International Journal of Advanced Research in Computer Science & Technology (IJARCST)

| ISSN: 2347-8446 | www.ijarcst.org | editor@ijarcst.org |A Bimonthly, Peer Reviewed & Scholarly Journal|

||Volume 8, Issue 5, September-October 2025||

DOI:10.15662/IJARCST.2025.0805002

A Comparative Study on Seismic Analysis of Elevated Water Tanks with Different Staging Arrangements as per IS 1893 (Part-2): 2014

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ABSTRACT: An earthquake is a natural phenomenon caused by the sudden release of stored energy within the Earth's crust, which propagates as seismic waves on the surface. Earthquakes typically manifest through ground shaking, displacement, and, in certain cases, the generation of tsunamis, often resulting in significant loss of life and damage to infrastructure. Ensuring the seismic safety of civil engineering structures is therefore of utmost importance. Among these, liquid storage tanks (both ground-supported and elevated) play a vital role in water supply, firefighting systems, and industrial use. Elevated liquid storage tanks, however, are particularly critical because a large lumped mass of liquid is supported at a considerable height on staging systems that are often vulnerable during seismic events. Consequently, the seismic analysis of such tanks requires special considerations to account for the hydrodynamic forces generated by the sloshing action of liquid on the tank walls during an earthquake.

This study presents a comparative seismic analysis of four different staging systems for rectangular elevated liquid storage tanks with a capacity of 250 m³. The analysis is carried out in accordance with IS 1893 (Part-2): 2014. To study the influence of staging configuration on seismic performance, four structural models (Model-I, Model-II, Model-III, and Model-IV) are developed, incorporating different arrangements of frames, shear walls, and bracings. The seismic behaviour is assessed for Zone IV conditions on hard soil, considering two tank-fill scenarios: full tank and empty tank. The study highlights the effect of staging patterns on the seismic response and structural performance of elevated liquid storage tanks.

A program has been developed in Microsoft Excel for the seismic analysis of elevated liquid storage tanks, based on the GSDMA guidelines provided by NICEE, IIT Kanpur. The study focuses on comparing key structural parameters such as lateral stiffness, displacement, fundamental time period, seismic base shear, and overturning moment at the base of staging and hydrodynamic pressure.

The present study will be helpful to Civil Engineers enabling a better understanding of the influence of staging system configurations on the seismic performance of elevated liquid storage tanks.

KEYWORDS: *Elevated liquid storage tank, IS: 1893- (Part-2) 2014, staging pattern,* lateral stiffness, displacement, time period, seismic base shear, overturning moment *seismic analysis.*

I. INTRODUCTION

According to seismic code IS: 1893(Part I):2002, more than 60% geographic part of India is prone to earthquakes. Ensuring the seismic safety of civil engineering structures is therefore of utmost importance. Among these, liquid storage tanks (both ground-supported and elevated) play a vital role in water supply, firefighting systems, and industrial use. Elevated liquid storage tanks, however, are particularly critical because a large lumped mass of liquid is supported at a considerable height on staging systems that are often vulnerable during seismic events. Consequently, the seismic analysis of such tanks requires special considerations to account for the hydrodynamic forces generated by the sloshing

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action of liquid on the tank walls during an earthquake. Again the knowledge about supporting systems is highly essential. In case of elevated tank the resistance against lateral forces exerted by earthquake is largely dependent of supporting system. Staging is considered to be a critical element as far as lateral resistance is concern. Satisfactory performance of staging during strong ground shaking is crucial. So it is very important to select proper supporting system.

II. MODELLING AND ANALYSIS

2.1 HYDRODYNAMIC PRESSURE IN TANKS

When the tank moves, it generates impulsive and convective pressures in the fluid. The impulsive pressures are those associated with the forces of inertia produced by impulsive movements of the walls of the container and the pressures developed are directly proportionally to the acceleration of the container walls. The convective pressures are those produced by oscillation of the fluid and are thus the consequences of the impulsive pressures. Hydrodynamic forces are being considered in the analysis in addition to hydrostatic forces. These both forces are evaluated with the help of spring mass model of tanks. Shown in figure 1.

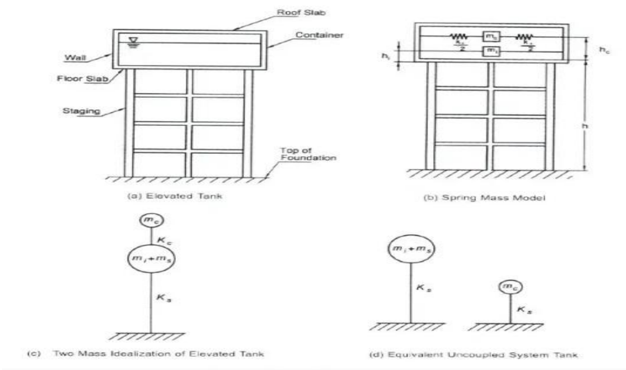

Figure 1: Two mass idealization of elevated tank [6]

2.2 SPRING MASS MODEL FOR SEISMIC ANALYSIS

Assuming the fluid to be in-compressible and fluid displacements small, the analytical results have been obtained such that the impulsive pressures are simulated by a rigid mass attached to the wall of the tank and the convective pressures by a spring mounted mass as shown in [figure.1 (b)]. The parameters of this model depend on geometry of the tank as well as its flexibility.[1]

For elevated tanks, the two degree of freedom system shown in [figure. 1(c)] can be treated as two uncoupled single degree of freedom systems [figure.1 (d)], one representing the impulsive plus structural mass behaving as an inverted pendulum with lateral stiffness equal to that of the staging, Ks and the other representing the convective mass with a spring of stiffness, Kc.[5].

Lateral stiffness of staging Ks is being calculated by modeling the staging in finite element based software package [ETABS-2013]. The staging is modeled and a rigid link is provided at the top of staging up to the height of container C.G to get the lateral stiffness of the staging. .[9]

The critical damping in the impulsive mode is considered as 5 % for the concrete tanks.

Approximate fundamental natural period of vibration, in seconds for Special Moment Resisting Frame i.e (S.M..R.F) is calculated using

2.2.1 Approximate fundamental natural period of vibration (T_i and T_c)

$$T_i = 2\pi\sqrt{\frac{(m_i+m_s)}{K_s}} \quad \text{And} \quad T_c = Cc\sqrt{\frac{D}{g}}$$

[Clause 4.3.1.3 & 4.3.2.2(a) of IS: 1893 - (Part-2):2014][6]

2.2.2 Base shear (V)

$V_i = (A_h)_i\ (m_i + m_s)\ g$ Impulsive mode

$V_c = (A_h)_c\ (m_c)\ g$ Convective mode

Total base shear at the bottom of staging

$$V = \sqrt{(V_i)^2 + (V_c)^2}$$

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2.2.3 Base moment (M).

$M_i = (A_h)_i \left((h_i^* + h_s)\ m_i + h_{cg}\ m_s\right)\ g$ Impulsive mode

$M_c = (A_h)_c\left((h_c^* + h_s)\ \ m_s\right) g$ Convective mode

Total overturning moment at the base of staging

$$M = \sqrt{(M_i)^2 + (M_c)^2}$$

[Clause 4.7.2 and 4.7.3 of IS: 1893 - (Part-2):2014][6]

[Clause 4.6.2 and 4.6.3 of IS: 1893 - (Part-2) :2014][6]

2.2.4 Total maximum hydrodynamic pressure

The maximum value of hydrodynamic pressure is being obtained by combining pressure due to horizontal and vertical excitation, which can be given as[6]

$$P = \sqrt{(P_{iw} + P_{ww})^2 + (P_{cw})^2 + (P_V)^2}$$

Where, P_{iw} and P_{cw} = Impulsive and convective hydrodynamic pressure respectively.

[CLAUSE 4.10.2 OF IS: 1893 - (PART-2):2014][6]

III. METHODOLOGY

The methodology includes the selection of type of water tank, fixing the dimensions of components for the selected water tank and performing equivalent static analysis by IS: 1893- 2002 (Part 2) 2014. In this study, a reinforced concrete 250 Cu.m capacity rectangular overhead water tank is considered for analysis. It is analysed for four different staging patterns with height of panel at each storey is considered as 4 m, single soil types, i.e. hard rock and for two tank-fill conditions, i.e. tank full, and tank empty conditions. Lastly, the results of the analysis of rectangular tank performed on the basis of IS: 1893-2002 (Part 2) 2014 have been compared. Grade of concrete and steel used are M30, Fe 415 & Special Moment Resisting Frames and shear walls or bracings are used appropriately. The analysis of staging was carried out using the software ETAB-2013.

Finally parameters such as base shear, displacement, moments and time period for the above four models are presented.

Models for earthquake analysis

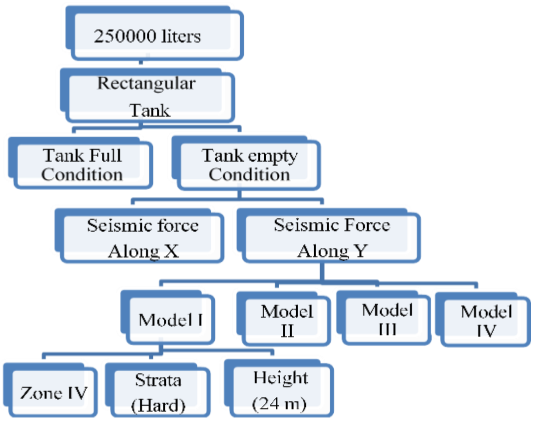
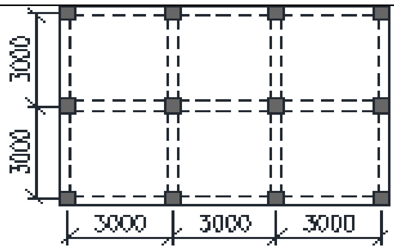
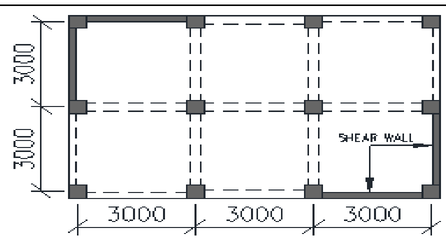


Figure 2. Models for earthquake analysis

Table 1: Description of models in plan view of **Model 1, Model 2, Model 3, and Model 4** elevated liquid storage tanks showing different staging system configurations.

 **Figure 3.** Model-1 –Frame Staging system	 **Figure 4.** Model-2- 90^o Shear wall staging system

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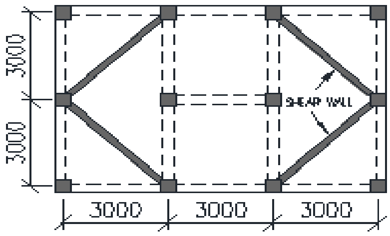

Figure 5. Model-3 45° Shear wall staging system

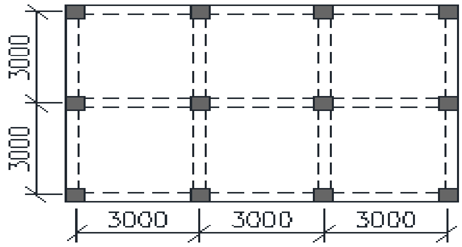

Figure 6. Model- 4-Braced-X frame staging system

IV. EXPERIMENTAL RESULTS

In this study, an attempt is made to evaluate the seismic performance of elevated liquid storage tanks supported on four different types of staging systems. The earthquake analysis is carried out for 2,50,000 liter's capacity reinforced cement concrete (RCC) elevated liquid storage tanks, each modelled with four different supporting systems having the same overall height of 24 m. To maintain uniformity in comparison, the same soil conditions, seismic zone parameters, and other influencing factors are considered. Both tank full and tank empty conditions are analyzed to assess the structural behaviour under varying loading scenarios. The analysis is performed to study parameters such as lateral stiffness, displacement, time period, seismic base shear, and overturning moment, hydrodynamic forces which help in understanding the effect of different staging systems on the seismic performance of elevated liquid storage tanks.

4.1.1 Displacement for ESR (Elevated Storage Tank) supported on different types of supporting system.

Figure7 and 8 illustrates lateral displacement for models M-1 to M-4 under EQ-X and EQ-Y. Model M-3 shows the least displacement in both tank fill conditions (i.e. full and empty) due to increased stiffness from diagonal shear walls. In contrast, Model M-4 exhibits higher displacement as reduced structural mass lowers stiffness.

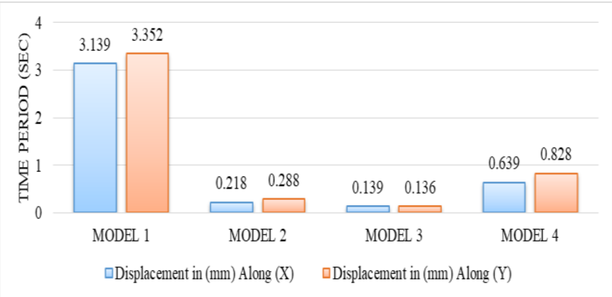

Figure 7. Lateral Displacement of ESR – Tank Full.

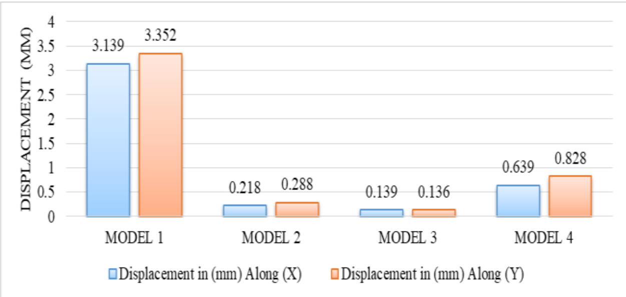

Figure 8. Lateral Displacement of ESR – Tank Empty.

4.1.2 **Time period for ESR supported on different types of supporting system**

Figure 8 and 9 shows, the Impulsive time period is minimum **for** Model M-3 in both seismic directions (EQ-X & EQ-Y) and for both tank conditions (full and empty), due to added stiffness from diagonal shear walls. In Model M-4**, it** increases again as structural mass decreases. Convective time period remains constant across models in the same direction, but varies between EQX and EQY due to the container's aspect ratio.

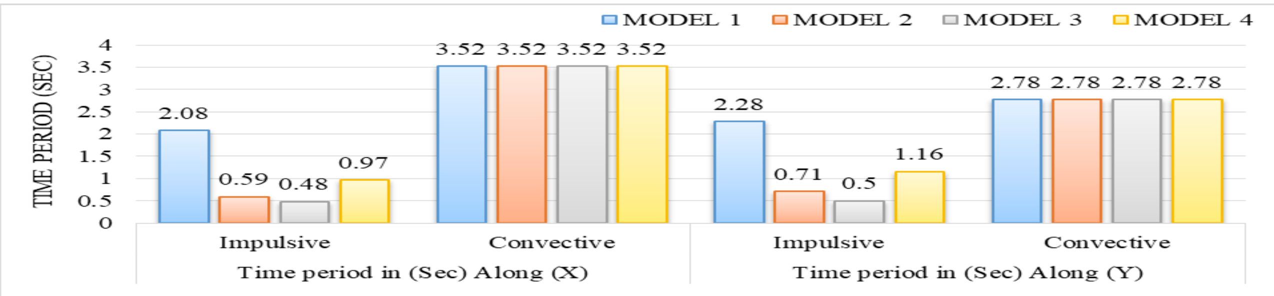

Figure 8. Time Period for ESR – Tank Full Condition

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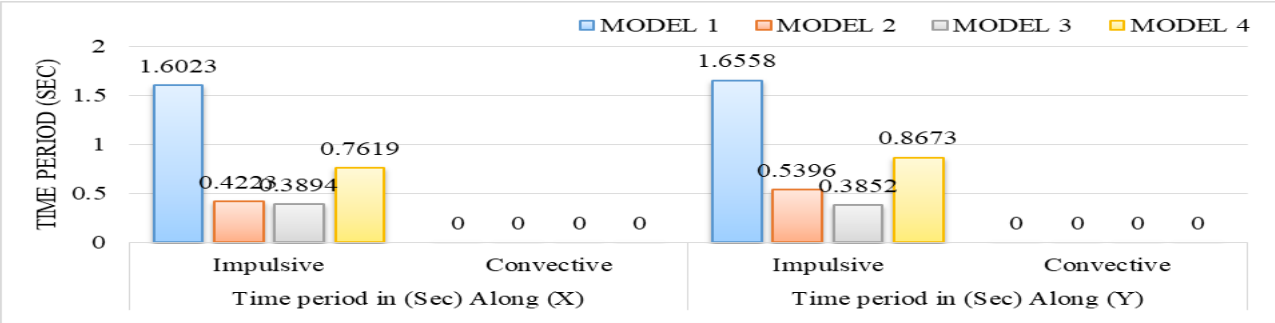

Figure 9. Time Period for ESR –Tank Empty Condition

4.1.3 **Base shear for ESR supported on different types of supporting system.**

Figure10 and 11 illustrates Base Shear represents the total horizontal seismic force acting at the base of the staging system. The analysis shows that:

- Model M-1 records the minimum base shear in both seismic directions (EQ-X & EQ-Y) and under both tank conditions (full and empty). This is because Model M-1 uses regular frame staging, which reduces the overall mass of the structural system. A lower mass directly results in reduced seismic forces, hence minimum base shear.
- Model M-3 attracts the maximum base shear. In this model, diagonal shear walls are provided along with the regular frame staging. This significantly increases the mass and stiffness of the staging system. Since seismic base shear is proportional to mass, the larger structural mass in Model M-3 leads to higher base shear compared to all other models.
- Model M-4 shows a reduction in base shear compared to Model M-3, as the structural mass decreases when the staging is modified. With less mass, the seismic force acting at the base is also reduced.
- Across all models, base shear values vary between EQ-X and EQ-Y directions due to the aspect ratio of the liquid container, which influences the dynamic characteristics of the tank.

Thus, Model M-1 is most efficient in minimizing base shear, while Model M-4 experiences the maximum demand due to its heavier structural configuration.

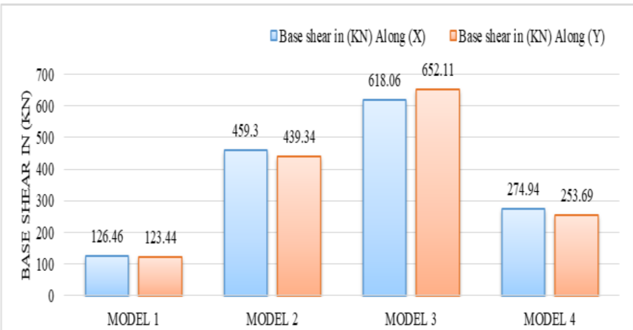

Figure 10. Base shear for ESR in Tank Full Condition

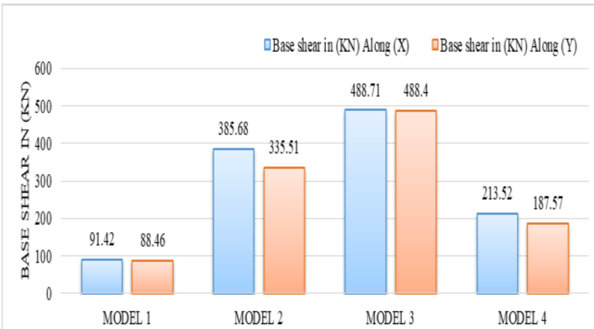

Figure 11. Base shear for ESR in Tank Empty Condition

4.1.4 **Overturning moment for ESR supported on different types of supporting system.**

Figure 11 and 12 illustrates Overturning Moment represents the rotational effect of seismic forces acting at the base of the staging system. The results of the analysis show the following trends:

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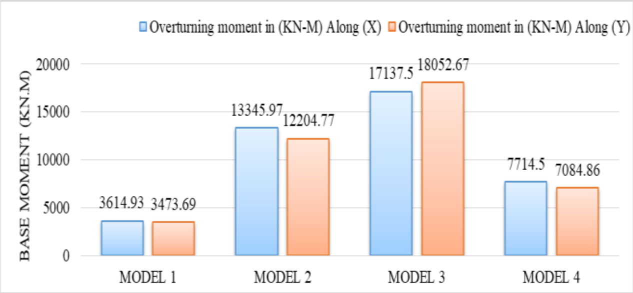

Figure 12. Base Moment for ESR in Tank Full Condition

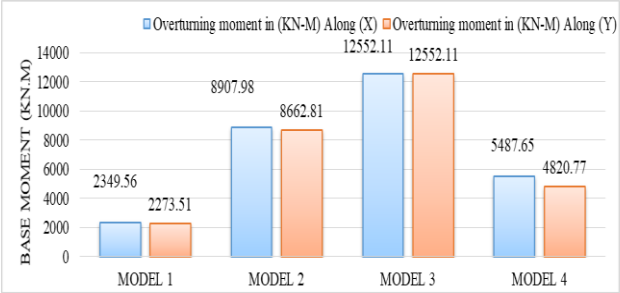

Figure 13. Base Moment for ESR in Tank Empty Condition

- Model M-1 experiences the minimum overturning moment in both seismic directions (EQ-X & EQ-Y) and for both tank conditions (full and empty). This is because regular frame staging provides comparatively lower mass in the structural system, and since overturning moment is directly influenced by the magnitude of seismic force and structural mass, the reduced mass leads to a smaller overturning effect.
- Model M-3 exhibits the maximum overturning moment. This model includes diagonal shear walls along with regular frame staging, which significantly increases the mass and stiffness of the staging system. As a result, the seismic forces acting on the structure are larger, and their lever arm effect at the base produces a greater overturning moment compared to other models.
- Model M-4 shows a reduction in overturning moment compared to Model M-3, as the staging mass is reduced. With less mass, the seismic forces decrease, which in turn lowers the overturning moment.
- For all models, the overturning moment values differ between EQ-X and EQ-Y directions due to the aspect ratio of the liquid container, which alters the dynamic response in each direction.

Thus, Model M-1 is most effective in reducing overturning moment because of its lighter structural mass, while Model M-3 attracts the maximum overturning moment due to its heavier staging configuration with diagonal shear walls.

4.1.5 **Hydrodynamic pressure for ESR supported on different types of supporting system.**

Graphs are plotted between models (M-1–M-4) and the corresponding hydrodynamic pressures under seismic excitation. The following observations are made:

1. **Impulsive Hydrodynamic Pressure (y = 0):**

- Minimum for Model M1, due to reduced mass from regular frame staging.
- Maximum for Model M3, as the addition of diagonal shear walls significantly increases the structural mass and stiffness, attracting higher impulsive pressure.
- This trend is consistent in both seismic directions **(**EQX and EQY**).**

2. **Impulsive Hydrodynamic Pressure (y = h):**

- Found to be zero for all models in both seismic directions.
- This is because, at the top liquid level, the impulsive pressure diminishes as the liquid motion is primarily convective.

3. **Convective Hydrodynamic Pressure (y = 0):**

- Remains constant across all models for both EQX and EQY.
- At the tank base, convective effects are negligible compared to impulsive effects, leading to uniformity in results.

4. **Convective Hydrodynamic Pressure (y = h):**

- Also found to be constant for all models in both directions.
- Since convective pressure primarily depends on the liquid sloshing behaviour, it is governed by the tank's liquid depth and geometry rather than the staging system.

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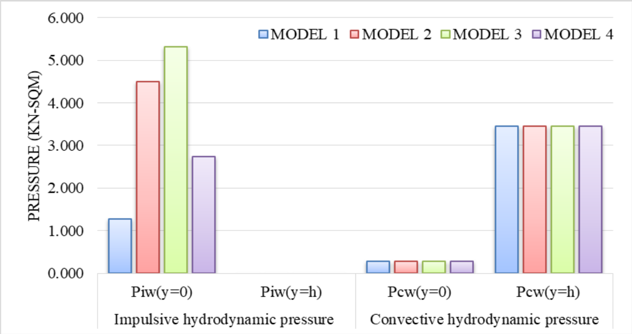

Figure 14. Hydrodynamic pressure in (kN-m^2) for ESR - (Tank full condition)

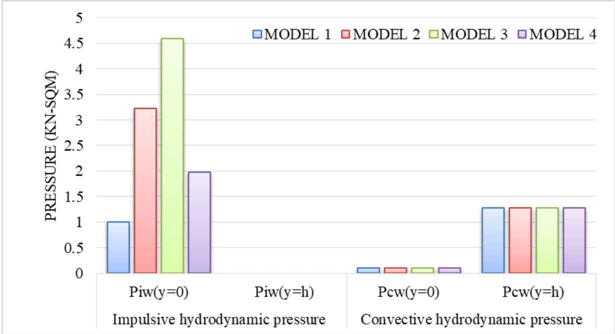

Figure 15. Hydrodynamic pressure in (kN-m^2) for ESR - (Tank Empty condition)

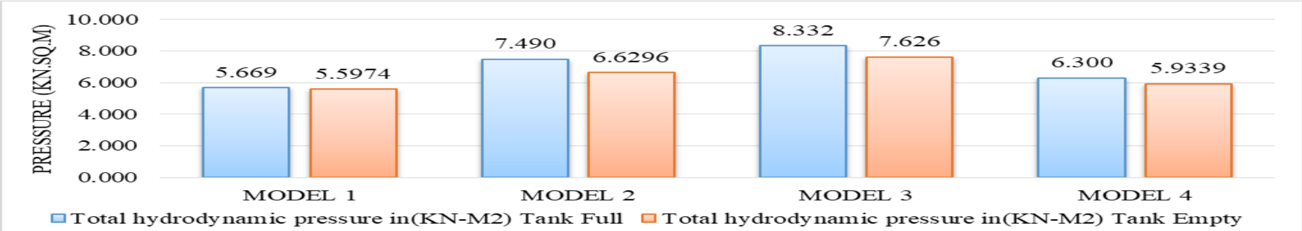

Figure 16. Total hydrodynamic pressure in (kN-m^2) (Tank Full and Empty condition)

V. CONCLUSION

From the seismic analysis, it is observed that lateral displacement and impulsive time period decrease with an increase in structural mass, with Model M**-3** showing minimum values. However, higher mass results in larger seismic demands: base shear, overturning moment, and hydrodynamic pressur**es** are maximum in Model M3 and minimum in Model M-1**.** The convective time period and convective hydrodynamic pressure remain constant across all models, independent of staging configuration. Thus, Model M3 provides better control on displacement but attracts maximum seismic forces, while Model M1 experiences lower forces but higher displacement.

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