IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Effect Of Bracing Patterns, Wall Thickness, And Staging Height On The Seismic Behaviour Of Elevated RC Water Tanks

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Abstract: The seismic safety of elevated water tanks is vital for reliable water supply systems in earthquake-prone regions. This study analyses and compares the seismic performance of reinforced concrete (RC) circular elevated tanks with different staging systems using STAAD.Pro Connect Edition.

The investigation considers various bracing configurations—unbraced, diagonal, cross (X), V, K, inverted V, diamond, and solid shaft—along with two staging wall thicknesses (180 mm and 200 mm) and two staging heights. Seismic effects are studied under Zones III, IV, and V as per IS 1893 (Part 2): 2014, accounting for dead load, live load, hydrostatic pressure, and hydrodynamic forces.

A parametric approach is adopted, developing multiple models under consistent loading. Key seismic response parameters such as lateral displacement, base shear, bending moment, shear force, and time period are evaluated. Results indicate that staging type strongly influences tank behaviour.

Shaft-supported models provide maximum stiffness and seismic stability, reducing displacement and time period by up to 92% and 90%, respectively. However, these attract higher base shear and shear force, reflecting greater seismic demand. Among braced frames, X-bracing offers the best performance, significantly improving over unbraced staging.

The study further shows that higher seismic zones and taller staging heights increase displacement and base shear. Despite their rigidity, shaft-supported tanks experience lower bending moments compared to braced frames.

In conclusion, shaft-supported staging proves to be the most efficient option for seismic resistance, while X-bracing is preferable among frame systems. The findings provide design recommendations for constructing safe and economical elevated water tanks in moderate to high seismic regions.

Keywords - STAAD.Pro Connect Edition, Elevated Water tank, Circular Water Tanks, Bracings and shaft, Seismic loads

Introduction: Water has always been central to human life, and with the growth of settlements into towns and cities, the demand for storing and supplying water in an efficient manner has only become more critical. Elevated water tanks are among the most common and effective solutions for ensuring that water can be delivered reliably, at sufficient pressure, and without excessive pumping costs. In both urban and rural contexts, these structures have become essential components of civic infrastructure, often rising prominently over the built environment as symbols of development.

Yet, the importance of elevated tanks is not limited to convenience alone. In times of crisis—whether floods, droughts, or earthquakes—they become lifelines for communities. This makes their structural safety, particularly under extreme events like earthquakes, a matter of both engineering concern and public safety. Unfortunately, history shows that water tanks have been especially vulnerable to seismic actions. Unlike many other structures, elevated tanks combine heavy masses of stored water with tall and often slender supporting systems, producing unique dynamic behaviour that can amplify earthquake effects.

Seismic vulnerability of water tanks: The vulnerability of these structures has been dramatically exposed in several past earthquakes. For instance, during the 1967 Koynanagar earthquake in Maharashtra, numerous elevated tanks collapsed or suffered serious damage, drawing early attention to their seismic weakness in India. The 1993 Latur earthquake and the 2001 Bhuj earthquake again highlighted the fragility of water tanks, where staging failures led to large-scale collapses. More recently, the 2015 Gorkha earthquake in Nepal saw multiple water towers either collapse or tilt dangerously, disrupting local water supply at a time when it was most needed. Similar incidents have been recorded worldwide, including the 1999 Izmit earthquake in Turkey and the 2011 Tohoku earthquake in Japan, each reinforcing the idea that the seismic design of water tanks deserves careful attention.

These repeated failures underline two important realities. First, it is often the staging system—the column and bracing arrangement supporting the container—that fails rather than the container itself. Second, failure of water tanks carries consequences beyond structural loss: it disrupts water supply for firefighting, sanitation, and emergency relief at the very moment when communities are most vulnerable. This dual significance makes seismic design of elevated tanks not just an engineering challenge but also a humanitarian necessity.

Role of staging systems: The staging of a water tank forms the backbone of the structure, carrying the container and its water load safely to the foundation. Traditionally, reinforced concrete (RC) frame staging with vertical columns has been popular for its simplicity and economy. However, such open frames are highly flexible and, under earthquakes, often undergo large lateral displacements and long vibration periods, reducing stability. To address this, engineers have introduced bracing systems such as diagonal, X, V, K, inverted V, and diamond bracing, each altering stiffness and load transfer. Alternatively, solid RC shafts provide higher rigidity and continuity, minimising displacement and vibration periods, though at the cost of attracting greater base shear. Thus, seismic efficiency depends strongly on the chosen staging system, as behaviour under service loads may differ drastically from seismic performance.

Previous research and limitations: Early studies focused on fluid-structure interaction, with Housner's work on impulsive and convective modes influencing seismic codes, including IS 1893 (Part 2): 2014. Later research highlighted the concept of staging vulnerability, showing that bracing improves stiffness, with X-bracing often being the most effective. Comparisons with shaft staging confirmed its seismic resistance, while studies on height effects showed taller tanks attract greater displacements and shear. Yet, gaps remain: most analyses examine limited bracing types, single seismic zones, or one staging height. Systematic comparisons between braced frames and shaft staging across varying conditions are scarce, leaving designers without comprehensive guidance for optimal seismic design.

Recent research has extensively explored the seismic performance, structural efficiency, and design optimisation of elevated water tanks, with a focus on staging configurations, bracing systems, and hydrodynamic effects. Landge & Murnal (2014) [11] conducted a comparative study on fixed-base shaft-staged tanks, analysing three capacities (500m³, 750m³, 1000m³) under multiple earthquake excitations. Their findings revealed that the two-mass model, as per modern codes (IS 1893:2002), consistently outperformed traditional single-mass models in reducing base shear and displacements, except for smaller 500m³ tanks, where responses were occasionally higher. Okonkwo et al. (2016) [14] shifted focus to steel tanks, demonstrating that bracing intervals significantly influence structural economy—wider spacing (e.g., 3m) reduced steel weight by minimising repeated connections, while closer bracing (1m) increased material usage without proportional safety benefits. Mallik (2017) [13] introduced an innovative hybrid construction method that combines slip-forming and heavy lifting for a 275m³ twin-chambered tank, achieving a 50% time reduction compared to conventional techniques. Meanwhile, Shrigondekar et al. (2017) [23] and Varughese & Philip (2017) [28] systematically evaluated bracing configurations, with the latter finding that X-bracing enhances lateral stiffness by 150% compared to unbraced systems, whereas radial bracing offers negligible improvements. Rathod & Ishwaragol (2018) [20] identified staging geometry as a critical factor, showing that increasing base width by 25% escalated bending moments by 38.8% and displacements by 46.4%, underscoring the need for balanced proportions. Bansode & Rajemahadik (2019) [2] further reinforced these insights, noting that lateral radial and vertical X-bracing reduced storey displacements by 7–8 times in full-tank conditions, though at the cost of higher base shear. Tokhi & Arora (2019) [27] expanded the discussion to tank shapes, revealing that rectangular tanks suffered 2.2× higher displacements than circular/Intze types in Zone V, while Soniwala (2020) [25] demonstrated octagonal bracing's superiority in maximizing stiffness (16.8% gain) for fully filled Intze tanks. Recent advancements by Singh & Dwivedi (2023) [24] highlighted shell staging's seismic resilience, reducing lateral displacement by 88.24% compared to conventional designs, whereas Rao (2023) [19] emphasised that seismic forces dominate wind loads in Zone V, necessitating robust reinforcement. Pathak & Mishra (2024) [15] concluded that cross-bracing quadruples staging stiffness but recommended diagonal bracing for cost-effectiveness. Collectively, these studies establish that seismic design must account for fluid-structure interaction, staging flexibility, and bracing topology, with modern analytical tools (e.g., SAP2000, STAAD.Pro) playing a pivotal role in optimising safety and economy

Motivation for the study: These gaps motivated the present work. Given the repeated failures of elevated tanks in past earthquakes and the variety of staging systems available, it is essential to conduct a systematic, parametric study that compares multiple configurations under realistic seismic conditions. Such a study can not only confirm earlier findings but also provide a broader understanding of how staging type, staging height, and member dimensions interact under earthquake loads. Importantly, the study focuses on evaluating the effectiveness of different staging systems by examining their displacement control, base shear, and bending moment performance. It also considers the influence of wall thickness on overall structural behaviour and explores whether shaft-supported systems consistently outperform braced configurations or if certain bracing arrangements provide a more balanced alternative. Through this analysis, the study aims to offer practical guidance for engineers and policymakers involved in the design and management of water infrastructure projects, particularly in seismically active regions.

Scope and objectives of the research: The scope of this study is deliberately wide, covering eight staging configurations—unbraced, diagonal, X, V, K, inverted V, diamond, and shaft-supported. To capture the influence of dimensions, two staging wall thicknesses (180 mm and 200 mm) are considered. To reflect practical variations in design, two staging heights are studied. Finally, to represent different seismic intensities, the analysis is carried out for Zones III, IV, and V as per IS 1893 (Part 2): 2014.

The study aims to contribute both to academic understanding and practical design. By presenting a comparative, parametric analysis of multiple staging systems, it provides a richer basis for design choices. The findings can guide engineers in selecting appropriate configurations for different seismic zones, avoiding under-designed systems that fail or over-designed ones that are uneconomical. Ultimately, this research contributes to improving the resilience of water supply infrastructure, ensuring that communities retain access to water in the critical aftermath of earthquakes.

The methodology employed was a comprehensive parametric study to analyse the seismic behaviour of reinforced concrete (RC) circular elevated water tanks. Utilising STAAD.The Pro Connect Edition software, based on the Finite Element Method (FEM), has developed a total of 54 distinct structural models. These models systematically varied bracing configurations (unbraced, diagonal, cross, V, K, inverted V, diamond, and solid shaft), staging wall thicknesses (180 mm and 200 mm), staging heights (six and seven levels), and Seismic Zones III, IV, and V as per IS 1893 (Part 2): 2014. Each model was subjected to combined dead, live, hydrostatic, and hydrodynamic forces, as well as seismic loads. Key structural response parameters such as maximum lateral displacement, shear force, bending moment, natural time period, and base shear were extracted and comparatively analysed to identify optimal designs.

(a) (b)

Fig.1 (a) Elevated Tank & Spring Mass Model (b) Two Mass Idealisation for Elevated Tank

Overview of Model Configurations:

A total of 54 structural models of reinforced concrete (RC) circular elevated water tanks were developed and analysed in this study. These models were designed to systematically evaluate the influence of four major parameters on the seismic performance of elevated water tanks:

Bracing configuration, Shaft wall thickness, Staging height, and Seismic zone.

Each of these parameters was varied while keeping all other geometric and material properties constant. The tanks were analysed under the combined effects of dead load, live load, hydrostatic and hydrodynamic pressure, and seismic forces as per relevant Indian Standards (IS 1893:2016, IS 3370, IS 456). Theoretical Basis for the Varying Parameters are (summary is shown in Table 1):

Bracing Configuration:

The type of lateral bracing has a significant influence on the stiffness and ductility of the staging system. Seven bracing configurations were studied — no bracing (C), diagonal (CD), diamond/box (CDD), inverted V (CIV), K-type (CK), V-type (CV), and X-type (CX). Additionally, two models (CS180 and CS200) with circular shafts of different wall thicknesses (180 mm and 200 mm) were included for comparison.

Shaft Wall Thickness:

The wall thickness of the circular shaft directly affects its flexural rigidity and the overall dynamic response of the tank. Two thicknesses were considered — 180 mm and 200 mm — to study this effect.

Staging Height:

Two staging heights were modelled, corresponding to six levels (23.1 m) and seven levels (26.95 m). Increasing the staging height increases flexibility and alters natural frequencies, which in turn affects seismic demand.

Seismic Zone:

To assess seismic vulnerability, the tanks were analysed under Zones III, IV, and V as per IS 1893, representing increasing levels of seismic intensity.

Table 1. Summary of Model Variations and Parameters

Parameter	**Variation**	**Details / Remarks**
Staging height	2 levels	- Six staging (23.1 m) - Seven staging (26.95 m)
Seismic zone (as per IS 1893:2016)	3 zones	Zone III, Zone IV, Zone V
Bracing configuration/support type	9 types	C – No bracing CD – Diagonal CDD – Diamond (box) CIV – Inverted V CK – K-type CV – V-type CX – X-type CS180 – Circular shaft (180 mm) CS200 – Circular shaft (200 mm)
Total models per combination	9 per case	Each case = one staging height × one seismic zone × nine configurations
Total cases considered	6	(2 staging heights × 3 seismic zones)
Total number of models	54	6 cases × 9 configurations = 54 models

Model Naming Convention

Each model is identified using the format:

(Number of stagings).(Seismic Zone).(Configuration)

For example:

- 6.3C → Six stagings, Zone III, no bracing
- 7.5CX → Seven stagings, Zone V, X bracing
- 6.4CS200 → Six stagings, Zone IV, circular shaft (200 mm)

Assigned Properties

The *assigned properties* define the geometric, material, and loading parameters attributed to each structural component of the elevated water tank. These parameters govern the stiffness, mass distribution, and dynamic behaviour of the models during seismic analysis. All models share identical assigned properties except for the varying parameters described earlier (bracing type, staging height, shaft thickness, and seismic zone) as described in table 2.

Table 2: Structural and Material Properties of the Tank Models

S. No.	**Parameter**	**Specification / Dimension**	**Remarks**
1	Thickness of peak dome	0.10 m	Reinforced concrete dome top
2	Rise of peak dome	2.25 m	Measured from crown to base of dome
3	Radius of peak dome at base	6.00 m	Circular tank geometry
4	Peak dome ring beam	0.34 m × 0.30 m	Provided at dome base
5	Cylindrical wall diameter	12.00 m	Measured to centreline of wall
6	Cylindrical wall height	3.80 m	Depth of water container
7	Cylindrical wall thickness	0.20 m	Uniform throughout height

8	Base slab thickness	0.40 m	Rigid base slab
9	Base ring beam	0.75 m × 0.70 m	Supports staging system
10	Number of columns	8	Uniformly spaced along periphery
11	Number of stagings	6 and 7	Corresponding to 23.1 m and 26.95 m total height
12	Height of each staging	3.85 m	Center-to-center spacing between bracing levels
13	Staging beam size	0.35 m × 0.30 m	Intermediate horizontal tie beams
14	Column size	0.60 m × 0.60 m	Square RC columns
15	Bracing size	0.30 m × 0.25 m	Cross or diagonal bracing elements
16	Shaft wall thickness	180 mm and 200 mm	For CS180 and CS200 models
17	Density of water	9.81 kN/m³	Hydrostatic and hydrodynamic mass
18	Concrete grade	M30	As per IS 456:2000
19	Soil type	Hard soil	As per IS 1893 (Part 1): 2016
20	Seismic zones considered	III, IV, and V	Representing increasing seismic intensity
21	Live load on tank roof	0.75 kN/m²	As per IS 3370 (Part II): 2021

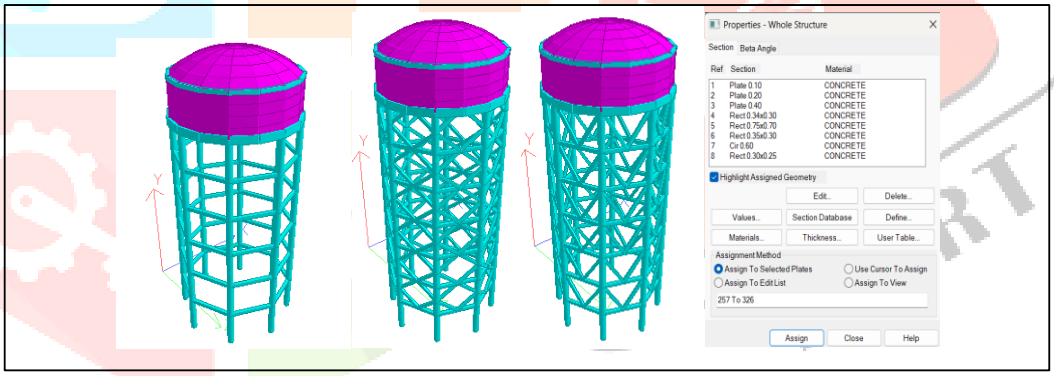


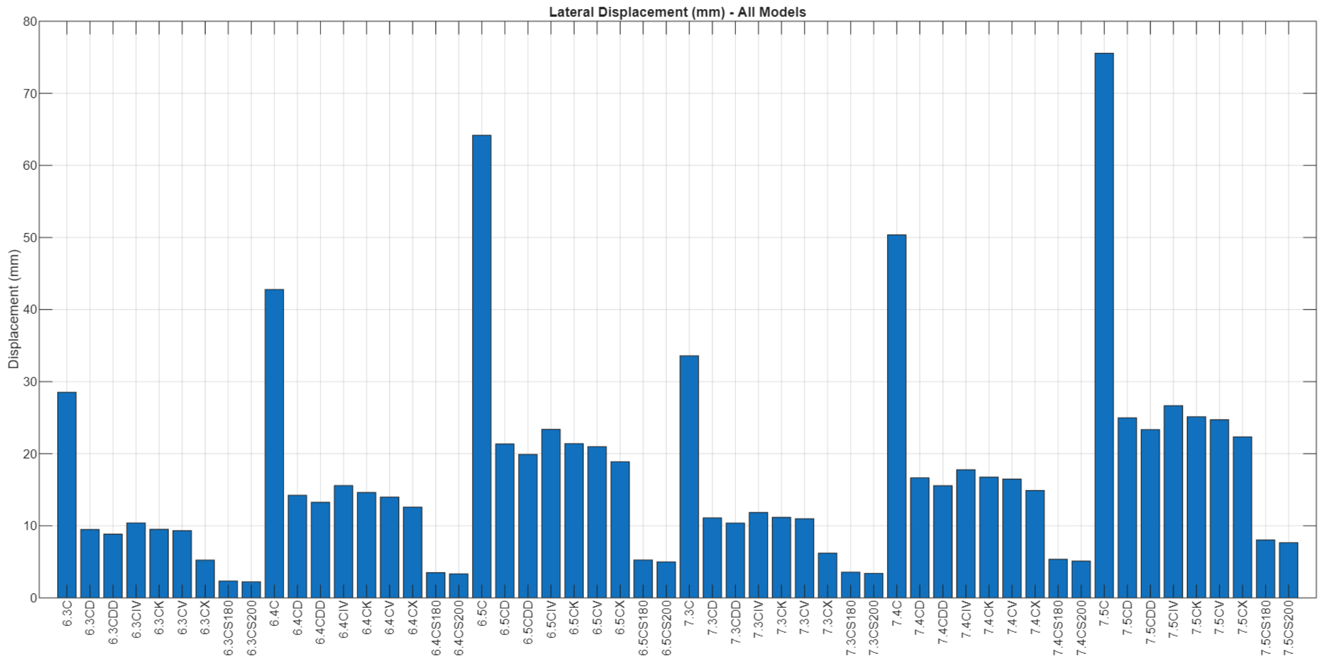
Figure 2: Illustrative Set of STAAD Models with Varied Parameters.
(A total of 54 models were generated.)

Result and Discussion

This chapter presents the seismic performance of elevated circular water tanks with different staging systems, analysed using STAAD.Pro. The parameters studied include lateral displacement, shear force, bending moment, time period, and base shear. Comparative results for unbraced, braced, and shaft-supported configurations under Zones 3, 4, and 5 are discussed.

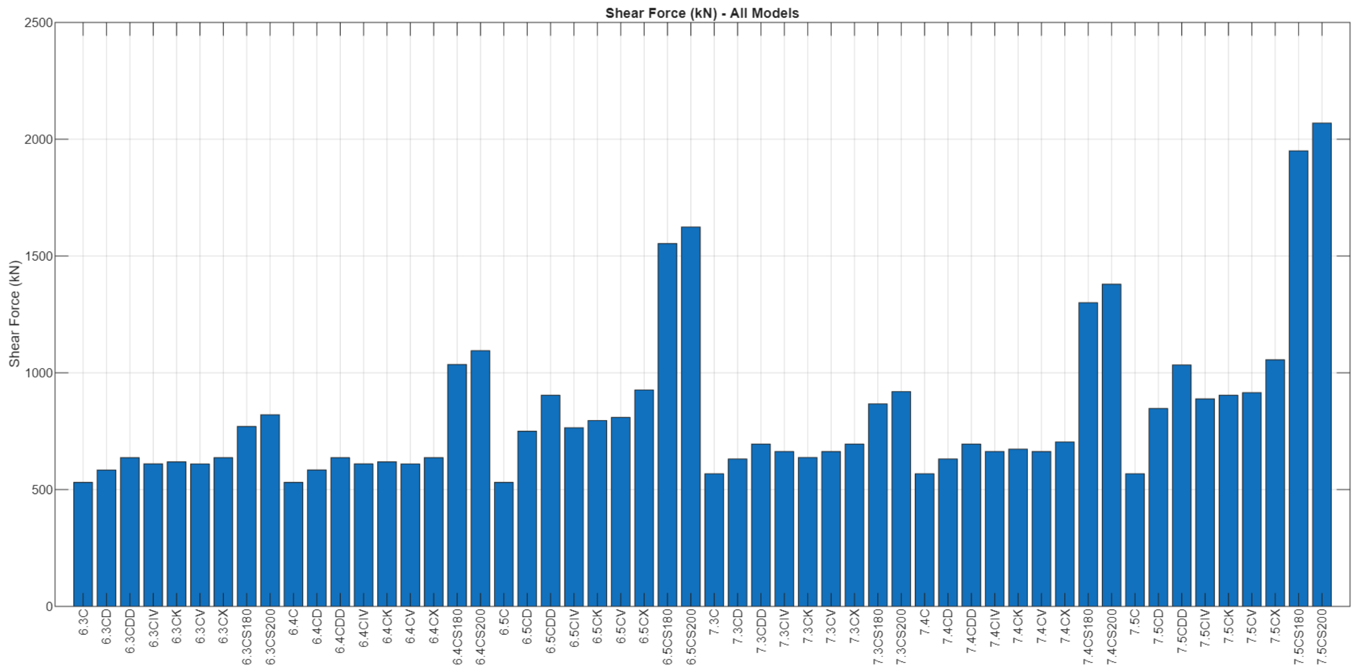
Seismic Performance Trends

Lateral Displacement



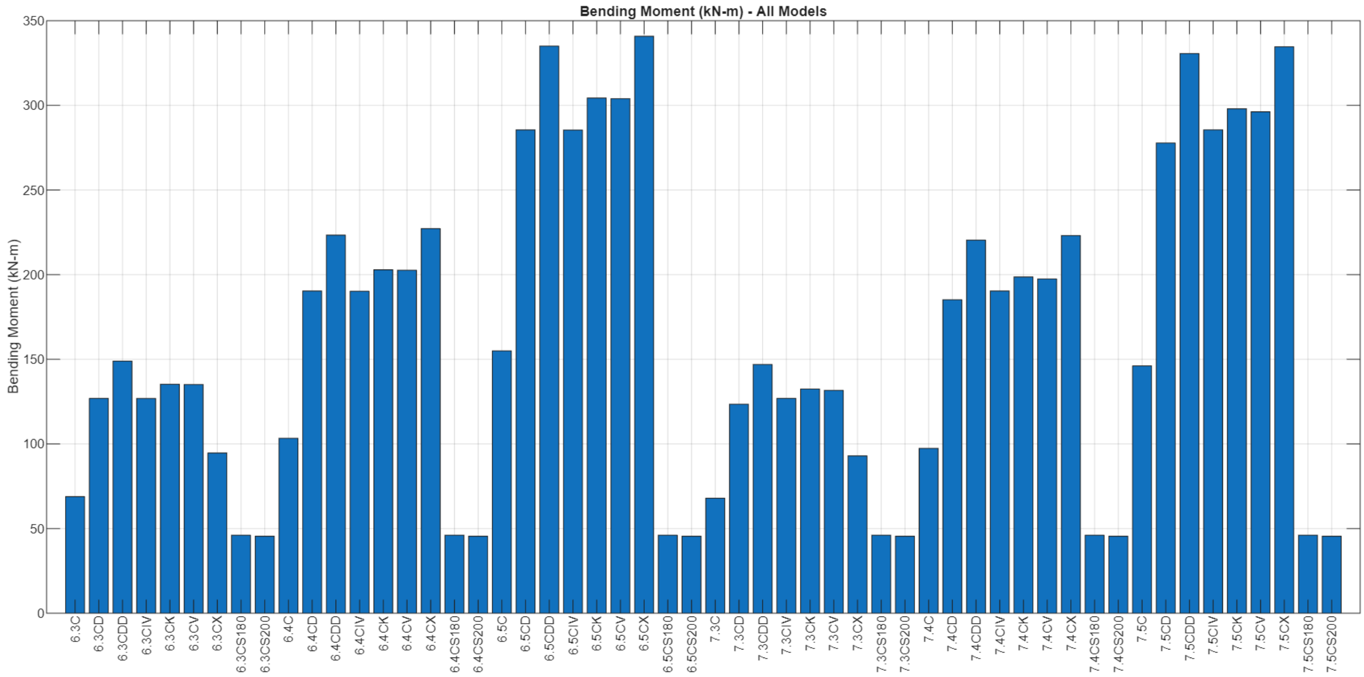
Unbraced models consistently exhibited the highest lateral displacements, confirming their poor resistance to seismic forces. Braced configurations (diagonal, cross, K, and V) reduced displacements by about 65–70%, with X-bracing providing the best performance among frame systems (≈70–81% reduction). Shaft-supported tanks (CS180 and CS200) performed exceptionally well, reducing displacements by over 90% across all seismic zones, proving their stiffness and superior stability.

Shear Force



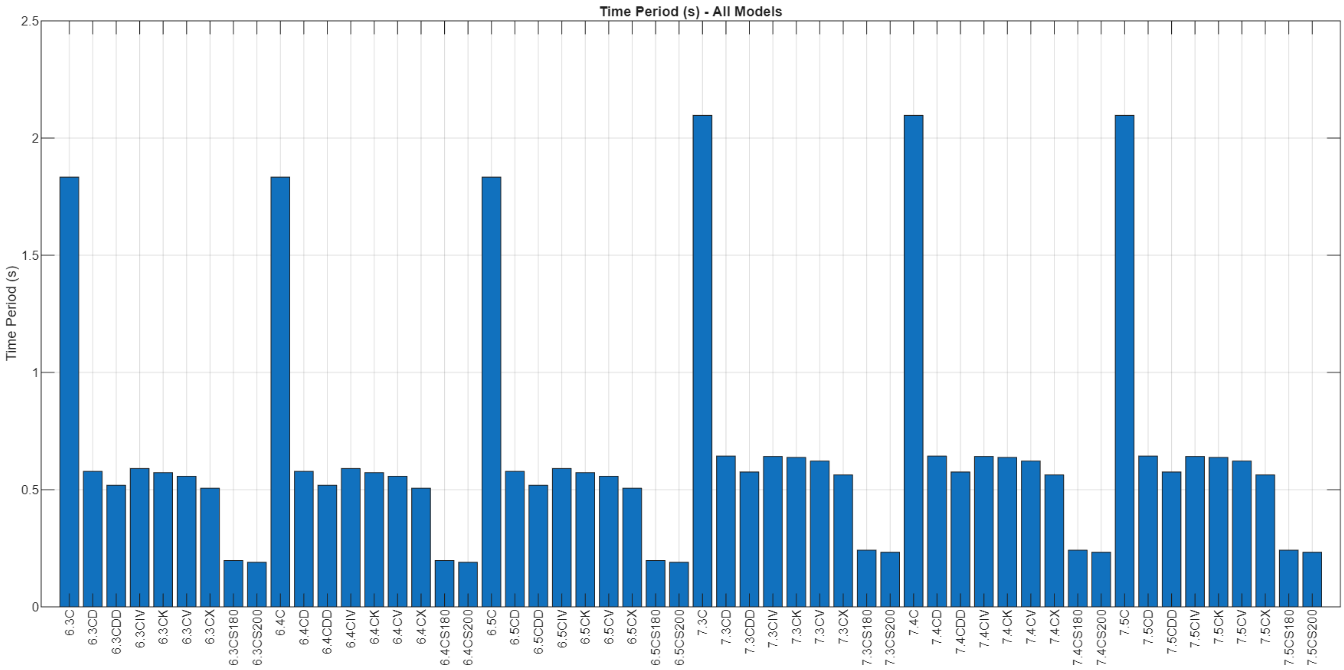
While displacement was reduced, all modifications increased shear force compared to the unbraced models. For braced frames, shear force generally rose by 10–20%, while shaft-supported systems showed drastic increases of 95–240%, indicating their ability to carry larger lateral loads. This reflects a trade-off where improved stiffness demands higher shear resistance in the staging.

Bending Moment:



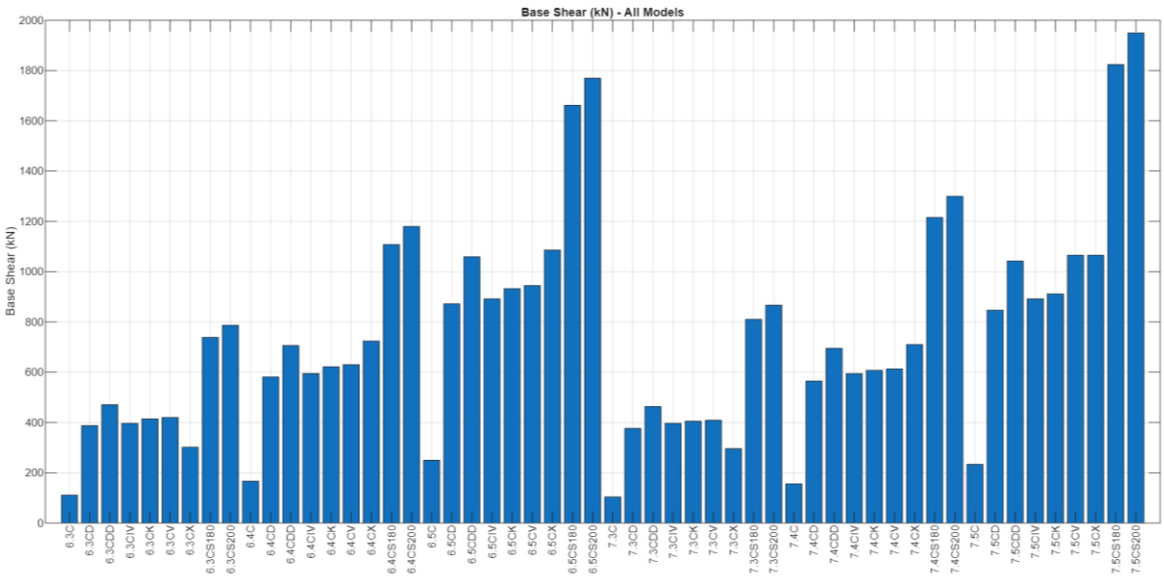
Bending moments in braced frame models increased significantly (80–120%) compared to unbraced staging, indicating higher demands on column sections. However, shaft-supported tanks recorded substantial reductions (30–70%), as the solid shaft redistributed forces more efficiently. This highlights the contrasting behaviour: frames experience higher bending demand, whereas shafts minimise it.

Time Period:



The fundamental time period of unbraced tanks was the longest (≈1.8–2.1 sec), making them more vulnerable to resonance. Braced configurations reduced the time period by 65–73%, enhancing dynamic stability. Shaft-supported models offered the shortest periods, with reductions of ≈89–90%, which demonstrates excellent stiffness and improved seismic safety.

Base Shear:



Base shear followed an increasing trend with the improvement of staging systems. Unbraced models showed the lowest values, while braced frames exhibited increases of 250–350%. The maximum rise occurred in shaft-supported tanks, reaching 560–730% higher than unbraced systems. Though these values indicate greater foundation demand, they also represent a higher seismic resistance capacity.

Comparative Observations

Unbraced staging (C models): High displacement and time period, low base shear—structurally weak in seismic zones.

Braced staging (CD, CDD, CIV, CK, CV, CX): Significant improvement in displacement and time period; however, bending and shear demands increase. Among them, X-bracing performed best.

Shaft-supported staging (CS180, CS200): Outstanding performance with minimal displacement and time period, lower bending moments, and maximum shear/base shear. These models demonstrated the best overall seismic response, particularly suitable for high-intensity zones.

The study demonstrates that the structural configuration has a significant impact on the seismic performance of elevated tanks. While bracing enhances frame behaviour, shaft-supported staging provides the most effective solution by combining minimal lateral displacement, a very short time period, and high shear resistance. For regions with high seismic risk, shaft-supported designs (CS models) are recommended as the most reliable staging system.

Conclusion:

The analysis conducted in this study provides a comprehensive understanding of how different bracing and staging configurations influence the seismic performance of reinforced concrete circular elevated water tanks. By using STAAD. For structural evaluation, the research provides clear evidence on how bracing strategies affect critical response parameters under varying seismic conditions and structural configurations. These insights are pivotal for civil and structural engineers aiming to optimise the seismic resilience of essential water infrastructure.

Key findings from the analysis are summarised as follows:

- Shaft-supported models (CS180, CS200) resulted in the greatest reduction in lateral displacement and time period (up to 92% and 90%, respectively) over unbraced tanks, indicating superior seismic stiffness and stability.
- X-bracing (CX) among frame bracing types substantially minimised lateral displacement, with improvements up to 81% compared to unbraced counterparts.
- The introduction of stiffer systems, especially shaft-supported models, led to significant increases in maximum shear force (up to 264%) and base shear (up to 734%), revealing the higher seismic demand attracted by greater rigidity.
- Braced frame designs tended to raise bending moments (up to 128%), whereas shaft-supported systems uniquely achieved reductions up to 70%, providing an advantage in controlling internal stresses.
- Both higher seismic zones and increased staging heights consistently amplified lateral displacement and base shear across all models, highlighting the elevated seismic risk in such scenarios.

- The optimal seismic design solution depends on balancing displacement control, stiffness, shear force, and bending moment requirements in line with project-specific objectives.
- For regions with moderate to high seismic risk, shaft-supported tanks are particularly recommended due to their advantageous performance, though it is essential to address the increased seismic force demands during design and construction.

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