MSW MANAGEMENT -Multidisciplinary, Scientific Work and Management Journal
ISSN: 1053-7899
Vol. 36 Issue 2, 2026, Pages 1580-1584

Comparative Study of Multi-Tier Tanks with Different Staging Systems and Shear Wall Systems Using Dynamic Analysis

Anusha.K.S[1], **Manu S E**[2]
[1]PG Scholar, Department of Civil Engineering, JAIN (Deemed-to-be University), Bengaluru- 562112, Karnataka, India
[2]Assisstant Professor, Department of Civil Engineering, JAIN (Deemed-to-be University), Bengaluru- 562112, Karnataka, India
Corresponding author's email: anushaks104@gmail.com

ABSTRACT

Elevated water tanks are critical lifeline structures whose functionality must be maintained during and after seismic events. Experiences from past earthquakes have repeatedly highlighted the vulnerability of poorly designed supporting systems (staging) to lateral loads, often leading to significant damage or collapse. This study presents a comparative investigation into the seismic behavior of multi-tier elevated reinforced concrete (RC) water tanks utilizing various staging configurations, including traditional moment-resisting frames, framed systems with bracing, and systems incorporating shear walls. The primary objective is to evaluate and compare the dynamic response of these different structural systems under seismic excitation. Multiple tank models, varying in staging height and configuration, are analyzed using the response spectrum method as per relevant seismic codes. The analysis considers the hydrodynamic effects of the contained liquid, idealizing the water mass into impulsive and convective components. Key engineering demand parameters such as base shear, overturning moments, nodal displacements, and time periods are extracted and contrasted for each model under both empty and fully-filled conditions. The results aim to quantify the effectiveness of shear walls and different bracing systems in enhancing structural stiffness and stability, thereby reducing seismic vulnerability. The study identifies the optimum staging and shear wall configuration that offers superior earthquake resistance and performance, providing valuable insights for the design of safe and economical elevated water storage facilities

Keywords: Elevated water tank, Seismic analysis, Dynamic analysis, Staging systems, Shear walls, Response spectrum method, Base shear, Overturning moment, Fluid-structure interaction

1. Introduction

Elevated water tanks play an indispensable role in urban and rural water distribution systems by ensuring gravity-based supply and maintaining adequate water pressure during emergency conditions. Due to their large mass concentrated at an elevated level and relatively slender supporting structures, these tanks are particularly vulnerable to lateral seismic forces. Earthquake reconnaissance studies repeatedly indicate that damage to elevated tanks often originates in the staging system, leading to excessive displacement, cracking, or collapse.

Seismic design of liquid-retaining structures is governed largely by serviceability requirements, as uninterrupted functionality after earthquakes is critical for firefighting, sanitation, and post-disaster recovery. Unlike ground-supported or underground tanks, elevated tanks experience amplified inertia forces, large overturning moments, and complex fluid–structure interaction (FSI) effects due to liquid sloshing.

Although numerous studies focus on single-tier elevated tanks, modern infrastructure increasingly adopts multi-tier tanks to improve storage efficiency, operational flexibility, and land utilization. However, multiple tiers introduce additional mass irregularity, stiffness variation, and complex dynamic response, which are not adequately addressed in existing literature.

This study addresses this research gap by presenting a comparative seismic assessment of multi-tier elevated RC water tanks with different staging systems, focusing on the effectiveness of shear walls versus conventional frame staging under dynamic seismic loading.

Fig.1.1: Elevated Water Tanks showing different staging configurations and shapes.

Multi-tier elevated tanks:A multi-tier tank is a storage tank system constructed with two or more vertical levels (tiers) instead of a single large chamber. The tiers may be physically stacked or internally partitioned, depending on the application.Multi-tier elevated storage typically refers to a design method used for large concrete (RCC) water towers, where the storage container itself is designed with multiple internal compartments or tiers, often sharing a common supporting structure (staging).

This design approach allows for greater storage capacity in a concentrated vertical footprint, making efficient use of space, especially in urban areas. Having multiple compartments (tanks) within one overall structure allows for increased operational flexibility. For instance, one tank can be kept in service while another is taken offline for maintenance or inspection, ensuring a continuous water supply to the distribution system. The immense weight of stored water places exceptionally high demands on the supporting system, making a robust and carefully engineered structural framework absolutely essential. To safely carry these loads, supports are typically constructed using reinforced concrete columns or steel lattice towers, both of which are specifically designed for high strength and stability.

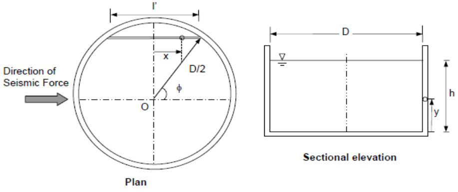
These structures must resist not only vertical loads—which include the self-weight of the tank, the weight of the water (often running into hundreds or thousands of tonnes), and live loads from maintenance but also lateral loads generated by environmental forces such as wind pressure and seismic activity. The supporting structure is the most vulnerable part of an elevated tank during seismic events. For multi-tier tanks, the staging must resist high lateral forces and the resulting bending moments and shear forces. Common staging systems include reinforced concrete (RC) frames with bracing (diagonal, X-bracing) or RC shafts, with braced systems generally offering more redundancy and energy absorption capacity.

The interaction between the stored liquid and the tank walls, along with the overall structure–soil interaction (SSI), plays a critical role in accurately predicting the seismic response of liquid storage tanks. During an earthquake, the contained liquid does not behave as a rigid mass; instead, it exerts hydrodynamic pressures on the tank walls that vary with height and time. These pressures arise from two primary components: the impulsive component, where a portion of the liquid moves in unison with the tank wall, and the convective (sloshing) component, where the liquid oscillates relative to the structure. Both components significantly influence the distribution of seismic forces, overturning moments, and stress demands on the tank shell and supporting system.

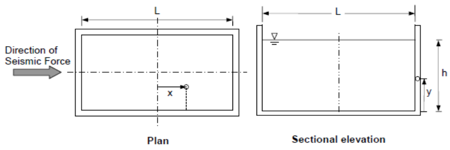
---

2. Hydrodynamic Behavior and Seismic Idealization

Hydrodynamic forces acting on tank walls depends on the shape or geometry of the tank such as circular or rectangular.



(a) Circular tank



(b) Rectangular tank

Fig.2.1: Direction of Seismic Force in Circular and Rectangular Tank

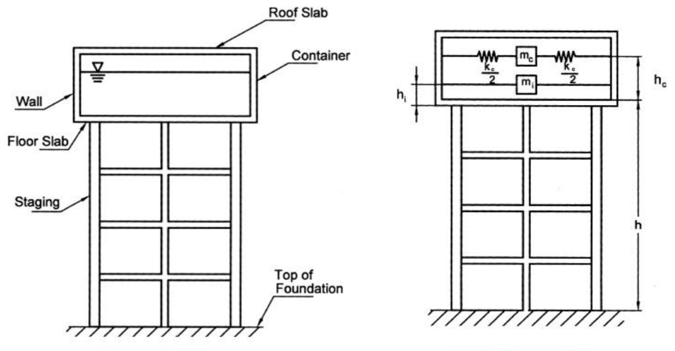
When subjected to ground motion, the liquid inside a tank does not behave as a rigid mass. As per IS 1893 (Part 2), the total liquid mass is divided into:

- Impulsive mass (mi): Moves synchronously with the tank wall and contributes directly to seismic inertia forces.
- Convective mass (mc): Represents sloshing liquid, oscillating relative to the tank wall.

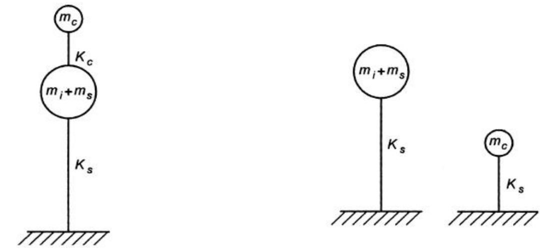
Elevated tanks are idealized using a two-degree-of-freedom spring–mass model, where:

- The impulsive mass (combined with structural mass) acts through staging stiffness.
- The convective mass is connected via a spring representing sloshing behavior.

This modeling accurately captures dynamic amplification, base shear, overturning moments, and wall hydrodynamic pressures.

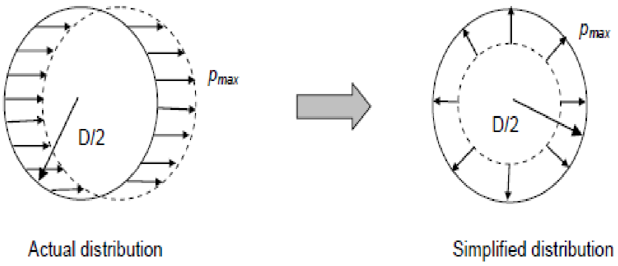


(a) Elevated Tank (b) Spring Mass Model

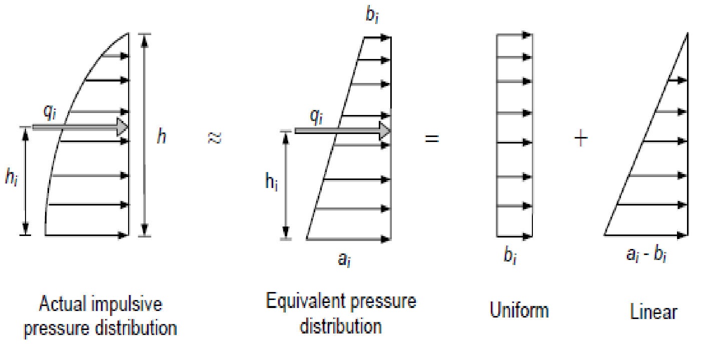


(c) Two Mass Idealization of Elevated Tank (d) Equivalent Uncoupled System Tank

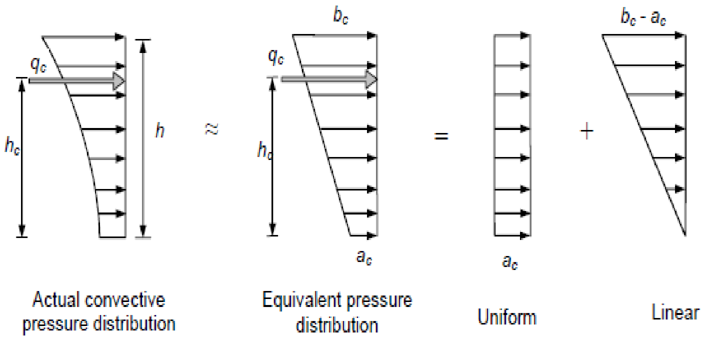
Fig 2.2: Spring mass model and two mass idealization for Elevated Tanks



(a) Simplified pressure distribution in circumferential direction on tank wall



(b) Equivalent linear distribution along wall height for impulsive pressure



(c) Equivalent linear distribution along wall height for convective pressure

Fig.2.3: Hydrodynamic pressure distribution for wall analysis

3. Model Description and Methodology

3.1 Tank Geometry and Configuration

A three-tier elevated RC water tank with the following configuration is considered:

- Plan dimension per tier: 20 m × 20 m
- Number of compartments: 4 (10 m × 10 m each)
- Water depth per tank: 4.5 m (+0.5 m freeboard)
- Number of tiers: 3
- Vertical spacing between tiers: 5 m

Two analytical models are developed:

- Model 1: Tank supported on beam-column framing
- Model 2: Tank supported on shear wall staging

3.2 Numerical Modeling

The models are developed in STAAD.Pro:

- Beams and columns are modeled using beam elements.
- Tank walls and shear walls are modeled using plate elements with refined meshing.
- Hydrostatic loads and Hydrodynamic loads are applied through linearly varying pressure.
- Impulsive liquid mass is included as lumped mass for seismic analysis.

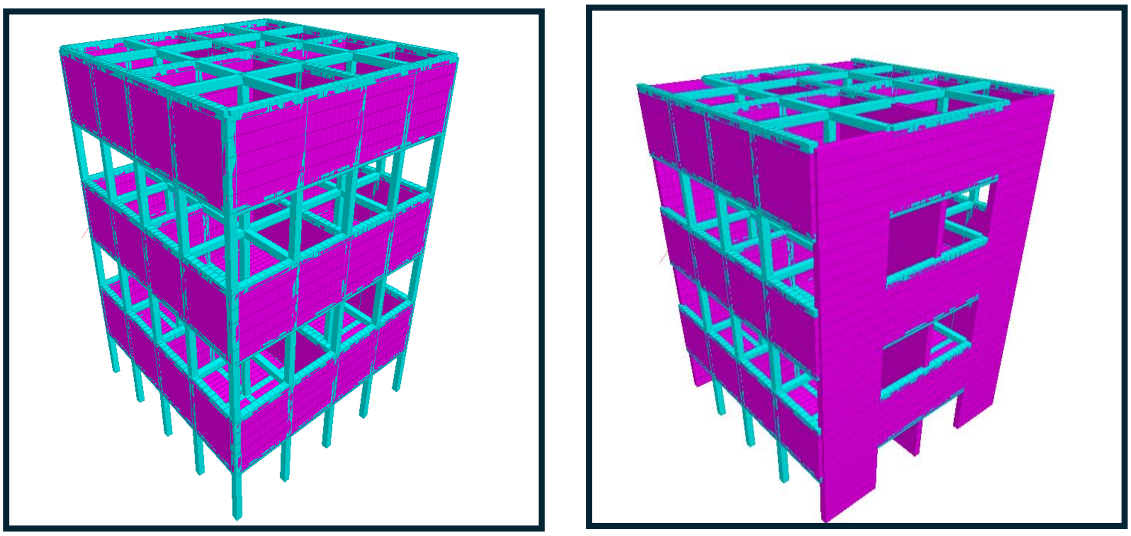


Fig 3.1: 3D View of Tank (with column beam framing)

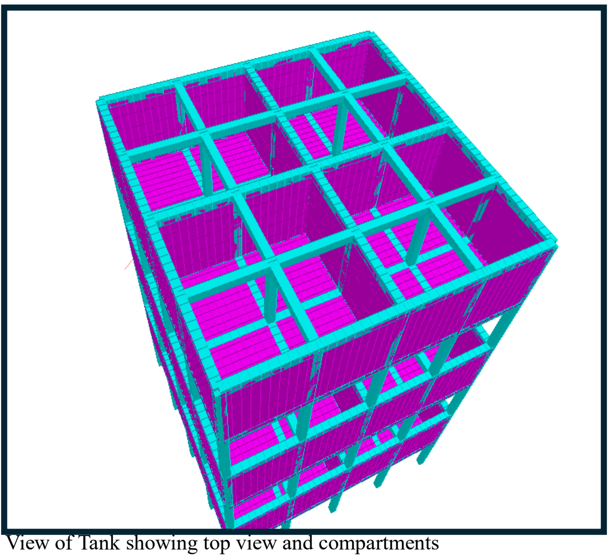


Fig 3.2: 3D View of Tank showing top view and compartments

3.3 Loading and Seismic Parameters

- Dead load: Self-weight of structural elements
- Fluid load: Hydrostatic water pressure (9.81 kN/m³)
- Seismic load: IS 1893 (Part 2), Zone III
    - Zone factor (Z) = 0.16
    - Importance factor (I) = 1.5
    - Response reduction factor (R) = 4
- Analysis method: Response Spectrum Method (RSM)
- Hydrodynamic Pressure in tank
- Hydrodynamic pressure is the pressure exerted by a fluid in motion on a surface or structure due to the velocity and acceleration of the fluid, in addition to hydrostatic effects.
- Hydrodynamic pressure has been calculated in accordance with IS 1893 (Part 2). The detailed calculations are presented below. Since the pressure values are influenced by the lateral stiffness of the staging, the stiffness is first evaluated, and the resulting values are then used as the basis for the pressure calculations.

The lateral stiffness of the staging system is an important parameter governing the seismic response of an elevated water tank. It is defined as the lateral force required to be applied at the center of gravity (CG) of the tank to produce a unit lateral displacement at that point. In other words, lateral stiffness represents the resistance offered by the staging system against horizontal movement when subjected to lateral loads such as earthquake or wind forces.

In practical terms, the lateral stiffness of the staging can be evaluated by applying an arbitrary known lateral force at the CG of the tank in the analytical model and computing the resulting lateral. deflection. The stiffness is then obtained as the ratio of the applied force to the corresponding displacement at the CG. Modal analysis ensures >90% cumulative mass participation, satisfying code requirements.

4. Results and Discussion

4.1 Lateral Displacement

Horizontal Displacement Comparison

The horizontal displacement response of the water tank was evaluated for two different structural systems under seismic loading:

i. Tank supported on column–beam framing
Maximum horizontal displacement = 52 mm
ii. Tank supported on shear wall system
Maximum horizontal displacement = 3.56 mm

The shear wall system reduces displacement by approximately 93%, demonstrating significantly higher stiffness and improved deformation control.

4.2 Dynamic Characteristics

Higher frequency and lower period for the shear wall system confirm a stiffer and more earthquake-resistant structure.

Parameter	Column–Beam Framing	Shear Wall System
Fundamental Frequency (Hz)	0.761	2.985
Fundamental Period (s)	1.314	0.335
Dominant Direction	X	X

Interpretation (IS 1893 2016):

1. The column–beam system exhibits a longer fundamental period, indicating a more flexible structure.
2. The shear wall system has a shorter period, reflecting higher lateral stiffness.
3. As per IS 1893, stiffer systems attract lower displacement demand, while flexible systems experience higher deformation.

4.3 Modal Mass Participation

Model	Modes Contributing Significantly	Cumulative Participation
Column–Beam Framing	Mode 1 (89.21%), Mode 3, Mode 4	≈ 99.99%
Shear Wall System	Mode 1 (77.73%), Mode 3, Mode 4, Mode 10	≈ 98.27%

- Beam-column system: ~89% mass concentrated in first mode
- Shear wall system: First-mode participation ~78%, with mass distributed across multiple modes
  Both models satisfy IS 1893 requirement of at least 90% cumulative modal mass participation in the principal horizontal direction.
  1. In the frame system, seismic response is highly concentrated in the first mode, typical of flexible elevated tanks.
  2. In the shear wall system, mass participation is distributed across a few more modes, indicating a more restrained and stable dynamic response.

Distributed modal participation indicates a more stable and controlled dynamic response for shear walls.

4.4 Base Shear: The shear wall-supported tank exhibits higher base shear due to increased seismic weight; however, this force is effectively resisted by enhanced stiffness without excessive displacement.

5. Conclusions

A comparative seismic performance assessment of elevated water tanks supported on column–beam framing and shear wall staging systems clearly demonstrates the superiority of the shear wall system in terms of stiffness, displacement control, and overall dynamic behavior.

The shear wall–supported configuration exhibits significantly higher lateral stiffness, which results in a substantial reduction in seismic displacements and enhanced resistance to horizontal forces induced by earthquake action. This improved stiffness effectively limits structural deformations, thereby reducing the likelihood of cracking in tank walls, distress in staging elements, and damage to connecting pipelines.

In contrast, the column–beam framing system behaves as a relatively flexible structural arrangement, leading to higher lateral displacement demands and a concentration of seismic response in the fundamental mode. Such flexibility increases vulnerability to serviceability issues and may compromise the operational safety of the tank during and after seismic events.

The shear wall system, on the other hand, distributes seismic forces more uniformly, exhibits a shorter natural period, and displays a more controlled and stable dynamic response.

Overall, the comparative evaluation indicates that while both systems satisfy code requirements, the shear wall staging system offers superior seismic performance by ensuring better displacement control, improved structural integrity, and enhanced post-earthquake functionality.

Horizontal Displacement:

The maximum horizontal displacement reduces from 52 mm (column–beam system) to 3.56 mm (shear wall system), representing a reduction of approximately 93%. This significant decrease highlights the effectiveness of shear walls in enhancing lateral stiffness and minimizing seismic deformation

Dynamic Characteristics:

The fundamental frequency increases from 0.761 Hz to 2.985 Hz, an increase of about 292%, indicating a much stiffer structural system. Correspondingly, the fundamental time period reduces from 1.314 s to 0.335 s, reflecting a reduction of nearly 74.5%, which is consistent with improved seismic performance as per IS 1893 provisions.

Modal Mass Participation:

In the column–beam system, about 89% of the seismic mass participation is concentrated in the first mode, whereas in the shear wall system, the first-mode participation reduces to around 78%, with mass distributed across multiple modes. This represents a more balanced and stable dynamic response in the shear wall configuration.

Base Shear:

The base shear is higher for the shear wall–supported tank due to increased seismic weight; however, the seismic demand parameters (Sa/g and Ah) remain unchanged. The higher base shear is effectively resisted by the increased stiffness without causing excessive displacement.

Future Scope

The present study provides a comparative evaluation of elevated water tanks supported on column–beam framing and shear wall staging systems under seismic loading. Based on the outcomes, the following areas are identified for future research and development:

Nonlinear Seismic Analysis:

Future studies may incorporate nonlinear time-history analysis to capture cracking, yielding, stiffness degradation, and post-elastic behavior of both staging systems under severe earthquakes.

Soil–Structure Interaction (SSI):

The current analysis assumes fixed base conditions. Including soil–structure interaction can provide more realistic seismic response, especially for soft and medium soil conditions.

Effect of Different Tank Geometries:

Extension of the study to tanks of various shapes and sizes (circular, rectangular, intze tanks) and varying height-to-diameter ratios will help generalize the findings.

References :

1. IS 1893 (Part 2): 2014, *Criteria for Earthquake Resistant Design of Structures – Liquid Retaining Tanks*, BIS, New Delhi.
2. IS 456: 2000, *Plain and Reinforced Concrete – Code of Practice*, BIS.
3. Aliakbar Qutubuddin Ali et. al., (2017):
4. Mor Vyankatesh K. et. al., (2017):
5. I.V.H.P.Yasasswi et. al., (2022):
6. Shahid Nazir et. al., (2022):
7. Aditya Agrawal et. al., (2025):
8. Prashant A Bansode et. al., (2018):
9. Gian Michele Calvi et. al., (2023):
10. Aub Patel et. al., :
11. Housner, G. W., "Dynamic Behavior of Water Tanks," Bulletin of the Seismological Society of America, 1963.
12. Calvi, G. M., and Nascimbene, R., Seismic Design and Analysis of Tanks, 2023.