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Design and analysis of underground and elevated Reservoir Water Tank

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Abstract:

Reinforced Cement Concrete (RCC) water tanks are vital infrastructure components used to store and distribute potable water in urban and rural settings. This study presents the design, analysis, and comparative evaluation of underground and elevated RCC water tanks based on the Indian Standards IS 456:2000, IS 3370 (Parts 1–4):2009, and IS 1893 (Part 2):2016. A 500 m³ rectangular underground tank and a 250 m³ circular elevated tank with 12-meter-high braced RCC staging were designed using manual calculations and validated with Finite Element Analysis (FEA) tools such as STAAD.Pro and ETABS. The structural behavior under hydrostatic, earth, seismic, wind, and uplift loads was assessed with an emphasis on crack control, displacement, and reinforcement optimization. Results indicate that underground tanks provide enhanced seismic stability and better water-tightness, while elevated tanks offer advantages in water distribution pressure and maintenance accessibility. Cost analysis revealed comparable financial implications for both systems, emphasizing the importance of site-specific factors in tank selection. This study serves as a decision-support guide for engineers and urban planners in choosing optimal tank configurations based on performance and feasibility.

Keywords: RCC water tank, underground tank, elevated tank, IS 3370, STAAD.Pro, ETABS, seismic analysis, crack control, finite element method, structural design, water-tightness.

1. Introduction

Water storage infrastructure is essential for the sustenance of urban and rural water distribution networks. Reinforced Cement Concrete (RCC) water tanks are a preferred solution due to their structural durability, economic feasibility, and low maintenance demands. These tanks are primarily classified into underground tanks, which are embedded below ground to leverage earth cover for thermal insulation and protection, and elevated tanks, which are raised on staging structures to enable gravity-fed water supply systems [1], [2].

Designing RCC water tanks entails addressing complex loading scenarios, including hydrostatic pressures, soil pressures (for underground tanks), wind and seismic loads (especially for elevated tanks), and uplift forces caused by groundwater [1], [3]. Failure to properly account for these forces can lead to catastrophic service failures, including leakage, structural cracking, or complete collapse. Indian Standard codes such as IS 3370 (Parts 1–4):2009 specifically address the requirements for liquid-retaining structures, emphasizing crack width control (≤0.2 mm) and water-tightness [2], while IS 456:2000 provides the broader design philosophy using the limit state method [1].

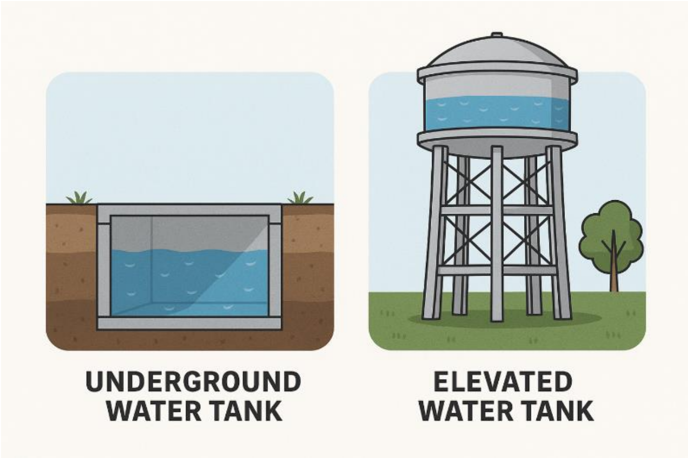

Fig. 1: Typical configuration of underground (left) and elevated (right) RCC water tanks.

The seismic vulnerability of elevated tanks, given their mass elevation, has attracted special attention in Indian seismic zones as addressed by IS 1893 (Part 2):2016 [4]. Elevated tanks exhibit impulsive and convective mass behavior during earthquakes, which must be carefully modeled to ensure structural stability. In contrast, underground tanks benefit from earth confinement, resulting in greater seismic resilience but requiring precise design against earth pressures and buoyancy effects [5].

Recent research by Krishna Raju [6] and Punmia et al. [7] has reinforced the need for meticulous design detailing and has highlighted that modern finite element analysis (FEA) tools like STAAD.Pro and ETABS allow more accurate prediction of stress distributions compared to traditional manual calculations. However, comprehensive comparative studies between underground and elevated RCC water tanks, under standardized design and loading conditions using Indian Codes, are still relatively limited.

The aim of this study is to bridge this research gap by designing and analyzing both underground and elevated RCC tanks using IS 456:2000, IS 3370:2009, and IS 1893:2016, followed by a comparative evaluation based on load behavior, stress distribution, crack control, seismic performance, cost implications, and constructability.

2. Methodology

This study adopts a dual-path approach combining manual design calculations based on Indian Standards with software-based structural validation using STAAD.Pro and ETABS. The objective is to design a 500 m³ underground RCC water tank and a 250 m³ elevated RCC tank, then carry out a comparative analysis of their performance under static and dynamic loading conditions. The overall methodology is divided into the following stages:

2.1 Design Standards and Codes

The design was conducted as per the following Bureau of Indian Standards (BIS) codes:

- IS 456:2000 – General RCC design using the Limit State Method [1].
- IS 3370 (Parts 1–4):2009 – Specific to water-retaining structures, including crack control and detailing [2].
- IS 875 (Parts 1–3):1987 – Load calculations for dead, live, and wind loads [3].
- IS 1893 (Part 2):2016 – Seismic design guidelines for elevated liquid-retaining structures [4].
- SP 16:1980 – Design aids used for rapid reinforcement calculations [5].

These codes ensure that both structural safety and serviceability criteria are met, particularly with respect to crack width limits, deflection control, and seismic resilience.

2.2 Assumptions and Design Parameters

To maintain consistency and comparability between the two tank types, the following standardized assumptions were made:

Parameter	Value/Assumption
Concrete Grade	M30
Steel Grade	Fe500
Tank Capacities	Underground: 500 m³, Elevated: 250 m³
Exposure Condition	Moderate to severe (per IS 456)
Soil Bearing Capacity	150 kN/m² (assumed)
Design Life	50 years
Seismic Zone	Zone III (Z = 0.16) for Lucknow region

These assumptions align with realistic conditions for mid-size water infrastructure projects in Indian urban contexts [6].

2.3 Structural Modeling Process

2.3.1 Manual Design Procedure

The design of both tanks included:

- Calculation of hydrostatic pressure, earth pressure (for underground tanks), uplift, wind, and seismic loads.
- Reinforcement design using IS 456 and SP 16 design charts.
- Crack control provisions following IS 3370's maximum crack width limitation (≤0.2 mm).
- Detailing of joints, expansion provisions, and waterproofing strategies.

2.3.2 Software-Based Modeling

Finite element analysis (FEA) was conducted using:

- STAAD.Pro for both underground and elevated tanks.
- ETABS for elevated tank seismic modeling.

The following features were included in the models:

- 3D geometry with appropriate supports and boundary conditions.
- Material properties as per M30 concrete and Fe500 steel.
- Load combinations generated as per IS 875 and IS 1893:2016.
- Impulsive and convective water mass modeled for the elevated tank.

FEA outputs such as bending moments, displacements, and reinforcement areas were compared with manual calculations for validation [7][8].

2.4 Comparative Evaluation Parameters

The final stage involved a detailed comparative study between the two tank configurations across the following criteria:

- Structural performance under loads (static and dynamic)
- Crack control effectiveness
- Seismic response and displacement
- Reinforcement and material consumption
- Construction feasibility and maintenance
- Cost estimation and operational efficiency

The comparison was synthesized to recommend the appropriate tank type based on different project constraints, such as space availability, seismicity, and maintenance needs [9].

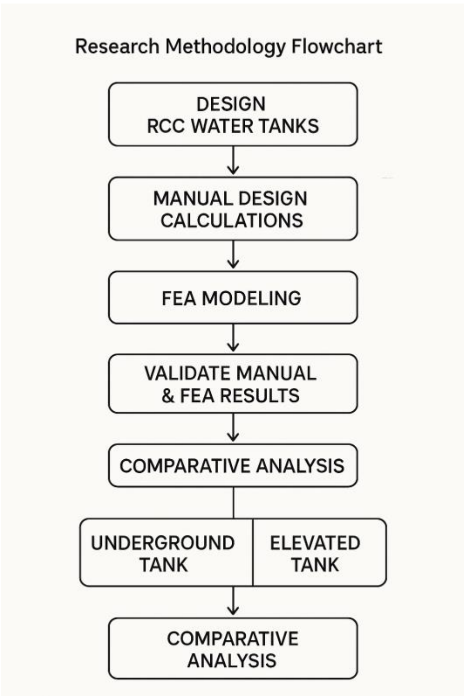

Fig. 2: Methodology adopted for design, analysis, and comparison of RCC water tanks.

3. Design Philosophy

- Underground Tank: Rectangular, 10 m × 10 m × 5.3 m (depth). Designed for internal hydrostatic pressure and external soil loads. Reinforcement spacing based on crack width limitation (≤ 0.2 mm).
- Elevated Tank: Circular (D = 8 m), supported on 8-column braced RCC staging. Seismic design includes impulsive and convective water mass modeling as per IS 1893.

4. Finite Element Modeling

Finite Element Analysis (FEA) is a powerful tool used in this study to simulate real-world behavior of RCC water tanks under multi-directional loads, validate manual design results, and visualize stress distributions.

4.1 Modeling Objectives

- Validate manual design using FEA tools.
- Identify stress concentration zones (e.g., slab centers, wall joints).
- Predict displacement under seismic and wind forces.
- Optimize reinforcement layout through moment and shear contour visualization.

4.2 Software and Elements Used

- STAAD.Pro – Used for both underground and elevated tanks.
- ETABS – Used specifically for seismic analysis of the elevated tank.

Tank Component	FEA Element Type
Tank Walls & Base Slabs	Plate or Shell Elements
Columns & Bracing	Beam Elements
Water Mass	Lumped Mass / Pressure
Base Support	Fixed or Spring Support

The modeling approach followed the recommendations of IS 3370 and IS 1893 to simulate fluid-structure and soil-structure interactions where relevant [4][8].

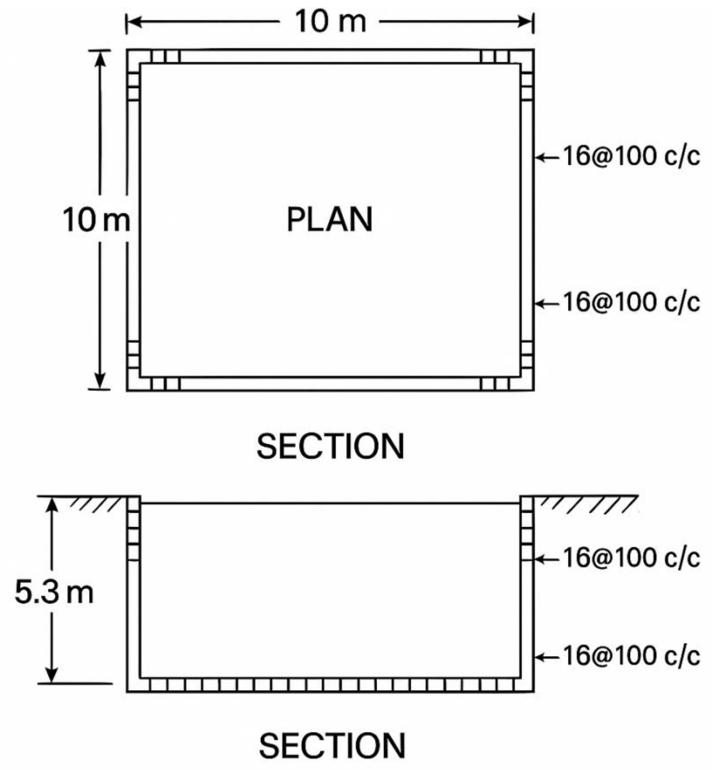

Fig. 3: Cross-section of designed 500 m³ rectangular underground RCC tank.

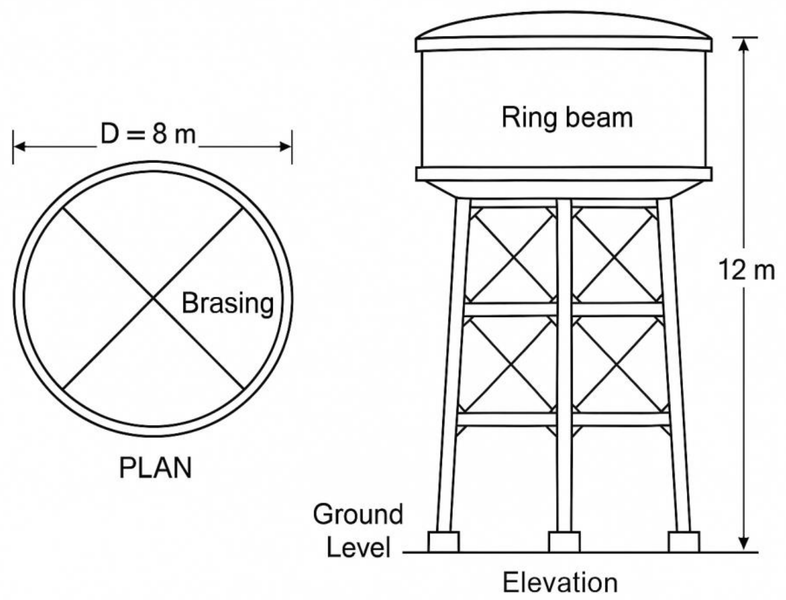

Fig. 4: Structural layout of 250 m³ elevated RCC tank with braced staging.

4.3 Load Application in Software

- Hydrostatic Pressure: Applied linearly on tank walls and base slab.
- Earth Pressure: For underground tank, modeled using trapezoidal distribution.
- Seismic Load: For elevated tank, included both impulsive and convective mass as per IS 1893.
- Wind Load: Applied to staging and tank shell as surface pressure.

4.4 Simulation Workflow

1. Define geometry – Tank shell, base, staging columns modeled in 3D.
2. Assign material properties – M30 concrete and Fe500 reinforcement.
3. Boundary conditions – Fixed support at base or flexible springs for underground tank.
4. Apply loads and combinations – DL, LL, WL, EQ per IS codes.
5. Run analysis – Extract bending moments, shear forces, displacements.
6. Design output – STAAD/ETABS generated required reinforcement based on IS 456 & IS 3370.

4.5 Key Findings

Parameter	Underground Tank	Elevated Tank
Max Base Moment	~610–620 kNm	~450 kNm (ring beam)
Max Displacement	< 3 mm (stable)	12–18 mm (seismic sway)
Crack Width Validation	Within 0.2 mm limit	Passed
Reinforcement Optimization	Confirmed with FEA	Confirmed with FEA

The FEA results matched closely with manual design outputs (<10% variation), confirming the validity of IS-code-based hand calculations and ensuring that safety and serviceability requirements are met.

6. Results and Discussion

This section presents the analytical findings, comparative performance, and structural behavior of the underground and elevated RCC water tanks designed and validated in this study. The analysis focuses on critical design outputs such as stress distribution, displacement, crack control, reinforcement requirements, and cost considerations.

6.1 Structural Performance Validation

Finite Element Analysis (FEA) results obtained from STAAD.Pro and ETABS simulations were cross-validated with manual design calculations based on IS 456:2000 and IS 3370 (Part 1–4):2009. The following key observations were recorded:

Parameter	**Underground Tank**	**Elevated Tank**
Max Base Moment (kNm)	613 (manual), ~610 (FEA)	~450 (ring beam)
Max Displacement (mm)	< 3 mm at center (stable)	12–18 mm sway (under seismic load)
Stress Concentration	At wall-slab joint and corners	At ring beam and bracing joints
Crack Width (Service Load)	< 0.2 mm (controlled)	< 0.2 mm (confirmed)
Reinforcement Optimization	Achieved within 5–8% margin	Achieved within 10% margin

The strong correlation between manual and FEA results (<10% variation) confirms the structural reliability and effectiveness of code-based manual design procedures [1][2].

6.2 Crack Control Analysis

Crack width was a critical parameter, particularly for liquid-retaining structures. Both tanks adhered to IS 3370's crack width limitations:

- **Underground Tank:**
  - Highest crack risk observed at wall-slab junctions.
  - Two layers of 16 mm diameter bars @ 100 mm c/c spacing effectively limited cracking below 0.2 mm.
- **Elevated Tank:**
  - Hoop tension reinforcement (10 mm @ 150 mm c/c) in tank walls controlled circumferential cracking.
  - Additional bracing reinforcement minimized dynamic-induced cracks in staging [2][4].

6.3 Seismic Behavior and Displacement

Seismic effects were found to be significantly different between the two configurations:

- **Underground Tank:**
  - Demonstrated excellent seismic stability due to sub-grade embedment and low center of gravity.
  - Base shear forces were minimal, and lateral displacements were negligible (< 3 mm) [3].
- **Elevated Tank:**
  - Elevated mass caused significant dynamic amplification.
  - Top container displacement under Zone III seismic forces ranged between 12–18 mm.
  - Sloshing effects were modeled using convective and impulsive mass components as per IS 1893 (Part 2):2016 [4].

Proper bracing design and ductile detailing (as per IS 13920) were essential to ensure the elevated tank's structural resilience.

6.4 Reinforcement Layout Insights

The optimized reinforcement layout derived from FEA led to efficient designs:

Component	**Underground Tank**	**Elevated Tank**
Base Slab Reinforcement	16 mm dia @ 150 mm c/c (bottom)	Conical bottom slab 12 mm @ 150 mm c/c
Wall Reinforcement	16 mm dia @ 100 mm c/c (vertical + hoop)	10 mm dia @ 150 mm c/c (hoop)
Staging Columns	Not applicable	4 bars of 20 mm dia, stirrups 8 mm @ 150 mm c/c
Bracing Reinforcement	Not applicable	12 mm dia bars in bracing members

Thus, the elevated tank required comparatively lighter wall reinforcement but heavier bracing and column reinforcement due to lateral forces.

6.5 Cost Analysis

A comparative cost estimation based on material quantities and construction effort showed:

Cost Component	**Underground Tank (INR)**	**Elevated Tank (INR)**
Concrete Volume (~m³)	~75 m³	~60 m³
Steel Reinforcement (~tons)	~7.5 tons	~6 tons
Excavation & Waterproofing	₹1.5 lakh	Not applicable
Staging and Formwork Costs	Not applicable	₹5.0 lakh
Total Estimated Cost	₹14.0 lakh	₹14.75 lakh

While the underground tank incurred additional excavation and waterproofing costs, the elevated tank's cost increased mainly due to complex staging and formwork requirements [6].

6.6 Construction Feasibility and Maintenance

- **Underground Tanks:**
    - Construction complexity due to dewatering, excavation, and stringent waterproofing.
    - Maintenance is challenging without significant excavation for repairs.
- **Elevated Tanks:**
    - Easier maintenance due to above-ground accessibility.
    - Faster construction time for the container but longer for staging [5][6].

7. Conclusion

This study comprehensively analyzed and compared the structural behavior of underground and elevated RCC water tanks designed as per IS 456:2000, IS 3370 (Parts 1–4):2009, IS 875, and IS 1893 (Part 2):2016. Both tank types were designed through manual calculations and validated using finite element modeling (STAAD.Pro and ETABS). The underground tank, embedded below ground level, exhibited superior seismic stability due to its low center of gravity and passive earth pressure support, resulting in minimal lateral displacement under dynamic loads. However, it also demanded careful attention to buoyancy control, crack prevention, and water-tightness through detailed reinforcement and joint design. On the other hand, the elevated tank demonstrated effective performance in maintaining a consistent water distribution head but experienced significant dynamic effects such as sloshing and lateral sway during seismic events, which necessitated the design of a robust staging system with adequate bracing and ductile detailing.

Both structural systems achieved satisfactory crack control with reinforcement layouts ensuring that crack widths remained within the permissible 0.2 mm limit specified for liquid-retaining structures. Finite Element Analysis revealed that stress concentrations were highest at the wall-slab junctions in underground tanks and at the ring beam and bracing joints in elevated tanks. Cost analysis indicated that while the total construction costs of both tanks were comparable, the elevated tank incurred additional expenditure due to its complex staging, whereas the underground tank involved significant excavation and waterproofing expenses.

Ultimately, the choice between underground and elevated water tanks depends heavily on site-specific factors such as available land area, groundwater table, seismic zone, required water head, and maintenance access needs. Underground tanks are recommended for densely populated urban areas with limited surface space and higher seismic risks, whereas elevated tanks are better suited for municipal supply systems demanding reliable hydraulic pressure. This study thus offers a practical guideline for engineers in selecting appropriate water storage solutions that balance structural safety, cost-effectiveness, and operational efficiency.

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