one level relative to the level above or below. It is a very important parameter to evaluate the response of the building under an earthquake. Fig. 15 shows the storey drift comparison among different systems.

Permissible storey drift = 0.004 * H = 0.004 * 3 = 0.012 m as per IS code of practice, where H is typical storey height.

For uncontrolled systems, maximum storey drift obtained = 0.0202 m which is greater than permissible storey drift. So it is unsafe regarding storey drift criteria.

For LVD installed at all stories, maximum storey drift obtained = 0.0101 m (Safe)

For LVD installed at the alternate storey, maximum storey drift obtained = 0.0134 m (Unsafe)

For TLCD of 4 m^2 cross-sectional area installed at roof level, maximum storey drift obtained = 0.0117 m (Safe)

XIII. CONCLUSION

The seismic response of linearly elastic, 10 storied buildings with linear viscous damper (LVD) and tuned liquid column damper (TLCD) under different earthquake excitations is investigated. The responses are assessed with parametric variations to study the effectiveness of LVD and TLCD for the considered building. Two parameters are considered for LVD in the numerical study, namely, the damping coefficient and exponent of velocity. Also, two parameters are considered for TLCD in the numerical study, namely, headloss coefficient and cross-sectional area of the tube. From the present numerical study, the following conclusions can be made,

1. For each building, there exists an optimum damping coefficient for linear viscous damper and optimum headloss coefficient for tuned liquid column damper.
2. Providing an adequate number of dampers at a suitable location may prove to be a feasible and practical solution to reduce the structural response.
3. Average percentage reduction in displacement is nearly the same by providing linear viscous damper at all storey or by providing tuned liquid column damper of the cross-sectional area of 4 m^2 at roof level only. So, it is economical to provide a tuned liquid column damper.
4. By increasing the cross-sectional area of the tuned liquid column damper, a higher reduction in terms of displacement and acceleration is observed.
5. Significant reduction in terms of displacement and acceleration is observed by providing multiple tuned liquid column damper at roof level only.
6. The average percentage reduction in displacement and acceleration is nearly the same by providing three TLCD of 0.25 m^2 or by providing a single TLCD of 1 m^2. So, based on target-required reduction, multiple TLCD of the lesser cross-sectional area can be provided.
7. The effectiveness of dampers depends on the dynamic properties of the building as well as on earthquake characteristics also.

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