Feasibility of Implementing Water Tank as Passive Tuned Mass Damper

Tejashri S. Gulve, Pranesh Murnal

Abstract- ***This paper presents analytical investigation carried out to study the feasibility of implementing water tank as passive TMD using SAP. Three multi-storey concrete structures, seven and ten storey were taken for the study. The water tank was placed at the roof. The mass and frequency of the tank including its water, walls, roof, beams and columns were tuned to the optimized values. The behavior of the tank subjected to five earthquake data, namely, El-centro, Bhuj, Kobe, Chichi and N-Palm was studied under four conditions, namely building only with damping, empty tank with damping, full tank with damping and full tank without damping. The results show if the tank is tuned properly it can reduce the peak response of structures subjected to seismic forces.***

Keywords: Vibration control; seismic excitation; passive TMD; water tank; optimization

I. INTRODUCTION

Recent devastating earthquakes around the world have underscored the tremendous importance of understanding the way in which civil engineering structures respond during such dynamic events. Today, one of the main challenges in structural engineering is to develop innovative design concepts to protect civil structures, including their material contents and human occupants from hazards like wind and earthquakes. The traditional approach to seismic hazard mitigation is to design structures with sufficient strength capacity and the ability to deform in a ductile manner. Alternately, newer concepts of structural control, including both passive and active control systems have been growing in acceptance and may preclude the necessity of allowing for inelastic deformations in the structural system. A passive control system does not require an external power for operation and utilizes the motion of the structure to develop the control forces. Systems in this category are very liable since they are unaffected by power outages which are common during earthquakes. Since they do not inject energy into the system, they are unable to stabilize the structure. Another advantage of such devices is their low maintenance requirements. Examples of passive systems are base isolation, visco-elastic dampers, liquid column dampers, liquid mass dampers, metallic yield dampers and friction dampers. An active control system requires external power for operation and has the ability to adapt to different loading conditions and to control different vibration modes of the structures. Active Tuned Mass Dampers (ATMD), active tendon systems and actuators/ controllers are examples of active systems.

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Active and passive control systems may be combined to form hybrid systems; operating both systems together enhances the robustness of the passive system and reduces the energy requirements of the active system. There are two main approaches for the implementation of hybrid systems: the Hybrid Mass Damper (HMD) and the hybrid seismic isolation system.

A compromise between passive and active control systems has been developed in the form of semi-active control systems, which are based on semi-active devices. A semi active control device has properties that can be adjusted in real time but can not inject energy into the controlled system. Frequently, such devices are referred to as controllable passive dampers. Because they offer the adaptability of active control devices without requiring large power sources, semi-active control systems have attracted a great deal of attention in recent years. Many of these systems can operate on battery power alone, proving advantageous during seismic events when the main power source to the structure may fail. Also, because semi-active devices cannot inject energy into the structural system, they do not have the potential to destabilize the system.

Of all these control devices passive control systems in the form of TMD's, base isolation and frictional dampers have been implemented in many building across the world. In India passive control system in the form of base isolation technique was first demonstrated after the 1993 Killari (Maharashtra) earthquake. Two single storey buildings (one school building and another shopping complex building) in newly relocated Killari town were built with rubber *base isolators* resting on hard ground. Both were brick masonry buildings with concrete roof. After the 2001 Bhuj (Gujarat) earthquake, the four-storey Bhuj Hospital building was built with base isolation Technique . Friction dampers have been provided in a 18-storey RC frame structure in Gurgaon (IITK-BMPTC-EQTip24). Buildings with such improved seismic performance usually cost more than normal buildings do. However, this cost is justified through improved earthquake performance.

The Bhuj earthquake left many low to medium rise buildings damaged, but only one important building ie., hospital building has installed a control device in the form of base isolation after the earthquake. The common man in a developing country like India may not be in a position to afford for implementing control device of any sort which may prove uneconomical. Hence in this paper an attempt has been made to study the feasibility of utilizing the water tank in the structure to resist seismic forces. The first implementation of water tank to resist natures force like wind was the 304m high Sydney center point tower.

This building is considered as one of the safest buildings in the world.

The tower has a 162,000 liter water tank at the top that acts as a stabilizer on windy days. In the Hafei 339m high TV tower, the 60 tonnes of water tank in the top serves to act as tuned mass dampers to resist the wind induced motion. Many researchers have carried out experimental and analytical work to study the use of Tuned Liquid Damper (TLD) to resist wind and earthquake forces. Kareem and Sun [1] have presented a perturbation based procedure to represent the modal properties of a system comprising of a fluid- containing appendages attached to a multi-degree-of-freedom system in terms of the individual dynamic properties of the primary and secondary system. The procedure is validated using a 10-storey building in which the water tank is located either at the top of the building or the fifth floor. The dimension of the water tank was assumed such that the second tank mode was tuned with the fundamental building mode. The mass ratio was taken as the mass of the sloshing fluid to building mass plus the water mass associated with the rigid body mode. The water level in the tank was varied and the results suggest that the water level, if not too shallow, has no significant effect on the combined frequency of the system. Sun and Fujino [2] presented an analytical model for a TLD using a rectangular tank filled with shallow liquid (1/2>h/L> 1/20- 1/25). It was assumed that the free surface is continuous; hence the model was valid as long as no breaking of waves occurs in the TLD. To account for breaking of waves two coefficients was introduced into the equation of motion. The response of a SDOF structure fitted with a TLD was experimentally studied and it was found that the TLD is very satisfactory for suppressing structural vibrations. Liquid motions in shallow TLDs with rectangular, circular and annular tanks, subject to harmonic excitation were measured experimentally by Sun et. Al [3]. Using a SDOF TMD analogy, equivalent mass, stiffness and damping of the TLD are calibrated from the experimental results. A virtual mass and a virtual damping for a TLD attached to an undamped linear SDOF structure were calculated and then amplitude- dependent equivalent mass, frequency and damping were obtained using the TMD analogy. The behavior of TLD under large amplitude excitation was presented by Dorothy Reed [4]. The authors found that to achieve the most robust system, the design frequency for the damper, if computed by the linearized water-wave theory, should be set at a value lower than that of the structure response frequency and even if the damper frequency has been mistuned slightly, the TLD always performed favorably. The literature shows that the mass of water alone was taken for mass ratio (mass of TMD to mass of structure) calculation and weight of tank was not included and the tank used for all study did not include staging for the tank. Hence in the present work the mass ratio and frequency ratio includes water, walls and roof of tank, beams and columns supporting the tank. A procedure to fix the dimensions of the tank and the optimum water level in the tank to reduce the peak response has been presented.

II. ANALYTICAL INVESTIGATION

The aim of the present work is analyzing the feasibility of implementing water tank as passive TMD and finding the optimum level of water which would reduce the peak response of the structure subjected to seismic forces using SAP.

2.1 Model

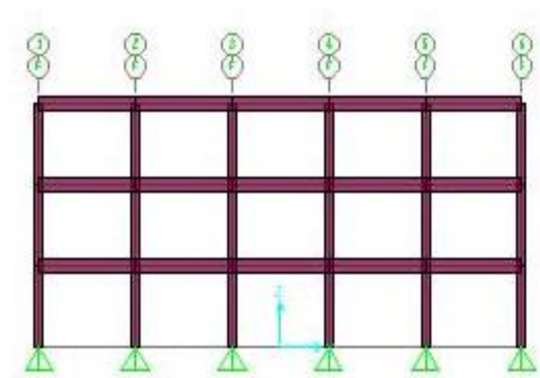
Analytical investigation was carried out using the routines of ANSYS. Three concrete models were taken for the study. The details of which are given in Table 1. The material properties used for the analysis are Young's Modulus of Concrete –0.35 kg/cm2, Poisson's ratio –0.16 and Density of concrete –2.5g/cc. The model of the structures is shown in Figure 1.

Table 1. Details Of The Models

Model Name	No. of Floors	No. of Bays	Floor Height (m)	Bay Size (m)	Dimension of column (m)	Dimension of Beam (m)	Time Period in sec
M3	3	5 x 5	3	4	0.30 x 0.30	0.23 x 0.53	0.14
M7	7	5 x 5	3	4	0.30 x 0.30	0.23 x 0.53	0.24
M10	10	5 x 5	3	4	0.30 x 0.30	0.23 x 0.53	0.34

2.2 Optimization

The effectiveness of the TMD depends on the proper tuning of the characteristics of TMD to that of the structure. In the present work the mass ratio μ (Mass of TMD to Mass of the Structure) and frequency ratio α (Frequency of TMD to the frequency of the structure) are optimized and the objective function is to reduce the peak structural response subjected to seismic excitation. For optimization the structure was modeled as lumped single degree of freedom spring-mass system as shown in Figure 2(a), with mass equal to that of the unit modal mass and stiffness adjusted to the natural frequency of the structure. The TMD was attached to the idealized system as spring mass system as shown in Figure 2(b).



(a) Three Storey

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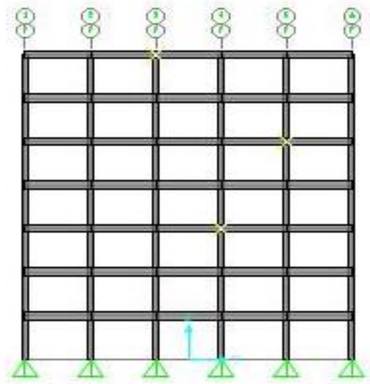
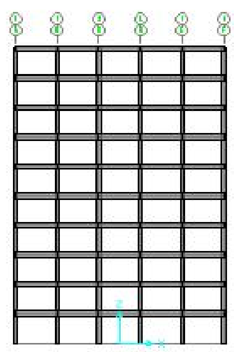


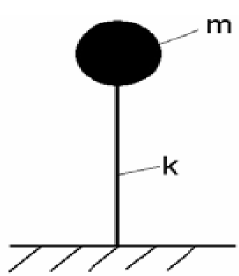
(b) Seven Storey



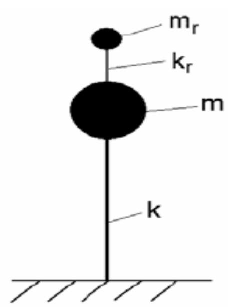
(c) Ten Storey

Fig. 1. SAP Model of Concrete Structures

Mass ratio was varied from 0.1 -1.5% in increments of 0.1% and frequency ratio was varied from 0.9-1.1 in increments of 0.01. For each increment of mass and frequency ratio time history analysis was carried out using the earthquake data as shown in Table 2.



(a) Idealized Structure



(b) Idealized Structure with TMD

Figure 2. Idealized structure and idealized structure with TMD

Table 2. Time history records summary

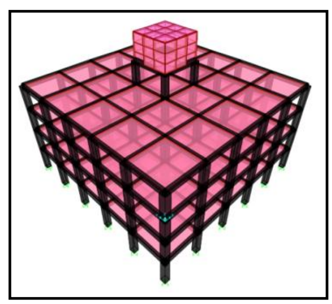
Record	Station / Year	Magnitude	PGA(g)
Bhuj	Chobari 2001	7.7	0.47
Chichi	Jiji 1999	7.6	0.55
Kobe	Kobe 1995	6.9	0.82
N-Palm	North Palm 1986	6.0	0.56
Imperial Valley (E1)	ElCentro 1940	6.9	0.32

The displacement-time history data was obtained for each earthquake loading. The parameters are then optimized by considering the quantity of reduction in displacement. The optimized values were arrived at for the parameters which provide maximum reduction in displacement. For each earthquake loading there was one optimized value.

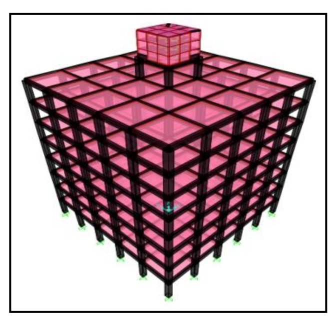
2.3 Water tank as TMD

Water tanks are integral part of all buildings and they impart large dead load on the structure. This additional mass can be utilized as TMD to absorb the extra energy imparted on the structure during earthquakes. In the present work the water tank was placed at centre so that the center of mass of structure and that of the tank coincided. The tank had a plan dimension of 4 x 4 m for both the models and 2m height for M3, 4 m height for M7 ,6m height for M10 and was placed over 1m high columns. The beam-column supports for the tank were rectangular concrete sections and the walls and roof were also modeled as concrete.

The dimensions of the tank were taken to suit the condition that the tank half full of water condition coincided with the optimized parametric values, i) mass ratio ie, ratio of mass of water tank (water + tank + beams and column) to the mass of the structure and ii) frequency ratio ie, ratio of frequency of water tank (water + tank + beams and columns) to the frequency of the structure coincided. Models of the tank with buildings is shown in Fig.2.



a) G+3 Building with tank of height 2 m for M3



b) G+7 Building with tank of height 4m for M7

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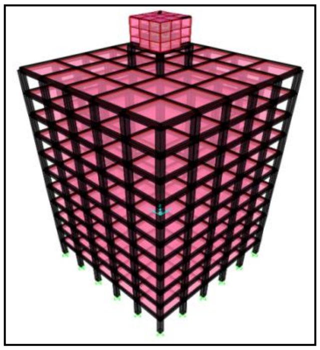

c) G+10 Building with tank of height 6m for M10

Figure 3. Model of building with water tank

2.4 Response of structure with various water levels of tank

The behaviour of the tank to seismic forces was studied under four conditions namely, building only with damping, empty tank with damping, full tank with damping and full tank without damping. Time history analysis was carried out for full structure without water tank and with water tank for the five tank conditions using the following data:

Building Geometry:

Each storey height = 3 m

Plan dimensions = 4 *x* 4 m for each bay

Member Cross Sections:

Beam = 230 *x* 530 mm

Slab Thickness = 150 mm

Table 3. details of Models

Building	Water Tank Size	Column Size
G+3	4 *x* 4 *x* 2 (32000 liters)	350 *x* 350
G+7	4 *x* 4 *x* 4 (64000 liters)	500 *x* 500
G+10	4 *x* 4 *x* 6 (96000 liters)	650 *x* 650

Earthquake Data:

Table 4. Details Of Earthquakes

Record	Time	Time Interval	No. Of output time steps
Bhuj	16.6 sec	0.005 sec	3320-4500
Chichi	88 sec	0.005 sec	17600-18600
Kobe	20.1 sec	0.005 sec	4020-5500
N-Palm	20 sec	0.005 sec	4020-5500
EL-Centro	7.78 sec	0.005 sec	1556-3000

Time History of Bhuj Earthquake is considered with acceleration values at 0.005 sec time interval.

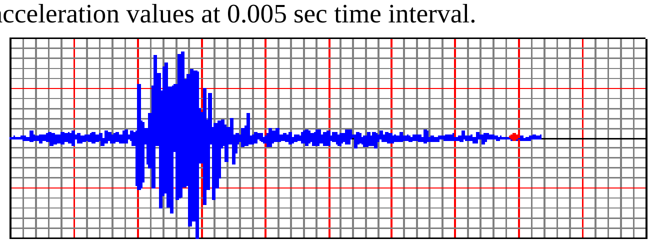

Fig.4. Acceleration Value of Bhuj Earthquake

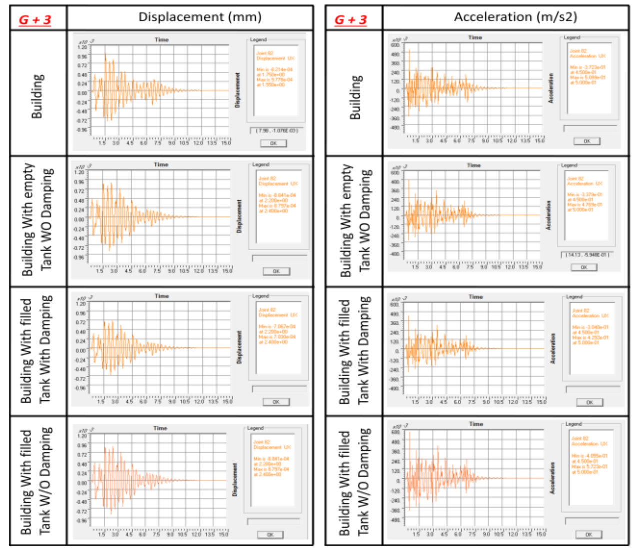

Fig 5. Displacement & Acceleration Pattern For Bhuj Earthquake data for M3

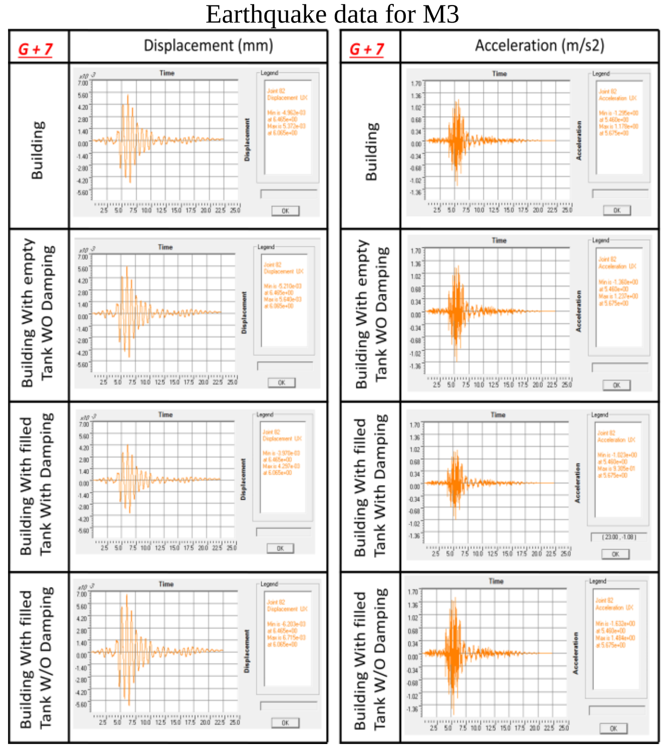

Fig 6. Displacement & Acceleration Pattern For Bhuj Earthquake data for M7

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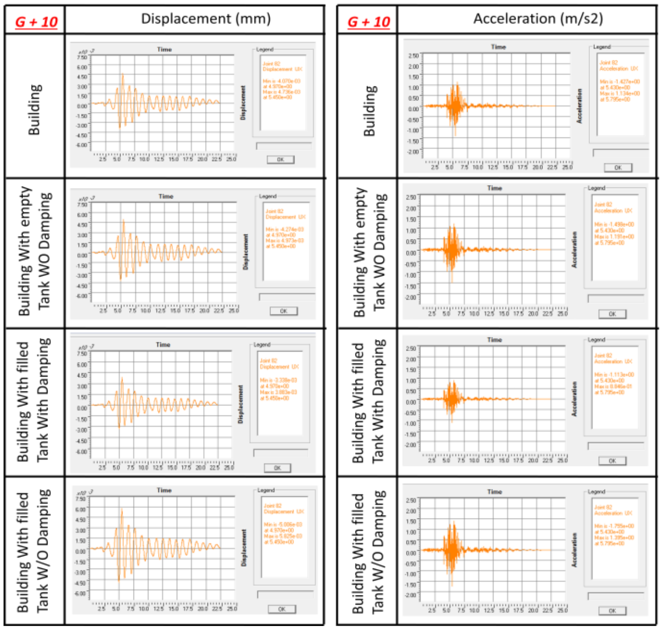

Fig 7. Displacement & Acceleration Pattern For Bhuj Earthquake data for M10

Time History of Chichi Earthquake is considered with acceleration values at 0.005 sec time interval.

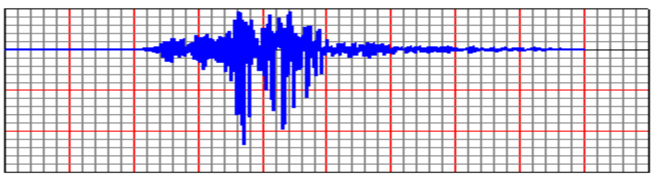

Fig.8. Acceleration value of Chichi Earthquake

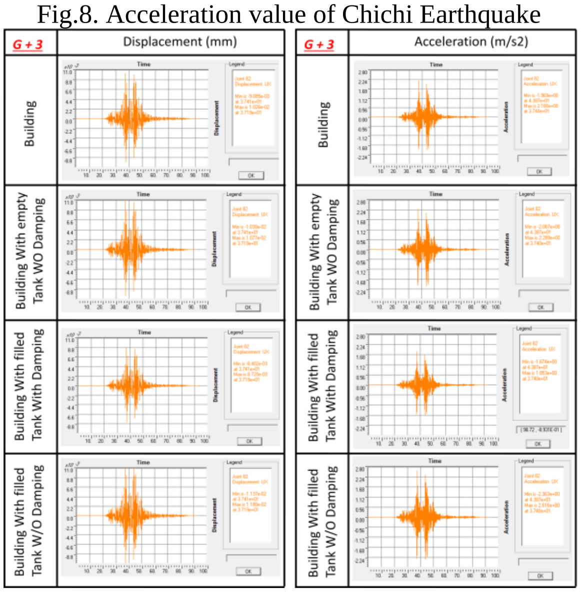

Fig 9. Displacement & Acceleration Pattern For Chichi Earthquake data for M3

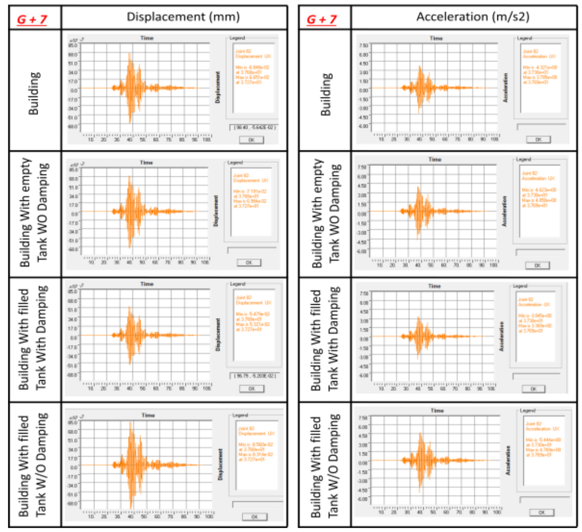

Fig 10. Displacement & Acceleration Pattern For Chichi Earthquake data for M7

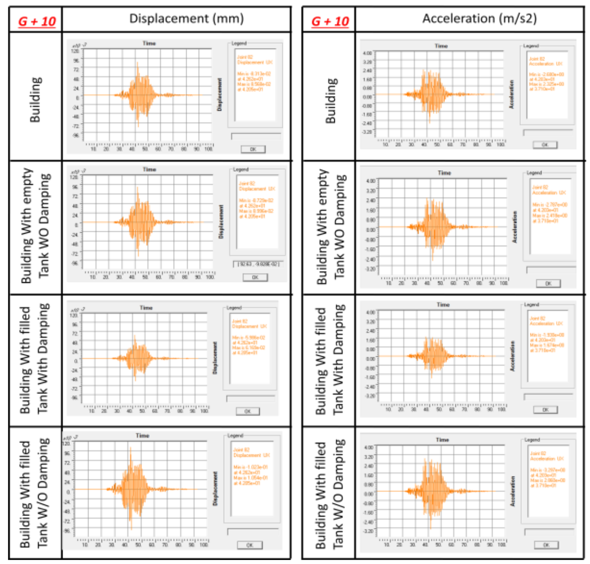

Fig 11. Displacement & Acceleration Pattern For Chichi Earthquake data for M10

Time History of Kobe Earthquake is considered with acceleration values at 0.005 sec time interval.

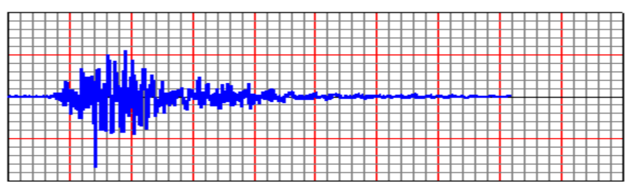

Fig.12. Acceleration value Of Kobe Earthquake

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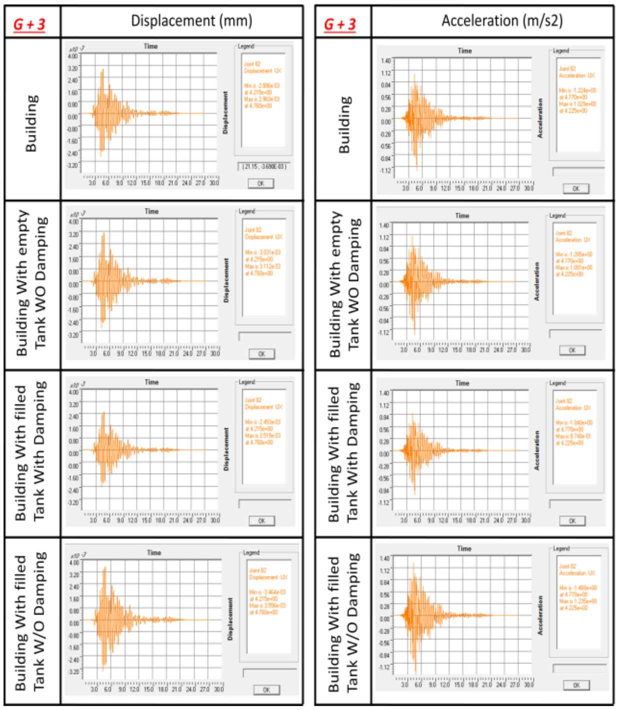

Fig 13. Displacement & Acceleration Pattern For Kobe Earthquake data for M3

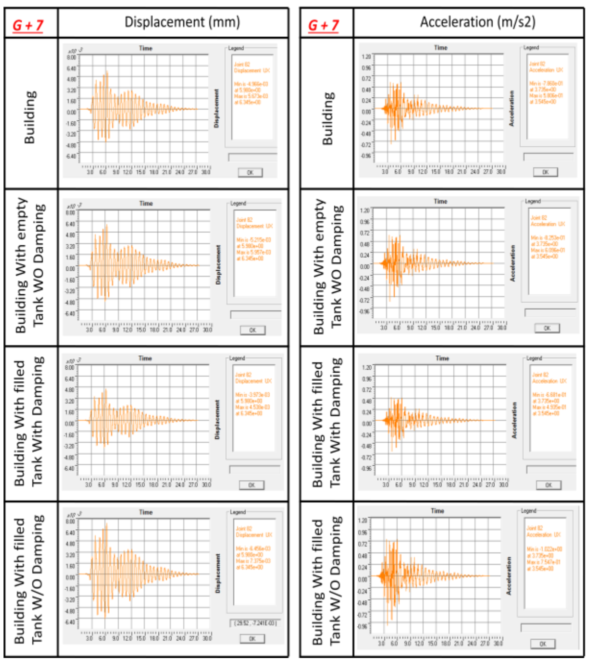

Fig 14. Displacement & Acceleration Pattern For Kobe Earthquake data for M7

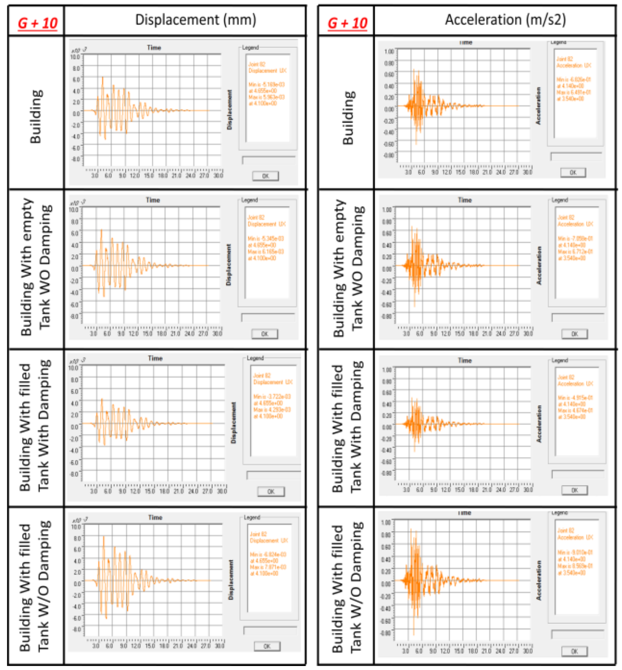

Fig 15. Displacement & Acceleration Pattern For Kobe Earthquake data for M10

Time History of N-Palm Earthquake is considered with acceleration values at 0.005 sec time interval.

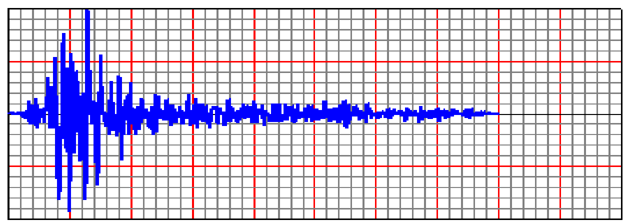

Fig.16. Acceleration Value of N-Palm Earthquake

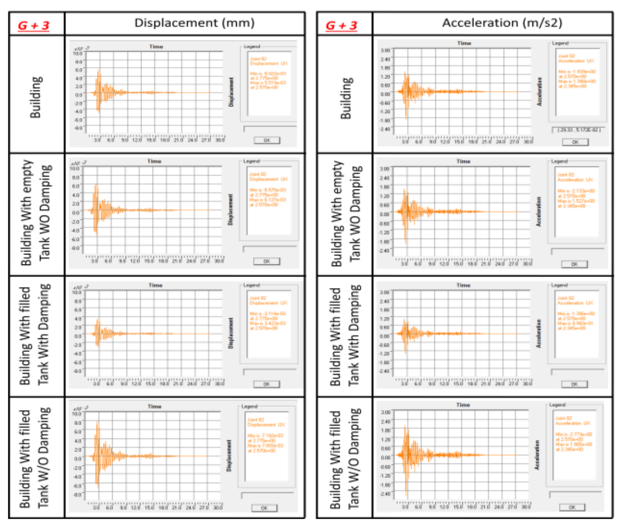

Fig 17. Displacement & Acceleration Pattern For N-Palm Earthquake data for M3

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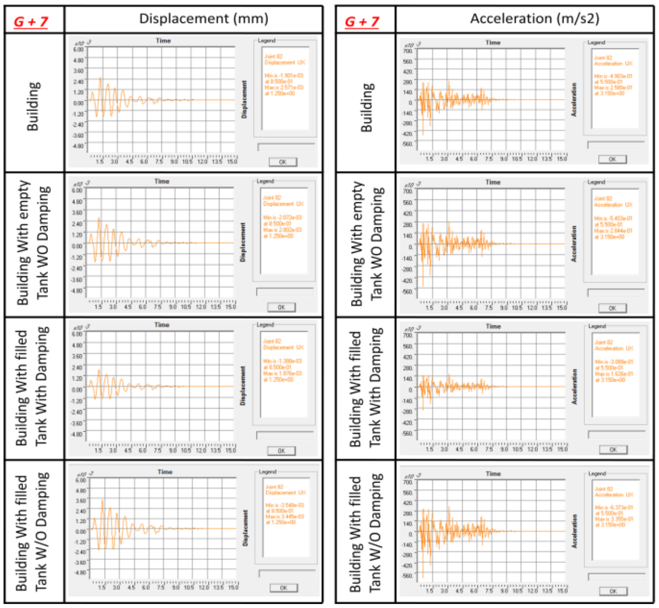

Fig 18. Displacement & Acceleration Pattern For N-Palm Earthquake data for M7

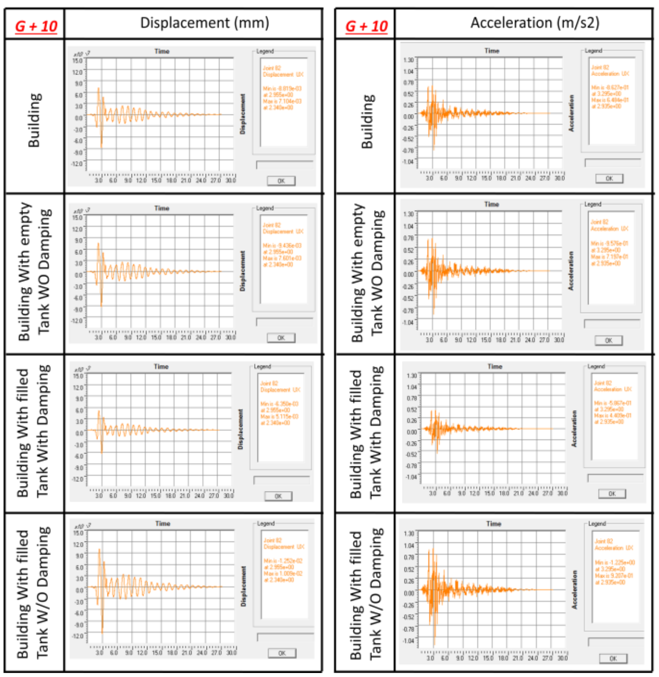

Fig 19. Displacement & Acceleration Pattern For N-Palm Earthquake data for M10

Time History of El-Centro Earthquake is considered with acceleration values at 0.005 sec time interval.

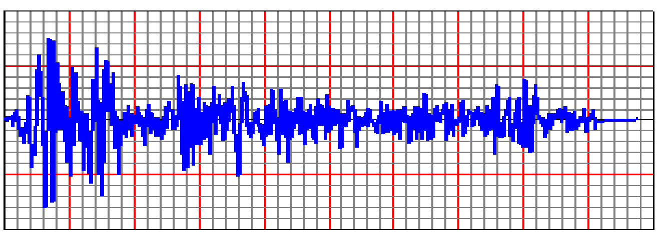

Fig.20.Acceleration Value of E1- Centro Earthquake

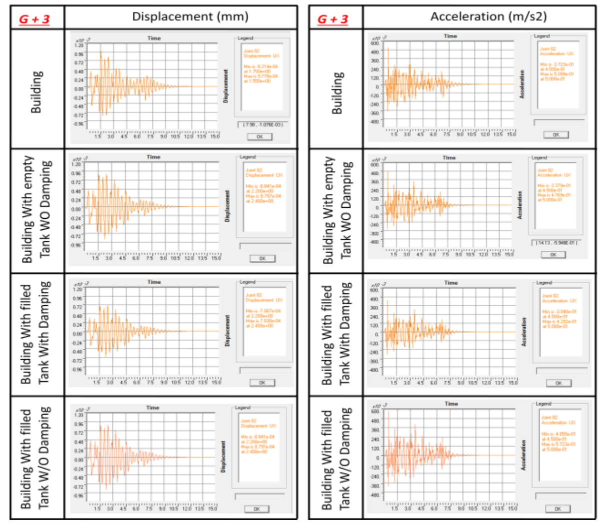

Fig 21. Displacement & Acceleration Pattern For E1-Centro Earthquake data for M3

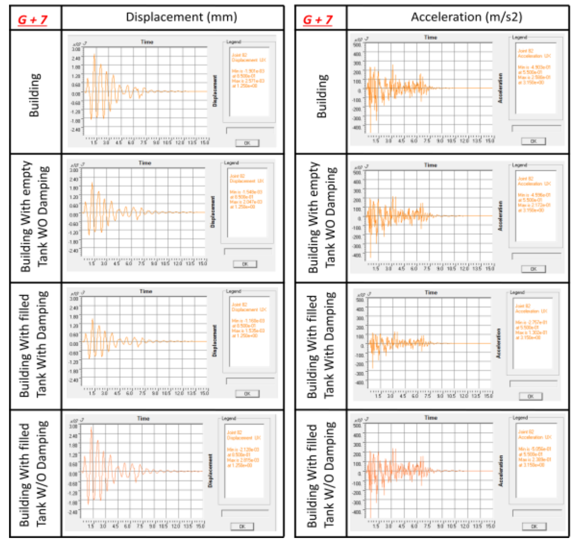

Fig 22. Displacement & Acceleration Pattern For E1-Centro Earthquake data for M7

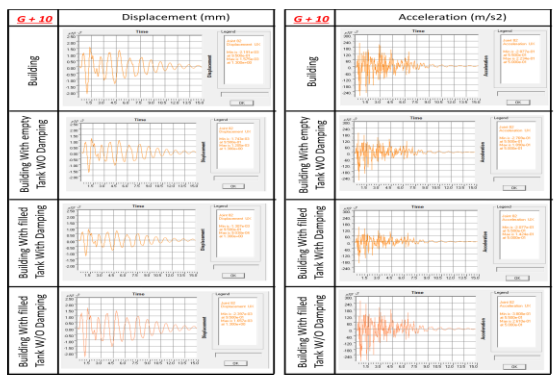

Fig 23. Displacement & Acceleration Pattern For E1-Centro Earthquake data for M10

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III. RESULTS AND DISCUSSION

Time History analysis has been carried out for all models namely full model without tank , model with empty tank without damping, model with filled tank with damping and model with filled tank without damping for models M3, M7 and M10. For all the models the maximum displacement and max acceleration was carried out by time history response were compared for all the conditions. The results of the observations are presented in the next sections.

3.1 Three storey model M3

The time history response at the roof level is presented in figures 5, 9, 13, 17, 21. The following inferences can be made from the figures.

i. For Bhuj data the maximum reduction in peak response is 30% and minimum is 10% when tank is full of water as in fig. 5. Therefore the response of water tank full mounted on structure is almost 30% less than for structure only.
ii. There is no reduction in peak response for Chichi data in fig. 9. It is more adverse when tank is full. But the displacement pattern is consistent for structure, empty tank without damping, and full tank without damping.
iii. The reduction in peak response is almost equal for structure and when tank is full for Kobe data in fig.13. the displacement pattern is nearly constant for all the conditions.
iv. For N-Palm data the maximum reduction in peak response is 40% and minimum is also 40% when the tank is full in fig17. The response of full water tank is 40% less than for structure only. Hence we can say that it is effective.
v. For El Centro data the reduction in maximum response in response is 10% for tank full than structure only in fig.21

From the above discussion it can be concluded that for all earthquake data and from all conditions tank full of water mounted on structure shows almost 40% reduction in response than for structure only.

3.2 Three storey model M7

The time history response at the roof level is presented in figures 6, 10, 14, 18and 22. The following inferences can be made from the figures.

i. For Bhuj data the maximum reduction in peak response is 30% and minimum is 20% when tank is full of water as in fig. 6. Therefore the response of water tank full mounted on structure is almost 30% less than for structure only.
ii. There is almost 20% reduction in maximum and minimum response is 20% for Chichi data in fig.10. Hence the response of tank with full water is also 20% less than for structure only.
iii. The reduction in peak response is10% when tank is full than for structure for Kobe data in fig.14. The displacement pattern is nearly constant for all the other conditions.
iv. For N-Palm data the maximum reduction in peak response is 50% and minimum is also 30% when the tank is full in fig18. The response of full water tank is 50% less than for structure only. Hence we can say that it is effective.
v. For El Centro data the reduction in maximum response is also 50% and minimum is 10% for tank full than structure in fig.22.

From the above discussion it can be concluded that for all earthquake data and from all conditions tank full of water mounted on structure shows almost 50% reduction in response than for structure only.

3.3 Three storey model M10

The time history response at the roof level is presented in figures 7, 11, 15, 19 and 23. The following inferences can be made from the figures.

i. For Bhuj data the maximum reduction in peak response is 20% and minimum is 10% when tank is full of water as in fig. 7. Therefore the response of water tank full mounted on structure is almost 20% less than for structure only.
ii. There is almost 30% reduction in maximum and minimum response is 30% for Chichi data in fig11. Hence the response of tank with full water is also 30% less than for structure only.
iii. The reduction in maximum peak response is 35% and minimum is also 30%when tank is full than for structure for Kobe data in fig.15.
iv. For N-Palm data the maximum reduction in peak response is 50% and minimum is also 30% when the tank is full in fig17. The response of full water tank is 50% less than for structure only. Hence we can say that it is effective.
v. For El Centro data the reduction in response is 50% for tank full than structure in fig.21.

From the above discussion it can be concluded that for all earthquake data and from all conditions tank full of water mounted on structure shows almost 40% reduction in response than for structure only.

IV. CONCLUSION

The feasibility of implementing water tanks as passive TMD and the optimum level of water was investigated analytically and the following conclusions can be drawn from the study.

i. Water tanks can be designed to serve as TMD provided, the parameters ie, mass ratio and frequency ratio are properly tuned.
ii. For tuning the parameters the combined effect of water, tank and staging can be considered since the models with water tank showed good response reduction for most of the earthquake data taken for the study.
iii. The dimensions of the tank should be fixed such that full level of water coincided with the optimum parametric values. All the models showed consistent results for optimized condition, ie, tank with full water level condition than structure only. Hence if water level in the tank is maintained it can reduce the peak response of structures to seismic forces.

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iv. For both the models water tank empty with damping showed consistent time history response pattern as that of for water tank full without damping.

v. Hence it is concluded that the procedure used for implementation of TMD can be satisfactorily used. The response of tank with full water level should be half of structure only so that it can be effective to implement water tank as a passive TMD. Water level can be maintained to reduce the peak response of structures subjected to seismic forces.

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