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WATER TANK AS PASSIVE TMD FOR SEISMICALLY EXCITED STRUCTURES

G. Hemalatha* and K.P. Jaya
Structural Engineering Division, Anna University, Chennai-600 025, India

Abstract

This paper presents analytical investigation carried out to study the feasibility of implementing water tank as passive TMD using ANSYS. Two multi-storey concrete structures, three and five 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 four earthquake data, namely, El-centro, Hachinohe, Kobe and Northridge was studied under five conditions, namely tank empty, 1/4th water, 1/2th water, 3/4th water and full tank. 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

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1. 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

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[*] E-mail address of the corresponding author: hema_gladston@yahoo.co.in (G. Hemalatha)

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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.

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

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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.

2. 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 ANSYS.

2.1 Model

Analytical investigation was carried out using the routines of ANSYS. Two 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/cm^2, Poisson's ratio –0.16 and Density of concrete –2.5g/cc. The model of the structures is shown in Figure 1. Columns and beams were modeled using Beam188 element and slab using Shell63 element.

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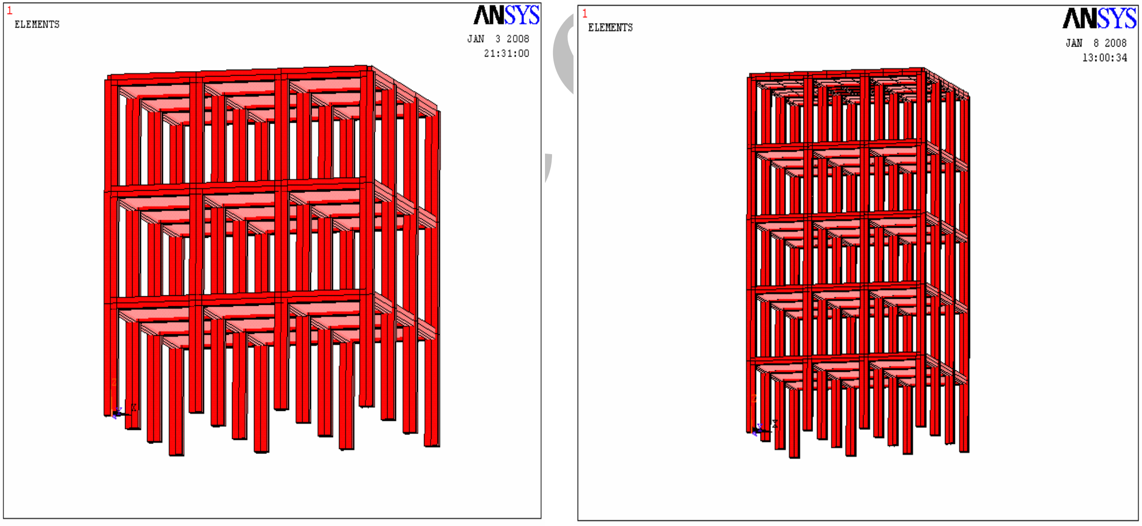
Table 1. Details of the models

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	3x3	3	3	0.3 x 0.45	0.3 x 0.3	0.14
M5	5	3x3	3	3	0.3 x 0.45	0.3 x 0.3	0.24

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



(a) Three storey (b) Five storey

Figure 1. ANSYS Model of Concrete Structures

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).

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.

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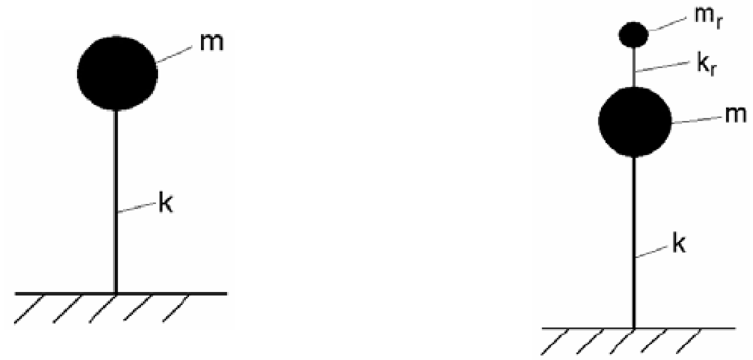

(a). Idealized Structure (b). Idealized Structure with TMD

Figure 2. Idealized structure and idealized structure with TMD

Table 2. Time history records summary

Record	**Station / Year**	**Magnitude**	**PGA(g)**
Imperial Valley (E1)	ElCentro 1940	6.9	0.32
Loma Prieta (L1)	Gilory 1989	7.0	0.55
Northridge(N1)	Rinaldi 1994	6.7	0.56
Kobe (K1)	Kobe 1995	6.9	0.82

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. Hence there were four optimized values for mass ratio and frequency ratio. The curve fit technique was used to arrive at a single optimized parameter. The optimum parametric values are given in Table 3.

Table 3. Optimized parametric values

Model	**Parameter**	**Optimized values**
M3	μ_{opt}	0.8361 %
	α_{opt}	0.9952
M5	μ_{opt}	0.9780 %
	α_{opt}	0.9880

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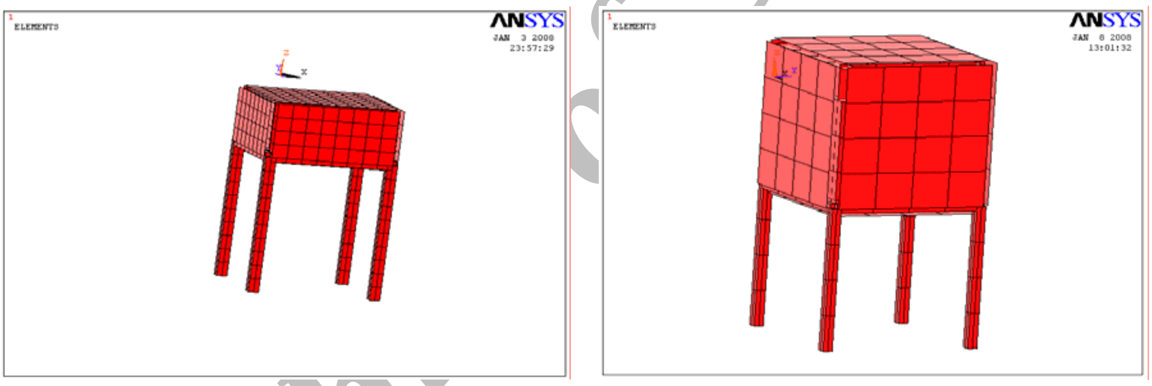
2.3 Water tank as TMD

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 1 x 1 m for both the models and 0.5m height for M3, 1 m height for M5 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. Beam188 was used to model columns and beams, shell63 to model walls and roof of tank and Fluid80 to model water in the tank.

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. The model of the tank is shown in Figure 3.



(a) Tank of height 0.5m for M3 (b) Tank of height 1m for M5

Figure 3. Model of water tank

2.4 Response of structure with various water levels of tank

The behaviour of the tank to seismic forces was studied under five conditions namely, Tank empty, 1/4th water level, 1/2 water level, 34th water and tank full. The mass ratio and frequency ratio for various conditions are shown in Table 4. The optimum values matched with the tank half full condition. Time history analysis was carried out for full structure without water tank and with water tank for the five tank conditions using the following four earthquake data: i) *El Centro (E2)*: The N-S component recorded at the Imperial Valley Irrigation District substation in El Centro, California, during the Imperial Valley California earthquake of May 18, 1940 with PGA of 0.35g.ii) *Hachinohe (H2):* The N-S component recorded at Hachinohe City during Takochi-oki earthquake of May 16, 1968 with PGA 0.229g. iii) *Kobe(K2):* The N-S component recorded at the Kobe Japanese Meteorological Agency (JMA) station during Hyogo-ken- Nanbu earthquake of January 17,1995, with PGA 0.59g. iv) *Northridge (N2):* The N-S component recorded at Sylmar County Hospital

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Parking lot in Sylmar, California, during Northridge, California earthquake of January 17, 1994 with PGA 0.843g.

Table 4. Mass and frequency ratios for various water levels

	M3		M5	
Condition	**μ (%)**	**α**	**μ(%)**	**α**
Tank Empty	0.658	1.1229	0.7575	1.1207
1/4 Water	0.748	1.0533	0.8669	1.0481
1/2 Water	0.836	0.9952	0.9780	0.9880
3/4 Water	0.928	0.9453	1.0860	0.9372
Full Water	1.019	0.9014	1.1952	0.8936

The maximum roof displacement was noted for each condition. Figure 4 and Figure 5 show the maximum roof top displacement for various tank conditions for the four earthquake data. The comparison of deflection pattern for M3 is shown in Figure 6 to Figure 9 and for M5 in Figure 10 to Figure 13.

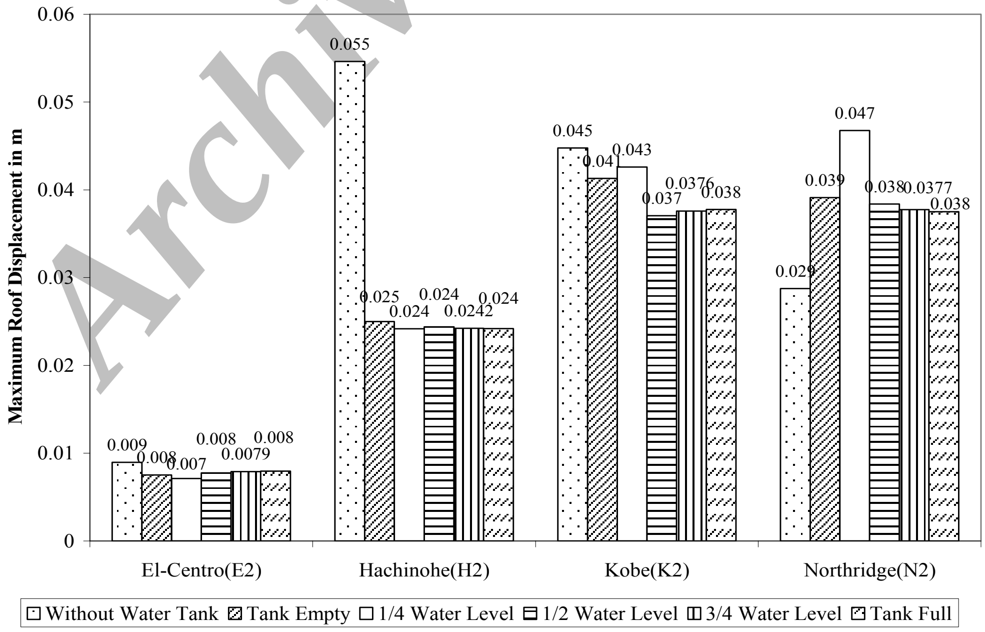

Figure 4. Maximum roof top displacement for M3

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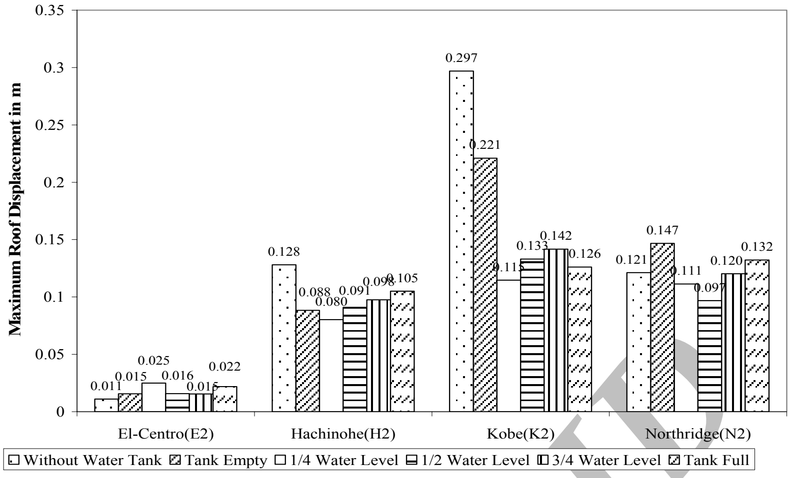
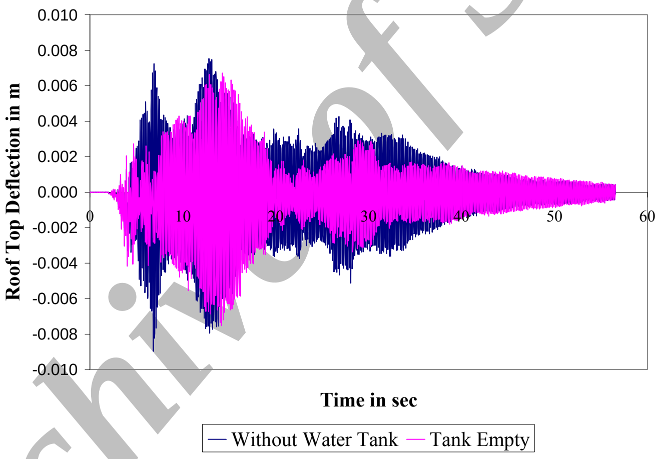
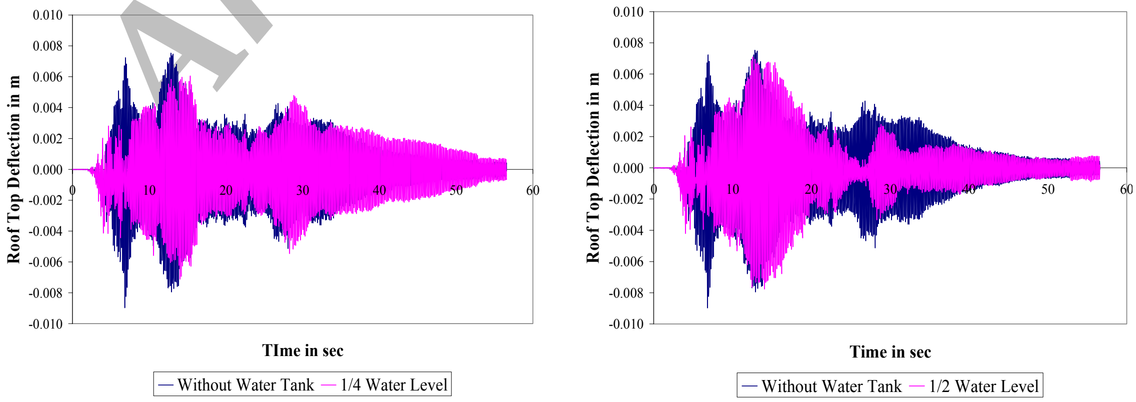


Figure 5. Maximum roof top displacement for M5



(a) Tank empty



(b) 1/4 Water level (c) 1/2 Water level

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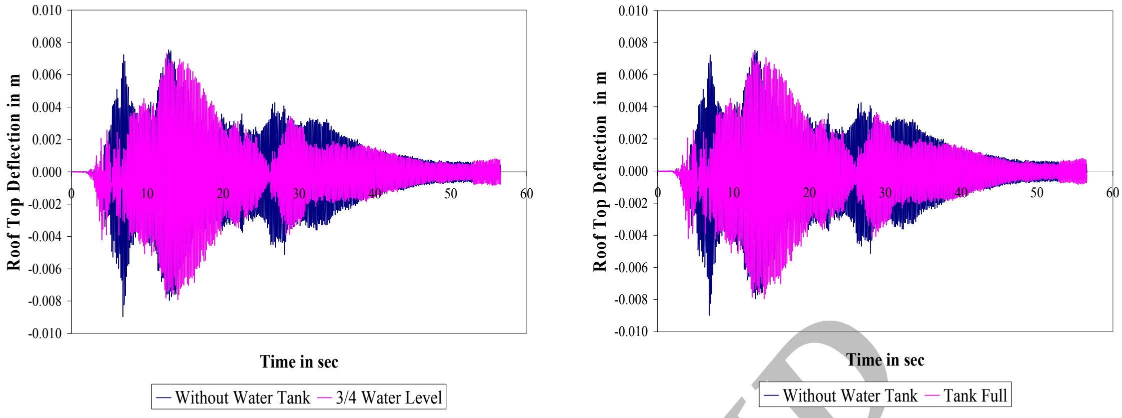
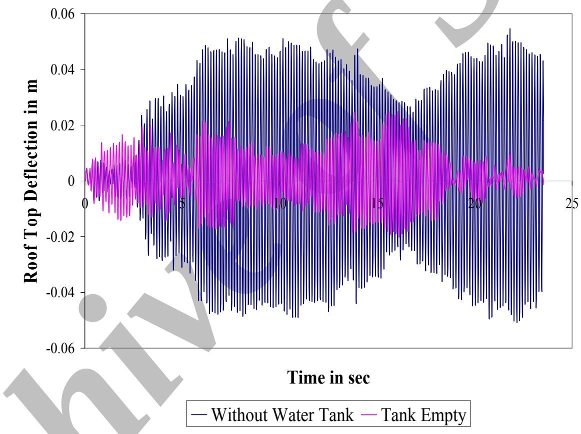


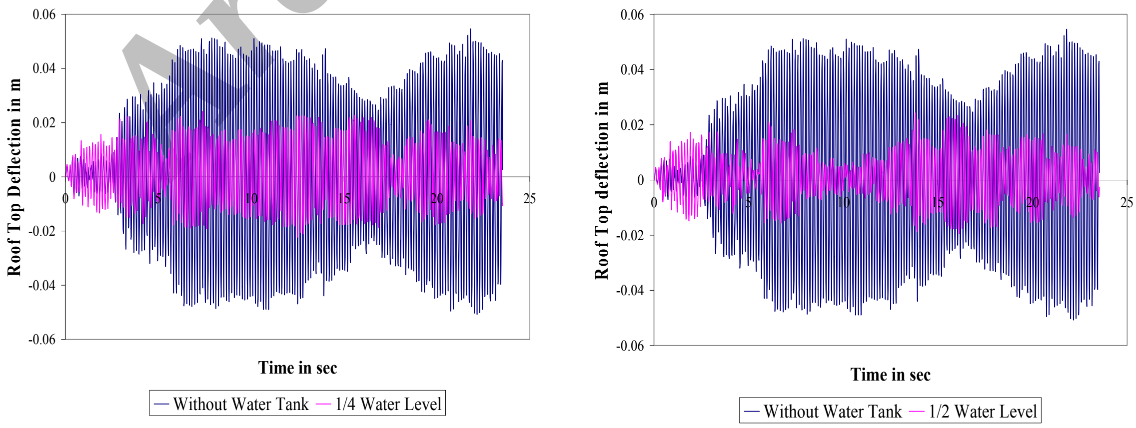
(d) 3/4 Water level

(e) Full tank

Figure 6. Deflection pattern for El-centro (E2) earthquake data for M3



(a) Tank empty



(b) 1/4 Water level

(c) 1/2 Water level

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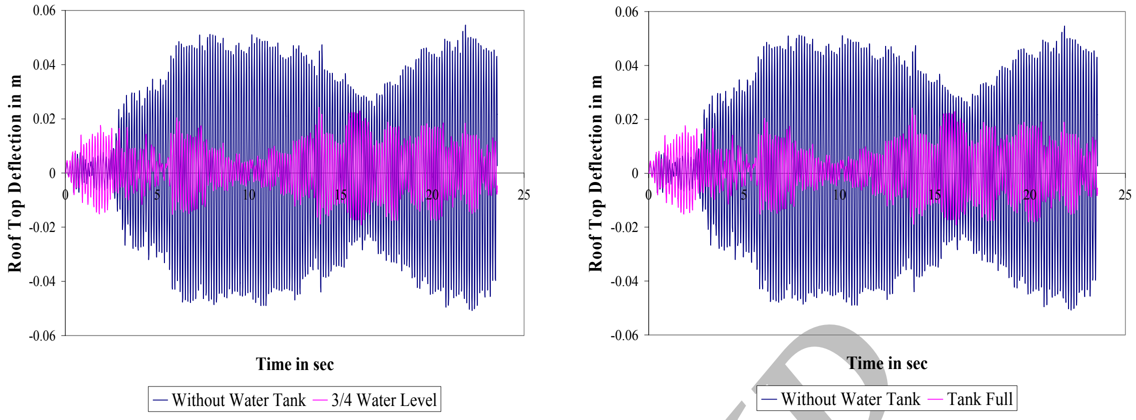
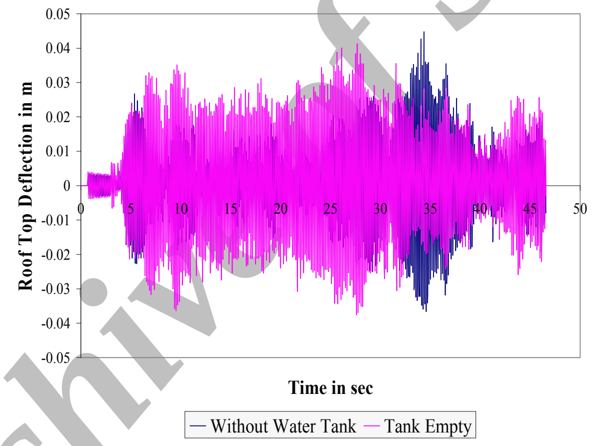
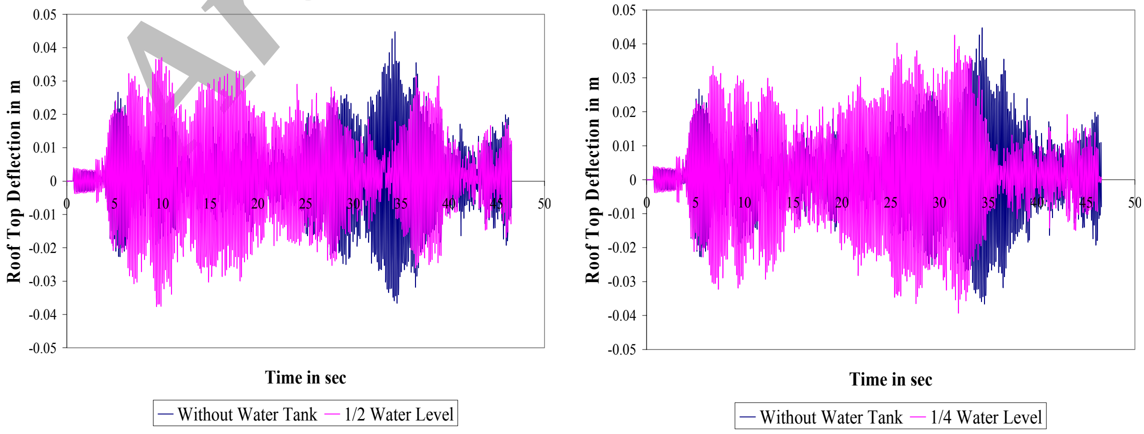


(d) 3/4 Water level (e) Full tank

Figure 7. Deflection pattern for Hachinohe (H2) earthquake data for M3



(a) Tank empty



(b) 1/4 Water level (c) 1/2 Water level

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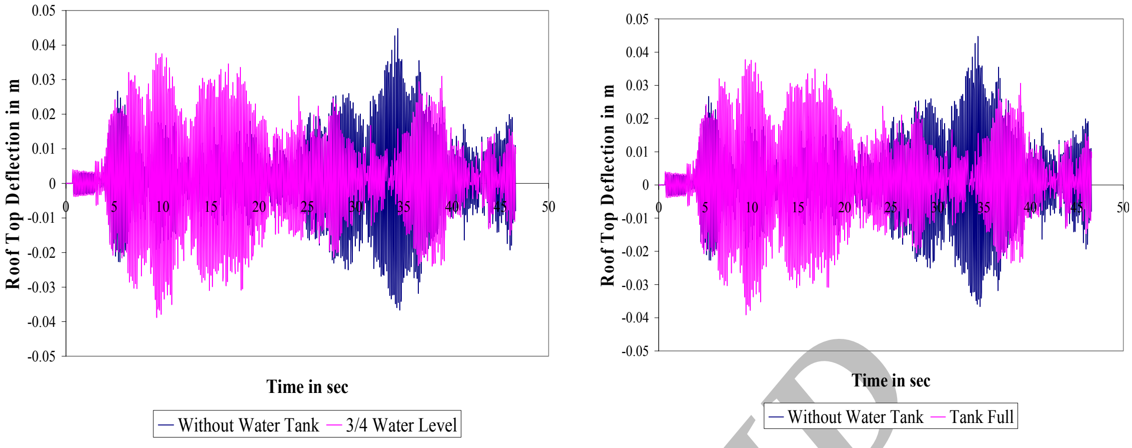
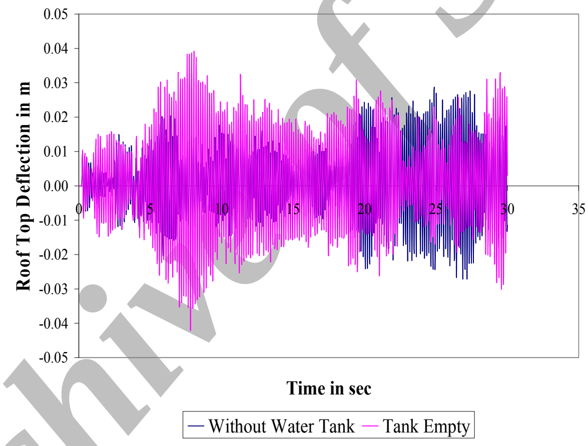
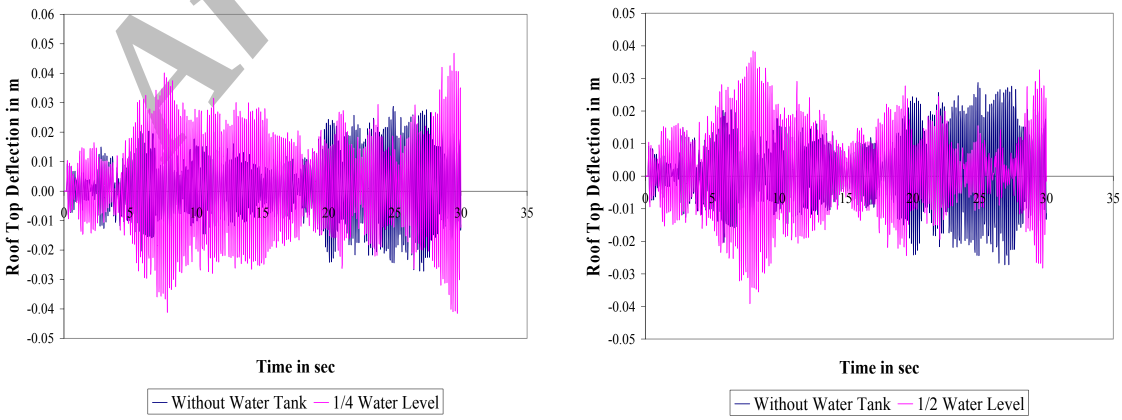


(d). 3/4 Water level (e). Full tank

Figure 8. Deflection pattern for Kobe (K2) earthquake data for M3



(a) Tank empty



(b) 1/4 Water level (c) 1/2 Water level

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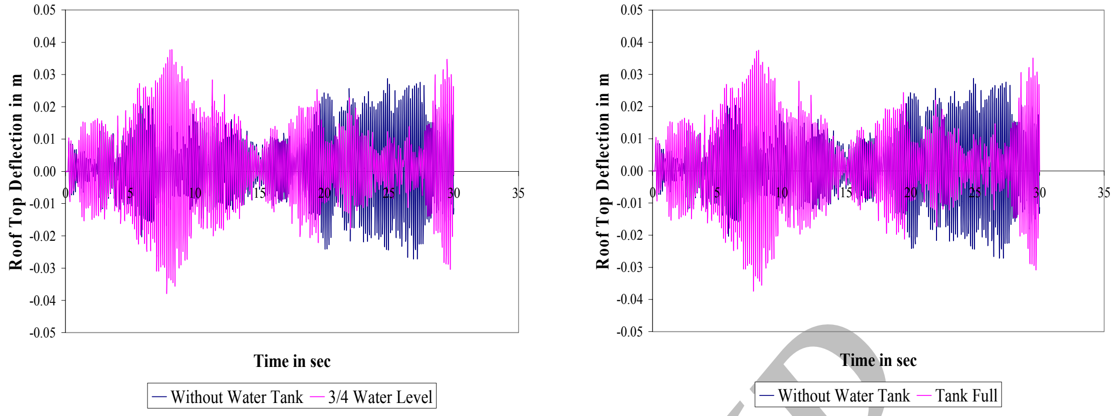
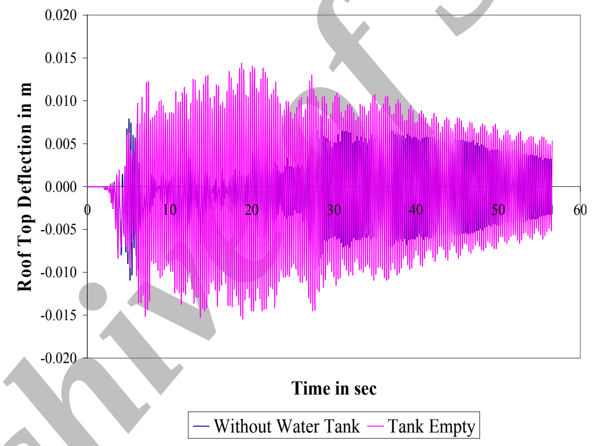
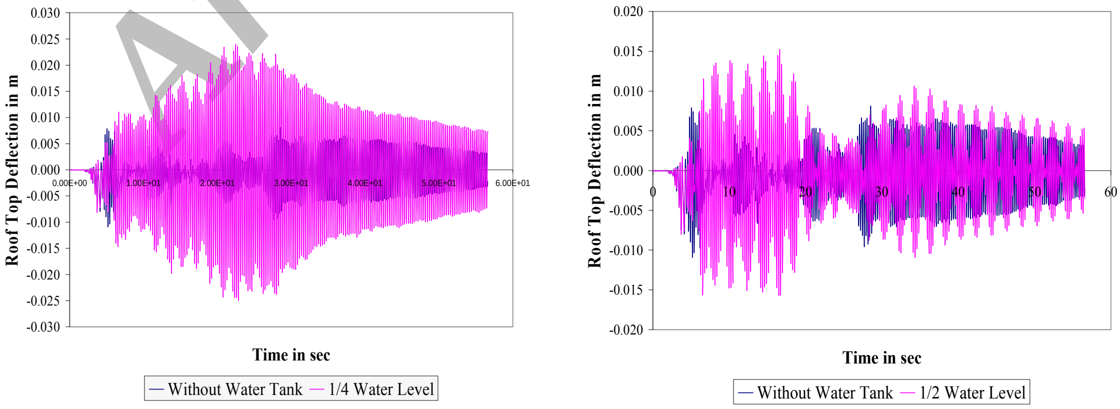


(d) 3/4 Water level (e) Full tank

Figure 9. Deflection pattern for Northridge (N2) earthquake data for M3



(a) Tank empty



(b) 1/4 Water level (c) 1/2 Water level

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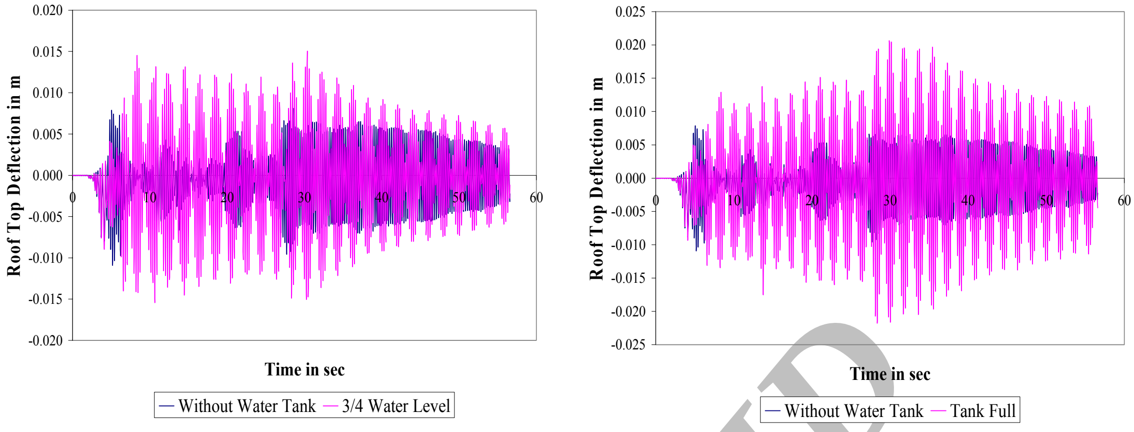
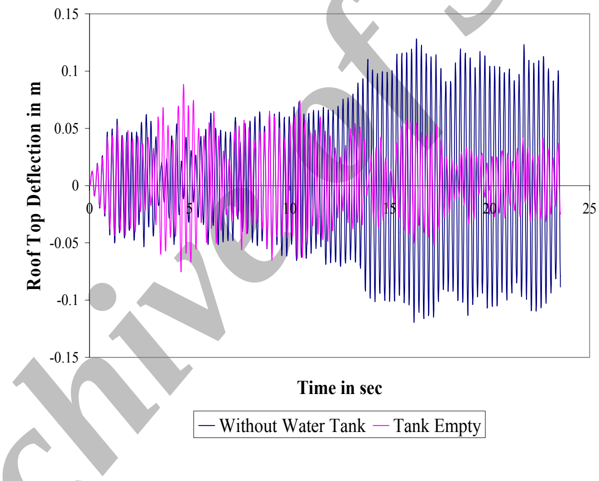
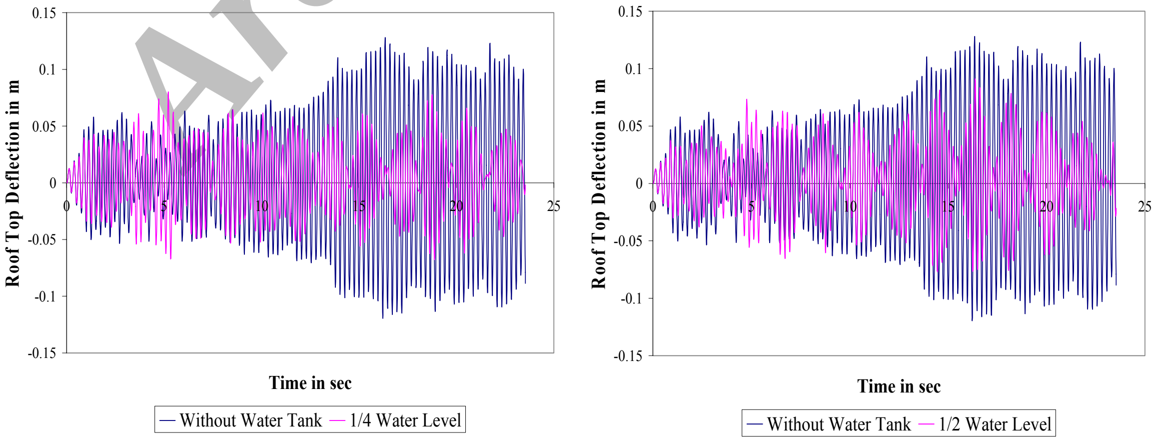


(d) 3/4 Water level (e) Full tank

Figure 10. Deflection pattern for El-centro (E2) earthquake data for M5



(a) Tank empty



(b) 1/4 Water level (c) 1/2 Water level

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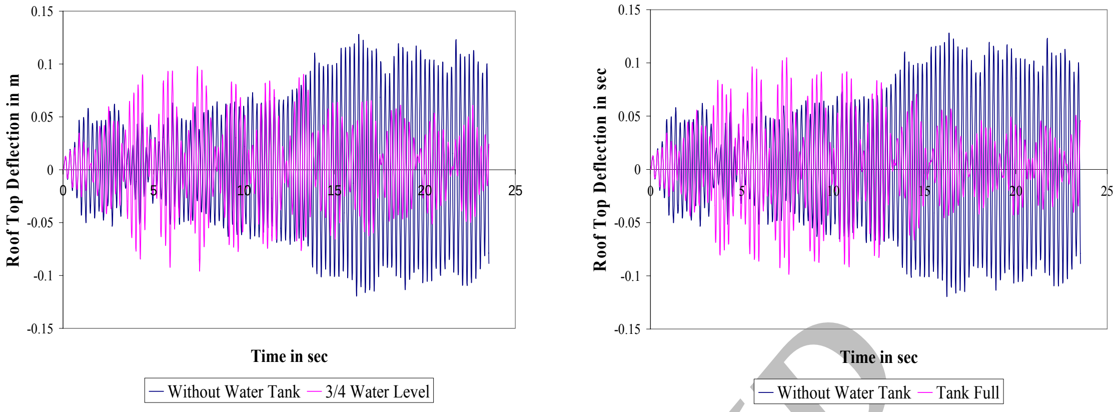
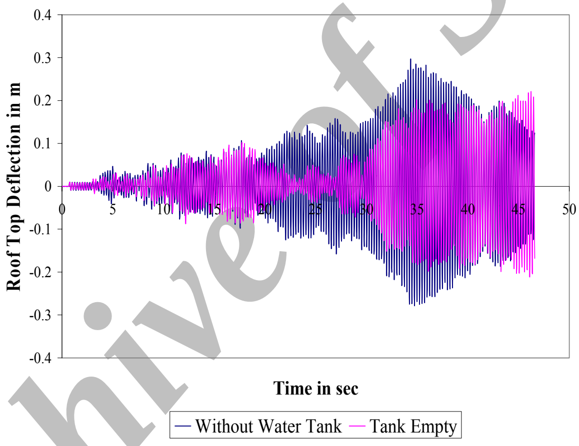


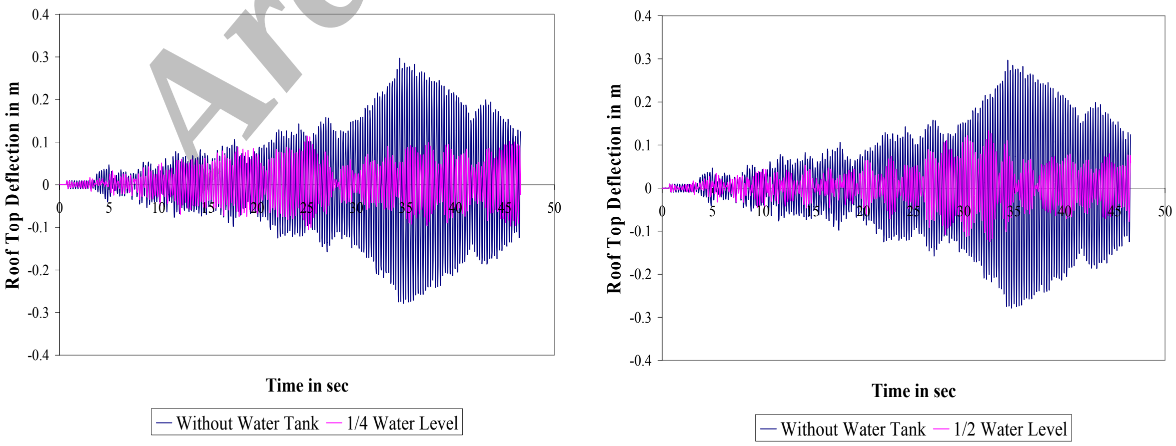
(d) 3/4 Water level

(e) Full tank

Figure 11. Deflection pattern for Hachinohe (H2) earthquake data for M5



(a) Tank empty



(b) 1/4 Water level

(c) 1/2 Water level

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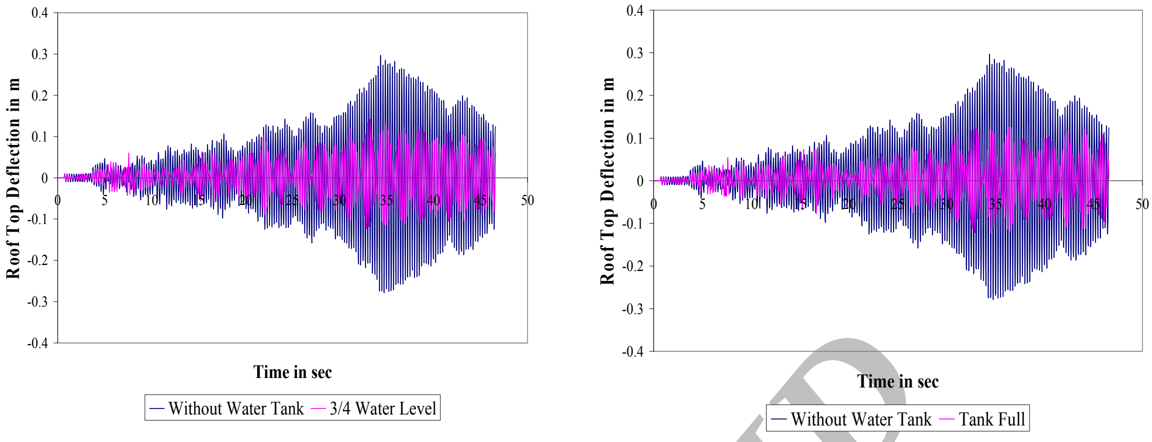
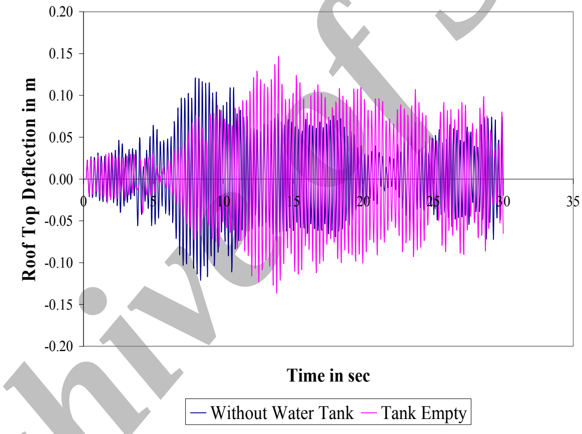
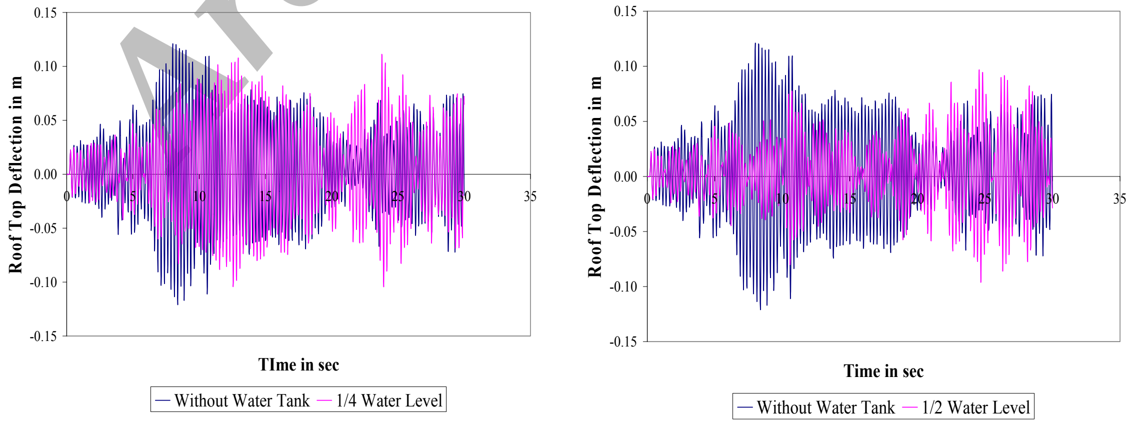


(d) 3/4 Water level (e) Full tank

Figure 12. Deflection pattern for Kobe (K2) earthquake data for M5



(a) Tank empty



(b) 1/4 Water level (c) 1/2 Water level

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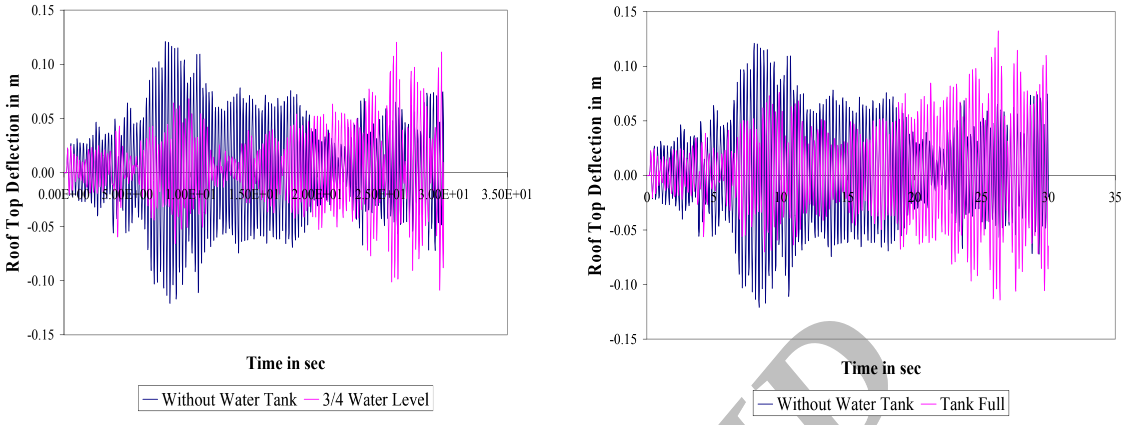

(d) 3/4 Water level (e) Full tank

Figure 13. Deflection pattern for Northridge (N2) earthquake data for M5

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3. Results and Discussion

Time history analysis has been carried out for the full model without water tank and water tank with five conditions of water level for models M3 and M5. For both the model tank with half level of water was taken as the optimum condition. The maximum roof top displacement and the 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 maximum roof top displacement is shown in Figure 4 and the time history response at the roof level is presented in Figure 6 to Figure 9. The following inferences can be made from the figures,

i. For E2 data the maximum reduction in peak response is 20.7% when tank is quarter full of water and minimum 11.35% when tank is full. The deflection pattern Figure 6 shows good reduction in deflection throughout for half water condition and reduction in response is less for quarter water level. 3/4 and tank full condition also show satisfactory reduction in deflection.

ii. The reduction in peak response is almost equal (≈55%) for all tank conditions for H2 data. Figure 7 shows very good response history for 1/2, 3/4 and full water condition.

iii. The peak response reduction for K2 data is maximum when tank is ¾ full of water condition (16%) and minimum (5%) when tank is ¼ full. The deflection pattern is good for 1/4 condition and consistent for 1/2, 3/4 and full condition as seen in Figure 8.

iv. There is no reduction in peak response for N2 data as seen in Figure 4 and it is more adverse for 1/4 water level, but the deflection pattern is consistent for 1/2, 3/4 and full condition.

From Figure 4. and the above discussion, it can be concluded that tank with quarter water level may be adverse. Tank with half water level shows consistent results for all earthquake data. Tank empty condition may be safe, but since 1/4 water level is adverse minimum half water level should be maintained. Since deflection pattern for all the cases is consistent for 1/2, 3/4 and full conditions these can be safe water levels.

3.2 Five storey model M5

The maximum roof top displacement is shown in Figure 5 and the time history response at the roof level is presented in Figure 10 to Figure 13. The following inferences can be made from the Figures,

i. For E2 data there is no reduction in peak response and it is adverse when tank is 1/4 water and tank full condition. The response time history (Figure 10) is better for 1/2 water condition and consistent for 3/4 and full water condition.
ii. The reduction in response for H_2 data is good for all the cases and it is maximum (37%) for 1/4 water condition and minimum (17%) for tank full condition.
iii. Response reduction is around 55% for 1/4 to full water condition for K2 data. For tank empty condition the peak response reduction is 26% but the response time history (Figure 12) does not show satisfactory pattern towards the end and the pattern is consistent for 1/2, 3/4 and full tank conditions.
iv. For N2 data tank empty and full condition does not show reduction in peak response. The reduction is maximum for 1/2 water condition and time history pattern (Figure 13) is satisfactory for 1/2 water condition and consistent 3/4 and full tank condition.

From Figure 5. and the above discussion, it can be concluded that tank with quarter water level, tank full and tank empty conditions may be adverse conditions. Tank with half water level shows consistent results for all earthquake data and tank with 3/4 water level will also be safe.

4. 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 half level of water coincided with the optimum parametric values. Both the models showed consistent results for optimized condition, ie, tank with half water level condition.
iv. Tank with 1/4 water level is adverse for both the models
v. For both the model 3/4 water level showed consistent time history response pattern as that of 1/2 water tank condition. Hence if water level in the tank is maintained between half and 3/4 it can reduce the peak response of structures to seismic forces.

Hence it is concluded that the procedure used for optimization of parameters of TMD can be satisfactorily used and tank with half water level should be optimized and water level

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maintained between 1/2 and 3/4 to reduce the peak response of structures subjected to seismic forces.

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