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Seismic Analysis of an Elevated Storage Reservoir in Different Seismic Zones

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Abstract - *Elevated Storage Reservoirs (ESRs) serve as critical municipal lifelines, yet their high-concentrated liquid mass atop slender staging frameworks creates severe seismic vulnerabilities. Standard lumped-mass approaches fail to capture dynamic fluid behavior, necessitating rigorous fluid-structure interaction analysis. This research evaluates the seismic performance and dynamic response of rectangular and circular RC elevated water tanks across Indian Seismic Zones II, III, IV, and V as per IS 1893 (Part 2). 3D finite element models were established using ETABS software, utilizing a two-mass mechanical idealization to isolate rigid impulsive and sloshing convective fluid responses. Dynamic Response Spectrum analysis was conducted on M40 grade, 4-story frame-staged models to quantify modal mass participation, natural vibration time periods, base shear, and lateral deflections. Analytical findings reveal that mode participation factors satisfy standard safety criteria across all seismic zones, with torsional modes appropriately restricted to the third mode. Base shear and lateral deflections increase progressively from Zone II to Zone V. Structural deflections remain within permissible safety thresholds up to Zone IV; however, exceedances in Zone V highlight the necessity for additional framing fixity or bracing systems to control dynamic sway. Furthermore, rectangular configurations demonstrate superior lateral rigidity, predictable orthogonal modal behavior, and enhanced structural performance compared to circular geometries.*

Key Words: Elevated Storage Reservoir (ESR), Response Spectrum Analysis, Seismic Vulnerability

1. INTRODUCTION

Elevated Storage Reservoirs (ESRs) are essential lifeline structures designed to supply potable water and aid firefighting immediately following seismic events. Unlike conventional multi-story buildings, ESRs present unique dynamic challenges due to their heavy, concentrated overhead fluid mass resting on relatively slender staging frameworks. Because their seismic response is too complex for a single-degree-of-freedom model, Indian Standard guidelines (IS 1893 Part 2) utilize a two-mass mechanical idealization that splits the fluid into a rigid lower impulsive mass and a sloshing upper convective mass. The cumulative hydrodynamic forces from both components generate the total base shear and overturning moments acting on the staging system. As seismic intensity increases from Zone II to Zone V, peak ground acceleration drastically amplifies structural vulnerabilities like torsional coupling, P-Delta effects, and excessive drift. Due to their low structural redundancy and ductility, ESRs require stringent safety criteria under IS codes, including higher Importance Factors (I = 1.5) and specialized ductile detailing provisions (IS 13920). Ultimately, evaluating ESRs across varying seismic zones using response spectrum or time-history analysis allows engineers to optimize structural resistance such as reinforcement demand and member sizing ensuring functional safety in high-hazard zones while avoiding unneeded costs in low-seismicity regions.

1.1 Benefits of Elevated Reservoir Over Underground Reservoir

Elevated Storage Reservoirs (ESRs) offer significant economic and operational advantages over underground storage systems primarily through gravity driven distribution and power independence. By utilizing potential energy to create natural hydrostatic pressure, ESRs distribute water throughout the municipal grid via gravity, eliminating the need for continuous pumping and reducing long-term energy costs. This gravity-led design easily buffers peak demand periods without straining mechanical systems. Furthermore, because the water supply relies on gravity rather than continuous electricity, elevated tanks maintain uninterrupted flow to communities and firefighting networks during power grid failures or generator outages.

In addition to operational reliability, elevated reservoirs provide superior structural maintenance advantages and strict water quality control. Unlike underground tanks, which require complex excavation or acoustic equipment to detect subsurface leaks caused by soil pressures, an ESR's fully exposed container allows for immediate visual inspection of cracks, seepage, and corrosion. Elevated structures are also physically isolated from the ground, eliminating the risk of subsurface contamination from sewage leakage, groundwater infiltration, or surface runoff. This structural separation makes it far easier to maintain high sanitary standards across public water distribution networks.

1.2 Performance of Water Tank Under Earthquake Forces

The dynamic performance of Elevated Storage Reservoirs (ESRs) under earthquake forces is heavily governed by fluid-structure interaction, container geometry, and the structural stiffness of the supporting staging configuration. Traditional single lumped-mass models fail to account for fluid motion, severely underestimating seismic demand parameters, whereas the codal two-mass mechanical idealization accurately separates stored liquids into a lower rigid impulsive mass and an upper sloshing convective mass. Across all container shapes, dynamic demand parameters such as base shear, overturning moments, and story displacements scale up significantly as seismic hazard levels increase from Zone II to Zone V. Fully laden tank states generally dictate peak base shear forces, though critical structural vulnerabilities can also emerge during empty or half-full operational states depending on ground motion frequency characteristics. Furthermore, optimizing the container's height-to-diameter (H/D) ratio is vital, as ratios below 0.4 induce excessive base slab deflections, while higher ratios concentrate fluid mass elevated above ground, driving up overall structural demands and construction costs.

The choice of container shape and staging arrangement critically impacts dynamic stability and torsional behavior during seismic events. Standard circular elevated tanks often exhibit a primary vibration mode dominated by structural torsion a highly destructive collapse mechanism that can be mitigated by introducing asymmetric column orientations whereas rectangular tanks display predictable, safe translational modes along orthogonal axes. In terms of staging resilience, unbraced bare-frame column configurations offer highly inadequate lateral stability under severe seismic shaking. Integrating intermediate bracing systems, such as X-type diagonal cross-bracings or hexagonal staging with internal radial tie-bracing, adds minor secondary mass to the structure but drastically enhances lateral stiffness. This stiffness gain dramatically restricts inter-story drift, reduces peak roof displacements by over 90%, and shortens natural vibration time periods, thereby securing structural integrity across active seismic zones.

2. AIM AND OBJECTIVE

2.1 Aim:

To evaluate and compare the seismic performance, modal behaviour, and dynamic response of reinforced concrete elevated water tanks with rectangular and circular/hexagonal geometries across Indian Seismic Zones II through V in accordance with IS 1893.

2.2 Objective:

1. To develop 3D finite element models of 20 m elevated water storage tanks in CSI ETABS incorporating both rectangular and circular/hexagonal geometric configurations.
2. To model fluid-structure interaction using a two-mass mechanical idealization by decoupling the fluid into rigid impulsive and sloshing convective masses across different operational fill capacities.
3. To perform linear dynamic Response Spectrum Analysis (RSA) across Seismic Zones II, III, IV, and V under standardized orthogonal load combinations.
4. To quantify and verify dynamic demand parameters, including fundamental vibration time periods, modal mass participation factors, and story displacements, against IS code compliance limits.
5. To conduct a parametric comparative assessment to determine the structural efficiency, torsional vulnerability, and lateral rigidity of rectangular versus circular tank geometries.

3. METHODOLOGY

A comprehensive three-dimensional finite element model (FEM) of elevated water storage tanks with a structural staging height of 20 m incorporating both rectangular (18x8 m) and hexagonal (24m diameter) geometric configurations was systematically developed and analyzed across all four seismic zones within CSI ETABS. The structural supporting system comprised framing beams of 400mm x 800 mm and columns of 600mm x 1000mm, while the tank container was modeled using 300mm thick shear walls supported by deep beams. To rigorously capture the fluid-structure interaction (FSI) and associated dynamic actions, the computational modeling explicitly incorporated static hydrostatic pressure alongside dynamic hydrodynamic forces. In accordance with standard two-mass mechanical approximations, the contained fluid was decoupled into impulsive mass acting rigidly with the container walls and convective mass representing the low-frequency sloshing effect of the liquid free surface. These hydrodynamic boundary conditions were simulated across three critical operational phases empty, half-full, and full water capacity allowing for an in-depth characterization of the structural behavior under varying mass distributions, modal contributions, and effective center-of-gravity shifts.

Dynamic response characteristics were evaluated by conducting linear dynamic Response Spectrum Analysis (RSA) across multiple standardized seismic hazard zones, applying orthogonal dynamic load combinations via modal combination rules (such as CQC and SRSS) to capture complete spatial responses. A parametric comparative investigation was subsequently performed across the geometric forms, seismic intensities, and fill levels to

quantify critical performance metrics, including fundamental time periods, base shear demand, overturning moments, storey drift ratios, and nodal displacements at the container and staging levels. The resulting comparative dataset provides critical insights into the structural efficiency, staging stress concentrations, and seismic vulnerability differences between circular and rectangular tank geometries, establishing a rigorous basis for performance-based design and code-compliant detailing of elevated liquid-retaining systems.

Table -1: Structural modelling

Building shape	**Ordinary (Regular) & L-Shaped (Irregular)**
Tank Height	20 m
Beam	400 mm x 800 mm
Column	600 mm x 1000 mm
Slab	250 mm
Wall	300 mm

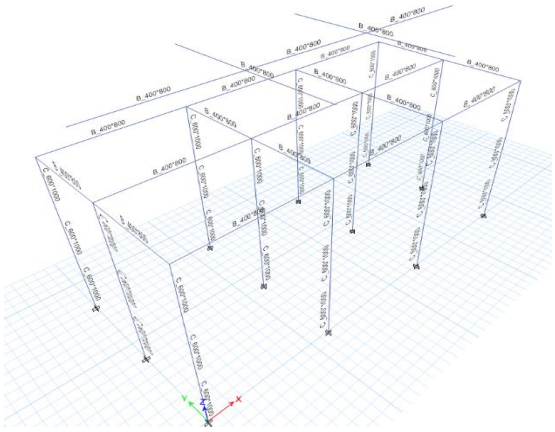


Fig -1: Assigned frame Sizes-Rectangular Tank (3D)

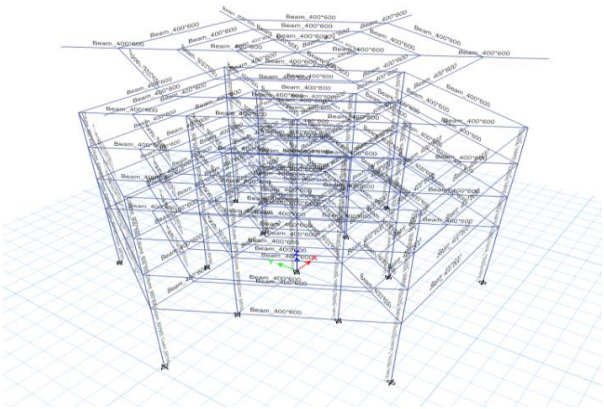


Fig -2: Assigned frame Sizes-Circular Tank (3D)

Table -2: Assigned Loads (kN/m²)

Live	1.2
Super Dead	2.5

Table -3: Assigned Hydro-Static Load (kN/m²)

0m to 1m	30 kN/m²
1m to 2m	20 kN/m²
2m to 3m	

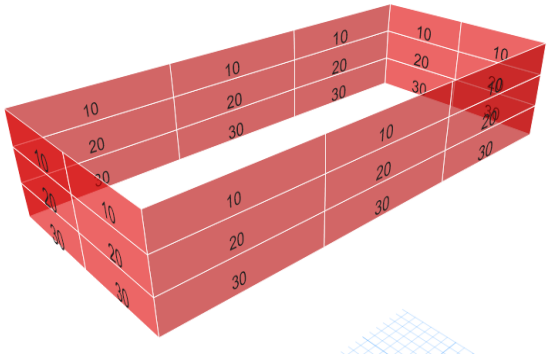


Fig -5: Assigned Hydro-static loads on rectangular tank (3D)

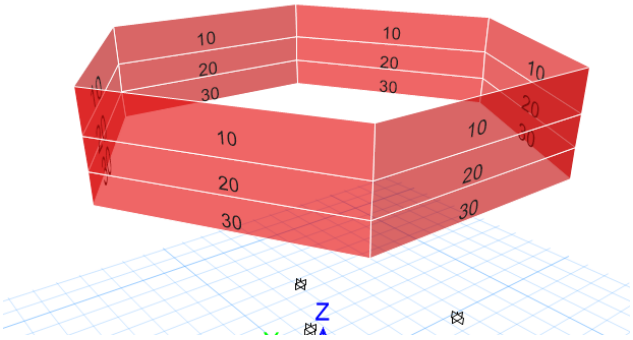


Fig -6: Assigned Hydro-static loads on Hexagonal tank (3D)

Table -4: Load Combinations

1.	DL
2.	DL+LL
3.	DL+LL+ELX
4.	DL+LL+ELY
5.	DL+LL-ELX
6.	DL+LL-ELY
7.	0.9DL-1.5ELX
8.	0.9DL-1.5ELY

9.	0.9DL+1.5ELX
10.	0.9DL+1.5ELY
11.	1.2(DL+LL+ELX)
12.	1.2(DL+LL+ELY)
13.	1.2(DL+LL-ELX)
14.	1.2(DL+LL-ELY)
15.	1.5(DL+ELX)
16.	1.5(DL+ELY)
17.	1.5(DL-ELX)
18.	1.5(DL-ELY)
19.	1.5DL

4. RESULTS

4.1 Modal Participation

Modal analysis across seismic zones II to V highlights contrasting dynamic behaviour between tank geometries. The rectangular tank demonstrates favourable seismic response with purely translational fundamental modes (Modes 1 and 2 in X and Y directions) and torsional excitation safely delayed to Mode 3. Conversely, the circular/hexagonal configuration exhibits critical torsional vulnerability, with Mode 1 dominated by rotational mass participation. Because IS 1893 disallows fundamental torsional modes to prevent eccentric twisting and stress concentrations, the rectangular geometry provides superior dynamic performance, greater lateral stiffness, shorter natural periods, and a safer modal sequence.

Table -5: Mode Participation Zone 2

Zone 2- RECTANGULAR					Zone 2- CIRCULAR				
TABLE: Modal Participating Mass Ratios					TABLE: Modal Participating Mass Ratios				
Case	Mode	Period			Case	Mode	Period		
		sec					sec		
Modal	1	0.732	0.6588	OKAY	Modal	1	1.266	1.1394	UNSAFE
Modal	2	0.549	0.4941	OKAY	Modal	2	1.187	1.0683	UNSAFE
Modal	3	0.423			Modal	3	1.187		

Table -6: Mode Participation Zone 3

Zone 3- RECTANGULAR					Zone 3- CIRCULAR				
TABLE: Modal Participating Mass Ratios					TABLE: Modal Participating Mass Ratios				
Case	Mode	Period			Case	Mode	Period		
		sec					sec		
Modal	1	0.732	0.6588	OKAY	Modal	1	1.266	1.1394	UNSAFE
Modal	2	0.549	0.4941	OKAY	Modal	2	1.187	1.0683	UNSAFE
Modal	3	0.423			Modal	3	1.187		

Table -7: Mode Participation Zone 4

Zone 4- RECTANGULAR					Zone 4- CIRCULAR				
TABLE: Modal Participating Mass Ratios					TABLE: Modal Participating Mass Ratios				
Case	Mode	Period			Case	Mode	Period		
		sec					sec		
Modal	1	0.732	0.6588	OKAY	Modal	1	1.266	1.1394	UNSAFE
Modal	2	0.549	0.4941	OKAY	Modal	2	1.187	1.0683	UNSAFE
Modal	3	0.423			Modal	3	1.187		

Table -8: Mode Participation Zone 5

Zone 5- RECTANGULAR						Zone 5- CIRCULAR					
TABLE: Modal Participating Mass Ratios						TABLE: Modal Participating Mass Ratios					
Case	Mode	Period	UX	UY	RZ	Case	Mode	Period	UX	UY	RZ
		sec						sec			
Modal	1	0.732	83%	0%	0%	Modal	1	1.266	0%	0%	95%
Modal	2	0.549	0%	86%	0%	Modal	2	1.187	3%	92%	0%
Modal	3	0.423	0%	0%	87%	Modal	3	1.187	92%	3%	0%

4.2 Time Period Check

Fundamental natural period verification across Seismic Zones II to V reveals a major difference in dynamic performance between tank configurations. The rectangular tank satisfies IS code limits for Modes 1 and 2 ("OKAY"), demonstrating adequate lateral stiffness and controlled flexibility. In contrast, the circular tank exhibits significantly longer periods in Modes 1 and 2, exceeding allowable thresholds and failing compliance checks ("UNSAFE"). These elongated periods indicate excessive flexibility, increasing vulnerability to resonance and large displacement demands. Thus, the rectangular geometry provides superior dynamic stability and strictly complies with Indian Standard provisions across all seismic zones.

Table -9: Time Period check for Zone 2

Zone 2- RECTANGULAR					Zone 2- CIRCULAR				
TABLE: Modal Participating Mass Ratios					TABLE: Modal Participating Mass Ratios				
Case	Mode	Period			Case	Mode	Period		
		sec					sec		
Modal	1	0.732	0.6588	OKAY	Modal	1	1.266	1.1394	UNSAFE
Modal	2	0.549	0.4941	OKAY	Modal	2	1.187	1.0683	UNSAFE
Modal	3	0.423			Modal	3	1.187		

Table -10: Time Period check for Zone 3

Zone 3- RECTANGULAR					Zone 3- CIRCULAR				
TABLE: Modal Participating Mass Ratios					TABLE: Modal Participating Mass Ratios				
Case	Mode	Period			Case	Mode	Period		
		sec					sec		
Modal	1	0.732	0.6588	OKAY	Modal	1	1.266	1.1394	UNSAFE
Modal	2	0.549	0.4941	OKAY	Modal	2	1.187	1.0683	UNSAFE
Modal	3	0.423			Modal	3	1.187		

Table -11: Time Period check for Zone 4

Zone 4- RECTANGULAR					Zone 4- CIRCULAR				
TABLE: Modal Participating Mass Ratios					TABLE: Modal Participating Mass Ratios				
Case	Mode	Period			Case	Mode	Period		
		sec					sec		
Modal	1	0.732	0.6588	OKAY	Modal	1	1.266	1.1394	UNSAFE
Modal	2	0.549	0.4941	OKAY	Modal	2	1.187	1.0683	UNSAFE
Modal	3	0.423			Modal	3	1.187		

Table -12: Time Period check for Zone 5

Zone 5- RECTANGULAR					Zone 5- CIRCULAR				
TABLE: Modal Participating Mass Ratios					TABLE: Modal Participating Mass Ratios				
Case	Mode	Period			Case	Mode	Period		
		sec					sec		
Modal	1	0.732	0.6588	OKAY	Modal	1	1.266	1.1394	UNSAFE
Modal	2	0.549	0.4941	OKAY	Modal	2	1.187	1.0683	UNSAFE
Modal	3	0.423			Modal	3	1.187		

4.3 Story Displacement

Lateral storey displacement analysis across Seismic Zones II to V confirms that both rectangular and circular elevated water tanks satisfy the IS code limit of H/250 (80 mm for a 20 m staging height). However, the rectangular tank consistently outperforms the circular tank by exhibiting lower lateral deflections in both orthogonal directions. Under Zone II loading, the rectangular model records displacements of 4.6 mm (EQX) and 3.4 mm (EQY) compared to 4.9 mm for the circular model. In Zone V, the rectangular configuration maintains superior lateral stiffness with deflections of 16.4 mm (EQX) and 12.1 mm (EQY), whereas the circular tank undergoes higher lateral drift of 17.5 mm. This reduced displacement demonstrates the enhanced structural rigidity and seismic serviceability of the rectangular framing system across all zones.

Table -13: Structural Displacement check for Zone 2

Zone 2- RECTANGULAR						Zone 2- CIRCULAR					
EQX	4.6	mm	EQY	3.4	mm	EQX	4.9	mm	EQY	4.9	mm
LIMIT	80	mm	LIMIT	80	mm	LIMIT	80	mm	LIMIT	80	mm
	OKAY			OKAY			OKAY			OKAY	

Table -14: Structural Displacement check for Zone 3

Zone 3- RECTANGULAR						Zone 3- CIRCULAR					
EQX	7.3	mm	EQY	5.4	mm	EQX	7.8	mm	EQY	7.8	mm
LIMIT	80	mm	LIMIT	80	mm	LIMIT	80	mm	LIMIT	80	mm
	OKAY			OKAY	mm		OKAY			OKAY	

Table -15: Structural Displacement check for Zone 4

Zone 4- RECTANGULAR						Zone 4- CIRCULAR					
EX	10.9	mm	EY	10.9	mm	EQX	11.7	mm	EQY	11.7	mm
limit	80	mm	limit	80	mm	LIMIT	80	mm	LIMIT	80	mm
	OKAY			OKAY			OKAY			OKAY	

Table -16: Structural Displacement check for Zone 5

Zone 5- RECTANGULAR						Zone 5- CIRCULAR					
EQX	16.4	mm	EQX	12.1	mm	EQX	17.5	mm	EQY	17.5	mm
LIMIT	80	mm	LIMIT	80	mm	LIMIT	80	mm	LIMIT	80	mm
	OKAY			OKAY			OKAY			OKAY	

3. CONCLUSIONS

1. **Study Scope and Methodology**: Linear dynamic response spectrum analysis was conducted for 20 m elevated RC water tanks of rectangular and circular/hexagonal geometries across Indian Seismic Zones II to V as per IS 1893.

2. **Impact of Geometry:** The geometric configuration and framing layout significantly dictate the dynamic behaviour, structural stiffness, and codal compliance of elevated liquid-retaining reservoirs under earthquake actions.

3. **Modal Sequence and Torsional Behavior:** The rectangular tank showed favourable dynamic response with pure orthogonal translational fundamental modes (Modes 1 and 2) and torsion delayed to Mode 3, whereas the circular tank exhibited critical Mode 1 torsional dominance with 95% rotational mass participation.

4. **Natural Time Period Compliance:** The rectangular configuration satisfied the permissible IS code time period criteria across all zones (0.732 s and 0.549 s), while the circular configuration exceeded the limits (1.266 s and 1.187 s), failing compliance due to excessive flexibility.

5. **Lateral Displacement Performance:** Both tank models remained within the maximum allowable storey displacement limit of H/250 (80 mm), but the rectangular tank consistently recorded lower lateral drifts up to Zone V (16.4 mm vs. 17.5 mm).

6. **Core Conclusion:** The rectangular elevated storage reservoir provides higher lateral stiffness, predictable modal behavior, and superior structural efficiency and resilience compared to the circular geometry under seismic loading.

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