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*Original Article*

# Behavior of Structures Under Dynamic Loading Having Water Tank Designed as Tuned Mass Damper

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***Abstract*** *- The water tanks are essential structures in many buildings and can be used for many purposes. The liquid in the overhead tanks moves out of phase when the structure is experiencing seismic vibration. These energy dissipation phenomena are used in liquid sloshing dampers to reduce the seismic response of structures. Water tanks with an isolation system on the rooftop of the building can be utilized as tuned mass dampers (TMD). So here, it is tried to investigate the efficiency of the water tank with an isolation system as a tuned mass damper. The main advantage of this method is that it does not require any additional components other than the isolation component. This technology could be simple to set up and inexpensive. Three various heights of frames, G+4, G+9, and G+19, are analyzed in this study, each with a different water tank arrangement. Water tank capacity is found for residential buildings for 2 days as per I.S. standard recommendation. The LRB isolators have limited damping values, which is unfavorable for getting a desirable response. Dynamic seismic analysis is done by the response spectrum method in ETABS. As it is a case of non-classical damping, the dynamic analysis modal combination rules like Complete Quadratic Combination (CQC) and Square Root of Sum of Squares (SRSS) work efficiently. Results show that the applicability of this technique gives positive results, and structural response is reduced.*

***Keywords*** *- Dynamic seismic analysis, Rcc buildings, Seismic isolation, Tuned mass damper, Water tank.*

## 1. Introduction

An earthquake or wind load on the structure frame makes the frame vibrate. Excessive decay can cause distress to the people living in the building, or it can be dangerous if it collapses. To reduce these excessive vibrations, various techniques or methods can be used. By strengthening the structural frame with the help of proper design, shear walls, and application of various frame systems like tube systems, braced systems, etc., we can also use the application of passive control systems like base isolation, viscous dampers, tuned mass dampers, friction dampers, etc. Properly designed systems can give the best efficiency and reduce seismic response to a greater extent so that building deflection is reduced and remains safe.

The use of liquid-containing structures is one of the techniques that can reduce the vibration of structures, which is why research on this technique has potential. Also, the water used in these dampers can be used for other purposes. Tuned liquid dampers, liquid column dampers, and liquid sloshing dampers can reduce the structure response. But the applications of these dampers are limited. Because of this, the dampers should be properly tuned for efficient response reduction. However, much past research shows that these devices' efficiency is less than other techniques. However, it can be said that using water tanks, which are already an integral part of many structures to reduce the seismic response, can prove cost-effective and efficient.

The liquid behavior in the tank is complex under lateral vibrations, so the proper methodology is needed to analyze this behavior. Much research has been done up till now to analyze the water tank. Firstly, a 2 mass model of a liquid water tank was developed by Housner[22] (1963), which is still considered for many standards for analyzing water tanks under seismic vibrations. Haroun[21] (1983) created three mass-produced flexible water tank models. In these models, liquid mass is divided into three parts: sloshing, impulsive, and rigid. As the frequency of the applied vibrations changes, the sloshing mass moves out of phase on the upper part of the water tank. The rigid mass is almost fixed to the water tank. Because these models are in a simple form, they are useful for numerical approaches. Software like ANSYS and ABAQUS proves useful in studying liquid-containing tanks because it is easy to use and accurate. This study has reviewed the response of liquid-containing tanks in different conditions.

## 2. Literature review

Joseph Asha and Joseph Glory(2018) [1] did the research on liquid containment tanks by the finite element method. Results show that behaviour depends mostly on the tank's geometry, liquid properties, and load application. The results of a full tank match the codal provisions, but the results do not match the standards for half-full tanks.

Muhammed Zain Kangda (2021) [2] has reviewed various approaches to analysing the liquid-containing tank using the finite element method. The author described the suitable method to model and analyse the tank in the ANSYS and other softwares.

Hitesh Kumar, S.M.ASCE, and Sandip Kumar Saha (2020) [3] studied the behaviour of Housner's (1963) [22] model tank under lateral loading while considering the soil-structure interaction. The author concludes that slender behaves better under seismic loading, reducing the base shear, displacement, and fragility.

D. Rupesh Kumar, M. Gopal Naik, Fahimeh Hoseinzadeh(2015) [4] Author studied the efficiency of a water tank modeled as TMD located at a different storey to reduce the seismic response. The mass ratio is set at 5%. The water tank is modelled with the help of 3-gauss points and situated at the mid-storey; it reduces max. Deflection, base shear, and period.

Deepak P. Kadam, Atul B. Pujari, and Vipul N. Khosla(2019) [5] studied the efficiency of TMD in reducing wind and lateral seismic loading. The mass ratios of 2, 3, and 5% are chosen for study. Results show that if the optimum parameters are selected for TMD, it will give the best efficiency.

Ayman Mohammad Mansour, Moustafa Moufid Kassem, Fadzli Mohamed Nazri (2020) [10] researched the best suitable staging system for the rcc water tank. Housner's(1963) [22] 2 mass model has been adopted. This study proves that cross and radial staging perform better under seismic loading.

M.K. Shrimali, R.S. Jangid (2004) [15] Researched adaptability of conventional methods of modal combination methods like CQC and SRSS to analyse the non-classical damping case where the water tanks are 3 mass models have 2 degrees of freedom of convective and impulsive mass and an additional degree of freedom of isolation. The author found that the damping difference is not much in each degree of freedom, so these methods are applicable.

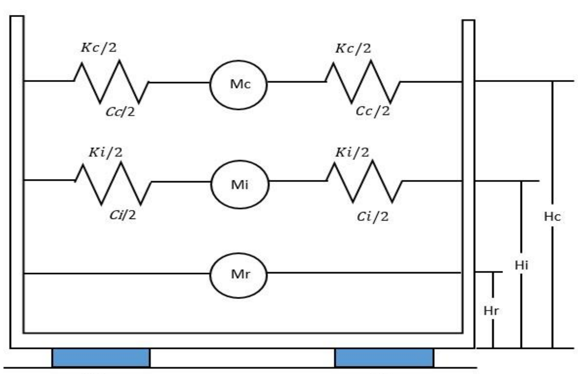


**Fig. 1 3 mass model of water tank**

Fahim Sadek, Bijan Mohraz, Andrew W. Taylor, and Riley M. Chung (1997) [16] have researched the optimum parameters of TMD for the SDOF and MDOF systems. Researchers found out that the best location for TMD in a building is on the top storey for the most effective results. Results show that an optimum tuned mass damper can reduce structure response by up to 50%.

G. Hemalatha and K.P. Jaya (2008) [17] analysed the G+2 and G+4 frames with a water tank modelled in the ANSYS software. The effectiveness of water tanks in reducing structure repose has been investigated. Fluid 80 elements were taken to model liquid in a tank. Results show that G+2 building response is reduced to a great extent compared to G+4 building when a water tank is used to work as TMD.

M.K. Shrimali, R.S. Jangid(2003) [20] In this numerical study, the author investigated the application of base isolation to reduce the response of elevated water tanks with the Haroun (1983) [21] 3 mass modal. In contrast, the staging mass is 5–10% of the mass of the water tank. In this study, the researchers concluded that irrespective of the isolation location in the frame, the overall response of the structure reduces considerably.

Medhat a. Haroun (1983) [21] has studied the behaviour of liquid-containing flexible tanks and developed a model (Fig.1). The researcher derived the parameters from investigating the performance, which concluded that it depends primarily upon the geometry and liquid properties for particular loading applied. The authors' numerical model mimics the actual liquid tank accurately.

## 3. Validation

Validation of two methods has been done here. When the structure is less than 15 m long and in zone II, it can be analysed using the equivalent static method; otherwise, the dynamic method is required according to IS 1893: 2016. For dynamic seismic analysis, it is necessary to approach the equivalent static method, modal analysis, and response spectrum. For equivalent static method validation, the numerical problem of IITK-GSDMA-EQ26 by H.J. Shah and S.K. Jain [27], G+6 Building, is taken. The validation results of this are shown in table 1.

Bharat Khanal and Hemchandra Chaulagain's (2020) [6] paper is taken to validate the response spectra method. In this, structural frames are analysed with response spectrum analysis. Using the analytical software ETABS, 3 random models from the paper were analyzed. The first model is a regular model, and the other two have irregularities. The results of modal analysis and response spectrum are shown in tables 2 and 3.

**Table 1. Equivalent static method Base shear and displacement**

| Storey | Numerical Model | ETABS Validation | % Accuracy |
|---|---|---|---|
| **Base Shear** | | | |
| **Base** | 1320 kN | 1325.69 kN | 99.56 % |
| **Story displacements** | | | |
| **Storey 7** | 79.43 mm | 81.88 mm | 96.91 % |
| **Storey 6** | 72.20 mm | 74.24 mm | 97.17 % |
| **Storey 5** | 60.01 mm | 61.57 mm | 97.4 % |
| **Storey 4** | 44.33 mm | 45.40 mm | 97.58 % |
| **Storey 3** | 26.75 mm | 27.34 mm | 97.79 % |
| **Storey 2** | 9.49 mm | 9.66 mm | 98.20 % |
| **Storey 1** | 0.41 mm | 0.42 mm | 97.56 % |
| **Base** | 0 mm | 0 mm | 100 % |

**Table 2. Modal analysis Period of the structure**

| Model | Research Paper | Validation | % Accuracy |
|---|---|---|---|
| **RRM** | 1.69 Sec | 1.66 Sec | 98.22 % |
| **IRM L2** | 1.68 Sec | 1.65 Sec | 98.21 % |
| **IRM L4** | 1.67 Sec | 1.63 Sec | 97.60 % |

**Table 3. Response spectrum max Displacement of the structures**

| Model | Research Paper | Validation | % Accuracy |
|---|---|---|---|
| RRM | 97.4mm | 90.69 mm | 93.11 % |
| IRM L2 | 99.2 mm | 91.51 mm | 92.24 % |
| IRM L4 | 101.20 mm | 95.08 mm | 1.95 |

## 4. Modeling

### *4.1 Modelling of structure*

For research, the structural frame which resembles a residential or commercial building is taken. This study creates G+4, G+9, and G+19 frames with and without a water tank. 5 models for each of the frames are created, in which the first frame is without a water tank, and the other four are with a water tank, as described in the table. ETABS-18 software was used for model creation and analysis.

All the models are symmetrical in plan and elevation from top to bottom. No irregularities like stiffness, mass, or re-entrant corners make the structure unsafe. The structure is assumed to be situated in zone IV. All floor heights are the same, at 3.5 m from top to bottom. Other details are shown below in Table 4. Here model images of only G+4 frames are shown. Other than optimized column sections and geometry, remaining elements, loading conditions, etc. are the same for G+4, G+9, and G+19. The column size varies as per requirement, but preliminarily optimized designed sections for the structures are displayed in Table 5.

**Table 4. Structure properties**

| Name | Property |
|---|---|
| Storey height | 3.5 m |
| Grid width | 3.5 m |
| Beam | 300 x 400 m |
| Slab | 150 mm |
| Material Property | |
| Reinforcement Steel | Fe 415 |
| Concrete | M 30 |
| Loading | |
| Dead Load | 2 kN/ m2 |
| Live Load | 4 kN/m2 |
| Seismic Load | As per IS -1893 |
| Zone | IV |
| Importance Factor | 1 |
| Soil type | Medium |
| Response Reduction Factor | 5 |

The steel material of the tank has a density of 7900 kg/m3 and a modulus of elasticity of 200 GPa. A rigid diaphragm is considered for all the floors. . All floors have 2 kN/m2 of dead load. The live load is 4 kN/m2 on all floors except the top floor. According to IS 1893, the live load is considered 50%. The grid cell dimension is 3.5 x 3.5 for every frame. The dimensions of G+4 and G+19 structures will be 17.5 x 17.5 m2, and for G+9, it will be 10.5 x 10.5 m2. The periphery wall loading of 230 mm is considered, which will exert a 17.5 kN/m load on beams. A perimeter wall is considered only on floors other than the rooftop.

### *4.2 Modelling of Water Tank*

#### *4.2.1 Calculation of water tank capacity*

For G+4 and G+9, both frames are assumed to have the same number of residents, so the water tank capacity is the same. Here the calculation for G+4 is displayed. It is assumed that residents occupy all the floors. The derived quantity is the same for G+9 but doubled for G+19, which is 72000 liters. Final dimensions of the tank in the tables taken to meet the nearer value of water requirement calculated below.

Per capita water requirement = 150 lpcd
The floor area of each floor is around = 3300 sq ft
Total residents assumed per floor = 24 Nos.
Total nos of floors are = 5 Nos.
Total residents in building will be = 24 x 5
= 120 Nos.

2 days Water requirement = 2 x 120 x 150
= 36000 liters

**Table 5. Optimized column section details**

| Floor Range | Section Size | Reinforcement |
|---|---|---|
| **G+19 Structure** | | |
| **17th-20th** | 320 x 320 mm | 12 - 20 ϕ |
| **13th – 16th** | 400 x 400 mm | 12 - 20 ϕ |
| **9th – 12th** | 400 x 400 mm | 14 - 20 ϕ |
| **5th – 8th** | 500 x 500 mm | 14 - 20 ϕ |
| **Upto 4th** | 500 x 500 mm | 16- 20 ϕ |
| **G+9 Structure** | | |
| **8-9** | 300 x 300 mm | 8-20 ϕ |
| **5-7** | 350 x 350 mm | 12-20 ϕ |
| **Up to 4th** | 450 x 450 mm | 14-20 ϕ |
| **G+4 Structure** | | |
| **3-4** | 320 x 320 | 12-20 ϕ |
| **Up to 2nd** | 400 x 400 | 12-20 ϕ |

Here in the study, flexibility of water tank is considered, so modelling of water tank is done as per the 3 mass model given in Haroun (1983), which is also described in Shrimali and Jangid (2003 and 2004). The liquid in the water tank will be divided into convective, impulsive, and rigid masses. The masses and heights can be calculated from the above papers. The property of links connect these masses can be calculated from the above papers for modelling in ETABS.

**Table 6. Water tank properties for G+4 and G+9**

| Model | Radius (m) | Slenderness ratio | Nos of Water tank |
|---|---|---|---|
| **Model 1** | - | - | - |
| **Model 2** | 1.8 | 1.94 | 1 |
| **Model 3** | 1.8 | 1.94 | 1 |
| **Model 4** | 2 | 0.70 | 2 |
| **Model 5** | 2.4 | 0.84 | 1 |

**Table 7. Water tank properties for G+19**

| Model | Radius (m) | Slenderness ratio | Nos of Water tank |
|---|---|---|---|
| **Model 1** | - | - | - |
| **Model 2** | 2.47 | 1.52 | 1 |
| **Model 3** | 2.47 | 1.52 | 1 |
| **Model 4** | 1.8 | 1.94 | 2 |
| **Model 5** | 2.0 | 2.47 | 1 |

Here Convective and impulsive mass are connected to the water tank with a linear elastic link. Damping is 0.5% and 2% for links connected to convective and impulsive mass, respectively. Ratio to find out the thickness of the shell is t/R= 0.004.

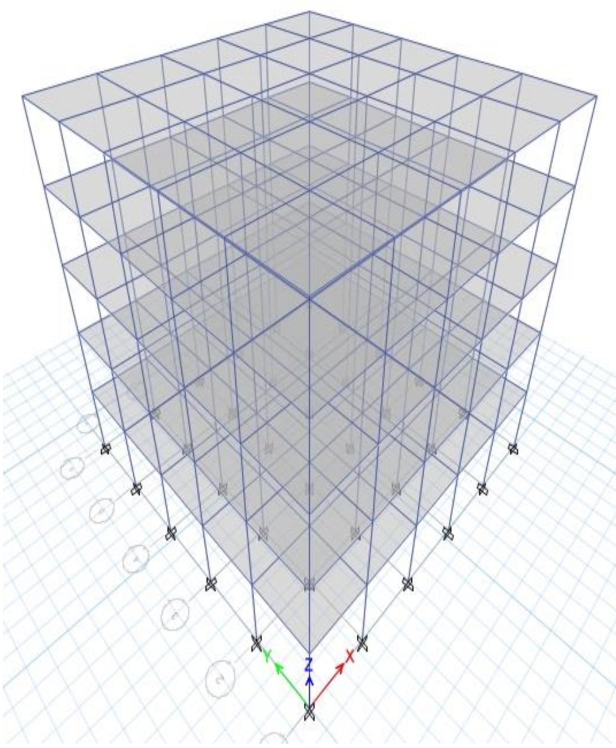

**Fig. 2 Model 1 (G+4)**

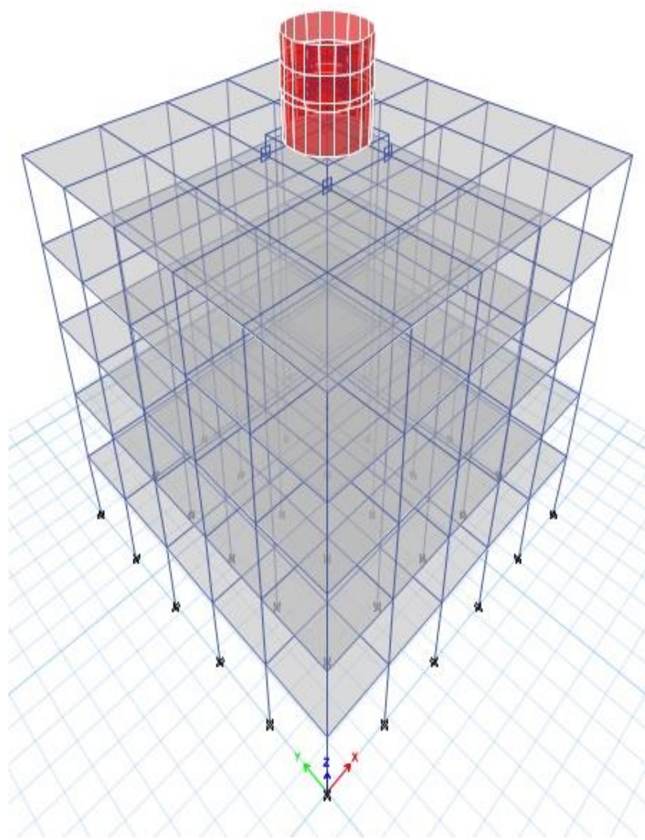

**Fig. 3 Model 2 (G+4)**

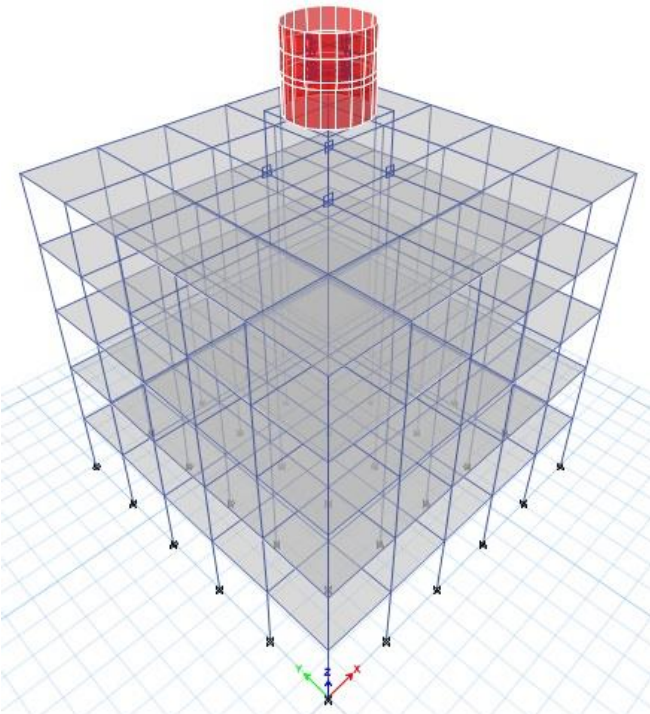

**Fig. 4 Model 3 (G+4)**

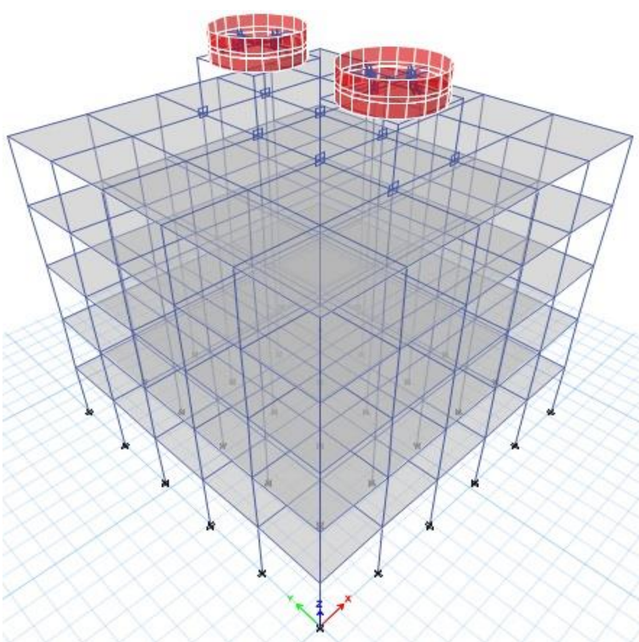

**Fig. 5 Model 4 (G+4)**

For this particular ratio, we can find out the height of this mass (Haroun (1983)). Water tanks are modelled for various slenderness ratios and positions, as shown in tables 6 and 7 for G+4, G+9, and G+19.

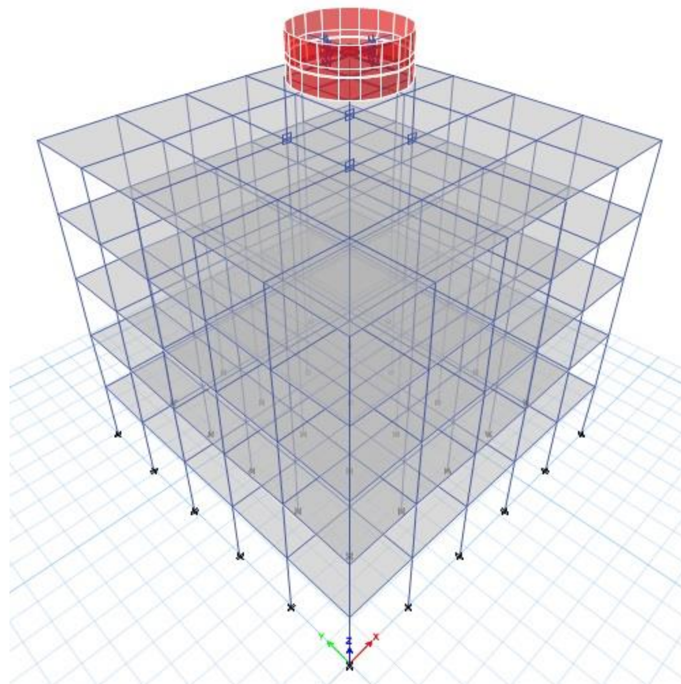

**Fig. 6 Model 5 (G+4)**

### *4.3. Modelling of Base isolation*

$$Tb = 2\pi * sqrt\left(\frac{Mi + Mc + Mr}{kb}\right)$$

$$\xi b = C\ b * (2 * (Mi + Mc + Mr) * \omega b)$$

The isolation system selected here is Lead Rubber Bearings (LRB). The behaviour of the isolation considered is linear elastic. Because the LRB has a limitation that the maximum damping that can be achieved in up to 30%, the damping of the isolation considered in this study is 30%. The period considered varies from 1 sec to 5 sec. Typically, isolation periods are chosen close to the structure's natural time. But here, it varies a little bit to meet the requirements of TMD.

## 5. Methodology

For seismic analysis, the parameters are as given in the table. For modal analysis of each frame, 3 modes per floor are considered, of which two are for X and Y directions, and the other is for torsional mode. The mass of every storey is considered at floor level. For water tanks, convective and impulsive mass can displace in the direction parallel to force, so an additional degree of freedom for mode must be considered. The same goes for the isolation system for

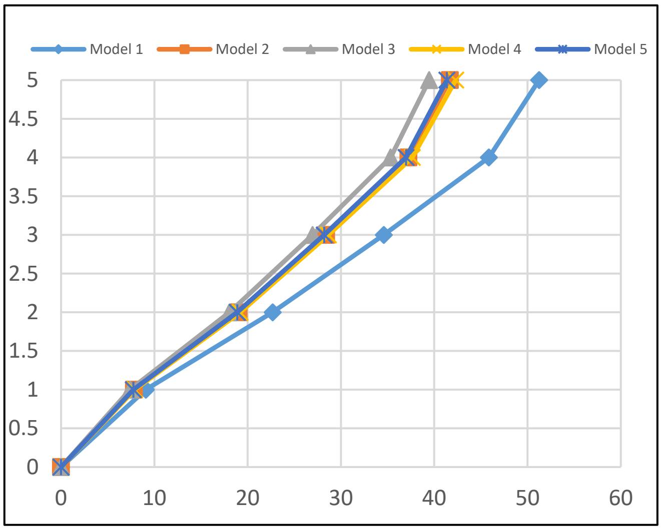

**Fig. 7 A-1 (Storey displacement values G+4 in mm)**

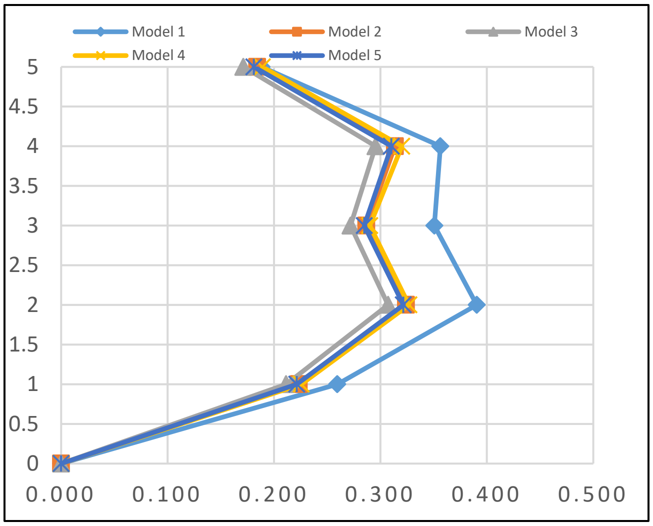

**Fig. 10 B-1 (Storey drift values G+4)**

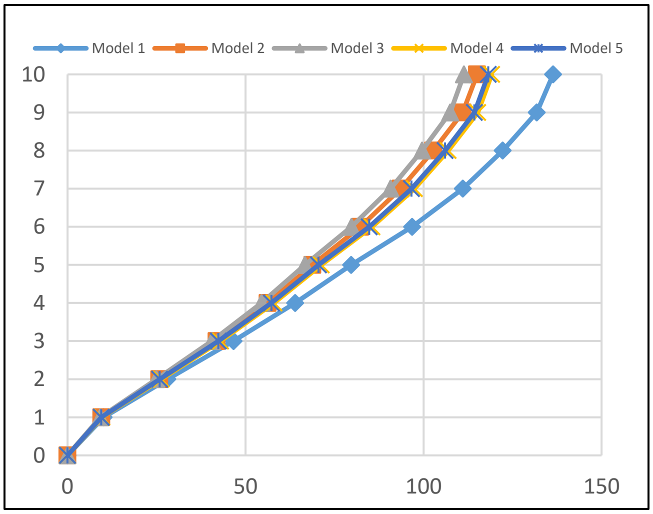

**Fig. 8 A-2 (Storey displacement valuesG+9 in mm)**

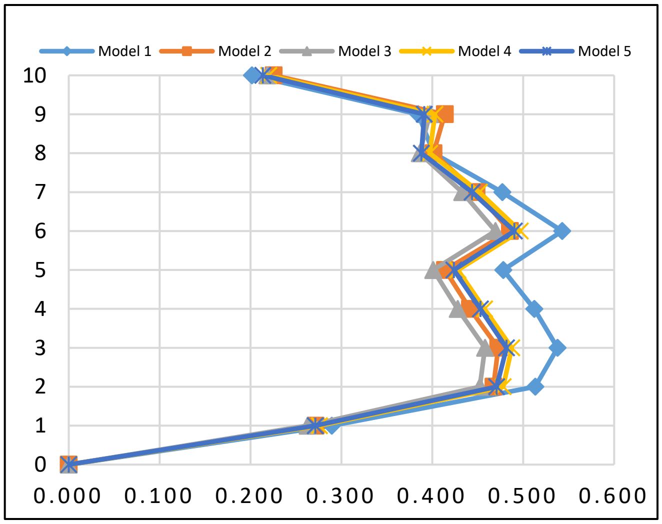

**Fig. 11 B-2 (Storey drift values G+9)**

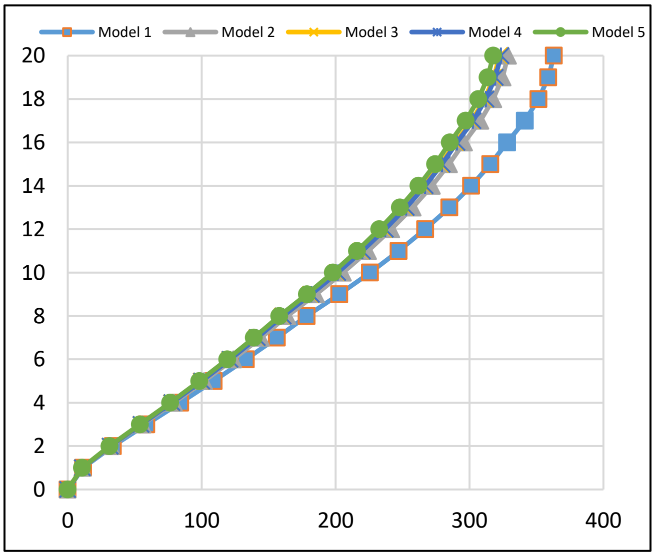

**Fig. 9 A-3 (Storey displacement valuesG+19 in mm)**

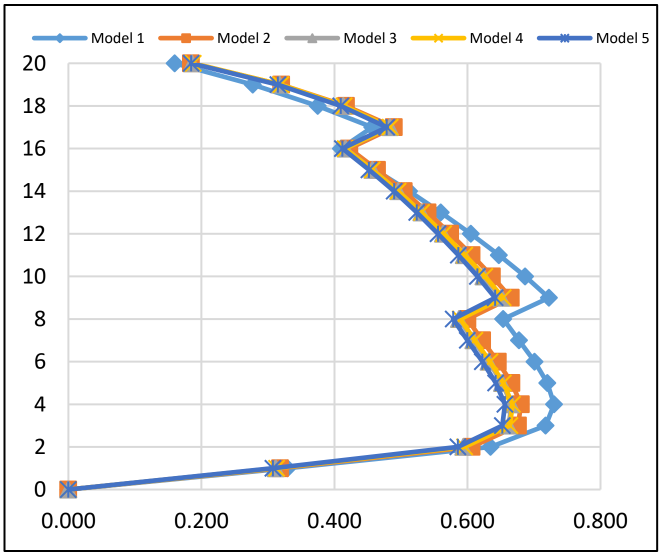

**Fig. 12 B-3 (Storey drift values G+19)**

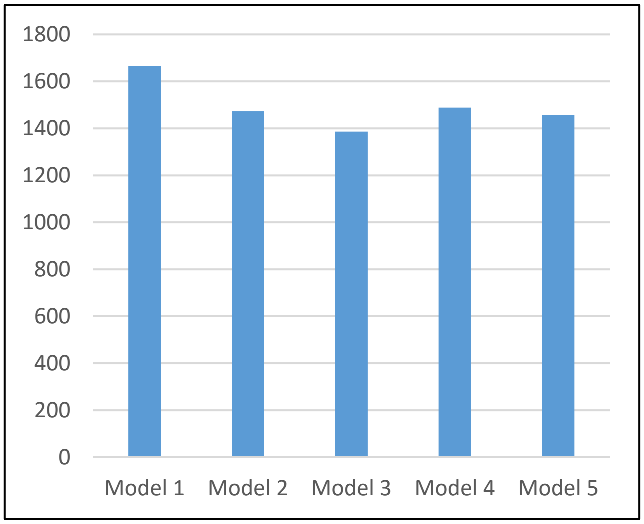


**Fig. 13 C-1 (Base Shear values G+4 in kN)**

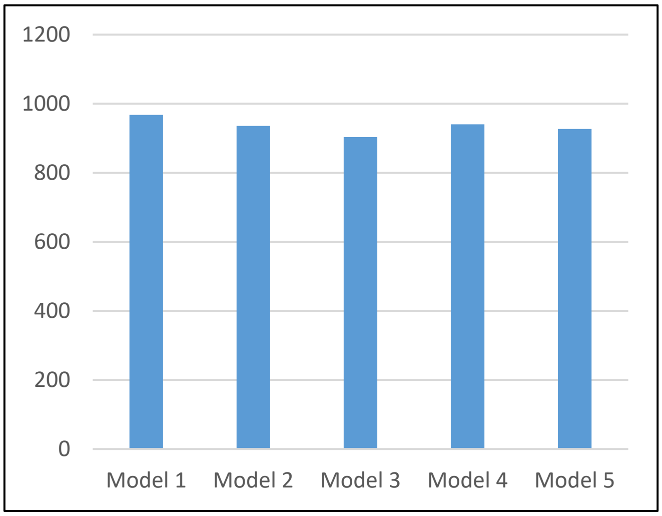


**Fig. 14 C-2 (Base Shear values G+9 in kN)**

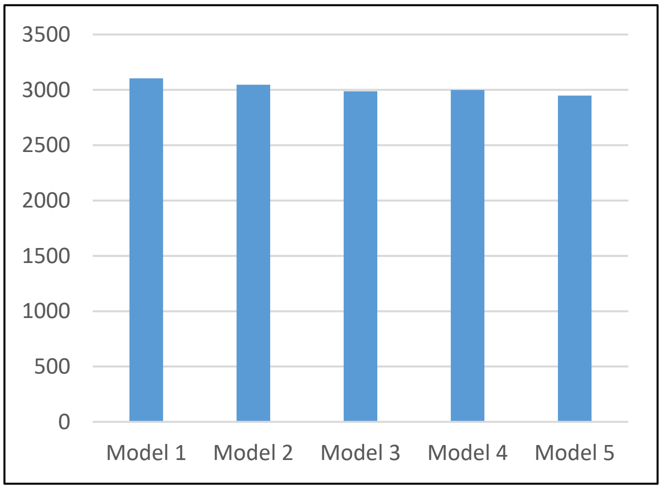


**Fig. 15 C-3 (Base Shear values G+19 in kN)**

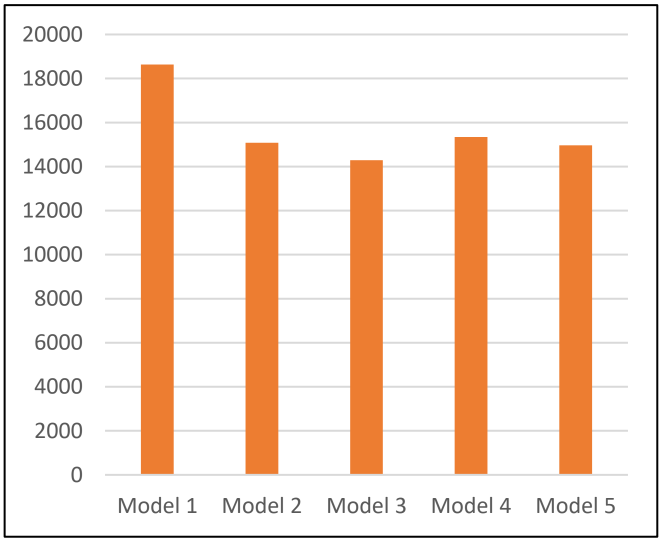


**Fig. 16 D-1 (Overturning moments G+4 in kNm)**

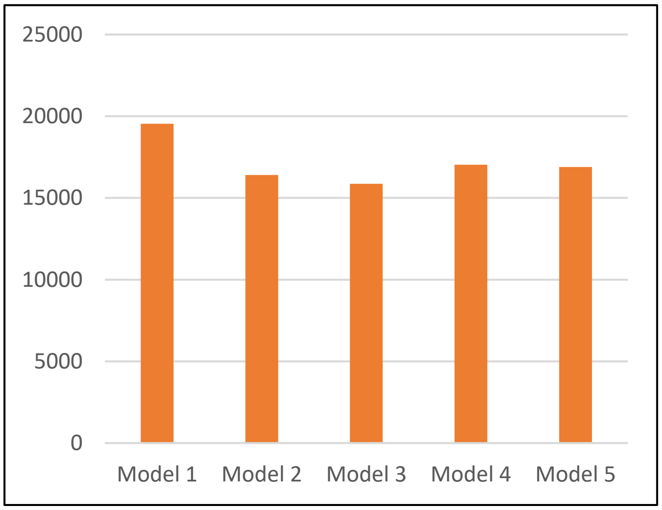


**Fig. 17 D-2 (Overturning moments G+9 in kNm)**

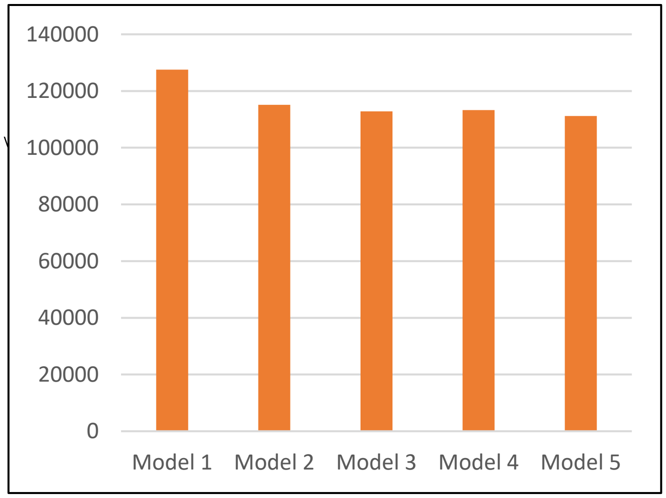


**Fig. 18 D-3 (Overturning moments G+19 in kNm)**

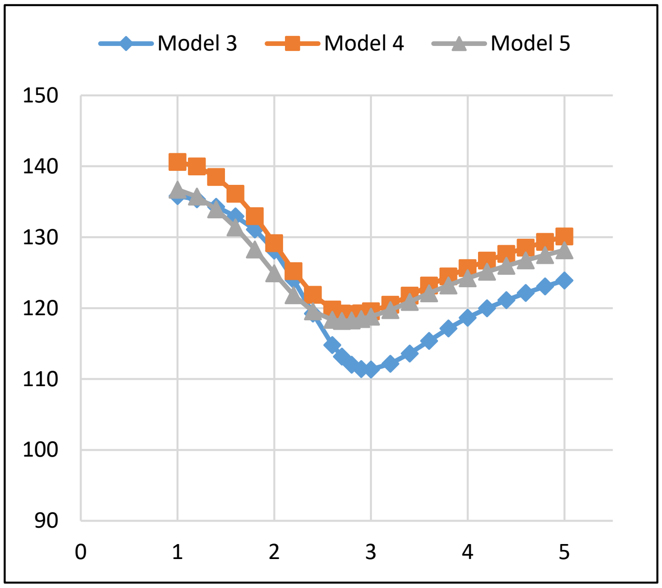


**Fig. 19 E (G+9 X- Period and Y-Max Displacement)**

Displacement parallel to loading an additional mode has to be considered. Here, the structure frame, convective, impulsive mass, and isolation system have different damping values, which is a case of non-classical damping. Still, modal combination rules like CQC and SRSS can be successfully applied as per previous research. The Response spectrum method is a conventional dynamic analysis method to analyse the behaviour of a structure under seismic loading. As per structural properties, natural vibration modes characterise the behaviour of a structure under applied seismic loading. Here, the Modal Combination Method of CQC is used for analysis in ETABS software. From this method, values like base shear, displacement, and drift for dynamic seismic loading can be gained.

In most cases, the modal mass ratio for particular axis mode shapes will be achieved in 90% of the $3^{rd}$ to $5^{th}$ mode for a particular direction. Suppose the value of base shear by dynamic analysis is less than the value by the equivalent static method. In that case, the base shear ratio by equivalent static to response spectrum should be taken as a multiplying factor. The I.S. 1893:2016 standard describes the analysis method adopted here. The water tank mass will make a Tuned Mass Damper system mass ratio range of 1.5-4%, and the frequency ratio range will be near 1.

## 6. Results

### *6.1. Storey Displacement*

An analysis is done, and each structure's maximum possible response reduction for an optimised value of damping and period of the isolator is found. After analysis, the maximum displacement is seen in the structure without a 363.094, 328.783, 322.409, 323.409, and 317.76 for Models 1, 2, 3, 4, and 5. The reduction seen in Model 5 is about 12.48%.

### *6.2. Storey Drifts*

In the chart, B-1, B-2, and B-3 storey drift values are multiples of 100. As seen in the max storey displacement here, storey drifts are the maximum for the structure without a water tank. And after the application of water tank storey drifts in all other models. The maximum reduction is seen in Model 3 of both G+4 and G+9. Model 5 has lower storey drifts for G+19 structures.

### *6.3. Base Shear*

For G+4 Models, the base shear values of Models 1, 2, 3, 4, and 5 are 1665.39, 1472.61, 1386.11, 1457.78, and 1488.54 kN. Here, the maximum possible base shear reduction is seen in Model 3, which is 16.77%. Base shear values for G+9 structural models 1, 2, 3, 4, and 5 are 967.543, 903.1, 935.5, 940.4, and 926.9 kN. As in the previous results, the maximum reduction in base shear is visible in Model 3, which is 6.67%. Models 1, 2, 3, 4, and 5 have base shear values of 3104.92, 3046.89, 2987.79, 2999.39, and 2947.70, respectively. The maximum possible reduction of base shear shown in Model 5 is 5%.

### *6.4. Overturning movements*

Graph D-1, D-2 and D-3 are overturning movement values for G+4, G+9, and G+19 buidings. The maximum reduction is seen in model 3, which is 23.32 % for G+4 building in graph D-1. Maximum reduction for G+9 building is also seen in model 3, which is 18.78%. For G+19, model 5 gives a max reduction of 12.78%.

## 7. Conclusion

The study's results suggest that applying an isolated water tank can reduce seismic response. The mass ratio is the major difference between this study and the previous studies on the 3-mass water tank. Previous studies were done on overhead tanks, which have the majority of the mass of the whole structure lumped at the water tank itself. Still, most of the results match up to some extent with the previous studies.

The overall water tank's vibration is out of phase, the sloshing mass also displaces, and the combined effect of both affects the overall response. Since the behaviour of the overall water tank and isolation system is complex, an optimised value of all the parameters must be found for the best efficiency. The natural period of the G+4 structure is less than G+9 and G+19. The results show that the response reduction seen in G+4 is greater compared to G+9 and G+19, which is consistent with previous findings that the response of rigid base structures reduces more. The response reduction is very small in G+19 as the building becomes more flexible and the natural period increases compared to others

When the flexibility of the isolation system increases, the sloshing mass displaces more. From the results, it can be seen that structure response increases for lower and higher periods of isolation, but the maximum response reduction seen (Graph E) in all structures is when the period of the isolation system is near to the natural period of the structure. The study shows that the percentage reduction in base shear values is not as much as the storey displacements.

In G+4 and G+9, model 3 has a more slender water tank; in G+19, model 5 has a slender tank that gives maximum reduction. That's why the geometry of the tank also considerably affects the response. One slender tank works better as a damper than a broad tank, and two water tanks adopt. Increasing the height of the water tank from the floor results in an increase in efficiency, which can be seen in the comparison of model 2 and model 3. The model 2 water tank almost directly rests upon the floor, while the model 3 water tank has a 2.5 m staging.

Overall damping factor does not affect considerably. Max reduction is possible in displacement and base shear when damping is maximum in LRB, which has a maximum possible value of damping factor of 30%.

Finally, it can be said that proper selection of geometry, location, and optimised Damper parameters is an efficient way to reduce seismic structure response.

## Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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