A novel approach for the design of elevated water tanks considering RCC and ferrocement lining

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by

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Chapter 7: Conclusions and future scope

7.1. Introduction

This study presents a pioneering effort, being the first of its kind in its approach towards Structural design of water tanks. This research introduces a novel and cost-effective design methodology for Elevated Water Tanks by integrating Reinforced Cement Concrete (RCC) with Ferrocement lining. Unlike conventional tanks governed strictly by IS 3370:2021 guidelines, the proposed Hybrid Water Tank approach offers a structurally optimized, impermeable, and materially efficient solution. This hybridization is unique in its strain-compatible integration of ferrocement—designed for impermeability—with RCC that bears structural loads, representing the first such application in Indian water tank design practice. In HWT, RCC is supposed to bear all the structural loads, designed in accordance with IS 456:2000 (Reaffirmed in 2021) which and ferrocement lining is specifically engineered to impart impermeability to the tanks and designed for Strain compatibility criteria using ACI standards.

This research presents several groundbreaking contributions to the field of structural and water infrastructure engineering, particularly in the design and optimization of elevated water tanks. The following are the original contributions of the thesis are given in section 7.2.

To evaluate the performance of HWT and conduct comparative studies against CWT, the following studies were undertaken:

- Comparative study of Hybrid and Conventional (Type I) Intze type tanks
- Comparative study of Hybrid and Conventional (Type II) Intze type tanks
- Comparative study of Hybrid with Conventional Type I and II Intze tanks
- Parametric study of Elevated Hybrid Circular tanks
- Comparative study of Hybrid and Conventional (Type I) & Hybrid and Conventional (type II) Elevated Circular type tanks
- Comparative study of Hybrid and Conventional (Type II) Elevated Intze & Circular type tanks across 16 major Indian Cities

Conclusions obtained from the above studies are as follows in section 7.3-7.10.

7.2. Original contributions of this work

1**. Introduction of a novel hybrid water tank design concept**

This thesis proposes a new structural concept — the Hybrid water tank which integrates RCC with ferrocement lining.

- RCC is engineered solely to resist structural loads,
- Ferrocement lining is introduced to ensure impermeability and serviceability.
- This concept challenges and improves upon existing IS 3370:2021-based monolithic RCC tank designs, offering a new way to enhance performance while reducing material and construction costs.

2. **First-Time use of ferrocement as an inner lining in RCC water tanks as a predesigned and functional component**:

This is the first known research to apply ferrocement as an inner lining in large-scale RCC elevated water tanks. Ferrocement has traditionally been used for standalone small tanks, panels, or architectural shells — but never structurally integrated as a lining in a load-carrying RCC system.

This work establishes the feasibility, benefits, and mechanical integration of ferrocement as a secondary but critical structural element — improving impermeability, crack control, and durability while enabling leaner RCC design.

3. Development of the first-ever design methodology for ferrocement linings

For the first time ferrocement lining methodology, details, guidelines, calculations, equations are proposed in this work. A complete and codified methodology is presented for designing ferrocement linings in elevated water tanks — addressing a long-standing gap in civil engineering practice. The methodology includes:

- Strain compatibility design with RCC tank walls,
- Crack width and crack spacing calculations specific to thin ferrocement layers,
- Hoop tension and flexural design under service loads,
- Guidelines for mesh selection, plaster thickness, and reinforcement detailing.

This is the first structural design method ever published for ferrocement used in lining applications, transforming it from an empirical practice into a scientifically designed solution.

4. Constitutive modeling of ferrocement in lining conditions

This thesis introduces new mechanical formulations to model the behavior of ferrocement when used as a lining:

- Stress-strain relationship under hoop tension,
- Crack width control in thin composite sections,
- Interface behavior between ferrocement and RCC.

These models are tailored for lining applications — distinct from traditional ferrocement shell design — and allow safe, serviceable, and replicable use in infrastructure-scale projects.

5. Development of modular software for hybrid and conventional tanks

Dedicated C++ software was developed to design both Conventional (Type I and II) and Hybrid tanks for both Intze and Circular types. Each design includes:

- Structural analysis,
- Reinforcement design,
- Staging and foundation design,
- Cost estimation,
- A unique eighth module for ferrocement lining design in hybrid tanks.

This makes the software a complete tool for practical design and comparison, suitable for engineers and infrastructure planners.

6. Heuristic optimization of design parameters

The software integrates heuristic optimization algorithms to determine:

- Members sizing for cost and material reduction.
- Optimal number of columns,

This ensures that the hybrid designs are not only functional but optimized for economy and constructability.

7. Extensive validation through manual calculations and case studies

Over 50 detailed manual design cases were computed and verified against software results, across:

- Multiple tank capacities (100–1000 kL),
- Intze and Circular type of tanks.
- Seismic Zones II–V,

- Wind speeds from 39 to 50 m/s,
- Soil bearing capacities and foundation conditions.

This dual-mode validation demonstrates the technical accuracy, consistency, and field readiness of the proposed method.

8. Global relevance with Pan-India simulation

Although simulations were conducted for 16 Indian cities, covering diverse wind and seismic zones, the methodology is:

- Covering all the type of critical combinations pan India.
- Globally applicable, due to its code-independent, modular structure,

- Adaptable to any national design standard (e.g., Eurocode, ACI),

Especially relevant to developing nations needing low-cost, high-performance water storage systems.

9. Quantified economic and structural advantages of the hybrid design

Through comparative studies with CWT I and CWT II, the hybrid system achieved:

- 20–38% reduction in total cost,
- 30–46% less steel and concrete,
- Up to 87% reduction in crack width,
- Up to 35% smaller foundation footprint,
- Enhanced performance in seismic and wind loading, especially in empty tank conditions.

These improvements were validated across multiple configurations and locations.

10. Practical costing framework using CPWD and market rates

The thesis includes a realistic costing framework using:

- The thesis integrates a practical and adaptable costing model based on CPWD DAR 2021 and demonstrates that any state-level Schedule of Rates (SOR) or departmental rate system can be incorporated by simply updating the input rate parameters in the software.
- This flexibility makes the model readily usable by public works departments, urban bodies, and private consultants across India and internationally —

allowing instant alignment with local pricing systems without requiring code modification beyond basic rate entries.

- Market prices for ferrocement components (mesh types, plaster, labor),
- Cost breakdowns for lining thickness from 10–20 mm.

This ensures that the research is directly usable in public infrastructure tenders and budgeting.

11. Engineering templates, drawings, and documentation

This study provides:

- Manual design sheets for 600 kL and 200 kL hybrid tanks,
- Software outputs for multiple tank types,
- Structural drawings of all components, including ferrocement layers.
- These serve as ready-to-use templates for engineers, consultants, and public agencies.

12. **Comprehensive coverage of all normal and critical design combinations across India**

The thesis evaluates hybrid and conventional water tank designs under **a wide range of structural scenarios**, including:

- **Various capacities**: from 100 kL to 1000 kL,
- **All seismic zones (II to V)** and **wind speeds (39–50 m/s)**,
- **Different soil conditions** and foundation requirements,
- **Both full and empty tank conditions**, capturing **worst-case scenarios** for deflection and base shear.

This level of parametric simulation ensures the hybrid design is **robust, reliable, and safe** under **both typical and extreme Indian conditions**, offering a complete design solution adaptable to any region.

13. Detailed parametric simulations for performance optimization

The thesis includes an extensive set of **parametric simulation studies** covering variations in:

- Tank capacities (100–1000 kL),
- Geometries (Intze and Circular tanks),
- Material usage (steel, concrete, ferrocement),

- Structural responses (crack width, deflection, seismic base shear),
- Environmental and site conditions (wind speeds, seismic zones, soil types).

These simulations enabled the identification of optimal design configurations for both performance and economy. The approach demonstrates how small changes in design parameters can lead to significant cost savings and efficiency improvements, adding a powerful decision-support layer to the proposed hybrid methodology.

7.3. Comparative study of HWT and CWT I Intze type tanks

The study systematically compared 200, 600 and 1000 kL Conventional and Hybrid Intze tanks keeping wind speed 39 m/s and Seismic Zone II (Section 4.3). Conclusions are as follows:

- The Hybrid approach of designing water tanks that integrate RCC with ferrocement results in huge savings in cost compared to traditional RCC Intze water tanks.
- Significant savings ranging from 28% to 38% are obtained, which are approximately 1/3rd of the entire cost of the structure. The percentage of savings rises alongside the augmentation of the water-carrying volume of the tank.
- Ferrocement lining cost is proportionate with the strain on the junction of the RCC and lining. The lining cost depends on the overall surface area of the water-facing.
- Its cost contributes about 3-3.5 %, which is little or almost negligible compared to the overall material cost.
- The ferrocement lining thus is cost-effective and provides impermeability, serviceability, and durability to water tanks.
- The value of Crack width observed in the HWTs is 0.022 mm, which is approximately one/tenth of the maximum permissible crack within the RCC tanks as per IS 3370:2021. The narrower crack width observed in HWTs underscores their enhanced impermeability.
- The observed value of the crack width is well below the allowable maximum crack width as per ACI norms for the Ferrocement construction of water retaining structures. Research indicates that with an increase in capacity of the Intze-type tanks, the Crack width observed is almost the same and is of the order of around 0.022 mm.
- Hybrid design showcases material optimization and a significant reduction in material quantities. HWTs result in a lightweight tank body, effectively reducing the overall load on the staging and annular raft. This contributes to a cost reduction in both staging and foundation.

- The Hybrid design consistently shows significant reductions in material (23-39 % in concrete, 26-32% in steel) across diverse tank capacities, emphasizing its efficacy in achieving material savings.
- In the Hybrid design, the foundation area is reduced by up to 10 – 15 %, and the reduced cost of columns, braces, and foundation is observed.
- The HWTs perform better as compared to the Standard RCC ones in response to lateral forces, i.e., wind and seismic forces, and also show reduced Deflections in both Full (F.T.) and Empty (E.T.) water tank conditions.
- Deflection is reduced to 10-11% in F.T., and 32-43% in E.T. Reduced base shear is also observed with a reduction of 7-15% in F.T. and 14-21% in E.T. Wind-induced forces are somewhat similar or marginally lesser in the Hybrid approach.

7.4. Comparative study of HWT and CWT II Intze type tanks

The study systematically compared 200, 600 and 1000 kL Conventional and Hybrid Intze tanks keeping wind speed 39 m/s and Seismic Zone II (Section 4.4). Conclusions are as follows:

- CWT designed according to criteria II, while achieving significant steel savings, remain bulky and costly due to stringent minimum dimension requirements. The substantial consumption of concrete contributes to high costs and the underutilization of materials. Hybrid design with ferrocement lining integration in Elevated Reinforced Cement Concrete Intze water tanks results in significant cost savings compared to CWT.
- A potential savings of 20-28% can be achieved, primarily attributed to the reduced costs of the tank body in comparison to the overall structure.
- It is evident that the percentage of savings increases with increase in capacity of the tank.
- The cost of ferrocement lining accounts for roughly 3-4% of the overall structure cost.
- The incorporation of hybrid construction allows for efficient material usage, resulting in substantial concrete savings of up to 30-36% and steel savings ranging from 11-20%. This not only promotes sustainability but also aligns with cost-effective project execution.
- The HWT design significantly reduces deflection, offering improved stability both in full and empty tank conditions. With a reduction of up to 10-16% in full tanks and an impressive 38-46% in empty tanks, the design enhances overall structural integrity.
- The implementation of a hybrid design results in a noteworthy decrease in the required raft area, ranging from 10-35%. This space-efficient characteristic is valuable, especially in projects where footprint constraints or optimization of land usage are critical considerations.

- The average savings across all soil bearing capacities show that Hybrid consistently outperforms Conventional in terms of reducing the designed area. The average percentage savings are 15% at 80 kN/m², 21% at 160 kN/m², and 28% at 240 kN/m².
- Percentage savings in Raft areas in Hybrid design as compared to conventional increases with increase in the in-Bearing capacity of soil.
- HWTs exhibit lower base shear, showcasing a decrease of 4-6% in full tanks and a substantial reduction of 16-23% in empty tanks.
- Rest conclusions are same as in Section 7.2.

7.5. Comparative study of HWT, CWT I and CWT II Intze tanks

The study systematically compared 200, 600 and 1000 kL Conventional and Hybrid Intze tanks keeping wind speed III (Section 4.5). The study focuses on the behavior of these tanks under different seismic zone and wind speed, with a particular emphasis on analyzing the cost differences between conventional type I and type II tanks. Conclusions are as follows:

- Hybrid design with ferrocement lining integration in Reinforced Cement Concrete Intze water tanks results in significant cost savings compared to conventionally designed RCC water tanks in Seismic Zone III and Wind speed 47 m/sec.
- HWT demonstrate significant cost-effectiveness over conventional designs, with percentage savings ranging from 28-37% compared to CWT I and 17-24% compared to CWT II, indicating higher efficiency and notable savings, especially with larger tank capacities.
- The HWT design consistently demonstrates significant material savings, evidenced by concrete savings ranging from 34-43% and steel savings varying between 3-11% for Conventional type II, and concrete savings of 35-38% and steel savings ranging from 24-48% for Conventional type I, underscoring its robust effectiveness across different tank capacities.
- The Hybrid design outperforms both CWT in deflection and seismic analyses. HWTs exhibit impressive reductions in deflection (9-14% for full tanks to 36-46% for empty tanks) and base shear (5-7% for full tanks to 17-23% for empty tanks) compared to both CWT I & CWT II.
- Percentage savings of Raft area in HWTs is 10-14% as compared to that of CWT.
- CWT I is costlier as compared to CWT II tanks. 5-13% savings can be achieved using CWT II tanks.
- Concrete Section sizes in CWT I are lesser than those in CWT II. Although Substantial steel savings can be achieved using CWT II tanks.
- CWT I outperforms CWT II tanks in terms of structural performance under seismic, wind, crack width & other parameters.

- The study emphasizes the cost-effectiveness of CWT II, demonstrating savings of up to 7-8% compared to CWT I, with CWT II experiencing a noteworthy 12-44% reduction in steel compared to CWT I. Conversely, CWT I exhibits concrete savings of up to 7% compared to CWT II.
- Rest conclusions are same as in Section 7.2.

7.6. Parametric study of hybrid circular water tanks

The study examined how height-to-diameter ratios impact the design of Hybrid Elevated Circular water tanks, focusing on capacities from 100 kL to 300 kL (Section 5.3).

- H/D ratios around 0.8 consistently balanced cost and structural integrity effectively across different tank sizes.
- For 100 kL tanks, the study recommended 4 columns at H/D 0.8 for optimal cost-efficiency and structural stability. Similarly, 6 columns at H/D 0.8 were found suitable for 150 kL-200 kL tanks, maintaining a balance between safety and expense.
- Larger capacities (250 kL, and 300 kL) benefited from 8 columns at H/D 0.8, providing robust support for expanded perimeters while managing construction costs.
- For capacities beyond 300 kL, the study highlighted challenges associated with extreme H/D ratios: lower ratios (0.2 to 0.4) reduced the tank height but necessitated more columns due to the increased periphery leading to huge costs. Conversely, higher ratios (>0.6) resulted in impractically tall tanks, posing construction difficulties.
- Future studies should focus on hybrid circular tanks within the 100-300 kL range, emphasizing their practicality and cost-effectiveness compared to conventional tank designs.
- Tanks beyond 300 kL should consider Intze designs for their lower construction heights and reduced column requirements, ensuring both practicality and cost-effectiveness in larger-scale water storage projects.
- Overall, the findings provide essential insights for designing Hybrid Elevated Circular water tanks, ensuring they meet structural demands while optimizing construction costs across various capacities and design parameters.

7.7. Comparative study of hybrid and conventional type I Elevated circular type tanks

The study compared economic and structural aspects of Hybrid Circular tank designs with CWT of capacities ranging from 100 to 300 kL (Section 5.4).

- HWT designs are significantly more cost-effective, with cost savings ranging from 19% to 24%.
- On average, hybrid designs save about 25% in material expenses, with savings increasing with tank capacity.
- The cost of ferrocement lining in hybrid designs is minimal, ranging from 0.4 to 0.8 currency units, or about 4.14% to 4.3% of the total tank cost.
- Hybrid designs show significant savings in the cost of the tank body due to weight reduction and diminished seismic base shear, leading to lower staging and foundation expenses.
- The cost difference between hybrid and conventional tank bodies increases linearly with tank capacity, with reductions ranging from 2.73 to 5.03 currency units.
- Hybrid designs consistently require less concrete and steel across all tank capacities, with concrete savings of approximately 23% and steel savings ranging from 25% to 33%.
- HWTs have lower deflection in both full and empty conditions, with reductions of 11%-14% for full tanks and 27%-30% for empty tanks.
- Seismic base shear is lower in HWTs for both full and empty conditions, with reductions of 6%-8% for full tanks and 14%-28% for empty tanks.
- Wind shear forces increase with tank capacity and become more significant for larger tanks, sometimes exceeding seismic base shear forces for empty tanks.
- HWTs exhibit significantly less crack width compared to CWT, especially with larger capacities.
- The designed area of annular raft footings is reduced in hybrid designs, with percentage savings ranging from 8%-9%.
- The minimum dimensions, stresses, and exposure criteria have been enhanced in IS 3370:2021 compared to IS 3370:2009 and are greater than those in IS 456:2000 to

reduce crack width and prevent leakage in water tanks. However, the excessive material quantities required by the stringent criteria of IS 3370:2021 are unnecessary, as the crack width in RCC as per IS 456:2000 is already minimal. Consequently, adhering to IS 3370:2021 leads to material wastage, particularly in tanks with lower capacities.

7.8. Comparative study of HWT and CWT II circular type tanks

- HWT designs are significantly more cost-effective, with cost savings ranging from 16% to 18%. On average, hybrid designs save about 17 % in material expenses, with savings increasing with tank capacity as discussed in (Section 5.5).
- Hybrid designs show significant savings in the cost of the tank body due to weight reduction and diminished seismic base shear, leading to lower staging and foundation expenses.
- The cost difference between hybrid and conventional tank bodies increases linearly with tank capacity, with reductions ranging from 1.88 to 3.7 Lakh Rs.
- Hybrid designs consistently require less concrete and steel across all tank capacities, with concrete savings of approximately 23% and steel savings ranging from 14% to 16%.
- HWTs have lower deflection in both full and empty conditions, with reductions of 11%-14% for full tanks and 27%-30% for empty tanks.
- Seismic base shear is lower in HWTs for both full and empty conditions, with reductions of 6%-8% for full tanks and 14%-28% for empty tanks.
- The designed area of annular raft footings is reduced in hybrid designs, with percentage savings ranging from 8%-9%.
- Rest the conclusions are same as in Section 7.6.

7.9. Comparative study of 600 kL HWT and CWT II Intze tanks across 16 major Indian cities

- Hybrid designs are considerably more cost-effective than conventional designs for all 16 cities (Section 6.3).
- The percentage difference in cost savings falls within the range of 16-21% in non-coastal cities and increases with an increase in Seismic zones. Coastal cities show a substantial savings of about 16%.
- The cost of the tanks increases with the increase in the seismic zones & wind speeds for both HWT and CWT. & the difference in the cost between hybrid & CWT increases with the increase in Seismic zones.
- The cost of the tanks in Coastal cities is highest in their Zones because of the increase in wind shear forces.
- The cost of ferrocement lining accounts for roughly 4-5% of the overall structure cost. Ferrocement proves to be a cost-effective choice, offering impermeability, and thus serviceability & durability to the structure.
- HWTs achieved a 25% reduction in total concrete usage compared to CWT, with approximately 38% less concrete in the body and around 7-8% less concrete required for staging.
- HWTs utilize approximately 15% less steel overall compared to CWT, with around 17% less steel in the body and about 13% of the steel quantity required for staging compared to CWT.
- The volume of steel and concrete in tank bodies remains consistent across all 16 cities for both HWT and CWT, while concrete usage in staging increases in seismic zones and coastal cities, and steel usage increases in seismic zones and coastal cities compared to non-coastal cities within the same seismic zone.
- Seismic forces increase with the increase in seismic zones. The difference in Seismic base shear increases with an increase in the seismic zone between hybrid & CWT.
- Across different seismic zones, the seismic base shear for CWT varies as follows: In Zone II, it is 151.28 kN for the F.T. condition and 90.31 kN for the E.T.

condition. In Zone III, it is 242 kN for the F.T. condition and 144.5 kN for the E.T. condition. In Zone IV, it is 363 kN for the F.T. condition and 216.4 kN for the E.T. condition. In Zone V, it is 544.6 kN for the F.T. condition and 325.1 kN for the E.T. condition.

- For HWTs, across different seismic zones, the seismic base shear varies as follows: In Zone II, it is 143.3 kN for the F.T. condition and 76.29 kN for the E.T. condition. In Zone III, it is 229.3 kN for the F.T. condition and 122 kN for the E.T. condition. In Zone IV, it is 344 kN for the F.T. condition and 183 kN for the E.T. condition. In Zone V, it is 516 kN for the F.T. condition and 274 kN for the E.T. condition.
- In Zone III, seismic base shear increases by approximately 60% for both Conventional and HWTs compared to Zone II, while in Zone IV, there's a notable spike with seismic base shear surging by roughly 140% for both tank types. Moving to Zone V, the increase is even more significant, with seismic base shear soaring by approximately 260% for both Conventional and HWTs compared to Zone II.
- The percentage savings for HWTs compared to CWT across different seismic zones range approximately between 5.24% to 5.27% for F.T. conditions and 15.46% to 15.70% for E.T. conditions.
- Wind forces acting on the tanks are similar in both HWT and CWT because height and dimensions are kept the same in all the tanks.
- The magnitude of wind forces escalates as wind speeds increase, with values ranging from 125.68 kN in cities experiencing winds at 39 m/s, 162.5 kN at 44 m/s, 185.4 kN at 47 m/s, and 214.5 kN at 50 m/s in non-coastal cities.
- Wind shear forces peak in coastal regions. In cities such as Alibag, where the wind speed is 44 m/s, the wind shear forces reach 275 kN. In cities like Puducherry in Zone II, Chennai in Zone III, and Dwaraka in Zone IV, where the wind speed is 50 m/s, the highest wind forces are experienced, reaching 361.2 kN.
- In Seismic Zone II, wind forces prevail over seismic base shear in E.T. conditions. However, in F.T. conditions, cities such as Bhopal exhibit wind forces that are lower than seismic base shear, whereas for cities like Hyderabad, Jaipur, and Puducherry wind forces exceed seismic base shear.

- In Zone III, wind forces are generally lower than seismic base shear for F.T. conditions, except for Chennai, a coastal city. However, in E.T. scenarios, wind forces are either comparable to or higher than seismic base shear for all cities in the zone.
- In Zone IV, wind forces are generally lower than seismic base shear for F.T. conditions, except for Dwaraka. In E.T. scenarios, wind forces are lower than seismic base shear for all cities in the zone, except for coastal cities like Alibag and Dwaraka.
- In Zone V Seismic base shear is higher than wind forces in both Full and E.T. conditions.
- HWTs consistently exhibit lower seismic base shear across all seismic zones compared to CWT.
- The maximum moment in the column is contingent upon the highest lateral forces stemming from either wind shear forces or seismic forces. The moment tends to be nearly the same or lower in HWTs when compared to CWT. The disparity in moments amplifies with the escalation of seismic Zones.
- In coastal areas, HWTs demonstrate superior performance, with wind shear forces exceeding seismic base shear in CWT but remaining optimized in HWTs.
- The results indicate that the deflection is consistently lower in the Hybrid design tank for both full and E.T. conditions.
- The deflection is nearly 10 - 11% lower in the F.T. condition and 27% to 28%, in the E.T. condition in comparison to the conventional approach.
- The crack width of the HWT RCC body is approximately 19.08% less than that of the conventional tank body.
- The crack width of the HWT ferrocement lining is approximately 87.28% less than that of the conventional tank body.
- HWTs offer enhanced structural integrity, ensuring better long-term serviceability compared to CWT, thanks to their superior control over crack width and Deflections.

7.10. Comparative study of 150 kL Hybrid and Conventional (Type II) Circular tanks across 16 major Indian Cities

- The percentage difference in cost savings falls within the range of 15-17% in non-coastal cities and coastal and increases with an increase in Seismic zones which is huge for such small tanks (Section 6.4).
- The cost of the tanks increases with the increase in the seismic zones & wind speeds for both HWT and CWT. & the difference in the cost between hybrid & CWT increases with the increase in Seismic zones.
- Cost of ferrocement lining depends on the strain occurring at the interface of RCC and ferrocement and Total surface area in contact with water.
- Remarkably, the Hybrid design consistently demonstrates lower concrete and steel requirements compared to the conventional design for all tanks.
- HWTs achieve a 23% reduction in total concrete usage compared to CWT, with approximately 39% less concrete in the body and around 7-8% less concrete required for staging.
- HWTs utilize approximately 6-7% less steel overall compared to CWT, with around 10-11% less steel in the body and about 2-4 % of the steel quantity required for staging compared to CWT.
- The volume of steel and concrete in tank bodies remains consistent across all 16 cities for both HWT and CWT, while concrete usage in staging increases in seismic zones and coastal cities, and steel usage increases in seismic zones and coastal cities compared to non-coastal cities within the same seismic zone.
- The Hybrid design outperforms the conventional one in deflection, seismic, and wind analyses as compared to CWT.
- Across different seismic zones, the seismic base shear for CWT varies as follows: In Zone II, it is 76.4 kN for full tank condition and 53.12 kN for empty tank condition. In Zone III, it is 122.1 kN for full tank condition and 85 kN for empty tank condition. In Zone IV, it is 183.2 kN for full tank condition and 127.5 kN for empty tank condition. In Zone V, it is 274.45 kN for full tank condition and 325.1 kN for empty tank condition.

- For HWTs, across different seismic zones, the seismic base shear varies as follows: In Zone II, it is 70.4 kN for full tank condition and 44.7 kN for empty tank condition. In Zone III, it is 112.6 kN for full tank condition and 71.5 kN for empty tank condition. In Zone IV, it is 168.9 kN for full tank condition and 107 kN for empty tank condition. In Zone V, it is 253.4 kN for full tank condition and 160 kN for empty tank condition.
- In Zone III, seismic base shear increases by approximately 60% for both Conventional and HWTs compared to Zone II, while in Zone IV, there's a notable spike with seismic base shear surging by roughly 140% for both tank types. Moving to Zone V, the increase is even more significant, with seismic base shear soaring by approximately 260% for both Conventional and HWTs compared to Zone II.
- The percentage savings for HWTs compared to CWT across different seismic zones range approximately between 7-8% for full tank conditions and 15.46% to 15.70% for empty tank conditions.
- The magnitude of wind forces escalates as wind speeds increase, with values ranging from 66.89 kN in cities experiencing winds at 39 m/s, 86.7 kN at 44 m/s, 98.99 kN at 47 m/s, and 114.3 kN at 50 m/s in non-coastal cities.
- Wind shear forces peak in coastal regions. In cities such as Alibag, where the wind speed is 44 m/s, the wind shear forces reach 146.6 kN. In cities like Puducherry in Zone II, Chennai in Zone III, and Dwaraka in Zone IV, where the wind speed is 50 m/s, the highest wind forces are experienced, reaching 192.4 kN.
- The bending moment in the column spans from 23.3 kN to 91 kNm across different cities.
- In Seismic Zone II, wind forces prevail over seismic base shear in empty tank conditions. However, in full tank conditions, cities such as Bhopal (wind speed 39 m/s) exhibit wind forces that are lower than seismic base shear, whereas cities like Hyderabad (44 m/s), Jaipur (47 m/s), and Puducherry (50 m/s), wind forces exceed seismic base shear.
- In Zone III, wind forces are generally lower than seismic base shear for full tank conditions, except for Chennai, a coastal city experiencing wind speeds of 50 m/s.

However, in empty tank scenarios, wind forces are either comparable to or higher than seismic base shear for all cities in the zone.

- In Zone IV, wind forces are generally lower than seismic base shear for full tank conditions, except for Dwaraka, a coastal city experiencing wind speeds of 50 m/s. For Dwaraka, wind shear forces exceed seismic base shear in HWTs and are equivalent in CWT. In empty tank scenarios, wind forces are lower than seismic base shear for all cities in the zone, except for coastal cities like Alibag with a wind speed of 44 m/s, and Dwaraka with a wind speed of 50 m/s.
- In Zone V Seismic base shear is higher than wind forces in both Full and empty tank conditions.
- The deflection is nearly 13 - 14% lower in the F.T. condition and 37% to 38%, in the E.T. condition in comparison to the conventional approach.
- Rest the conclusions are same as in Section 7.8.

7.11. Major findings and recommendations

- This study proposes a paradigm shift in water tank design, introducing a hybrid structural system that is more efficient, durable, and sustainable than existing monolithic RCC tanks.
- The research addresses a long-standing engineering gap by formally designing ferrocement as a strain-compatible, structural lining material, which has never been done before in large-scale infrastructure.
- For the first time Ferrocement lining methodology, details, guidelines, calculations, equations are proposed in this work.
- The work establishes a new class of water storage structures — Hybrid Water Tanks — by merging established RCC practices with advanced material applications in ferrocement.
- The methodology developed is code-independent and modular, allowing effortless adaptation across international design standards, making the solution globally deployable.
- The hybrid tank concept not only enhances crack control and impermeability, but also redefines material efficiency and structural design logic for water-retaining systems.
- The integration of heuristic optimization techniques into the custom-developed software sets a new benchmark for smart, performance-driven tank design.
- The study fills a critical void in existing literature by offering a systematic design and validation framework for ferrocement-lined water tanks — covering material behavior, structural performance, cost efficiency, and environmental adaptability.
- The Hybrid Intze tank costs approximately one-third less than Conventional type I tanks and one-fourth less than Conventional type II tanks, while Circular tanks, even of lower capacity, demonstrate savings of up to 20% of the total structure cost, equating to about one-fifth of the expense.
- The percentage of savings rises alongside the augmentation of the water-carrying volume of the tank.

- In the Hybrid design, the foundation area is reduced by up to 10 – 15 %, and the reduced cost of columns, braces, and foundation is observed.
- The incorporation of hybrid construction allows for efficient material usage, resulting in substantial concrete savings of up to 39% and steel savings ranging upto 32 % in different tanks with different capacities. This not only promotes sustainability but also aligns with cost-effective project execution.
- Cost of the ferrocement lining is about 3-5% of the Total Cost of the tanks and by application of lining significant savings of upto 33 % are achieved.
- Cost of ferrocement lining depends on the strain occurring at the interface of RCC and ferrocement and Total surface area in contact with water.
- Remarkably, the Hybrid design consistently demonstrates lower concrete and steel requirements compared to the conventional design for all tanks.
- HWT features a lightweight tank body and staging & raft as compared to CWT. The staging & raft is lightened due to the reduced dead weight of the tank body.
- In the Hybrid design, both the annular raft area and the cost of staging and foundation are reduced, contributing to overall efficiency and cost-effectiveness.
- Percentage savings in Raft areas in Hybrid design as compared to conventional increases with increase in the in Bearing capacity of soil.
- CWT face persistent leakage issues despite their substantial material consumption. In contrast, HWTs, with ferrocement lining, are designed to be leak-proof, addressing and mitigating the persistent problem of leaks.
- The ferrocement lining design, with a permissible crack width of 0.0022 mm (1/10th of the allowable crack width in RCC), is intended to enhance the water tank's impermeability. The observed crack width is below the limits set by ACI standards. Research findings indicate that as the tank capacity increases, the crack width in HWTs is consistently lower compared to CWT. Hence HWTs are more durable.
- The minimum dimensions, stresses, and exposure criteria have been enhanced in IS 3370:2021 compared to IS 3370:2009 and are greater than those in IS 456:2000 to reduce crack width and prevent leakage in water tanks. However, the excessive material quantities required by the stringent criteria of IS 3370:2021 are unnecessary, as the crack width in RCC as per IS 456:2000 is already minimal.

Consequently, adhering to IS 3370:2021 leads to material wastage, particularly in tanks with lower capacities particularly in case of Circular tanks.

- The Hybrid design outperforms the conventional one in deflection, seismic, and wind analyses as compared to CWT.
- The HWTs perform better as compared to the Standard RCC ones in response to lateral forces, i.e., wind and seismic forces, and also show reduced Deflections in both Full (F.T.) and Empty (E.T.) water tank conditions.
- Base shear increases with an increase in seismic zones in both Full & empty tank conditions.
- Wind shear forces are almost similar in all the tanks.
- tanks beyond 300 kL should consider Intze designs as compared to Circular ones for their lower construction heights and reduced column requirements, ensuring both practicality and cost-effectiveness in larger-scale water storage projects.
- The maximum moment in the column is contingent upon the highest lateral forces stemming from either wind shear forces or seismic forces. The moment tends to be nearly the same or lower in HWTs when compared to CWT. The disparity in moments amplifies with the escalation of seismic Zones.
- In coastal areas, HWTs demonstrate superior performance, with wind shear forces exceeding seismic base shear in CWT but remaining optimized in HWTs.
- HWTs offer enhanced structural integrity, ensuring better long-term serviceability compared to CWT, thanks to their superior control over crack width and Deflections.
- Versatile and User-Friendly Software for Efficient Structural design- The software tool developed for this study is user-friendly, precise, and quick. The program allows easy modifications and is beneficial in case of any revisions in the provisions of Indian standards or Item rates of the concerned departments.

7.12. Future scope of study

1. **Investigate underground, partially underground, or ground supported water tanks.**
2. **Abaqus simulation**: Advancements in simulation techniques using Abaqus software will allow for more detailed and accurate modeling of HWT, facilitating better understanding and optimization of their structural behavior.
3. **Hybrid underground tanks**: The future of hybrid underground tanks lies in exploring novel construction materials and techniques, as well as integrating smart technologies for monitoring and maintenance, enhancing their longevity and performance.
4. **Composite tanks**: HWT will continue to utilize ferrocement linings capable of bearing specific structural loads, though currently treated as non-structural elements. Further investigation will focus on Composite tanks, where ferrocement and RCC collaborate as a composite material. Innovations in composite materials and manufacturing processes will drive the development of lighter, stronger, and more corrosion-resistant water tanks, offering improved durability and sustainability.
5. **Parametric studies**: Ongoing parametric studies will enable the optimization of various design parameters, such as tank geometry, material properties, and construction methods, to achieve optimal performance and cost-effectiveness.
6. **Optimization of ferrocement lining**: Further research into the optimization of ferrocement lining techniques will enhance the durability and longevity of water tanks, particularly in challenging environmental conditions, ensuring reliable water storage solutions for the future