Indian Journal of Engineering & Materials Sciences
Vol. 33, June 2026, pp. 269-278
DOI: 10.56042/ijems.v33i03.23249

A novel hybrid design approach for elevated circular water tanks and parametric optimization

Sukanya Saxena* & Krishna Kant Pathak

Department of Civil Engineering, Indian Institute of Technology (B.H.U) Varanasi 221 005, Uttar Pradesh, India

Received: 29 August 2025; accepted: 23 March 2026

This research has introduced hybrid elevated circular water tanks and has outlined the associated design methodology and guidelines. A detailed parametric study has also been conducted on hybrid elevated circular water tanks (HWTs) with capacities ranging from 100 kL to 300 kL to determine the optimum design parameters for cost-effective and structurally efficient construction. The study has investigated the influence of varying height-to-diameter (H/D) ratios and the number of supporting columns on tank cost and feasibility. Results have indicated that an H/D ratio of approximately 0.8 provides the best balance between structural integrity and economic efficiency. Optimal column configurations have been found to be 4 columns for 100 kL, 6 columns for 150–200 kL, and 8 columns for 250–300 kL tanks. Analysis of higher capacities (400–600 kL) has revealed practical limitations due to increased height or excessive column requirements, suggesting the preference for Intze tanks for larger volumes. The study has established critical design guidelines for Hybrid Circular tanks, ensuring cost-effective construction while maintaining structural stability.

Keywords: Circular tanks, Columns, Hybrid water tanks, Optimization, Parametric study

1 Introduction

The concept of Hybrid water tanks (HWT) was first introduced by Saxena and Pathak[1] in 2024. They worked on Intze type of elevated water tanks. In HWT, RCC is supposed to bear all the structural loads, designed in accordance to IS 456:2000 (Reaffirmed in 2021) unlike conventional tanks which are designed as per IS 3370:2021 and ferrocement lining is specifically engineered to impart impermeability to the tanks.

Cost challenges with conventional tanks: The cost of RCC water tanks is a critical concern worldwide, and researchers across various countries have undertaken efforts to achieve optimal and economical designs. Worldwide, numerous studies have focused on reducing the cost of water tanks while adhering to codal provisions. Saxena et al.[2, 3] explored Intze-type water tanks of various capacities, employing nonlinear optimization techniques through computational analysis to achieve minimum structural cost. Titiksh[4] performed a parametric investigation on cylindrical tanks, varying the H/D ratio and using Staad.Pro software in accordance with IS 3370:2009 to identify cost-effective designs. Thevendran and Thambiratnam analyzed both cylindrical[5] and conical tanks[6], concentrating on minimum weight criteria, optimizing tank shapes[7], and reducing material usage[8] using BS 8007 standards and the Beam-on-Elastic-Foundation approach. In these studies, tank radius and height were kept fixed, while wall thickness was adjusted to maintain stresses within allowable limits. Additionally, tank geometry was modified by incorporating one or two slopes. Tan et al.[9] investigated minimum weight designs using BS 5337 with finite element and numerical methods. Reddy *et al.*[10] applied machine learning techniques to optimize Intze water tanks for minimum cost while complying with codal standards. Workeluel et al.[11] conducted a comparative analysis of Intze tanks according to American, Ethiopian, European, and Indian standards using SAP software, finding that the Indian Standard code offered the most economical solution. Furthermore, several studies[12-13] have examined seismic performance to determine optimal staging configurations for cost-effective and structurally safe tank designs. Previous studies have highlighted the importance of geometric optimization in water tank design, particularly through appropriate selection of H/D ratios and structural configurations, leading to improved structural efficiency and reduced material and construction costs.

*Corresponding author
(E-mail: sukanyasaxena.rs.civ22@itbhu.ac.in)

Leakage and failures associated with conventional tanks: In addition to construction costs, leakage remains a significant issue worldwide, with numerous tanks being abandoned post-construction owing to excessive maintenance requirements and persistent water loss. Cracking and leakage in concrete water tanks remain critical challenges that compromise both durability and operational performance. Bhadauria[14] reported extensive deterioration in a survey of existing tanks, with many exhibiting seepage and reinforcement corrosion, highlighting a strong correlation between tank age and structural degradation and emphasizing the necessity of regular maintenance. In a follow-up study, Bhadauria[15] stressed the importance of systematic field monitoring to validate laboratory results, noting that modern concrete structures often deteriorate more rapidly due to cracking from accelerated hydration. Sangiorgio *et al.*[16] identified leakage as a leading factor in the degradation of water tanks in Spain, reinforcing the need for careful design and maintenance strategies. Saeed *et al*.[17] examined cracking caused by restrained shrinkage and heat of hydration in the arid Arabian Gulf region, observing tensile stresses that exceeded concrete capacity and recommending repair methods and preventive guidelines. Rodd & Castel[18]analyzed horizontal cracking in on-ground circular tanks in Australia, associating these defects with leakage and reduced durability, and proposed a unified design methodology including a practical model to predict bending moments and crack widths.Prakash and Bansal[19] stress the need for pre-disaster mitigation in public structures, using non-destructive tests to assess the structural integrity of an old OHSR in India.

Concept of hybrid water tanks: To address the dual challenges of cost and leakage, Saxena and Pathak[1] proposed the Hybrid Water Tank (HWT) concept. They worked on Intze type of elevated water tanks. In HWT, RCC is supposed to bear all the structural loads, designed in accordance to IS 456:2000 (Reaffirmed in 2021) unlike conventional tanks which are designed as per IS 3370:2021 and ferrocement lining is specifically engineered to impart impermeability to the tanks. The approach incorporates an impermeable ferrocement lining in accordance with clause 4.4.3.3 of IS 3370:2021 Part 2, which deals with concrete structures for liquid storage. Unlike conventional practice, where linings are applied mainly as a remedial measure for leakage, the HWT design integrates the ferrocement lining as an essential component of the tank. In this system, RCC, designed per IS 456, carries all structural loads while maintaining crack widths within 0.2 mm, whereas the ferrocement lining, designed following ACI standards, ensures impermeability with cracks below 0.05 mm. The lining is engineered for strain compatibility at the RCC interface, creating a composite system that enhances both structural performance and water-tightness. Saxena and Pathak[20]in their study provided detailed design guidelines for Intze Hybrid tanks and demonstrates 28–38% cost savings, reduced material use, lower crack widths, and improved structural performance compared to standard RCC tanks.

Research gaps: While earlier research was confined to Hybrid Intze-type tanks, the current study broadens the scope to include Hybrid Circular tanks. The present study expands this approach to Hybrid circular tanks, which are often preferred in rural regions because of their simpler construction and, for smaller capacities, greater cost-effectiveness compared to Intze tanks. In this research, parametric study was conducted to assess the Optimum H/D Ratio and Number of Columns for HWTs. A comprehensive parametric study was carried out on Hybrid Elevated Circular water tanks (HWTs) with capacities ranging from 100 kL to 300 kL to identify the optimum design parameters for both cost-effectiveness and structural efficiency. The analysis systematically evaluated the impact of varying height-to-diameter (H/D) ratios and the number of supporting columns on overall tank cost, structural feasibility, and constructability. Cylindrical heights, top ring beam diameters, and column spans were examined for each configuration to ensure practical construction while minimizing material use. This study will also check the cost of Intze vs circular tanks for lower capacities. This study also aimed to achieve the Optimum Cost and provided insights into the structural preferences for Intze tanks over Circular tanks as capacity increases.

2 Materials and Methods

Hybrid circular water tanks consist of RCC tank with inner lining of ferrocement with staging and foundation. The methodology adopted in this study comprised five major components: (i) Analysis and design of RCC tank, tank is designed in accordance with IS 456:2000; (ii) Ferrocement lining, where a thin ferrocement layer was introduced on the inner face of the RCC container to improve impermeability, crack control, and durability through strain

compatibility and optimized reinforcement; (iii) Staging and foundation, which involved the analysis and design of columns and braces for gravity, wind, and seismic loads to ensure overall stability and Foundation design, in which an annular raft with ring beam was designed to safely transmit loads to the supporting soil while satisfying stability requirements against sliding, overturning, and settlement as per relevant IS standards; and (iv) Software Development, where a computational tool comprising multiple modules was developed to automate the design and estimation of hybrid circular tanks and (v) Application and comparision criteria for parametric study.

2.1 Analysis and design of hybrid circular water tanks

Circular water tanks are an essential part of water storage systems, consisting of several key structural components. The tanks are divided into two main joints. The top joint connects three members, while the bottom joint connects four members. This configuration is crucial for maintaining the tank's stability under different loading conditions. Table 1 outlines the primary joints of circular water tanks and the members connected to each joint. The sectional elevation diagram outlines the structural components of a circular water tank, including the lantern, top ring beam, cylindrical wall, water depth, bottom dome, main ring beam, columns, bracings, staging height, foundation depth, foundation ring beam, and annular raft. This diagram offers a comprehensive view of the tank's construction and design. Table 2 specifies the Stiffnesses and displacement for Circular water tanks and equations are formed as shown below for the analysis purposes. Design is done by Limit state method using IS 456: 2000 with calculation of crack width at every stage.

Table 1 — Joint details of circular water tanks.

Joint	Members connected
Top	Top ring beam, top dome, and cylindrical wall
Bottom	Cylindrical wall, middle beam, bottom dome & bottom ring beam

Equations for analysis of circular water tanks:

For Eq. (1), R_1 and R_2 are the radii of the top and bottom domes, respectively; r_1–r_3 are the radii of the top, middle and bottom ring beams, respectively; b_1 and d_1 are the width and depth of the top ring beam; t_1 is the top-dome thickness; k_{td} is the top-dome stiffness coefficient; λ_{td} is the top-dome lambda parameter; ψ_1 and ψ_{td} are the joint and reference rotations; θ_{td} is the top-dome half-angle; x_1 and x_{td} are the joint and reference displacements; μ is the cylindrical-wall coefficient; z is the wall moment of inertia; and E is the modulus of elasticity.

For Eq. (2), H.F. denotes the horizontal force at the support; the remaining symbols have the meanings defined for Eq. (1).

For Eq. (3), b_4 and d_4 are the width and depth of the middle ring beam; t_6 is the bottom-dome thickness; k_{bd} is the bottom-dome stiffness coefficient; λ_{bd} is the bottom-dome lambda parameter; ψ_2 and ψ_{bd} are the bottom-joint and bottom-dome reference rotations; θ_{bd} is the bottom-dome half-angle; and x_2 and x_{bd} are the bottom-joint and bottom-dome reference displacements.

For Eq. (4), b_7 and d_7 are the width and depth of the bottom ring beam; ψ_{wall} and x_{wall} are the wall reference rotation and displacement; the equation gives the net horizontal thrust and total vertical load.

2.2 Design of lining for RCC tank made up of ferrocement

This section outlines the design methodology adopted for the ferrocement lining, covering the governing assumptions, the three-stage design

$$\frac{R_1 \times E \times t_1 \times (k_{td} + k_{td}^{-1})}{4 \times {\lambda_{td}}^3}(\psi_1 - \psi_{td}) - \frac{Et_1}{2{\lambda_{td}}^2 k_{td} sin\theta_{td}}(x_1 - x_{td}) + \frac{E \times b_1 \times d_1^3}{12 \times {r_1}^2}(\psi_1) + 2\mu z \times (\psi_1 - \psi_{wall}) + 2\mu^2 z x_1 = 0; \quad \ldots(1)$$

$$\frac{Et_1}{\lambda_{td} R_1 k_{td} sin^2\theta_{td}}(x_1 - x_{td}) - \frac{Et_1}{2{\lambda_{td}}^2 k_{td} sin\theta_{td}}(\psi_1 - \psi_{td}) + \frac{Eb_1 d_1}{{r_1}^2}x_1 + 4\mu^3 z(x_1 - x_{wall}) + 2\mu^2 z(\psi_1 - \psi_{wall}) = H.F. on\ support; \quad \ldots(2)$$

$$\{2\mu z\}\{\psi_2 - \psi_{wall}\} - \{2\mu^2 z\}\{x_2 - x_{wall}\} + \frac{Eb_4 {d_4}^3}{12{r_2}^2}\psi_2 + \frac{Eb_4 {d_4}^3}{12{r_2}^2}\psi_2 + \frac{R_2 Et_{bd}(k_{bd} + k_{bd}^{-1})}{4 \times {\lambda_{bd}}^3}\{\psi_2 - \psi_{bd}\} - \frac{Et_{bd}}{2{\lambda_{bd}}^2 k_{bd} sin\theta_{bd}}\{x_2 - x_{bd}\} = \text{B. M. at Balcony} \quad \ldots(3)$$

$$\{4\mu^3 z\}\{x_2 - x_{wall}\} - \{2\mu^2 z\}\{\psi_2 - \psi_{wall}\} + \frac{Eb_7 d_7}{{r_2}^2}x_2 + \frac{Eb_7 d_7}{12{r_3}^2}\psi_2 + \frac{R_2 Et_6(k_{bd} + k_{bd}^{-1})}{4 \times {\lambda_{bd}}^3}\{x_2 - x_{bd}\} + \frac{Et_6}{2{\lambda_{bd}}^2 k_{bd} sin\theta_{bd}}\{\psi_2 - \psi_{bd}\} =$$

$$\text{Net Horizontal thrust} + \text{ Total vertical load}; \quad \ldots(4)$$

Table 2 — Stiffnesses and displacement for circular water tanks.

Joint	Member	Moment stiffness	Corresponding stiffness	Thrust stiffness	Rotation	Disp.
Top	TD	$\frac{R_1 E t_1 (k_{td} + k_{td}^{-1})}{4 \times {\lambda_{td}}^3}$	$\frac{E t_1}{2{\lambda_{td}}^2 k_{td} sin\theta_{td}}$	$\frac{E t_1}{\lambda_{td} R_1 k_{td} sin^2\theta_{td}}$	$\psi_1 - \psi_{td}$	$x_1 - x_{td}$
	TRB	$\frac{E b_2 {d_2}^3}{12 {r_1}^2}$	-	$\frac{E b_2 d_2}{{r_1}^2}$	ψ_1	x_1
	Wall Top	$2\mu z$	$2\mu^2 z$	$4\mu^3 z$	$\psi_1 - \psi_w$	x_1
	Wall Bottom	$2\mu z$	$2\mu^2 z$	$4\mu^3 z$	$\psi_2 - \psi_w$	$x_{2-} x_w$
Bottom	MRB	$\frac{E b_4 {d_4}^3}{12 {r_2}^2}$	-	$\frac{E b_4 d_4}{{r_2}^2}$	ψ_2	x_2
	BRB	$\frac{E b_7 {d_7}^3}{12 {r_2}^2}$	-	$\frac{E b_7 d_7}{{r_2}^2}$	ψ_2	x_2
	BD	$\frac{R_2 E t_6 (k_{bd} + k_{bd}^{-1})}{4 \times {\lambda_{bd}}^3}$	$\frac{E t_6}{2{\lambda_{bd}}^2 k_{bd} sin\theta_{bd}}$	$\frac{E t_6}{\lambda_{bd} R_2 k_{bd} sin^2\theta_{bd}}$	$\psi_2 - \psi_{bd}$	$x_2 - x_{bd}$

process, and the iterative thickness and reinforcement optimization used to satisfy strain compatibility and crack-width limits. Following assumptions are taken for the design of lining

- Composite member consists of a brittle cement-based matrix reinforced with steel.
- Matrix is linear-elastic until failure; reinforcement provides post-cracking strength.
- Bond stress between matrix and reinforcement is constant; strains in matrix and reinforcement equalize beyond a certain distance

The design process consists of three main stages:

2.2.1 Strain calculation in RCC

Determine maximum strains for hoop and bending using IS 456:2000. Maximum strain for ferrocement lining: 0.001583.

2.2.2 Determination of lining thickness and reinforcement

Apply bending theory to calculate thickness. Optimize mesh reinforcement to maintain strain compatibility.

2.2.3 Crack width verification

Primary and secondary checks ensure leakage prevention. Crack widths are checked for hoop tension and flexural effects.

2.2.4 Stress-strain & bending analysis

- Modulus of elasticity is calculated using the rule of mixtures.
- Crack spacing and widths (minimum, maximum, average) are computed based on tensile strain and reinforcement geometry.
- Neutral axis, compressive and tensile forces are determined; forces are balanced across layers.
- Hoop tension and crack width undergo secondary verification to ensure structural durability.

2.2.5 Iterative design process

- Calculate reinforcement area, mesh numbers, spacing, and volume fraction.
- Verify service stress and maximum crack width check.
- Adjust mesh and repeat until optimum configuration is achieved.

This methodology ensures the ferrocement lining is impermeable, strain-compatible, and fully integrated with the RCC tank, guaranteeing long-term performance and structural safety.

2.3 Analysis and design of foundation and staging

The design of staging in elevated water tanks is aimed at providing adequate height and stability to safely support the container under both vertical and lateral loads. It involves determining staging height, panel configuration, and spacing of columns and braces, followed by the computation of axial forces, bending moments, and reinforcement requirements as per IS codes. The staging must resist self-weight, water load, wind, and seismic forces while

maintaining serviceability and economy. The foundation, typically an annular raft, is then designed to transfer these loads safely to the soil by ensuring uniform pressure distribution, checking against overturning and settlement, and providing adequate reinforcement to withstand bending and shear. Together, the staging and foundation form a robust support system, ensuring the long-term safety and reliability of the elevated water tank.

2.4 Design and software development

For this study, a software program has been developed consisting of eight distinct modules, one of which is specifically dedicated to the design of ferrocement lining. Following the development of the software, tanks with capacities ranging from 100 to 300 kL were selected, as lower-capacity tanks are easier to construct, particularly in rural areas. Additionally, tanks up to 600 kL were analyzed to evaluate the suitability of different designs, comparing Hybrid Intze-type tanks with circular tanks, in order to determine the most efficient and practical solution for higher-capacity water storage.

2.4.1 Module I: Input and dimensioning

The first step involves determining tank dimensions based on desired capacity. Essential inputs include: staging height, soil bearing capacity, foundation depth, seismic zone, wind speed, terrain type (coastal/non-coastal), H/D ratio, number of columns, and material properties (concrete and steel strengths). Iterative calculations using mensuration formulas determine tank dimensions, including cylinder radius, dome heights, top and bottom dome radii, and free board. Minimum member dimensions are assigned per IS 456:2000.

2.4.2 Module II: RCC tank body analysis

Structural analysis computes member forces (self-weight, water load, outward thrust, hoop tension, and bending moments) for top dome, ring beams, cylindrical wall, balcony/middle ring beam, and bottom dome. Stiffness matrices are established for the two-joint system (top joint with 3 members, bottom joint with 4 members), and joint displacements are solved using the direct stiffness method (Member forces are used to calculate hoop tension, outward thrust, and moments. Reinforcement design and serviceability checks are applied, incorporating heuristic optimization similar to Intze tank design, excluding conical dome effects.

2.4.3 Module III: Member design

Design of tank elements (top dome, ring beams, cylindrical wall, bottom dome, and middle/bottom beams) follows standard circular tank procedures, ensuring structural adequacy under applied loads. Here in case of circular tanks there are only two joints with top joint having three members and bottom joints having four members. Design of RCC tank is done by IS 456: 2000. For coding Global stiffness matrix are created for both the joints.

2.4.3.1 Joint I- Top joint

Global stiffness matrix Constitutes of stiffnesses of members joining at joint I that are top dome, top ring beam and wall. Global stiffness matrix at Joint I

For Eqs. (5)–(9), MS and TS denote the moment and thrust stiffness of a member; CorrMS and CorrTS denote the corresponding coupled moment and thrust stiffness terms. Subscripts 1, 2, 3t, 3b, 4, 6 and 7 identify the top dome, top ring beam, wall-top, wall-bottom, middle ring beam, bottom dome and bottom ring beam, respectively; K_1 is the global stiffness matrix at Joint I.

In Eq. (6), Z_{top} denotes the top-joint moment-of-inertia term; the other symbols retain the meanings defined above. Force vector at Joint I

For Eq. (7), P_1 is the force vector at Joint I and H1 is the horizontal force at Joint I. Displacement vector at Joint I

For Eqs. (8)–(9), Δ_1 is the displacement vector at Joint I; x1 and ψ1 are the corresponding displacement and rotation components.

2.4.3.2 Joint II- Bottom joint

This joint has four members- Wall (connected at bottom), bottom dome, middle ring beam & bottom ring beam. Global stiffness matrix at Joint II

For Eqs. (10)–(14), K_2 is the global stiffness matrix at Joint II; Z_b denotes the bottom-joint moment-of-inertia term. The subscripts 3b, 4, 6 and 7 identify the wall-bottom, middle ring beam, bottom dome and bottom ring beam, respectively. Force vector at Joint II

For Eq. (12), P_2 is the force vector at Joint II; HNET is the net horizontal thrust and HFatMRB is the horizontal force at the middle ring beam. Displacement vector at Joint II

For Eqs. (13)–(14), Δ_2 is the displacement vector at Joint II; x2 and ψ2 are the corresponding displacement and rotation components.

2.4.3.3 Module IV

This module focuses on staging configuration and lateral analysis, determining total staging height, panel lengths, column spacing, and brace dimensions, and computing vertical loads from columns, braces, and stairs. It also analyzes lateral forces due to wind and seismic effects, calculating wind pressures, shear forces, effective weights, deflections, time periods, and base shear to identify critical load cases for a safe and stable staging design.

2.4.3.4 Module V

This module addresses the design of columns and braces, calculating maximum bending moments, axial load and bending ratios, and determining optimal reinforcement using IS 456 guidelines, including main and distribution steel, concrete volumes, and structural checks for deflection and nominal reinforcement.

2.4.3.5 Module VI

This module covers foundation design, specifically annular raft footings, computing foundation beam dimensions, effective depth, reinforcement for moment, shear and distribution, soil pressures under full and empty tank conditions, and ensuring uniform load distribution while adhering to IS 3370 and IS 456 standards.

2.4.3.6 Module VII – Design of ferrocement lining

This module is an addition to the hybrid tank design and is not present in conventional water tanks. This module systematically evaluates and optimizes the ferrocement lining for the tank. The process begins with retrieving strain values from Module III for both hoop and bending, identifying the maximum strain, usually at the bottom of the cylindrical wall, to ensure uniformity in the lining. A strain threshold check is performed to verify that the maximum strain does not exceed 0.035. Initially, a 12 mm thick lining is implemented with a 2 mm cover on both sides and three layers of reinforcement, ensuring bar spacing is less than the lining thickness, typically using around 85 bars in the first iteration. Fundamental calculations are then carried out, checking steel stresses against strain to ensure they remain below 450 N/mm², in accordance with ACI standards. Crack spacing and

$$\{K_1\}_{2\times2} = \begin{bmatrix} MS1 + MS2 + MS3t & \text{CorrTS1} + \text{CorrTS3t} \\ \text{CorrMS1} + \text{CorrMS3} & TS1 + TS2 + TS3t \end{bmatrix} \quad \ldots(5)$$

$$\{K_1\}_{2\times2} = \begin{bmatrix} \frac{R_1 Et_1 (k_{td} + k_{td}^{-1})}{4\times\lambda_{td}^{\ 3}} + \frac{Eb_1 {d_1}^3}{12{r_1}^2} + 2\mu Z_{top} & \frac{Et_1}{2\lambda_{td}^{\ 2} k_{td} sin\theta_{td}} + 2\mu^2 Z_{top} \\ \frac{Et_1}{2\lambda_{td}^{\ 2} k_{td} sin\theta_{td}} + 2\mu^2 Z_{top} & \frac{Et_1}{\lambda_{td} R_1 k_{td} sin^2\theta_{td}} + \frac{Eb_1 d_1}{{r_1}^2} + 4\mu^3 Z_{top} \end{bmatrix} \quad \ldots(6)$$

$$\{P_1\}_{2\times1} = \begin{pmatrix} 0 - (MS1(-\psi_{td}) + CorrTS1(-x_{td}) + MS3t(-\psi_{wall}) \\ H1 - (CorrMS1(-\psi_{td}) + TS1(-x_{td}) + CorrMS3t(-\psi_{wall})) \end{pmatrix} \quad \ldots(7)$$

$$\{\Delta_1\}_{2\times1} = \{K_1\}_{2\times2}^{-1} \times \{P_1\}_{2\times1} \quad \ldots(8)$$

$$\begin{pmatrix} x_1 \\ \psi_1 \end{pmatrix} = \begin{bmatrix} MS1 + MS2 + MS3t & \text{CorrTS1} + \text{CorrTS3t} \\ \text{CorrMS1} + \text{CorrMS3} & TS1 + TS2 + TS3t \end{bmatrix}^{-1} \begin{pmatrix} {P_1}' \\ {P_1}'' \end{pmatrix} \quad \ldots(9)$$

$$\{K_2\}_{2\times2} = \begin{bmatrix} MS3b + MS4 + MS6 + MS7 & \text{CorrTS3b} + \text{CorrTS6} \\ \text{CorrMS3b} + \text{CorrMS6} & \text{TS3b} + \text{TS4} + \text{TS6} + \text{TS7} \end{bmatrix} \quad \ldots(10)$$

$$\{K_2\}_{2\times2} = \begin{bmatrix} 2\mu Z_b + \frac{Eb_4 {d_4}^3}{12{r_1}^2} + \frac{R_2 Et_6 (k_{bd} + k_{bd}^{-1})}{4\times\lambda_{bd}^{\ 3}} + \frac{Eb_7 {d_7}^3}{12{r_7}^2} & 2\mu^2 Z_b + \frac{Et_6}{2\lambda_{bd}^{\ 2} k_{bd} sin\theta_{bd}} \\ 2\mu^2 Z_b + \frac{Et_6}{2\lambda_{bd}^{\ 2} k_{bd} sin\theta_{bd}} & 4\mu^3 Z_b + \frac{Et_6}{\lambda_{bd} R_2 k_{bd} sin^2\theta_{bd}} + \frac{Eb_4 d_4}{{r_1}^2} + \frac{Eb_7 d_7}{{r_1}^2} \end{bmatrix} \quad \ldots(11)$$

$$\{P_2\}_{2\times1} = \begin{pmatrix} BMat\ MRB - (MS3b(-\psi_w) + CorrTS3b(-x_w) + MS6(-\psi_{bd}) + CorrTS6(-x_{bd}) \\ \text{HNET} + HFatMRB - (CorrMS3b(-\psi_w) + TS3b(-x_w) + CorrMS6(-\psi_{bd}) + TS6(-x_{bd})) \end{pmatrix} \quad \ldots(12)$$

$$\{\Delta_2\}_{2\times1} = \{K_2\}_{2\times2}^{-1} \times \{P_2\}_{2\times1} \quad \ldots(13)$$

$$\begin{pmatrix} x_2 \\ \psi_2 \end{pmatrix} = \begin{bmatrix} MS3b + MS4 + MS6 + MS7 & \text{CorrTS3b} + \text{CorrTS6} \\ \text{CorrMS3b} + \text{CorrMS6} & \text{TS3b} + \text{TS4} + \text{TS6} + \text{TS7} \end{bmatrix}^{-1} \begin{pmatrix} {P_2}' \\ {P_2}'' \end{pmatrix} \quad \ldots(14)$$

width in the ferrocement are also evaluated. If the Section is unsafe, lining thickness is increased to 15 mm with six layers of reinforcement. Bending analysis is performed to determine whether the tension or compression zone dominates; reinforcement is adjusted accordingly, and the process is iterated until a balanced Section is achieved. A secondary assessment of crack width under hoop tension is conducted, adjusting reinforcement and lining thickness as needed, with a maximum lining thickness of 20 mm and three to six layers of reinforcement. Strain values for ferrocement are initially calculated manually and verified using the software. Thickness and reinforcement configurations, determined from manual calculations, are then validated by the software to ensure compliance with safety and structural integrity standards.

2.4.3.7 Module VIII – Estimation and costing

This module provides estimation and costing, aggregating concrete, steel, and shuttering quantities for the entire tank, staging, and foundation, and computing costs based on CPWD DAR 2021 rates, allowing detailed budgeting and efficient resource management. with the addition of calculating the cost of ferrocement lining. This includes the expenses for cement mortar and steel bars, providing a comprehensive estimation for the hybrid tank that accounts for all structural and lining components.

2.5 Application and comparison criteria for parametric study

For this investigation, deliberate consideration was given to the selection of tanks, keeping the above-mentioned points in mind. Therefore, Hybrid Circular tanks with capacities ranging from 100 kL to 300 kL, in intervals of 50 kL, are analyzed in this study, each with varying staging heights. The specific details pertaining to each tank are delineated in Table 3. The study focuses on specific criteria for evaluating the optimum H/D ratio and the optimum number of columns for further comparative studies.

Additionally, 400 kL, 500 kL, and 600 kL tanks are examined to assess the feasibility of their construction.

3 Results and Discussion

The results obtained from the parametric and comparative analyses of the hybrid elevated water tanks are presented and discussed in this section. The influence of key design parameters on structural configuration, feasibility, and cost has been evaluated to identify the most suitable tank configurations.

3.1 Parametric study of hybrid circular tanks

A study has been done to comprehensively investigate the influence of varying Cylindrical Height-to-Diameter (H/D) ratios on the design of Hybrid Elevated Circular water tanks, as well as to determine the optimum number of columns necessary for further studies. Elevated Circular water tanks are typically not preferred for capacities above 200 or 250 kL. This is due to the fact that, beyond such capacities, the height of the tank body (container) often exceeds 5-6 meters when H/D ratios are greater than 0.6, making construction both challenging and, at times, impractical. Maintaining a lower H/D ratio, around 0.2-0.4 or even less, can effectively control the height of the tank. However, this adjustment leads to an increase in the diameter, which in turn requires a greater number of supporting columns. The need for additional columns significantly raises the overall construction costs, making it far more expensive compared to Elevated Intze water tanks. Given these considerations, it is more feasible and cost-effective to focus on the study of tanks with capacities up to a maximum of 300 kL. This range allows for a manageable height while avoiding the excessive costs and construction difficulties associated with larger circular tanks. Therefore, this study aims to explore and establish the most efficient design parameters for Hybrid Elevated Circular water tanks within this capacity range. The main objective of this study is to determine whether HWTs (Intze or Circular) are cost-effective and structurally superior to CWT. After identifying the minimum cost structure at the optimum number of columns, a comparative study with CWT will commence. Given the practical significance of this topic and considering the points

Table 3 — Specifications of circular water tanks used for the study.

Parameters	**Specifications**				
Quantity (in kL)	100	150	200	250	300
Staging Height (m)	12	14	14	14	14
Column Variations	4,6, 8	4,6,8	4,6,8,10	4,6,8 and 10	4,6,8,10 and 12
Foundation depth	2				
Net safe bearing capacity of soil	80 kN/m^2				
Wind and seismic parameters	47 m/s, Terrain category 4, Non-Coastal region, Seismic zone II.				

mentioned above, only tanks with capacities up to 300 kL will be examined against CWT. Hybrid Circular tanks are analyzed to determine the optimum H/D ratio and the optimum number of columns for capacities ranging from 100 to 300 kL, as detailed in Table 4. Additionally, 400 kL, 500 kL, and 600 kL tanks are examined to assess the feasibility of their construction.

3.1.1 100 kL hybrid circular tanks

This analysis covers H/D ratios from 0.2 to 0.8 using 4, 6, and 8 columns. At an H/D ratio of 0.2, the radius of the top ring beam is 5.8 meters, resulting in a circumference of 36.4 meters. Each span would be approximately 18.3 meters. Therefore, it is impractical to use a small number of columns for perimeters of this size. Similarly, for a 100-kL tank, using 10 or 12 columns is not cost-effective due to the rising costs involved.

The Optimum Cost is observed at H/D 0.8 with 4 columns for a 100 kL tank.

3.1.2 150 kL hybrid circular tanks

The optimum cost is observed at an H/D ratio of 0.8 with both 4, showing minimal cost difference between the two configurations. Therefore, this study recommends using 4 and even 6 columns for structural safety and stability.This analysis spans H/D ratios from 0.2 to 0.8 using 4, 6, and 8 columns. At an H/D ratio of 0.2, similar issues as observed in the 100 kL tank can occur, making it impractical to use a small number of columns for larger perimeters such as those required for 200 kL tanks. Similarly, for a 200 kL tank, using 10 or 12 columns is not cost-effective due to increased costs.

3.1.3 200 kL hybrid circular tanks

The optimum cost is observed at an H/D ratio of 0.8 with both 4 and 6 columns, showing minimal cost difference between the two configurations. Therefore, this study recommends using 6 columns for structural safety and stability.This analysis spans H/D ratios from 0.2 to 0.8 using 4, 6, and 8 columns. At an H/D ratio of 0.2, similar issues as observed in the 100 kL tank can occur, making it impractical to use a small number of columns for larger perimeters such as those required for 200 kL tanks. Similarly, for a 200 kL tank, using 10 or 12 columns is not cost-effective.

3.1.4 250 kL hybrid circular tanks

The optimum cost is observed at an H/D ratio of 0.8 with both 6 and 8 columns, showing minimal cost difference between the two configurations. Therefore, this study recommends using 8 columns for structural

Table 4 — Parametric study of circular HWTs.

Capacity	H/D	Cost of hybrid circular tanks				
		Column				
		4	6	8	10	12
100 kL	0.2	-	15.86	16.74	-	-
	0.4	10.66	11.47	12.1	-	-
	0.6	9.88	10.43	11.16	-	-
	0.8	9.06	9.71	10.44	-	-
150 kL	0.2	-	19.33	19.35	-	-
	0.4	13.34	12.92	13.52	-	-
	0.6	11.9	12.07	12.76	-	-
	0.8	11.12	11.59	11.179	-	-
200 kL	0.2	-	22.69	19.33	21.29	-
	0.4	-	15.36	15.73	16.8	-
	0.6	14.47	13.64	14.78	15.56	-
	0.8	13.03	13.13	14.78	15.9	-
250 kL	0.2	-	-	26.45	22.6	-
	0.4	-	18.33	18.27	18.92	-
	0.6	-	16.48	16.76	17.48	-
	0.8	15.91	15.64	15.95	16.79	-
300 kL	0.2	-	-	28.9	28.69	28.53
	0.4	-	-	20.18	20.44	21.21
	0.6	-	18.55	18.65	19.08	19.89
	0.8	-	17.49	17.8	18.37	19.26

Table 5 — Cylindrical height and diameter analysis for different capacity circular tanks.

Capacity	H/D Ratio			
	0.2		0.8	
	Height of cylindrical tank	Diameter of TRB	Height of cylindrical tank	Diameter of TRB
400 KL	3.71 m	18 m	7.8 m	9.4 m
500 KL	4 m	19.4 m	8 m	10 m
600 Kl	4.4	20.6 m	8.5	10.6

safety and stability. This analysis spans H/D ratios from 0.2 to 0.8 using 4, 6, 8 and 10 columns. At an H/D ratio of 0.2, similar issues as observed in the 100 kL tank can occur, making it impractical to use a small number of columns for larger perimeters such as those required for 200 kL tanks. Similarly, for a 250 kL tank, using 12 columns is not cost-effective.

3.1.5 300 kL hybrid circular tanks

The optimum cost is observed at an H/D ratio of 0.8 with both 6 and 8 columns, showing minimal cost difference between the two configurations. Therefore, this study recommends using 8 columns for structural safety and stability.This analysis spans H/D ratios from 0.2 to 0.8 using 4, 6, 8, 10 & 12 columns. At an H/D ratio of 0.2-0.4, similar issues as observed in the 100 kL tank can occur, making it impractical to use a small number of columns for larger perimeters such as those required for 200 kL tanks. Similarly, for a 300 kL tank, using 12 or more columns is not cost-effective due to increased costs. This large perimeter poses a general construction challenge because supporting such a span with a small number of columns would compromise the structural integrity and stability of the tank. Therefore, it becomes impractical to use a limited number of columns for tanks designed with such proportions, as they are unable to adequately support the structural requirements imposed by the large perimeter.

3.2 Checking the feasibility of 400 – 600 kL hybrid circular or general elevated circular tanks

Table 5 presents an analysis of cylindrical height and diameter for various capacities of Circular tanks across different H/D ratios. These dimensions play a crucial role in evaluating the feasibility and practicality of constructing Hybrid Circular or General Elevated Circular tanks within these capacity ranges.At smaller H/D ratios, it is possible to achieve a lower height of construction, but this results in a larger diameter. This increase in diameter necessitates the use of more columns, thereby escalating costs and rendering the construction impractical.Conversely, higher H/D ratios make it challenging to construct tanks of such Cylindrical heights for construction. Therefore, based on this study, it is recommended to opt for Intze tanks for capacities beyond 300 kL to ensure practicality and cost-effectiveness in construction**.**

Therefore, the subsequent study comparing hybrid circular tanks with Conventional Circular tanks will exclusively focus on tanks within the 100-300 kL capacity range.

4 Conclusion

The study investigated the impact of height-to-diameter (H/D) ratios on Hybrid Elevated Circular water tanks ranging from 100 kL to 300 kL capacities. It identified that H/D ratios around 0.8 effectively balance cost and structural integrity across different tank sizes. Specifically, for 100 kL tanks, optimal cost-efficiency and stability were achieved with 4 columns at H/D 0.8, while 6 columns at the same ratio were suitable for 150 kL to 200 kL tanks. Larger capacities (250 kL and 300 kL) benefited from 8 columns at H/D 0.8, providing robust support without excessive construction costs. Challenges were noted for capacities beyond 300 kL, where extreme H/D ratios either increased column requirements and costs (at lower ratios) or posed impractical construction challenges (at higher ratios). The study underscores the practicality and cost-effectiveness of hybrid circular tanks within the 100-300 kL range compared to conventional designs, with recommendations favoring Intze tanks for capacities exceeding 300 kL due to their lower construction heights and reduced column needs. These insights are crucial for optimizing the design and construction of water storage tanks to meet both structural demands and economic considerations.

References

1 Saxena S & Pathak K K, *Innov Infrastruct Solut*, 9(4) (2024) 122.
2 Saxena M, Sharma S P & Mohan C, *Eng Optim*, 9(2) (1985) 143.
3 Saxena M, Sharma S P & Mohan C, *Eng Optim*, 10(4) (1987) 279.
4 Titiksh A, *Asian J Civ Eng*, 20(2) (2019) 187.

5 Thevendran V & Thambiratnam D P, *Numerical Techniques for Engineering Analysis and Design*, edited by Pande G N & Middleton J (Springer, Dordrecht), 1987.

6 Thevendran V & Thambiratnam D P, *Comput Struct*, 26(5) (1987) 805.

7 Thevendran V & Thambiratnam D P, *Comput Struct*, 29(4) (1988) 699.

8 Thevendran V & Thambiratnam D P, *Int J Numer Methods Eng*, 23(9) (1986) 1679.

9 Tan G H, Thevendran V, Das Gupta N C & Thambiratnam D P, *Comput Struct*, 48(5) (1993) 803.

10 Reddy G S, Komaravolu A, Devi K, Saduwale S & Obulesh A, *Latest Developments in Civil Engineering*, edited by Pathak K K, Bandara J M S J & Agrawal R (Springer, Singapore), 2024, pp. 437-461.

11 Workeluel N, Saha P, Matiyas S & Mohanty T, *Mater Today Proc*, (2023).

12 Moslemi M, Kianoush M R & Pogorzelski W, *Eng Struct*, 33(6) (2011) 2074.

13 Nirmal S, Pawar P M & Jadhav R P, *Techno-Societal 2022*, edited by Pawar P M, Ronge B P, Gidde R R, Pawar M M, Misal N D, Budhewar A S, More V V & Venkata Reddy P (Springer, Cham), 2024, pp. 195-201.

14 Bhadauria S S & Gupta M C, *J Perform Constr Facil*, 20(2) (2006) 136.

15 Bhadauria S S & Gupta D M C, *J Perform Constr Facil*, 21(3) (2007) 234.

16 Sangiorgio V, Uva G, Adam J M & Scarcelli L, *Eng Fail Anal*, 115 (2020) 104637.

17 Saeed M K, Rahman M K, Baluch M H & Tooti L A, *J Perform Constr Facil*, 34(1) (2020) 04019100.

18 Rodd J & Castel A, Struct, 40 (2022) 1091.

19 Prakash & Bansal, Adv Constr Mater Sustain Environ, (2021) 151.

20 Saxena S & Pathak K K, *J Struct Des Constr Pract*, 30(1) (2025) 04024080.