# 1. Chapter 1: Introduction

## 1.1. Introduction

Water, often described as the elixir of life, is fundamental to the existence of all living organisms. Every day, life depends on access to potable water, and modern civilization relies heavily on stored water for various needs, from drinking and sanitation to agriculture and industry. Its vital role in the genesis and sustenance of life cannot be overstated. Despite water's abundance, only a small fraction is available for human use, making efficient storage and transmission systems crucial. This highlights the pressing need to address the challenges associated with water storage and distribution to ensure its availability for all.

**The paradox of water: Abundance and scarcity**: While water covers approximately 70% of the Earth's surface, only a small portion is accessible and suitable for human consumption. Most of the Earth's water is saline, with less than 3% classified as freshwater. Furthermore, a significant portion of this freshwater is locked in glaciers and polar ice caps. This scarcity of usable water highlights the need for efficient management and storage systems to ensure an adequate supply for human activities.

### 1.1.1. Historical development of water storage systems

From ancient civilizations to modern urban centers, water storage and management have been vital for human survival and development. Early civilizations, such as those in the Indus Valley, Mesopotamia, Ancient Egypt, and China, thrived along major rivers, utilizing them for drinking, agriculture, transportation, and trade.

- **Ancient water tanks:** water tanks have been used for millennia, with ancient societies demonstrating remarkable engineering skills in their construction. The Great bath of Mohenjo-Daro, dating back to 2500 BCE, and the expansive reservoirs of the Maya civilization are early examples of sophisticated water management systems. These early water tanks facilitated communal bathing, religious rituals, and agricultural irrigation.
- **Elevated water tanks in ancient Rome:** The concept of elevated water storage was pioneered by ancient Rome with the construction of "castella

aquae" as early as the 4th century BCE. These elevated tanks regulated water flow and distribution, setting the foundation for modern water storage systems. The Roman engineering marvels, including aqueducts and elevated reservoirs, were critical in supplying water to urban populations and are still admired today for their ingenuity.

- **Evolution and technological advancements:** The modern concept of elevated water tanks began to take shape in the 19th century with advancements in civil engineering. Elevated water tanks provide a gravitational advantage, enabling efficient water distribution without the need for complex pumping systems. This gravity-fed distribution system ensures a consistent water supply, even in areas with varying elevations. The Intze Principle, developed by Engineer Otto Intze, revolutionized water tank design by minimizing horizontal forces and enhancing structural stability.

### 1.1.2. Importance of Elevated water tanks

Elevated water tanks have played a crucial role in ensuring reliable access to clean water for communities throughout history. These structures have been instrumental in storing and distributing water efficiently, particularly in areas where gravity-fed systems are utilized. By storing water at an elevated height, these tanks harness the force of gravity to maintain pressure in the distribution system, thereby enabling water to reach every household of the community. Moreover, elevated water tanks help to stabilize water supply during periods of high demand or low water availability. Additionally, elevated water tanks contribute to water conservation efforts by reducing the need for excessive pumping and energy consumption. Furthermore, elevated water tanks play a crucial role in improving water quality by minimizing the risk of contamination. By storing water above ground level, these tanks reduce the likelihood of pollutants, debris, or pathogens entering the water supply, thus safeguarding public health and hygiene.

Elevated water tanks are indispensable components of modern water supply systems. They play a crucial role in urban development and civil engineering by ensuring reliable access to clean water, regulating water pressure, stabilizing supply, conserving resources, and protecting public health. As urban populations continue to grow, the significance of elevated water tanks in sustaining life and development will only increase, highlighting the need for continued innovation and investment in this critical infrastructure.

### 1.1.3. Government initiatives for water supply in India

Even after 75 years of independence, many rural households in India still lack access to potable or tap water. Through initiatives such as the "Jal Jeevan Mission" and "Nal se Jal Yojna," the Government of India is striving to provide tap water to every rural and urban locality. To achieve this, the government is currently making significant efforts to construct numerous water tanks in both urban and rural areas as part of its infrastructure development projects.

This research focuses on reducing the construction costs associated with elevated water tanks, aiming to amplify the impact of India's initiative to provide clean water. By achieving cost efficiencies, the study aims to enhance the project's sustainability and scalability, ultimately improving the quality of life for millions of residents nationwide. This strategic approach will ensure that more communities, whether rural or urban, benefit from dependable access to clean water, thereby supporting sustainable development and public health advancements across the country.

## 1.2. Classification of water tanks

Water tanks are essential structures for storing and distributing water in various settings. Their design and construction depend on factors such as location, material, capacity and shape. This Section of the thesis provides an in-depth classification of water tanks based on these key parameters, offering insights into their characteristics and applications.

### 1.2.1. Classification based on location of water tank with respect to the ground level

- **Ground-supported water tanks-** These tanks are supported on the ground. They can be circular or rectangular in shape. They are relatively easy to construct and cost-effective compared to elevated tanks. However, they may require additional land space and excavation for installation.
- **Underground water tanks-** These tanks are constructed below the ground surface. These are designed to bear water pressure along with the soil pressures.
- **Partial ground-supported water tanks-** These tanks are partially ground-supported and partially underground tanks.
- **Elevated water tanks-** Elevated water tanks, positioned on raised structures or towers, utilize gravity to maintain water pressure in municipal water supply systems. This reduces the need for pumping, making them cost-effective and efficient. Their height ensures reliable access to water, especially in varied terrains, benefiting both urban and rural communities. The shape of these tanks is chosen based on several factors to optimize their performance

Thus, the classification of water tanks based on their location relative to ground level is crucial in determining their design, functionality, and application. Each type—whether ground-supported, underground, partially ground-supported, or elevated—offers distinct advantages suited to specific site conditions, usage requirements, and economic considerations. A proper selection ensures efficient water storage, structural safety, and long-term serviceability

### 1.2.2. Classification based on material used for the construction

- **RCC water tanks:** These are the most common type of water tanks constructed of RCC. Known for their durability and corrosion resistance, RCC tanks are widely used for various water storage applications.
- **Steel water tanks:** Fabricated from steel plates, these versatile tanks are commonly used in industrial, commercial, and residential settings due to their strength and durability.
- **Ferrocement water tanks:** Made of cement mortar reinforced with mesh or rods, these lightweight tanks are ideal for small to medium-sized water storage needs. In India there is a separate Indian standard for the design of Ferrocement water tanks IS 13356:1992. Capacity of tanks are limited to 10 kL only.
- **Prestressed concrete water tanks:** Constructed using prestressed concrete, these tanks offer enhanced strength and durability, making them suitable for large-scale water storage.
- **Plastic and fiberglass water tanks:** Lightweight and corrosion-resistant, these tanks are made of materials like fiberglass-reinforced plastic (FRP), polyethylene (PE), or polypropylene (PP). They are suitable for single residential houses.

  In India, Reinforced Cement Concrete (RCC) tanks are commonly constructed for water storage. There are specific Indian Standards (IS) codes for the construction of concrete water tanks, established since 1967.

**Therefore, RCC water tanks are used for this study.**

### 1.2.3. Classification based on geometrical shape of tanks

- **Intze tank:** Characterized by a cylindrical shape with a conical dome, Intze tanks are known for their structural stability and efficient use of space.
- **Circular tank**: Cylindrical in shape with a flat or domed roof, circular tanks are commonly used for water storage in various applications in rural India.

- **Rectangular tank:** Featuring a box-like shape with straight sides and a flat bottom, rectangular tanks are suitable for limited-space applications.
- **Funnel-shaped tank:** Also known as conical tanks, these tanks have a conical bottom that slopes inward towards a central drain.

### 1.2.4. Classification based on the capacity of the tanks

Although there is no clear demarcation of tank capacities, the classification based on capacity helps in understanding their usage and applications:

- **Low-capacity tank:** tanks typically holding 200 kL or less are commonly classified as low-capacity tanks. These tanks are often utilized for applications requiring the in rural areas or city colonies.
- **Medium capacity tanks:** tanks with capacities ranging between 200 kL and 600 kL are generally categorized as medium capacity tanks. Typically, these tanks are constructed in urban cities, particularly in residential colonies.
- **High-capacity tanks:** High-capacity tanks, with capacities over 600 kL, are designed for large volumes of liquids. Commonly used in industries and large localities, they provide substantial storage for continuous or bulk needs.

### 1.2.5. Selection of tanks for this study

The elevated Intze water tank structure minimizes the footprint, maximizing the use of available land. In essence, the choice of an elevated water tank is a strategic decision, balancing efficiency, space utilization, and structural integrity to meet the vital needs of water storage for thriving civilizations. However, the construction of Intze water tanks is complex. Hence, in rural areas where land availability is not an issue and the required storage quantity is less, cylindrical water tanks are generally constructed. Whereas, rectangular tanks have higher leakage issues, and funnel-shaped tanks are considered obsolete nowadays. Therefore, for this study**, Intze and Circular tanks are being adopted.**

Fig. 1.1: Intze and Circular water tanks
(Source: Picture (a) Taken from B.H.U and (b) Internet)

## 1.3. Load acting on water tanks

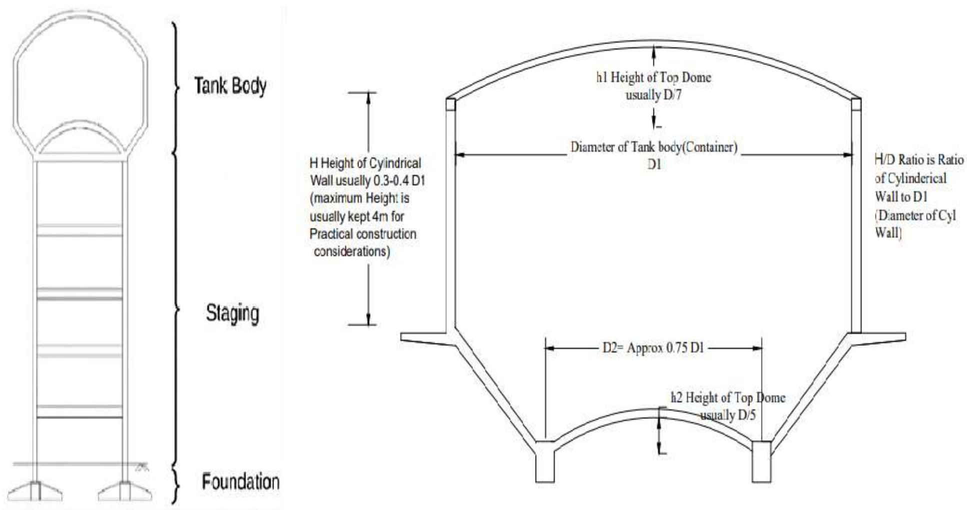
Concrete structures designed to retain liquids must carefully consider various loads acting on them to ensure their structural integrity over time. These loads include dead load, imposed load, earthquake load, wind load, earth pressure, snow load (if applicable), and liquid load. Each load presents unique challenges and considerations for engineers and designers:

- **Dead load (DL):** Dead load encompasses the weight of permanent components such as the structure itself, earth covering, and roof plants, as well as construction loads from plant and heaped earth.
- **Imposed load (IL):** Imposed load comprises transient loads resulting from equipment operation, material storage, and normal live loads from personnel. It is assumed in accordance with standards (IS 875 Part II).
- **Earthquake load (EL):** Earthquake load denotes the forces induced by seismic activity, capable of causing significant horizontal and overturning forces in structures. Calculation follows standards outlined in IS 1893 (Part I and II ).
- **Wind load (WL):** Wind load represents the force exerted by wind on the structure and is determined according to IS 875 (Part III). It includes considerations for wind pressure acting perpendicular to the surfaces of the structure.
- **Earth pressure (EP):** Earth pressure accounts for pressures exerted by the surrounding soil on the structure's walls. Calculation considers factors such as soil compaction, surcharge, and the construction and service condition of the structure.
- **Snow load:** Snow load considers the weight of accumulated snow on the structure and is assumed in accordance with IS 875 (Part 4).
- **Liquid load (FL):** Liquid load encompasses the mass or pressure exerted by retained liquids on the structure. It includes dead storage, liquid pressure, and the static and dynamic effects of liquid mass.

By addressing these loads effectively, structures can be designed to guarantee safety, stability, and durability in various environmental conditions.

## 1.4. Components of Elevated water tanks

Elevated water tanks consist of mainly three parts-tank for storing water consisting of domes, beams and walls, Staging comprising of column and braces and foundations using annular raft foundations. Details are given as below-




(a ) (b)

Fig. 1.2: (a) Elements of water tanks; (b) Proportioning of elements w.r.t. diameter of tank body.

- **Top dome-** The top dome of an elevated water tank, typically with a rise around H/7, is crucial for structural integrity. It supports its own weight and live loads, with a lantern for maintenance access. The dome endures meridional thrust and circumferential forces, requiring careful design to handle bending, tensile, compressive, circumferential, and meridional stresses. Engineers meticulously ensure its durability under various loads.
- **Top ring beam-** The top ring beam (TRB) in an elevated water tank provides crucial horizontal support around the tank's upper perimeter. It resists hoop forces and withstands bending moments. Assessing the maximum tensile stress in concrete is essential to ensure structural integrity and prevent failure.
- **Cylindrical wall-** The cylindrical wall of an elevated water tank encloses the water storage space, providing vertical support and containing water under

pressure. It is designed to withstand hydrostatic pressure. Main reinforcement is provided as rings, with increased spacing at the top, and vertical reinforcement handles secondary stresses. This wall is crucial for the tank's functionality and reliability.

- **Middle ring beam-** The middle ring beam, or balcony, provides walkway or balcony for access. designed to resist hoop forces and bending moments due to its cantilever action, the beam is analyzed for hoop stress, bending stress, and required reinforcement to ensure it withstands these forces safely.
- **Conical dome-**This is a member of Intze tank only**.** The conical dome connects to the cylindrical wall at its top, tapering at an angle known as the angle of the conical dome. This design ensures a smooth structural transition and effective load distribution from the cylindrical wall to the supporting structure below. Key forces acting on the conical dome include hoop tension and bending moments at both the top and bottom junctions, along with meridional forces. Main reinforcement is determined for hoop and bending stresses, with radial reinforcement calculated for the top and bottom edges. Hoop steel counteracts hoop tension, and meridional and bending stresses are evaluated to ensure safety.
- **Bottom dome-** The bottom dome of an elevated water tank supports a significant load, including its own self-load and the weight of the aqueous fluid it contains. Its height is typically about H/5. Structural stability is ensured by assessing maximum hoop force, meridional force at the edge, and horizontal thrust on the support. Its design parallels that of the top dome for robust structural integrity.
- **Main (Bottom) ring beam-** The main ring beam of the elevated water tank is a pivotal structural component tasked with the crucial role of distributing various loads throughout the structure. Supported on multiple columns and encircling the central diameter of the ring beam, it ensures that loads from the top dome, top ring beam, wall, balcony, self-load of the conical dome, and the water weight are uniformly dispersed among the supporting columns. Key design considerations for the main ring beam analyzing hoop tension, bending moments, shear, and torsional loads at critical Sections. Reinforcement

requirements, such as radial reinforcement and hoop steel, are meticulously calculated to ensure safety and compliance within the stress limits.

- **Staging -**Staging of water tanks composed of Column and Braces designed for Axial load and Maximum Lateral loadings and Moments generated. In depth, wind and seismic analysis are required to predict the behavior of Staging under lateral loads.
- **Foundation-** In usual practice annular raft foundation is designed for Elevated water tanks.

## 1.5. Properties of shells

When the loads are symmetrical about the axis of revolution, such shells develop only membrane forces and moments are absent. Membrane forces consists of Hoop forces acting at horizontal plane and meridional forces acting tangential to meridians at every point. For water tanks, the structural components include spherical shells (top and bottom domes), cylindrical shells (walls), and conical shells (conical domes). Therefore, understanding the membrane analysis of these shells is crucial. All equations and formulations presented in this section on Properties of Shell are either directly taken from or derived based on the principles outlined in J. Krishna and O.P. Jain, Plain and Reinforced Concrete, Volume II, Nem Chand & Bros., 2017. Books like N.K. Raju, Advanced reinforced concrete design (IS 456:2000), 2005 is also used in this study.

### 1.5.1. Top and Bottom dome

Considering the Spherical Domes of tanks that are Top and Bottom dome, The dome has a uniform thickness and Radius of curvature and subtends a semi angle at its center of curvature. $T_1$ and $T_2$ are the meridional and hoop forces per unit length, taken positively when tensile. Change of the slope is taken as $\psi$ and horizontal movement is denoted by x, poisons ratio is taken as zero in these properties.

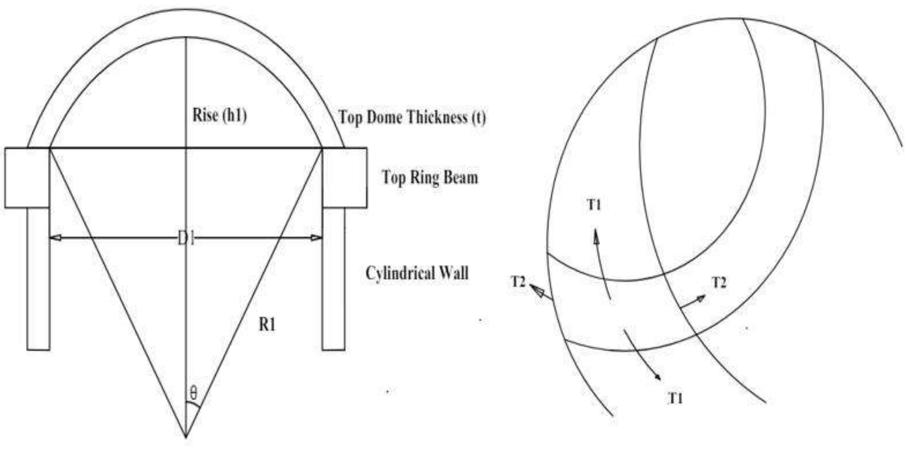



Fig. 1.3 (a). Spherical Dome analysis (b) Forces acting on Spherical dome.

Source: J. Krishna and O.P. Jain (2017)

Under the influence of forces such as self-weight or live load acting on the members, as well as the water pressure, forces develop within the members. These forces can be calculated using specific formula given below.

- **Case I-** Domes subjected to a uniform vertical load w per unit surface area (can be self or live load)-

Meridional forces $$T_1 = \frac{wR}{(1+\cos\theta)} \quad (1.1)$$

Hoop forces $$T_2 = wR\{cos\,\theta - (1 + cos\ \theta)^{-1}\} \quad (1.2)$$

Slope at the edge $$\psi = 2wR\,sin\,\theta\,/Et \quad (1.3)$$

Horizontal displacement $$x = wR^2\{(1+\cos\theta)^{-1} - cos\,\theta\}/Et \quad (1.4)$$

General equations $$\lambda^4 = \{3(R/t)^2\};\ k = 1 - \cot\theta/2\lambda \quad (1.5)$$

- **Case II-** Hydrostatic pressure acting radially from zero at the crown to maximum near edges-

Meridional forces $$T_1 = \frac{-wR^2\{1+\cos\alpha - 2\ \cos^2\alpha\}}{6(1+\cos\alpha)} \quad (1.6)$$

Hoop forces $$T_2 = \frac{-wR^2\{4\ \cos^2\alpha + \cos\alpha - 5)\}}{6(1+\cos\alpha)} \quad (1.7)$$

Slope at the edge $$\psi = wR^2\sin\theta\,/Et \quad (1.8)$$

Horizontal displacement $$x = \frac{wR^3\sin\theta\,\{2\ \cos\theta + \cos\theta - 3\}}{6(1+\cos\theta)} \quad (1.9)$$

- **Case III-** Moment and Thrust stiffnesses- Moment and Thrust stiffnesses develop in the shells. Moment stiffnesses i.e. moment /unit length of the periphery at the edges cause unit clockwise rotation without any displacement of the edges. Thrust stiffnesses i.e. thrust per unit length needed to cause a into outward movement of edges without any rotation of tangent.

Moment stiffness $$M.S. = \frac{R_1 Et_{td}(k_{td} + k_{td}^{-1})}{4 \times {\lambda_{td}}^3} \quad (1.10)$$

Corresponding stiffness $$C.S. = \frac{Et_{td}}{2{\lambda_{td}}^2 k_{td} sin\theta_{td}} \quad (1.11)$$

Thrust stiffness $$T.S. = \frac{Et_{td}}{\lambda_{td} R_1 k_{td} sin^2\theta_{td}} \quad (1.12)$$

## 1.5.2. Cylindrical shells

For shells where μ/h is more than 4, The effect of change of curvature or displacement of one edge is negligible on the other edge. This condition is fulfilled in most practical cases of tanks. If the edges are free to move, the shell develops only hoop stresses under hydrostatic or uniform pressure. 'p' is the radial pressure at any depth.

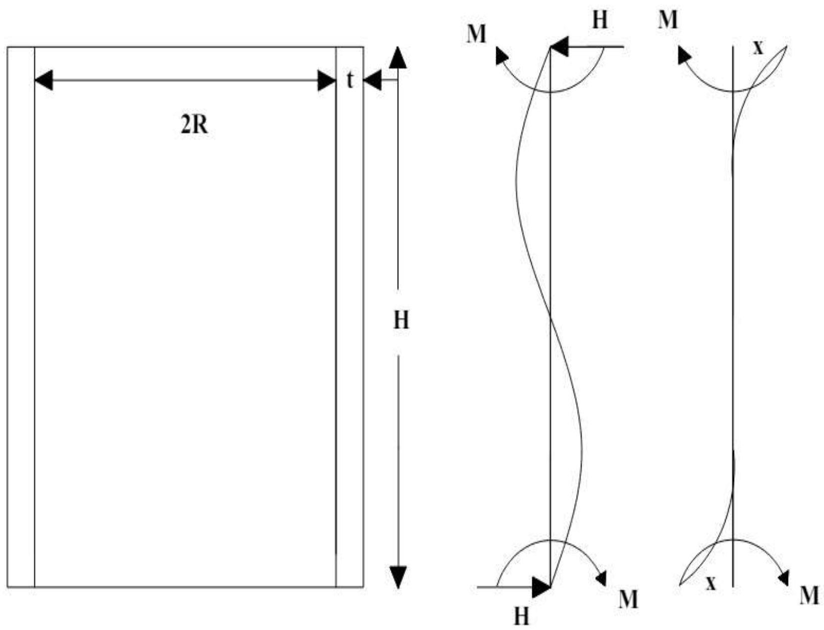



Fig. 1.4: Cylindrical shell analysis

Source: J. Krishna and O.P. Jain (2017)

| | | |
|---|---|---|
| Meridional forces | $T_1 = 0$ | (1.13) |
| Hoop forces | $T_2 = pR$ | (1.14) |
| Slope at the edge | $\psi = pR^2/Et$ | (1.15) |
| Horizontal displacement | $x = \dfrac{\gamma_w \times H \times (\mathrm{r})^2}{Et}$ | (1.16) |
| Moment stiffness | $M.S. = 2\mu z$ | (1.17) |
| Corresponding Stiffness | $C.S. = 2\mu^2 z$ | (1.18) |
| Thrust stiffness | $T.S. = 4\mu^3 z$ | (1.19) |

## 1.5.3. Conical shells

For conical dome the following calculations are done-

| | | |
|---|---|---|
| Meridional forces | $T_1 = -\frac{W_z}{\pi y \sin 2\theta}$ | (1.20) |
| Hoop forces | $T_2 = -W_{z.} y \tan\theta$ | (1.21) |
| Slope at the edge | $\psi = \tan\theta\,(2T_2 - T_1)/Et$ | (1.22) |
| Horizontal displacement At top and bottom | $x_{cd1} = \frac{T_{2top} \times r_1}{Et_{top}}; x_{cd2} = \frac{T_{2b} \times r_2}{Et_b}$ | (1.23) |
| General formulas | $\Delta^4 = \cot^2\theta/t^2\,;\ \xi = 2\Delta\sqrt{l};\ \xi' = 2\Delta\sqrt{l'}$ | (1.24) |
| Moment stiffness at Top | $M.S. = \frac{Et_{cd1}k_4}{l\tan^2\theta_{cd}K}$ | (1.25) |
| Corresponding Stiffness Top | $C.S. = \frac{Et_{cd1}k_2}{l\tan^2\theta_{cd}K}$ | (1.26) |
| Thrust stiffness at Top | $T.S. = \frac{Et_{cd1}k_1}{l\tan^2\theta_{cd}K}$ | (1.27) |
| Moment stiffness at Bottom | $M.S. = \frac{Et_{cd2}k_4}{l\tan^2\theta_{cd}K'}$ | (1.28) |
| Corresponding stiffness at Bottom | $C.S. = \frac{Et_{cd2}k_2}{l\tan^2\theta_{cd}K'}$ | (1.29) |
| Thrust stiffness at Bottom | $T.S. = \frac{Et_{cd1}k_1}{l\tan^2\theta_{cd}K'}$ | (1.30) |

These are the formulas for calculating the forces acting on the shells. Similarly, beams Hoop forces will act and Middle beam bending moments will act. These forces will together constitute the Right-hand side of the equations. Moment & thrust stiffnesses are compiled in form of a Table to make the process easy to understand.

## 1.6. Methods of analysis of water tanks

There are two different approaches for the design of water tanks-

- **Membrane analysis-** Typically, in tank design, a membrane analysis is utilized for each structural element. This theory, grounded in equilibrium principles, evaluates the structure as a thin, continuous membrane rather than discrete components. Despite a tank's overall structural strength, neglecting the compatibility of displacement at element junctions, especially in RCC structures, can result in cracking and leakage. To mitigate this risk, it's advisable to ensure joint displacement compatibility or add nominal reinforcement near joints.
- **Continuity analysis method-** The Continuity analysis method is a structural analysis technique employed in the design of water tanks to ensure structural integrity and prevent leaks. This method focuses on the continuity of joints within the tank structure. Ensuring continuity among these components is essential for minimizing the risk of leaks and maintaining the tank's stability. It is an interesting fact that the Continuity analysis method incorporates both membrane analysis and the effect of joint continuity. In the membrane analysis phase, total vertical loads, meridional stresses, circumferential stresses, Horizontal displacement of edges, and rotation of edges of various members are calculated. Subsequently, the effect of continuity is applied to calculate actual forces such as bending moments, outward thrust, and hoop tension. This method enables a comprehensive analysis of the water tank's behavior under different loading conditions. It considers how loads are distributed and transferred throughout the structure, optimizing the use of materials and leading to smaller member sizes compared to membrane analysis alone. By adopting the Continuity analysis method, designers can achieve more efficient and cost-effective designs for water tanks, ensuring their structural stability and longevity while minimizing the risk of leaks and other structural issues. To calculate the effect of continuity each joint needs to be analyzed and net rotation of the joint i.e. $\theta$ radians and net horizontal displacement i.e. y mm at each joint are the primary

unknowns at each joint. Calculation of the effect of continuity involves following steps-

- **Step 1-** Calculation of Stiffnesses of each member. Stiffnesses include Moment stiffnesses, Thrust stiffnesses and Corresponding Thrust or Moment stiffnesses
- **Step 2-**Calculating the clockwise moments and Outward thrusts in terms of $\theta$ & y and equating to external force imposed on the joint. In this way we get numeric value of the primary unknowns.
- **Step 3-** After these clockwise moments, Outward thrusts & Hoop tensions are obtained at each joint.
- **Step 4-** After the calculation of actual member forces the member reinforcement is calculated

This Step 1 and Step 2 are explained in tabular form to understand & simplify the process with Formulation of equation are discussed in Section below.

## 1.7. Analysis of Intze and circular RCC water tank body

Analysis and design of water tanks are divided into 3 major portions- RCC tank body, staging and foundation.

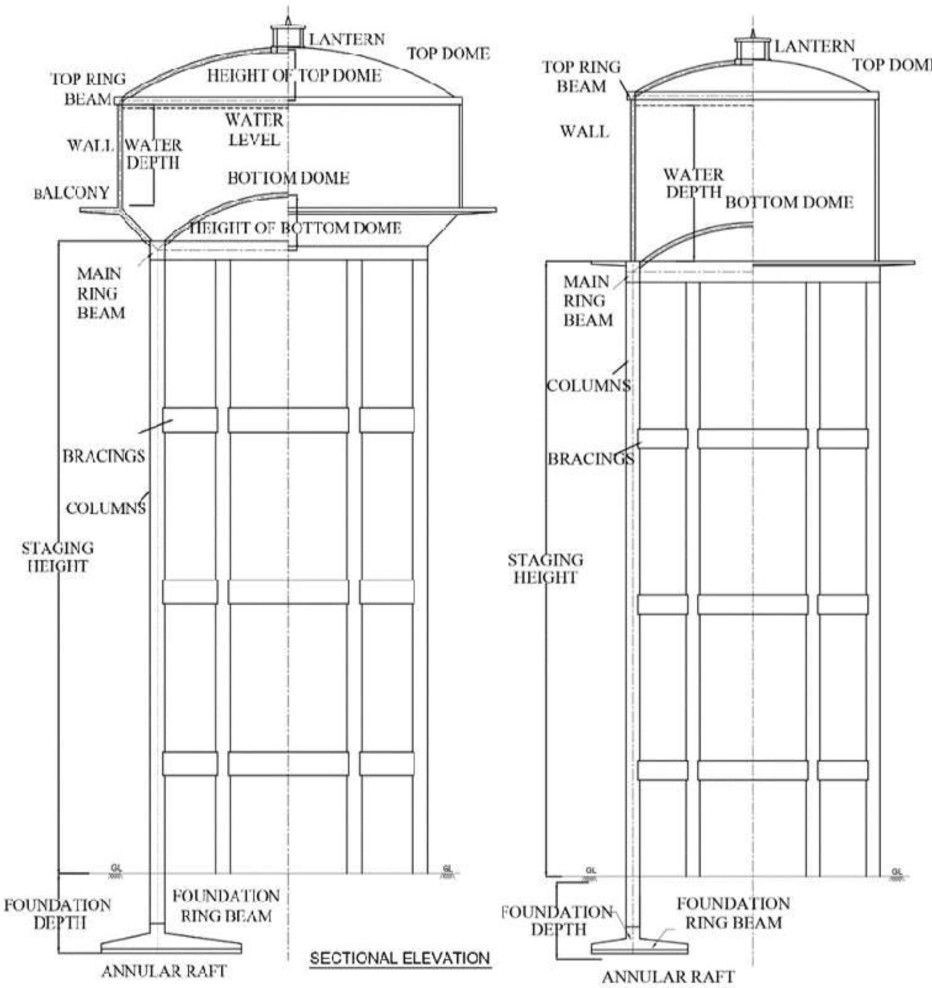



Fig. 1.5: (a) Intze water tank and (b) Circular tank

### 1.7.1. Analysis of Intze water tank body (container)

Intze water tanks consist of three joints: the Top joint, the Middle joint, and the Bottom joint. Each joint connects three members. All the members are subjected to various forces such as outward thrusts, Hoop tension and bending moments etc. Figure 1.4 (a) illustrates the various structural components of an Intze water tank, including the top dome, cylindrical wall, bottom dome, ring beam, and supporting columns. Table 1.1 displays the joint details of Intze tanks, outlining the specific members connected at each joint.

Table 1.1 Joint details of Intze water tanks

| Sr.No | Joint | Member connected |
|---|---|---|
| 1 | Top | Top ring beam, top dome and cylindrical wall |
| 2 | Middle | Middle ring beam, conical dome and cylindrical wall |
| 3 | Bottom | Conical dome, bottom dome & bottom ring beam |

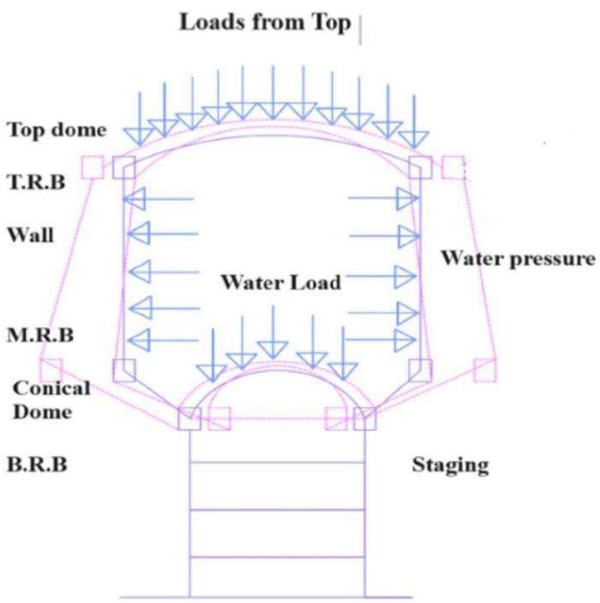



Fig. 1.6: Deformation of each part of the Intze water tank

Tables 1.2 and provide a comprehensive analysis framework for Intze water tanks. Table 1.2 delves into stiffness and displacement considerations for tank components such as the dome, ring beams, and walls, detailing their respective stiffness equations and displacement parameters.

The nomenclature for the members is assigned according to their Member Numbers to streamline the software development process. beam sizes are denoted as b x d along with their respective member numbers. Dome thicknesses are indicated by 't' followed by the member number, such as $t_1$ etc.

Table 1.2: Stiffnesses and displacement for Intze water tanks

| Sr.No | Member | Moment stiffness | Corr. Stiffness | Thrust stiffness | Rotation | Disp |
|---|---|---|---|---|---|---|
| Top | TD | $\frac{R_1 Et_1(k_{td}+k_{td}^{-1})}{4\times\lambda_{td}{}^3}$ | $\frac{Et_1}{2\lambda_{td}{}^2 k_{td} sin\theta_{td}}$ | $\frac{Et_1}{\lambda_{td} R_1 k_{td} sin^2\theta_{td}}$ | $\psi_1 - \psi_{td}$ | $x_1 - x_{td}$ |
| | TRB | $\frac{Eb_2 d_2{}^3}{12r_1{}^2}$ | - | $\frac{Eb_2 d_2}{r_1{}^2}$ | $\psi_1$ | $x_1$ |
| | Wall Top | $2\mu z$ | $2\mu^2 z$ | $4\mu^3 z$ | $\psi_1 - \psi_w$ | $x_1$ |
| Middle | Wall Bottom | $2\mu z$ | $2\mu^2 z$ | $4\mu^3 z$ | $\psi_2 - \psi_w$ | $x_{2-}x_w$ |
| | MRB | $\frac{Eb_4 d_4{}^3}{12r_2{}^2}$ | - | $\frac{Eb_4 d_4}{r_2{}^2}$ | $\psi_2$ | $x_2$ |
| | CD (top) | $\frac{Et_{5top}k_4}{l\tan^2\theta_{cd}K}$ | $\frac{Et_{5top}k_2}{l\tan^2\theta_{cd}K}$ | $\frac{Et_{5top}k_1}{l\tan^2\theta_{cd}K}$ | $\psi_2 - \psi_{cd1}$ | $x_2 - x_{cd1}$ |
| Bottom | CD Bottom | $\frac{Et_{5bottom}k_4}{l\tan^2\theta_{cd}K'}$ | $\frac{Et_{5bottom}k_2}{l\tan^2\theta_{cd}K'}$ | $\frac{Et_{5bottom}k_1}{l\tan^2\theta_{cd}K'}$ | $\psi_3 - \psi_{cd2}$ | $x_3 - x_{cd2}$ |
| | BD | $\frac{R_2 Et_6(k_{bd}+k_{bd}^{-1})}{4\times\lambda_{bd}{}^3}$ | $\frac{Et_6}{2\lambda_{bd}{}^2 k_{bd} sin\theta_{bd}}$ | $\frac{Et_6}{\lambda_{bd} R_2 k_{bd} sin^2\theta_{bd}}$ | $\psi_3 - \psi_{bd}$ | $x_3 - x_{bd}$ |
| | BRB | $\frac{Eb_7 d_7{}^3}{12r_2{}^2}$ | - | $\frac{Eb_7 d_7}{r_2{}^2}$ | $\psi_3$ | $x_3$ |

Meanwhile a series of equations crucial for the structural analysis of these tanks are given below-

Equations for analysis of Intze water tank

- $\frac{R_1\times E\times t_1\times(k_{td}+k_{td}^{-1})}{4\times\lambda_{td}{}^3}\times(\psi_1-\psi_{td}) - \frac{Et_1}{2\lambda_{td}{}^2 k_{td} sin\theta_{td}}\times(x_1 - x_{td}) + \frac{E\times b_2\times d_2^3}{12\times r_1{}^2}\times(\psi_1) + 2\times\mu\times z\times(\psi_1-\psi_{wall}) + 2\times\mu^2\times z\times x_1 = 0$ (1.31)
- $\frac{Et_1}{\lambda_{td} R_1 k_{td} sin^2\theta_{td}}(x_1 - x_{td}) - \frac{Et_1}{2\lambda_{td}{}^2 k_{td} sin\theta_{td}}(\psi_1 - \psi_{td}) + \frac{Eb_2 d_2}{r_1{}^2}x_1 + 4\mu^3 z(x_1 - x_{wall}) + 2\mu^2 z(\psi_1 - \psi_{wall}) = \text{Horizontal force at joint}$ (1.32)
- $\{2\mu z\}\{\psi_2 - \psi_{wall}\} - \{2\mu^2 z\}\{x_{2-}x_{wall}\} + \frac{Eb_4 d_4{}^3}{12r_2{}^2}\psi_2 + \frac{Et_{5top}k_4}{l\tan^2\theta_{cd}K}\{\psi_2 - \psi_{cd1}\} + \frac{Et_{5top}k_2}{l\tan^2\theta_{cd}K}\{x_{2-}x_{cd1}\} = \text{B.M. at Balcony beam}$ (1.33)

- $\{4\mu^3 z\}\{x_2 - x_{wall}\} - \{2\mu^2 z\}\{\psi_2 - \psi_{wall}\} + \frac{Et_{5top}k_1}{l\tan^2\phi_2 K}\{x_2 - x_{cd1}\} + \frac{Eb_4 d_4}{{r_2}^2}x_2 + \frac{Et_{5top}k_2}{l\tan^2\phi_2 K}\{\psi_2 - \psi_{cd1}\} = \text{Total vertical load} + \text{Horizontal thrust at MRB}$ (1.34)
- $\frac{Et_{5bottom}k_4}{l\tan^2\theta_{cd}K}\{\psi_3 - \psi_{cd2}\} - \frac{Et_{5bottom}k_2}{l\tan^2\theta_{cd}K}\{x_3 - x_{cd2}\} + \frac{Eb_7 {d_7}^3}{12{r_3}^2}\psi_3 + \frac{R_2 Et_6(k_{bd} + k_{bd}^{-1})}{4\times{\lambda_{bd}}^3}\{\psi_3 - \psi_{bd}\} - \frac{Et_6}{2{\lambda_{bd}}^2 k_{bd} sin\theta_{bd}}\{x_3 - x_{bd}\} = 0$ (1.35)

## 1.7.2. Analysis of circular water tank body

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 1.3. 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 1.3: 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 |

Fig 1.6 depicts the deformation experienced by different parts of the circular water tanks under various load conditions. This visual representation helps in understanding how each component contributes to the overall structural stability and integrity of the tank.

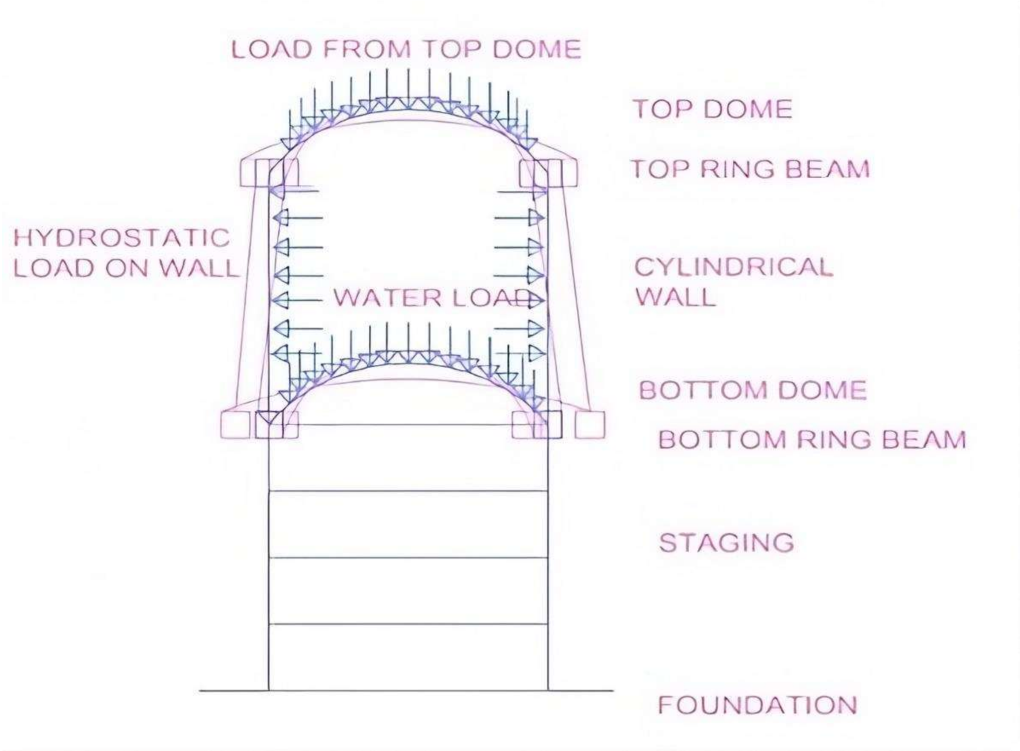



Fig. 1.7: Deformation of each part of the circular water tanks

Table 1.4. presents the Moment stiffness, corresponding stiffness, thrust stiffness, rotation, and displacement for various members of the circular water tank.

The following are the essential equations for analyzing the structural behavior of circular water tanks. These equations help in calculating Moment stiffness, horizontal forces, bending moments, and net horizontal thrusts acting on the tank's joints. Accurate analysis using these equations ensures the tank's design is robust and can handle the stresses imposed by water loads and other environmental factors. The structural analysis of a tank involves understanding the forces and moments acting on different parts of the tank, derived from shell theory. Overall, the right-hand side of these equations is derived from the properties of shell structures, specifically considering the distribution of axial and circumferential stresses, influenced by the shape, height, and water pressure, ensuring the tank can safely store and support the water load. This detailed understanding of forces and moments is crucial for the design and safety assessment of tanks.

Table 1.4 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 | $\frac{E b_2 d_2^3}{12 r_1^2}$ | - | $\frac{E b_2 d_2}{r_1^2}$ | $\psi_1$ | $x_1$ |
| | Wall Top | $2\mu z$ | $2\mu^2 z$ | $4\mu^3 z$ | $\psi_1 - \psi_w$ | $x_1$ |
| Bottom | Wall Bottom | $2\mu z$ | $2\mu^2 z$ | $4\mu^3 z$ | $\psi_2 - \psi_w$ | $x_{2-}x_w$ |
| | MRB | $\frac{E b_4 d_4^3}{12 r_2^2}$ | - | $\frac{E b_4 d_4}{r_2^2}$ | $\psi_2$ | $x_2$ |
| | BRB | $\frac{E b_7 d_7^3}{12 r_2^2}$ | - | $\frac{E b_7 d_7}{r_2^2}$ | $\psi_2$ | $x_2$ |
| | BD | $\frac{R_2 E t_6 (k_{bd}+k_{bd}^{-1})}{4\times\lambda_{bd}^3}$ | $\frac{E t_6}{2\lambda_{bd}^2 k_{bd} sin\theta_{bd}}$ | $\frac{E t_6}{\lambda_{bd} R_2 k_{bd} sin^2\theta_{bd}}$ | $\psi_2 - \psi_{bd}$ | $x_2 - x_{bd}$ |

Equations for analysis of Circular water tanks

- $$\frac{R_1\times E\times t_1\times(k_{td}+k_{td}^{-1})}{4\times\lambda_{td}^3}(\psi_1-\psi_{td}) - \frac{E t_1}{2\lambda_{td}^2 k_{td} sin\theta_{td}}(x_1 - x_{td}) + \frac{E\times b_1\times d_1^3}{12\times r_1^2}(\psi_1) + 2\mu z\times(\psi_1-\psi_{wall}) + 2\mu^2 z x_1 = 0; \quad (1.37)$$
- $$\frac{E t_1}{\lambda_{td} R_1 k_{td} sin^2\theta_{td}}(x_1 - x_{td}) - \frac{E t_1}{2\lambda_{td}^2 k_{td} sin\theta_{td}}(\psi_1-\psi_{td}) + \frac{E b_1 d_1}{r_1^2}x_1 + 4\mu^3 z(x_1 - x_{wall}) + 2\mu^2 z(\psi_1 - \psi_{wall}) = H.F.\ on\ support; \quad (1.38)$$
- $$\{2\mu z\}\{\psi_2 - \psi_{wall}\} - \{2\mu^2 z\}\{x_{2-}x_{wall}\} + \frac{E b_4 d_4^3}{12 r_2^2}\psi_2 + \frac{E b_4 d_4^3}{12 r_2^2}\psi_2 + \frac{R_2 E t_{bd}(k_{bd}+k_{bd}^{-1})}{4\times\lambda_{bd}^3}\{\psi_2-\psi_{bd}\} - \frac{E t_{bd}}{2\lambda_{bd}^2 k_{bd} sin\theta_{bd}}\{x_2 - x_{bd}\} = \text{B.M. at Balcony} \quad (1.39)$$
- $$\{4\mu^3 z\}\{x_{2-}x_{wall}\} - \{2\mu^2 z\}\{\psi_2 - \psi_{wall}\} + \frac{E b_7 d_7}{r_2^2}x_2 + \frac{E b_7 d_7}{12 r_3^2}\psi_2 + \frac{R_2 E t_6(k_{bd}+k_{bd}^{-1})}{4\times\lambda_{bd}^3}\{x_2 - x_{bd}\} + \frac{E t_6}{2\lambda_{bd}^2 k_{bd} sin\theta_{bd}}\{\psi_2 - \psi_{bd}\} = \text{Net Horizontal thrust} + \text{Total vertical load}; \quad (1.40)$$

## 1.8. Design of conventional Intze and circular RCC water tank body

In this study, tanks designed in accordance with the latest Indian standard for retaining aqueous liquids, I.S. 3370:2021, will be referred to **as Conventional water tanks or Standard RCC tanks.** These tanks adhere to the guidelines and specifications outlined in the standard to ensure structural integrity, safety, and functionality for the storage of liquids.

The Working stress method (WSM) and Limit state method (LSM) are two fundamental approaches used in the design and analysis of water tanks. WSM, being the earlier method, is based on the principle that materials remain within their elastic limits under working loads. It ensures safety by applying a factor of safety to the yield stress of materials, keeping the working stresses within permissible limits. However, when applied to water tank design, WSM often results in conservative and potentially uneconomical structures due to its reliance on elastic behavior and blanket safety factors.

On the other hand, LSM is a more modern approach that considers both the ultimate and serviceability limit states. In the context of water tanks, LSM ensures that the structure has adequate strength to withstand maximum loads, including the weight of the water and any additional environmental loads, without collapsing (ultimate limit state). Simultaneously, it ensures that the tank performs satisfactorily under regular conditions without issues like excessive deflection or cracking (serviceability limit state). LSM uses partial safety factors for loads and material strengths, which allows for a more efficient and economical design compared to WSM. This method provides a realistic assessment of the water tank's behavior by considering non-linearity, material variability, and load uncertainties.  In summary, while WSM focuses on the elastic behavior and simpler calculations for water tank design, LSM offers a more comprehensive and economical approach by addressing the full range of structural performance and safety requirements.

## 1.8.1. Indian standard code of practice for water tanks

The BIS introduced IS 3370: 1967 for the design of water tanks, initially titled Code of Practice for concrete Structures for the Storage of Liquids. This code was updated in 2009, retaining the title Code of Practice for Concrete Structures for the Storage of Liquids. It was revised again in 2021, with the updated title Concrete Structures for Retaining Aqueous Liquids. Following are the key differences between the IS codes so far-

- **IS 3370: 1967**

  The initial version of IS 3370, published in 1967 and titled "Code of Practice for Concrete Structures for the Storage of Liquids," predates the publication of IS 456:1978, "Limit State design of reinforced concrete." As a result, IS 3370 did not initially incorporate the limit state design methodology for liquid retaining structures. The absence of limit state design in the original IS 3370 meant that the code primarily relied on working stress design principles, which were standard at that time. The working stress method, while effective, does not fully leverage the material properties' strengths and potential, often leading to more conservative and sometimes less economical design. In conclusion, the publication of IS 3370:1967, titled "Code of Practice for Concrete Structures for the Storage of Liquids," marked a significant milestone in India's engineering standards. Despite its initial focus on working stress design principles and predating the introduction of limit state design methodologies, this code laid a robust foundation for the design and construction of liquid retaining structures. Its enduring legacy lies in providing essential guidelines that have guided subsequent revisions and updates, facilitating the evolution towards more modern and comprehensive standards. Through its pioneering contributions, IS 3370:1967 remains a cornerstone in ensuring the safety, reliability, and longevity of concrete structures used for storing liquids in India.

- **IS 3370: 2009 and IS 3370 :2021**

  The following comparative study unveils the evolution in specifications between two significant iterations of the Indian standard code IS 3370, namely the 2009 and 2021 versions, focusing on concrete structures for the storage of liquids. This analysis scrutinizes various parameters including concrete grades, temperature considerations, crack width clauses, and reinforcement details, among others. Through a meticulous examination of these revisions, we gain insight into the progressive standards and the enhanced considerations incorporated into the newer iteration of the code. The ensuing table meticulously delineates the alterations and enhancements, shedding light on the advancements made in ensuring the structural integrity and longevity of concrete structures utilized for the containment of aqueous liquids.

**All the conventional tanks are designed as per the latest code IS 3370:2021**.

The Indian Standard IS 3370 has undergone significant revisions over the years to align with modern engineering practices and construction technologies. The initial version, IS 3370:1967, was based on the working stress method, providing fundamental guidelines for the design of liquid-retaining concrete structures. However, with advancements in reinforced concrete design, the Bureau of Indian Standards (BIS) introduced IS 3370:2009, incorporating limit state design principles in line with IS 456:2000. This revision brought significant improvements, including better crack width control measures and updated reinforcement detailing.

Further refinements were made in IS 3370:2021, which introduced additional considerations for durability, temperature effects, and serviceability. The latest version ensures enhanced structural performance and long-term reliability of liquid-retaining structures. These progressive changes in the IS 3370 series reflect the industry's commitment to evolving design methodologies and improving the efficiency of concrete storage structures.

Table 1.5 Comparative study of IS Code 3370 (2009) & IS Code 3370 (2021)

| **Parameter** | **IS Code 3370 (2009)** | **IS Code 3370 (2021)** |
|---|---|---|
| Name & Scope | Concrete structures for storage of liquids | Concrete structures for retaining aqueous liquids |
| W.S.M | Updated from previous code | Eliminated |
| L.S.M | Introduced. But steel stresses were limited to 130 $N/mm^2$ | Updated. Provisions aligned with Limit State Method |
| Liquids for storage | Only water | All Aqueous Liquids |
| Temperature | No specific clause | Maximum allowed: 50°C |
| Terminology | Not available | Added |
| Durability clause | Durability clause added | Clauses updated |
| Type of loads | Brief discussions | Detailed discussion of all type of loadings incl. Dead, Live, Wind, Seismic, Snow, water etc |
| Exposure Conditions | General conditions | Modified conditions |
| Crack width | Clause added | Updated crack width clause with tightness clauses added |
| Tightness Clauses | Not available | Three Tightness classes added (Class I, II & III) |
| Wall thickness | 100 mm (Minimum) | 200 mm (Minimum) |
| Minimum concrete grades | PCC M20 RCC-M30 Prestressed concrete M40 | PCC-M20; RCC-M30; Prestressed Concrete M40 |
| Steel stresses | Limited to 130 $N/mm^2$ for HYSD | Limited to 130 $N/mm^2$ for HYSD in absence of crack width calculations or up to ultimate stresses with maintaining crack width as per tightness clause |
| Cement Content | Changed from 1967 | Maximum content updated |
| Detailed loadings | Not specified | Detailed loadings provided |
| Minimum reinforcement | 0.24% | Minimum reinforcement increased to 0.28%, with additional increase with the length of tanks |

## 1.8.2. Design criteria as per IS 3370:2021

**a) Design criteria-**

Conventional tank designs follow the guidelines outlined in IS 3370:2021, specifically adopting the limit state design. The code mentions two criteria. The first criterion states that, in the absence of crack width calculations, steel stresses in the tank body will be limited to 130 N/mm² to ensure the crack width is within the permissible limit of 0.2 mm (clause 4.4.3.3). The second criterion states that steel stresses can be taken up to the limit state of collapse as guided by IS 456:2000, i.e., up to the characteristic strength of steel, ensuring the maximum allowable crack width is 0.2 mm (clause 4.4.1.1). Crack width calculations are mandatory for the second criterion as per Annexures A and B. The tanks designed according to criteria I refer to as **Conventional type I tanks**, while those designed according to criteria II are known as **Conventional type II tanks**.

**a). Tightness classes**

IS 3370:2021 specifies three water tightness classes: Tightness Class I, II, and III. Class III applies to prestressed concrete tanks, Class II involves special water bars in the RCC tank body with a 0.2 mm crack width limit, or alternatively, a stricter 0.1 mm limit without water bars. Incorporating water bars incurs additional costs, and achieving a 0.1 mm crack width limit also increases costs due to augmented concrete Sections and substantial steel requirements. This study adopts the 0.2 mm crack width limit for Tightness Class I, as per clause 4.4.3.3.

**b) Minimum dimension & exposure criteria**

As per IS 3370:2021 the minimum dimension of the cylindrical wall is given as 200 mm. The minimum cover to the reinforcement is kept as severe or very severe conditions of IS 456:2000. All water-facing elements, including the roof or top dome, must be provided with a minimum cover of 50 mm under very severe conditions. Therefore, the minimum size of the top/ bottom dome comes out to be around 120 mm.

**c) The direct tensile strength**

The direct tensile strength of the immature concrete is given in Table 7 of IS 3370 which is given as below Table. Crack widths due to the temperature and moisture effects shall be calculated as given in Annex A for immature concrete and Annex B for mature concrete of IS 3370. Calculation steps are mentioned in the methodology Section of this study.

Table 1.6: Direct tensile strength of immature concrete

| Concrete Grade | M25 | M30 | M35 | M40 | M45 | M50 | M55 |
|---|---|---|---|---|---|---|---|
| $f_{ct}$ (N/mm$^2$) | 1.15 | 1.30 | 1.45 | 1.60 | 1.70 | 1.80 | 1.90 |

**d) Crack width calculations**

Strain is obtained from the calculation of RCC tank body design. IS 456:2000 mandates the calculation of the crack width at the regular intervals and it should be well within permissible limits of 0.2 mm for Tightness class 1.

- **Average strain in flexure or tension -** The average strain at the level where cracking is being considered, is assessed by calculating the apparent strain using characteristic loads and normal elastic theory.

$$\varepsilon_m = \varepsilon_1 - \varepsilon_2 \tag{1.41}$$

$$\varepsilon_1 = {f_s}/{E_s} \tag{1.42}$$

- **Strain due to stiffening effect of concrete in flexure-** The stiffening effect of the concrete may be assessed by deducting from the apparent strain, a value obtained from the following expressions for deformed bars. For a limiting design surface crack width of 0.2 mm

$$\varepsilon_2 = \frac{b_t(D-x)(a'-x)}{3E_sA_s(d-x)} \tag{1.43}$$

- **Assessment of the crack width in flexure -** Provided that the strain in the tension reinforcement is limited to 0.6 fy /Es and the stress in the concrete is limited to 0.4 fck, the design surface crack width should not exceed the appropriate value given in 0.2 mm and may be calculated as follows-

$$w = \frac{(3a_{cr}\varepsilon_m)}{1 + \frac{2(a_{cr} - C_{min})}{D - x}} \qquad (1.44)$$

- **Assessment of crack widths in direct tension-** Provided that the strain in the reinforcement is limited to 0.5 fy /Es, the design crack width should not exceed 0.2 mm and is calculated from the following expression:

$$w = 3a_{cr}\varepsilon_m \qquad (1.45)$$

- **Stiffening effect of concrete in direct tension-** The stiffening effect of the concrete may be assessed by deducting from the apparent strain a value obtained from the following expressions: For a limiting design surface crack width of 0.2 mm:

$$\varepsilon_2 = \frac{2b_t D}{3E_s A_s} \qquad (1.46)$$

## 1.9. Analysis and design of staging of water tanks

The staging of water tanks consists of Columns and Braces. It is mandatory to do the Seismic and wind force calculations in both empty and fully filled case conditions. Seismic and wind calculations are to be done in accordance with IS 1893: 2016 Part I and Part II along with IITK-GSDMA guidelines and IS 875: Part III, respectively. Response Spectrum Method is used for seismic calculations. The equivalent weight of the structure has been calculated in both full and empty tank conditions, further deflection and response time is calculated, and then Base shear is calculated. Wind force calculation details such as terrain category, wind speed opted is mentioned in Table 2. Usually, annular raft footing is preferred and is designed as per IS foundation IS 11089:1984. design is done as per IS 456:2000 (Reaffirmed 2021).

### 1.9.1. Analysis of column and braces

To analyze and design the columns of a supporting tower for elevated tanks, it is essential to begin by understanding how the load from the tank is transferred to the columns. The load from the tank is transmitted through a circular beam at the top of the columns. This beam receives a uniformly distributed load from the tank along its entire length, leading to bending moments and shear forces. The columns themselves must bear the vertical load of the entire tank, which is equally divided among all the columns.

In addition to this vertical load, the columns are subjected to lateral forces due to wind or seismic activities. These lateral forces induce additional bending moments, shear forces, and axial forces in the columns. The magnitude of these forces depends on the conditions of fixity at the top and bottom ends of the columns. When columns are rigidly connected to the tank base and foundations, they develop points of inflexion at mid-heights, creating a structural system that can be analyzed similarly to a vertical cantilever beam. To ensure stability and manage lateral forces effectively, **intermediate bracing between columns is essential**. These braces constrain the columns, keeping their axes nearly vertical and distributing the lateral loads. The internal reactions at the columns' inflexion points can be approximated using the principles of vertical cantilever beams, simplifying the calculation of bending moments and shear forces acting on each column. When designing the columns, the Sectional area and spacing are critical factors. The bending moments and stresses in these columns reach their maximum at the points farthest from the bending axis. The total bending moment is distributed among the columns based on their relative positions to this axis, with columns on the windward side experiencing compressive forces and those on the leeward side experiencing tensile forces. The total forces acting on each column include vertical loads from the tank's weight, water, and the structure itself, as well as horizontal forces due to wind or seismic activities. These forces create combined moments and shears that must be accounted for in the design. By analyzing these forces and their effects, the reactions at the column bases and inflexion points can be determined. These reactions inform the design of the columns and their foundations, ensuring that they can withstand the applied loads without excessive deformation or failure. Finally, the foundation of the columns must be designed to handle the combined vertical and lateral forces. Proper anchoring and proportioning of the foundations are crucial to ensure the overall stability and structural integrity of the supporting tower. Bracing is a structural element used to stabilize a structure against lateral forces such as wind and seismic activities. The analysis of bracing involves understanding the forces and moments acting on the bracing members and joints to ensure structural integrity. The notes and figures provided detail the mathematical and conceptual framework for analyzing braces in a structural system.

- Moment analysis at joints- At the junction of columns and braces, the columns impose a moment on the joint. Moments in the braces are influenced by the columns they support and the wind direction.
- Hogging moments- Hogging moments $M_1$ and $M_2$ are developed at the joints due to the imposed moment $M_b$ and must be balanced by the braces. The moments are calculated using trigonometric functions based on the $\theta$ between the brace and the direction of the wind.
- Moment equations- The moments at the braces are given by:

$$M_1 = \frac{(Q_1h_1 + Q_2h_2)(\cos\theta\ \sin(\theta + \pi/n\ )}{n\ \sin\left(\frac{2\pi}{n}\right)} \tag{1.47}$$

$$M_2 = \frac{(Q_1h_1 + Q_2h_2)(\cos^2\theta\ \sin(\theta - \pi/n\ )}{n\ \sin\left(\frac{2\pi}{n}\right)} \tag{1 .48}$$

Max shear force in braces- $Q_1$ and $Q_2$ are shear forces and $h_1$ and $h_2$ are heights of panels above and below the brace.

$$SF_{max} = \frac{(Q_1h_1 + Q_2h_2)(\cos^2\theta\ \sin(\pi/n\ ))}{ln\ \sin\left(\frac{2\pi}{n}\right)} \tag{1 .49}$$

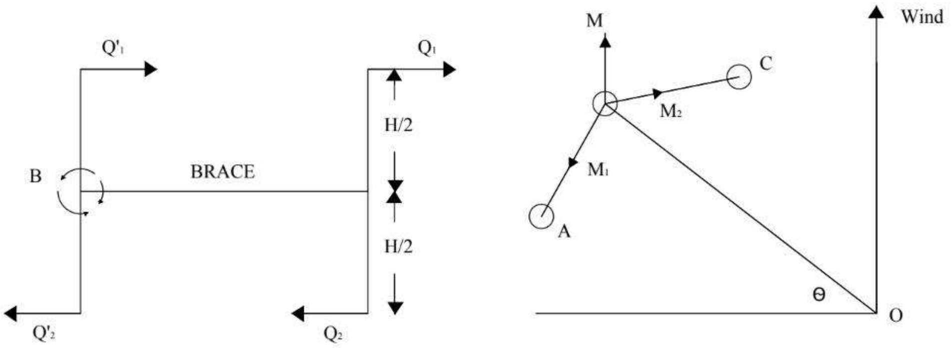



Fig. 1.8: Forces on Braces and Equilibrium of forces at joint B

The analysis of bracing involves calculating the moments and shear forces at the joints where braces meet columns. The moments induced by lateral forces like wind are balanced by the braces, which are designed to handle specific loads and angles. Trigonometric functions are used to determine the distribution of these forces and moments in the braces. Understanding these principles ensures that the structural system remains stable and performs effectively under various loading conditions.

## 1.9.2. Wind analysis

Wind, defined as air in motion relative to the Earth's surface, is primarily caused by the planet's rotation and differences in terrestrial radiation, leading to atmospheric convection. Although wind typically moves horizontally, it includes small vertical atmospheric motion components. Strong winds exceeding 80 km/h often accompany cyclonic storms, thunderstorms, dust storms, or vigorous monsoons, with cyclonic storms influencing regions up to 60-120 km inland after crossing coasts. In Northeast India, "Kal Baisaki" or Norwesters frequently occur during the summer months.

Structures are susceptible to wind effects, with highly variable wind speeds and gusts lasting only a few seconds. While gusts affect air pressure, they typically do not significantly impact the main structure due to inertia. However, high slenderness ratio structures are more sensitive to gusts. water tanks stability against wind depends on factors such as geographic location, surrounding obstructions, and structure characteristics. Wind effects involve combined external and internal pressures acting normal to the surface, necessitating stability calculations that consider combined and separate effects of imposed and wind loads. In terms of human comfort, building designs should account for wind effects on occupants' comfort levels. Wind speed increases with height, reaching its peak at the gradient height, and consists of both average values and fluctuating components known as gusts. In India, the basic wind speed map represents peak gust velocities averaged over 3 seconds at 10 meters above ground in open terrain, based on a 50-year return period. The design wind speed (Vz) is derived from the basic wind speed ($V_b$) and factors such as the risk coefficient ($\boldsymbol{k_1}$), terrain roughness and height ($\boldsymbol{k_2}$), topography ($\boldsymbol{k_3}$), and importance factor for cyclonic regions ($\boldsymbol{k_4}$).
These factors are incorporated into the formula:

$$\boldsymbol{V_z = V_b \times k_1 \times k_2 \times k_3 \times k_4} \tag{1.50}$$

The risk coefficient ($\boldsymbol{k_1}$) is determined based on a 50-year mean return period. Table 1 provides factors for different structure classes and wind zones. The terrain and height factor ($\boldsymbol{k_2}$) categorize terrain based on obstructions influencing ground surface roughness and are given in Table below. The categories include exposed open terrain, open terrain with low vegetation/buildings, terrain with numerous closely spaced buildings/structures up to 10m in height, and terrain with large, high closely spaced obstructions. The topography factor ($\boldsymbol{k_3}$) is significant for slopes greater than 3°, with values ranging from 1.0 to 1.36. The importance factor for cyclonic regions ($k_4$) accounts for cyclonic storms, especially on India's east coast and Gujarat. The values are as follows: emergency services structures (1.30), industrial structures (1.15), and other structures (1.00).

The design wind pressure ($P_d$) is determined using the formula-

$$\mathbf{P_z = 0.6 \times V_z^2} \tag{1.51}$$

$$\boldsymbol{P_d = K_d \times K_a \times K_c \times P_z} \tag{1.52}$$

where $P_z$ represents the wind pressure at height z, and $V_z$ is the design wind speed at that height. $K_d$ denotes the wind directionality factor, $K_a$ signifies the area averaging factor, and $K_c$ represents the combination factor. It's essential to ensure that the minimum design wind pressure is not less than 70% of the wind pressure at the given height $P_z$. For directionality and averaging factors, $K_d$ holds a value of 0.90 for buildings/structures and 1.0 for circular forms and cyclone-affected regions. Meanwhile, $K_a$ varies based on the tributary area, as detailed in Table 4 of IS 875:2015.

Table 1.7: Values of $k_2$

| Height (m) | Category I | Category II | Category III | Category IV |
|---|---|---|---|---|
| 10 | 1.05 | 1.00 | 0.91 | 0.8 |
| 15 | 1.09 | 1.05 | 0.97 | 0.8 |
| 20 | 1.12 | 1.07 | 1.01 | 0.8 |
| 30 | 1.15 | 1.12 | 1.06 | 0.97 |
| 50 | 1.20 | 1.17 | 1.12 | 1.00 |

Wind analysis is a critical aspect of structural design, ensuring stability and safety against varying wind pressures. The evaluation of wind loads involves multiple factors, including basic wind speed, terrain conditions, topography, and structural importance, all of which influence the design wind speed and pressure. By incorporating these parameters, engineers can accurately assess wind effects and develop resilient structures, particularly for elevated water tanks and high-rise buildings. Adhering to IS 875:2015 guidelines ensures that wind-induced forces are effectively accounted for, minimizing risks associated with extreme weather events.

## 1.9.3. Seismic analysis

Water tanks are crucial infrastructure elements that must be designed to withstand seismic forces to maintain functionality during and after an earthquake. The Indian Standard IS 1893 Part 2 (2014) provides comprehensive guidelines for the seismic analysis and design of liquid retaining structures, including water tanks. This Section delves into the specific methodologies, formulas, and considerations for ensuring the seismic resilience of water tank. Seismic Zones and Parameters-

- **Zone factor (Z):** India's seismic zoning divides the country into four seismic zones, each with a corresponding

  Zone II: Z = 0.10

  Zone III: Z = 0.16

  Zone IV: Z = 0.24

  Zone V: Z = 0.36

- **Importance factor (I):** Reflects the tank's significance, with typical values ranging from 1.0 to 1.5. 1.5 value is for critical and lifeline structures such as water tanks.
- **The response reduction factor (R)** takes into consideration the ductility and overstrength of a structure. Its value depends on factors such as the type and construction of the tank. For elevated tanks constructed with RC frame special moment resisting frames conforming to IS 13920: 2016, the Response reduction factor (R) is set at 4.
- **Natural period calculation**: The natural period (T) of the tank depends on its geometry and construction. For elevated tanks, it is typically calculated using empirical formula-

$$\boldsymbol{T = 2\pi\sqrt{\frac{m}{k}}} \tag{1.53}$$

  Where m = Mass of the tank (including liquid); k = Stiffness of the supporting structure;

- **Spectral acceleration coefficient ($S_a$/g)-** The spectral acceleration coefficient is derived from the design response spectrum, which varies with the natural period (T) of the tank is calculated from Fig 2. (Fig 2 b of IS1893:2016).

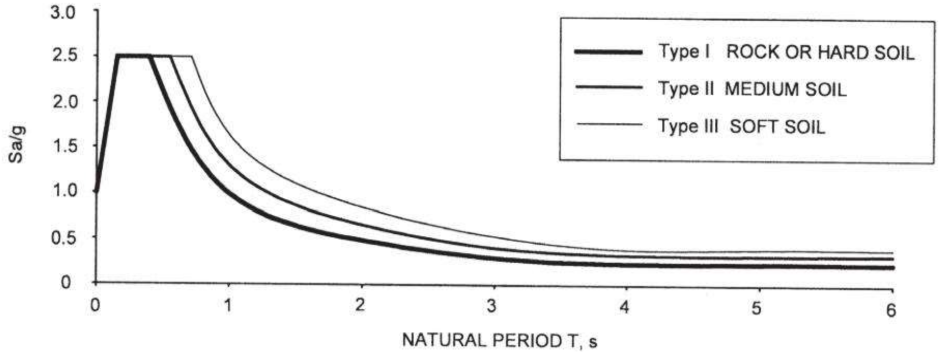



Fig. 1.9: Spectral acceleration coefficient ($S_a$/g) corresponding to 5% damping.

- **Design horizontal earthquake acceleration coefficient $A_h$** refers to a seismic design parameter used in structural engineering to quantify the intensity of horizontal ground acceleration that a structure may experience during an earthquake event.

$$A_H = \frac{Z \times 0.5 \times \frac{S_a}{g}}{[R/I]} \tag{1.54}$$

- **Base shear calculation $V_B$**: The seismic base shear is a fundamental measure in seismic design, representing the total lateral force exerted by an earthquake on the tank. It is calculated as:

$$V_B = A_H \times W \tag{1.55}$$

- **Analysis methods-** In accordance with IS 1893 Part I, there are primarily two approaches to structural design: the Equivalent Static Method and the Dynamic analysis Method. Within the Dynamic analysis Method, there are two sub-methods: the Time History Method and the Response Spectra Method. In this study response spectrum method is used.
- **The response spectrum**, as defined in IS 1893 (Part 1), illustrates the peak response of idealized single-degree-of-freedom systems with specific periods and damping ratios subjected to earthquake ground motion. It charts the maximum response against the undamped natural period across different damping values. This graph enables the representation of maximum absolute

acceleration, maximum relative velocity, or maximum relative displacement. In the context of earthquake-resistant design of liquid retaining tanks as per IS 1893 Part 2, both single mass and two mass idealizations are employed to simplify the complex dynamic behavior of the tank-liquid system into more manageable models. These models help in evaluating the seismic response of the tanks using response spectra.

- **Single mass idealization**: This method treats the entire mass of the tank and the liquid as a single lumped mass. It simplifies the analysis by considering the tank structure and the liquid as a single entity that responds uniformly to seismic excitation
- **Two mass idealization**: This method divides the mass of the tank-liquid system into two separate masses. One mass represents the impulsive component (which moves with the tank structure), and the other represents the convective component (which models the sloshing effect of the liquid). This approach provides a more accurate representation of the dynamic behavior of the tank-liquid system during an earthquake.

**IS 1893 :**2014 Part II says that for elevated water single mass idealization is done away with and the two mass idealization is used for analysis. However clause 5.2 says that tank upto capacity 1000 kL single mass idealization can be used.

## 1.9.4. Design of staging

**a) Design constraints as per clause 8.1 of IS 1893 Part II-**

- Minimum size of column should be 400 mm (diameter and/or side of rectangular column) except for tanks having 200 $m^3$ or less capacity, columns of 300 mm size may be used.
- Clear height of column between braces should not be more than ten times the size of the column.
- Reinforcement detailing including overlaps in longitudinal bars should follow as shown in IS 13920:2016.

- During construction and casting of columns, some eccentricity in the verticality of the column may develop. Eccentricity up to 20 mm may be allowed in the column between two brace levels. Additional moment due to this eccentricity should be considered in the analysis.
- Minimum width of unflanged brace shall not be less than 1/30th of its clear length between junctions.
- In Zones IV and V, use of diagonal bracings in vertical plane shall be encouraged. Information on detailing of RC and steel diagonal bracings is given in IS 11682.

**b) Determine structural requirements computation of vertical loads -** Identify the number of columns needed, Specify the dimensions and total height of the columns and determine the number of bracings above ground level & dimensions.

**c) Compute vertical loads** Assess the vertical load from the structure above, Calculate the self-weight of columns, Include loads from bracings and additional elements such as stairs, and Sum the total load on each column.

**d) Structural forces assessment and evaluation –**

- **Wind forces calculations-** To assess wind forces, utilize relevant standards (e.g., IS 875) to determine basic wind speed and modification factors, compute the design wind speed and wind pressure, calculate the effective wind pressure on the structure, distribute the wind pressure across columns and bracings, compute the shear forces acting in various panels of the structure, and sum the shear forces to understand their distribution across different levels.
- **Seismic forces-** To evaluate seismic forces and calculate overturning moments, use the response spectrum method to determine the effective weight and deflection, calculate the seismic coefficient and resultant seismic force in both full and empty load case conditions.
- **Compare seismic forces to wind forces** to determine the critical load case, compute the overturning moments acting on the staging, determine the

maximum thrust on leeward columns due to bending, and sum the total load on leeward columns considering additional factors.

- **Hydrostatic and hydrodynamic pressures**, calculate pressures due to the structure's inertia and hydrodynamic effects and compare these pressures to allowable limits to ensure structural safety.

## 1.9.5. Design columns and bracings

Steps involved in the design of column and bracings-

- Calculate maximum bending moments and shear forces for the columns emerging from maximum lateral forces.
- Load combinations are applied as IS 456: 2000.
- Design the columns with help of SP charts and using IS 456:2000.
- Calculate moments and shear forces for bracings.
- Designing the braces as singly reinforced beams

These steps ensure a comprehensive and methodical approach to the design of staging structures, focusing on safety, stability, and compliance with structural standards.

## 1.10. Foundation for water tanks

Designing foundations for tanks involves considering various factors such as the type of soil, load-bearing capacity, and groundwater table levels. The primary objective is to ensure stability and minimize settlement. Following are the main types of foundations used for tanks:

- **Solid raft foundation**: A raft foundation, also known as a mat foundation, is used when the soil has low bearing capacity. It consists of a large slab that supports multiple columns. The load is distributed evenly over a large area, reducing the pressure on the soil. The raft foundation is particularly useful for where differential settlement needs to be minimized.
- **Pile foundation:** Pile foundations are employed at sites with low-lying ground and a high-water table. They involve driving piles into the ground to transfer the load to deeper, more stable soil layers.
- **Combined footing:** Combined footings are used when columns are closely spaced, and individual footings would overlap. They can be rectangular or trapezoidal in shape and are designed to distribute the load evenly between two or more columns.
- **Annular circular raft:** An annular circular raft foundation is a variation of the raft foundation where the slab is circular. This type is particularly suited for cylindrical structures like water tanks. The circular shape helps in uniformly distributing the load around the perimeter, reducing the bending moments at the center. This foundation consists of an annular ring that supports the walls of the tank, providing stability and minimizing differential settlement.

Hence Annular raft footing are generally used in water tanks.

**Key considerations in foundation design**

- **Soil bearing capacity**: The foundation must be designed according to the soil's ability to bear the load without excessive settlement.
- **Groundwater table**: High groundwater levels can affect the stability of the foundation. Proper drainage and waterproofing measures should be implemented.

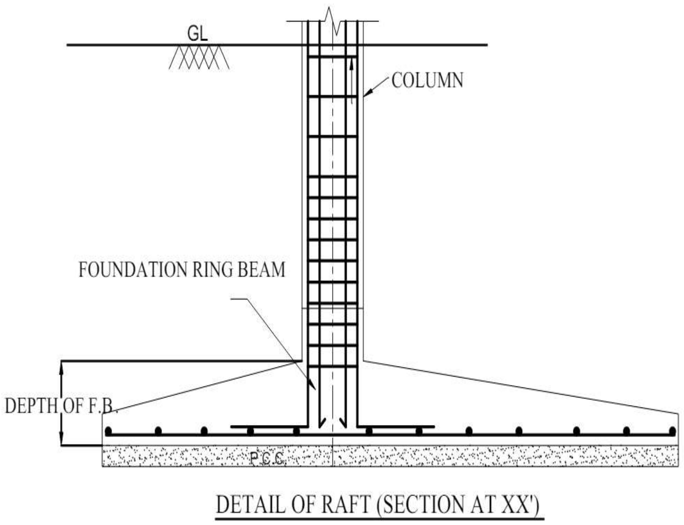
- **Load distribution:** The foundation should distribute the load evenly to prevent differential settlement, which can cause structural issues.
- **Material selection:** The materials used for the foundation must be durable and capable of withstanding environmental conditions.
- **Junction of columns and beams:** The junction of columns and beams is critical in managing loads and ensuring structural integrity.

Proper foundation design ensures the stability, durability, and long-term performance of water tanks by addressing soil conditions, load distribution, and structural integrity.

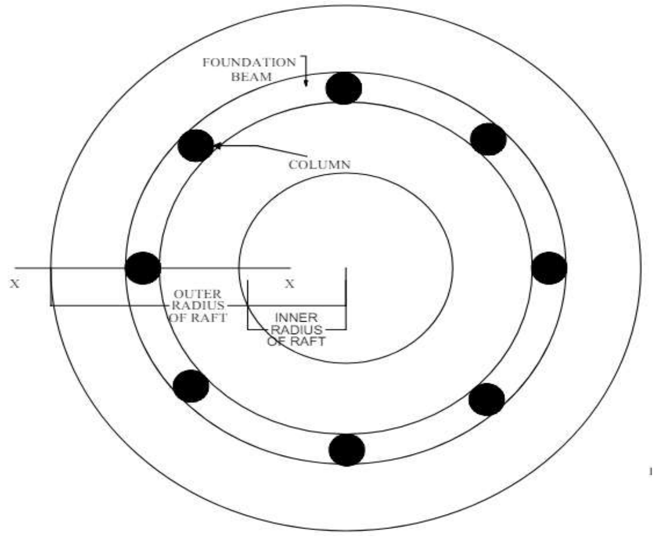
### 1.10.1. Analysis and design of foundation

The foundation design, adhering to IS 456:2000 (reaffirmed 2021), is crucial, with a particular focus on annular raft foundations whose specifications are guided by IS 11089:1984. Soil properties impact the design, especially in context of seismic and wind forces. Load combinations are given in standards considering dead loads, live loads, wind loads and seismic loads and as per the critical loading combination, Raft foundation is designed.

Allowable soil pressure affects the Raft foundation design. Parameters like upward and downward pressures, when the tank is full or empty, overturning moments due to critical lateral forces, maximum pressure on soil, minimum downward pressure, maximum upthrust at the outer edge, bending moment at the inner and outer face of the beam, are carefully assessed to calculate raft dimensions and are also important in analyzing the structural behavior of the tank. In order to distribute the column load to the raft uniformly, column are connected by a circular beam at its base. The annular area of the raft depends upon the bearing capacity of soil, which can be increased by 33.33 % while considering the wind loads along with the superimposed loads. If the additional soil pressure due to wind load is less than 33.33% of the uniform soil pressure due to superimposed load, the raft slab is designed only for pressure due to superimposed load. Also when the tank is empty and the wind is blowing the pressure at the windward edge of the raft should be in the downward direction.




(a)




**(b)**

Fig. 1.10: (a) Raft foundation; (b) Sectional elevation.

Design of foundation is divided into two main parts-

- Design of foundation beam
- Design of annular raft

## 1.10.2. Design of foundation beam

Design of foundation beam involves the following steps**-** In order to distribute the column load to the raft uniformly, column are connected by a circular beam at its base. Following steps are used to design the foundation beam.

- **Calculate the dimensions**: Establish the width, depth, and effective depth of the beam based on structural requirements
- **Calculate loads**: Identify the direct load applied to the beam from the structure above and any bending moments at supports
- **Moment capacity**: Compute the ultimate moment capacity (Mu) of the beam. This involves using the bending moment formula and considering the reinforcement steel's strength
- **Reinforcement design**: Use standard design tables (e.g., from S.P. 16) to determine the percentage of steel reinforcement required (pt). Calculate the area of steel reinforcement needed.
- **Shear and torsion:** Analyze the shear forces and torsional moments acting on the beam. Calculate the ultimate and design shear stresses to ensure they are within safe limits
- **Stirrups and reinforcement:** design shear reinforcement, typically stirrups, to handle shear forces. Determine the number and spacing of stirrups required.
- **Placement of steel bars:** Specify the number and size of steel bars to be placed at the top and bottom of the beam. Curtailment of bars may be done to optimize the reinforcement.
- **Compliance with standards:** Ensure the design follows relevant codes and standards to guarantee structural safety and durability.

The design of a foundation beam is crucial for ensuring uniform load distribution and structural stability, requiring careful consideration of dimensions, reinforcement, shear resistance, and compliance with standard codes**.**

### 1.10.3. Design of annular raft

The following steps are used to design the annular raft foundation –

- **Load calculation and soil bearing capacity**: The design process begins with calculating the total load from the columns and any additional loads from the foundation. This total load is then assessed in conjunction with the net safe bearing capacity of the soil, as provided in the soil report.
- **Determine area and dimensions of raft**: Based on the total load and the soil bearing capacity, the required area of the raft is calculated. The annular raft must have sufficient area to distribute the load uniformly. The outer and inner radii of the annular raft are determined to provide the necessary area while fitting within the site constraints and ensuring structural stability**.**
- **Calculate upward pressure and overturning moment:** The upward pressure exerted on the raft is calculated for both the full and empty conditions of the tank. Additionally, the raft design must account for overturning moments caused by critical lateral forces. Ensuring the raft can resist these moments is essential to maintain stability and prevent structural failure
- **Soil pressure analysis:** The maximum pressure on the soil due to lateral forces is calculated to ensure it remains within safe limits. This involves analyzing the distribution of forces and ensuring the design does not exceed the bearing capacity of the soil, thereby preventing any potential soil failure or excessive settlement.
- **Moment capacity and reinforcement design:** The effective depth and ultimate moment capacity of the raft are computed. Using standard design tables, such as those in S.P. 16, the required reinforcement is determined. The design specifies the placement and spacing of steel bars at the top and bottom of the raft, as well as the shear reinforcement. Curtailment of bars is considered to optimize the reinforcement layout while maintaining structural integrity.

- **Compliance and detailing:** The final step ensures that the entire design complies with relevant codes and standards, guaranteeing structural safety and durability. Detailed drawings and specifications for the placement and spacing of all reinforcement are provided to ensure accurate implementation during construction. This comprehensive detailing is essential for the successful execution of the design and the long-term performance of the structure.

By following these steps, the design process ensures that the annular raft is capable of supporting the applied loads and stresses, maintaining structural integrity, and adhering to engineering standards

## 1.11. Major concerns regarding conventional tanks

The stringent criteria outlined in IS 3370:2021 for conventional tank designs result in the underutilization of materials due to conservative steel stress limits and crack width restrictions. Additionally, the minimum dimensions and cover requirements along with the crack width criteria contribute to bulky tank designs, further exacerbating material underutilization. These concerns highlight the economic and practical challenges faced in achieving cost-effective and structurally sound CWT. Furthermore, leakage is a persistent issue in water tanks.

### 1.11.1. Failure analysis of conventional water tanks

Leakage in the water tanks can occur through

- Joints of tank
- RCC tank body

The leading factor contributing to leakage problems is concrete cracking. Leakage failures in CWT stem from multiple interrelated factors that compromise their durability, functionality, and economic efficiency. This attribute is pivotal, not solely for its direct impact on preventing leakage, but also because it significantly influences various other factors critical for durability. These encompass resistance to leaching, chemical attack, erosion, abrasion, frost damage, and the safeguarding against corrosion of embedded steel. Consequently, the standard IS 3370 incorporates provisions in design and construction to address this essential aspect. Following are the main reasons of leakages-

- **Crack formation and leakage:** A primary issue is crack formation and leakage, often due to restrained shrinkage, thermal stresses from the heat of hydration, and the rapid hydration of modern concrete mixes. These cracks allow water to seep out, leading to the corrosion of reinforcement and a subsequent weakening of the tank's structural integrity over time. Additionally, leakage can occur through joints or the tank body itself, further exacerbating the problem.
- **Aging and deterioration** significantly contribute to leakage failures. As tanks age, they become more susceptible to seepage, cracks, and reinforcement

corrosion. Regular maintenance is crucial to mitigate these issues, but it is often overlooked, resulting in accelerated deterioration.

- **Environmental factors** also exacerbate leakage problems. tanks in harsh environments, such as arid regions, endure extreme temperatures and low humidity, which cause cracking due to thermal expansion, contraction, and shrinkage. These conditions necessitate specific design and repair strategies to ensure the tanks' long-term durability.
- **The lack of systematic performance monitoring and maintenance** further worsens leakage failures. Regular inspections and maintenance are essential for identifying and addressing issues like cracks and leaks before they lead to severe structural problems.

Leakage further leads to chemical attacks, erosion, abrasion, frost damage, corrosion of embedded steel.

The latest version imposes minimum dimension criteria, steel stress criteria, exposure conditions, and crack width criteria to reduce cracks and prevent leakage. Despite these stringent measures, leakage remains a persistent issue in water tanks. Failure to tackle these issues often results in high maintenance costs, the need for retrofitting, and, in some cases, post-construction abandonment.

### 1.11.2. Post-construction leakage: A precursor to escalated maintenance costs and abandonment

Failure to effectively address these issues frequently leads to a cascade of challenges, including escalated maintenance expenditures, the imperative for retrofitting measures, and, in more severe instances, the abandonment of the structure post-construction. This failure not only imposes financial burdens but also compromises the safety, functionality, and longevity of the water tank, potentially jeopardizing the reliability of the entire water supply system. Therefore, proactively addressing these concerns is not only prudent but essential for ensuring the sustained performance and resilience of CWT. It is very important to address this issue and take remedial measures to prevent the post-construction leakages.

## 1.12. Bridging the Gap: Hybrid water tanks address conventional tank challenges

For water storage purposes RCC water tanks act as the most vital infrastructural component. One of the significant hurdle is the high costs arising from substantial material consumption. According to the latest Indian standards, water tank designs adhere primarily to two criteria based on steel stress limits: either 130 $N/mm^2$ or compliance with the characteristic strength of steel, with limiting crack width. Despite the cost-effectiveness of the latter criterion, both often result in bulky designs characterized by significant material underutilization because of minimum dimension criteria.

However, the challenges go beyond mere material consumption. These water tanks frequently encounter leakage issues, which pose substantial threats to their functionality and longevity. Leakage can occur through joints within the tank structure or even within the RCC tank body itself, often stemming from concrete cracking. Despite the stringent criteria as discussed earlier, leakage is a persistent issue in water tanks. The underlying cause of these failures is multifaceted, influenced by factors such as restrained shrinkage, thermal stresses from the heat of hydration, and rapid hydration of modern concrete mixes. These cracks not only allow water to seep out but also accelerate the corrosion of embedded steel, weakening the tank's structural integrity over time.

Furthermore, the aging process exacerbates these challenges. As water tanks age, they become increasingly susceptible to seepage, cracks, and corrosion of reinforcement. While regular maintenance is crucial for mitigating these issues, it is often overlooked, leading to accelerated deterioration. Environmental factors also play a significant role, particularly in harsh climates where extreme temperatures and low humidity can cause thermal expansion, contraction, and shrinkage, further contributing to cracking and leakage.

The lack of systematic performance monitoring and maintenance exacerbates these challenges, as issues like cracks and leaks go unidentified and unaddressed, ultimately resulting in severe structural problems and high maintenance costs. Failure to address these issues in a timely manner can lead to the need for retrofitting or even post-construction abandonment, underscoring the urgent need for innovative solutions to enhance the economic and structural efficiency of conventional water tank designs.

In response to the challenges posed by conventional tanks, this study introduces an innovative approach termed "**Hybrid water tanks**". This methodology incorporates ferrocement lining into elevated RCC water tanks, representing an unexplored path in tank construction. These tanks have RCC tank body with integrated Ferrocement lining where Ferrocement lining will impart impermeability to the structure and RCC is supposed to bear all the loads. Ferrocement lining emerged as a promising alternative to conventional methods due to its remarkable resistance to tension, compression, bending, molding, and impressive waterproofing capabilities, as suggested by various studies. Moreover, research indicates a synergistic behavior between ferrocement and RCC, highlighting its potential for effective integration.

However, the Ferrocement lining will impose an additional cost to the structure. Hence to reduce the overall cost of the structure this study proposes use of IS 456:2000 (Reaffirmed 2021) which is a generalized code for the RCC design in India and water tanks are primarily an RCC structure. Bureau of Indian Standards has given a separate for the design of water tanks i.e. IS 3370 which was introduced for the water Retaining RCC structures as they are susceptible to leakages and crack formations and once crack/ leakage occurs a water retaining structure is no more a water retaining one. Mainly the Stringent material stresses, exposure and most importantly minimum dimension criteria separate IS 456 and IS 3370:2021. Here in HWT, Ferrocement lining is there to take care of leakage and Crack issues. It is an additional lining to the structure which will act as an impermeable membrane between water and RCC.

Hence IS 456: 2000 is used for the RCC structure design and American concrete institute standards for Ferrocement lining design for Strain compatibility criteria. It is an interesting fact that minimum dimension criteria for IS 456: 2000 (Reaffirmed 2021) is like that of IS 3370: 2009.

This integration of RCC and Ferrocement lining in HWT represents an uncharted avenue holding significant promise for substantial reductions in overall structural costs, all while adhering to crucial allowable stress standards in hybrid design.

## 1.13. Hybrid water tanks

In search of an optimal solution to look after both material savings and leak proofing, this study presents a Novel hybrid approach for designing the water tanks to be called **Hybrid tanks.** HWT consists of RCC tank body with integrated ferrocement lining.

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. While exploring lining options such as epoxy, stainless steel, and ferrocement, this study opts for ferrocement, as RCC and ferrocement both belong to the same family of construction materials which will help in minimizing the friction between lining and RCC.

The concept of incorporating an impermeable lining aligns with the recommendations of clause 4.4.3.3 of IS 3370:2021 Part 2, the Indian standard code of Practice for concrete structures for liquid storage. However, a key distinction lies in their suggestion of using the lining as a remedial measure for tank body leakage. In contrast, this hybrid design approach integrates the ferrocement lining as an essential component of the water tank design. In the case of HWT, IS 456 is employed, serving as a general code for RCC in India. This choice helps mitigate the stringent limits of IS 3370, although IS 456 also has its own set of limits, they are comparatively lesser. Additionally, to ensure waterproofing, lining is used. RCC is responsible for bearing structural loads while maintaining a crack width of 0.2 mm, as specified in both IS 3370 and IS 456. Simultaneously, the lining contributes to impermeability, achieving a crack width of less than 0.05 mm as per ACI standards.

The design of a HWT, combining ferrocement lining with RCC, represents a groundbreaking initiative. This pioneering work marks the first of its kind, where RCC water tanks are designed integrating ferrocement lining as an essential component which acts as a membrane or a barrier between RCC and water turning a water retaining structure as a non-water retaining one. RCC is supposed to bear all the Structural Loads coming on the structure. The ferrocement lining is to be designed for strain compatibility criteria at the interface of RCC and ferrocement lining using ACI standards.

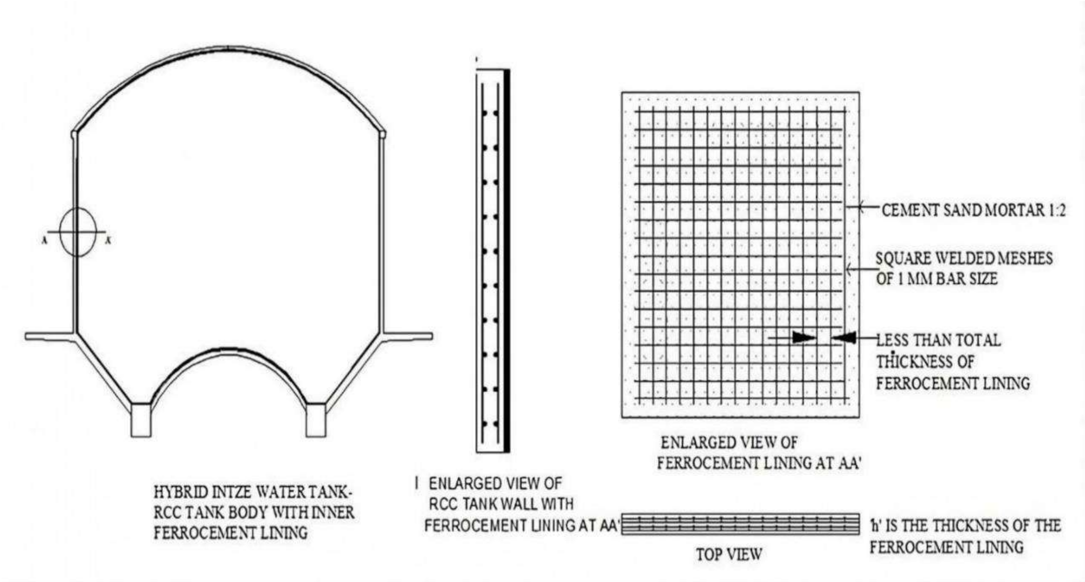



Fig. 1.11: Hybrid Intze type tank.

Reinforcement can be provided in both side of the wall or single side of the wall as per requirements.

## 1.13.1. Major differences between hybrid and conventional tanks

This Table 1.8 summarizes the design standards and provisions used in both hybrid and conventional design approaches for water tanks, highlighting key differences and commonalities.

Table 1.8: Design standard used in hybrid and conventional design approaches.

| Sr. No | Element | Standards & Provisions Used for the design | |
|---|---|---|---|
| | | Hybrid design approach | Conventional design |
| 1. | Tank body | IS 456:2000 (Reaff. 2021) | IS 3370:2021 |
| 2. | Ferrocement lining | ACI standards | - |
| 3. | Crack width | In ferrocement lining the crack width should be less than 0.05 mm | Less than 0.2 mm in the tank body |
| 4. | Analysis and design for tank body | Continuity analysis approach & limit state design method | |
| 5. | Staging & foundation | Same for both Hybrid and Conventional design | |

## 1.14. Ferrocement

Ferrocement, also known as 'fercement,' is essentially the first form of RCC. Ferrocement is about 150 year old technology and is considered as environmentally sound technology. Joseph-Louis Lambot, the inventor of ferrocement laid the foundation for the evolution of what we recognize today as RCC. Ferrocement is a type of thin wall-reinforced concrete commonly constructed of hydraulic cement mortar reinforced with closely spaced layers of continuous and relatively small size wire mesh. The mesh may be made of metallic or other suitable materials. Lambot built two row boats in 1848 and 1849 as shown in Fig. 1.12.

Fig. 1.12: Lambot's First Boat at Museum in France

The main difference between RCC and ferrocement is that RCC uses large reinforcing bars and a concrete binder, while ferrocement utilizes a mesh of fine wire reinforcement with a cement paste or mortar binder**.** Ferrocement is characterized by its impermeability, corrosion resistance, mouldability, and durability, and stands out as a composite material with superior structural integrity. The material's high strength and fatigue resistance contribute to its long service life, while its versatility enables the construction of complex shapes. Its resistance to biological attacks further underscores its suitability for diverse applications, rendering it a dependable and multifaceted construction material in academic contexts. studies demonstrate that ferrocement is impermeable, making it an ideal material for structures such as water-retaining structures. Canal lining is usually done with ferrocement in India.

Thickness of ferrocement is generally smaller than 25 mm and in some cases can be upto 50 mm. The analysis and design of follow ACI standards.

All the Data Related to Ferrocement is taken from ACI Standards, Book: Ferrocement and Laminated Composites by A.E. Naaman.

### 1.14.1. Properties of Ferrocement

- **High strength and fatigue resistance**: Contributes to long service life and durability under repetitive loading conditions.
- **Versatility:** Enables the construction of complex shapes and adapts to various structural requirements and can be molded into various shapes and sizes for custom applications.
- **Impermeability:** Ideal for water retaining structures, preventing leakage and seepage. Ferrocement has very low crack width, making it almost impermeable.
- **Resistance to biological attacks:** Withstands microorganisms, ensuring longevity in diverse applications.
- **Cost-effectiveness:** Reduces overall construction and maintenance costs.
- **Cohesive behavior with RCC:** Enhances structural integrity when combined with RCC.
- **Resistance to various forces:** High resistance to tension, compression, bending, and molding.
- **Durability in harsh environments:** Resists leaching, chemical attacks, erosion, abrasion, and frost damage.
- **Low permeability:** Provides excellent resistance to water infiltration and moisture penetration.
- **Lightweight and thin sections:** Easier to handle and install compared to traditional materials, reducing labor costs and allows for thinner structural Sections, saving on material use.

### 1.14.2. Practical applications of Ferrocement

Ferrocement is a highly adaptable material that finds application in a wide array of practical uses due to its distinct properties such as high strength, flexibility, and impermeability. In the realm of housing, ferrocement is employed to construct robust and cost-effective components, including roofs and walls, contributing to durable and affordable housing solutions. In the maritime sector, it is favored for constructing boat hulls because of its lightweight and waterproof qualities, ensuring durability and longevity in aquatic environments. Moreover, ferrocement is extensively used in the construction of reservoirs and pipelines. Its excellent impermeability makes it ideal for these applications, preventing leaks and ensuring reliable water storage. The material's ability to be molded into various shapes makes it suitable for creating sculptures and art installations, enabling the production of intricate and complex designs. In urban infrastructure, ferrocement is utilized in the construction of pipes, manholes, and drainage systems due to its durability and resistance to chemical attacks. It is also used in agriculture for building silos and grain storage facilities, providing strong and long-lasting storage solutions. Additionally, ferrocement is also used for prefabricated construction elements, which can be easily transported and assembled on-site, enhancing construction efficiency. For repair and retrofitting, ferrocement is an excellent choice. Its strong adhesion properties and flexibility make it ideal for repairing and strengthening existing structures, offering a cost-effective and durable solution.

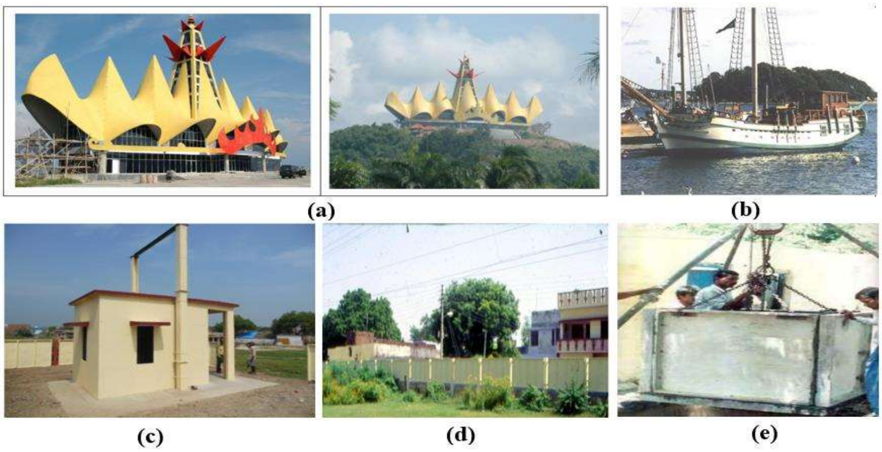



Fig. 1.13: Ferrocement roof of the Siger Landmark, Indonesia; (b) Ferrocement boat LARINDA – replica of 1770's British coastal shoner; (c) Pump House in Sultanpur U.P. (d). Boundry Wall in Prayagraj; (e). Sewage Plant Sultanpur (U.P.)

These various applications underscore ferrocement's versatility and effectiveness in modern construction, making it a reliable and multifunctional construction material.

## 1.14.3. Using ferrocement as lining for RCC tanks

For the first time, ferrocement is being utilized as a lining material for water tanks, integrated into the tank's design and construction from the outset. This innovative use of ferrocement aims to leverage its unique properties to improve the durability, impermeability, and overall performance of water storage systems. Ferrocement lining is to be designed for strain compatibility criteria at the interface of RCC & ferrocement lining. Ferrocement lining will act like Reinforced Plaster. The primary purpose of the lining is to provide impermeability to the structure design has been done as per the text available and mentioned in the references using American concrete institute standards. Following are the key aspects of ferrocement lining-

- Ferrocement lining will be a non-structural member of the water tank. It will act like a reinforced plaster to the RCC water tank lining is not supposed to take any kind of structural loading. All the structural loads will be transferred to the RCC. structures outside lining.
- lining will be designed for the strain compatibility at the interface of RCC and ferrocement lining.
- In general, the thickness of the ferrocement lining provided is 15 mm or 12 mm as per the strain compatibility requirements.
- Reinforcement in the ferrocement lining will be provided in layers, generally 1 mm diameter bars are provided both in longitudinal and traverse directions (mesh) in each layer are to be designed meticulously for the strain at the interface.
- Distance between the reinforcing bars in the ferrocement will not exceed thickness of lining.
- A suitable cover should be provided at the ends of the lining. The minimum cover for the reinforcement is 1.5 mm. A 2 mm cover is provided.
- Crack width of the lining for the water retaining structure should not exceed 0.05 mm. lining will be constructed using 1: 2 cement mortar or above grades.

- Tensile Strength of the wires should not be less than mild steel in any case.
- As per recommendations of ACI 549 minimum value of yield strength of steel from welded square mesh is 450 $N/mm^2$ & modulus of elasticity is 200000 $N/mm^2$.Tensile strength of the bar is taken as 200 $N/mm^2$. Hard bright wire can also be used.
- Volume of reinforcement in the lining is approximately 3-4% of the total volume.
- The lining will be constructed cast in situ and will be connected to the tank body with shear connectors at every 500 mm.
- Shear connectors should be properly inserted in the RCC at the time of casting of the RCC. water tank body.

## 1.14.4. Constituents of ferrocement

As mentioned above ferrocement is composed of Cement mortar and Mesh Reinforcement and are discussed below. This study referenced the mechanical properties of ferrocement using ACI standards, "Ferrocement & Laminated Cementitious Composites" by A.E. Naaman, standards from the Ferrocement Society of India, and "Ferrocrete Technology: A Construction Manual" by Dr. B.N. Divekar.

- **Cement mortar matrix-** The hydraulic cement matrix for ferrocement should be designed according to standard mix design procedures for mortar and concrete. Its components generally include Portland cement, sand (fine aggregates), water and various admixtures as per requirements.

Table 1.9: Cement mortar ratios and compressive strength

| Sr.No. | Cement | Sand | water | Compressive strength |
|---|---|---|---|---|
| 1 | 1 | 2.5 | 0.6 | 39 |
| 2 | 1 | 2 | 0.55 | 52 |
| 3 | 1 | 2 | 0.5 | 58 |
| 4 | 1 | 1.5 | 0.4 | 60 |
| 5 | 1 | 1 | 0.5 | 62 |

The materials should satisfy standard similar to those used for quality reinforced concrete construction. Common ranges proportion by weight of cement are given in table and their corresponding compressive strength as per ACI standards.

- **Mesh reinforcement-** Steel meshes for ferrocement include square welded or woven meshes, the chicken wire mesh of hexagonal shape, and expanded metal lath or sheet similar to those used in plaster and stucco applications. Common types of meshes used are shown in Fig.

  In this study Square welded mesh is used. Mesh minimum values of yield strength for square welded mesh and effective modulus of steel mash and bars recommended for design as per ACI 549 as per ACI 549 are given in Table 1.11.

Table 1.10 Properties of square welded mesh

| Type | Yield strength | Effective Modulus Longitudinal | Effective Modulus Traverse |
|---|---|---|---|
| Square welded mesh | 450 | 200 GPa | 200 GPa |

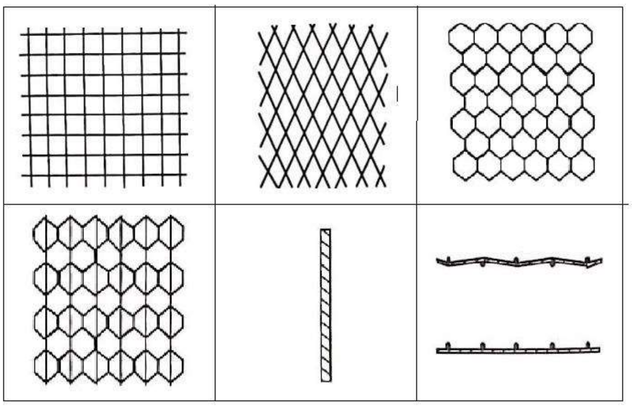


Fig. 1.14: Difference types of mesh (a) Square welded mesh; (b) Expanded metal mesh; (c) Hexagonal mesh; (d) Improved hexagonal mesh; (e) Wire brand or strand (Skeletal reinforcement); (f) Woven and welded mesh section

Table 1.11: Mechanical properties of ferrocement

| Sr.No. | Property | Details/Value |
|---|---|---|
| 1 | Ultimate tensile strength | up to 35 MPa |
| 2 | Modulus of rupture | Up to 70 Mpa |
| 3 | Compressive strength | 80-100% of mortar matrix strength |
| 4 | Ultimate tensile strain | Upto tensile strain of reinforcement |
| 5 | Crack width | Up to 100 times lesser than in reinforced concrete for same composite tensile stress. |

(Source: ACI Standard and ferrocement and Composite Laminate by A.E. Naaman)

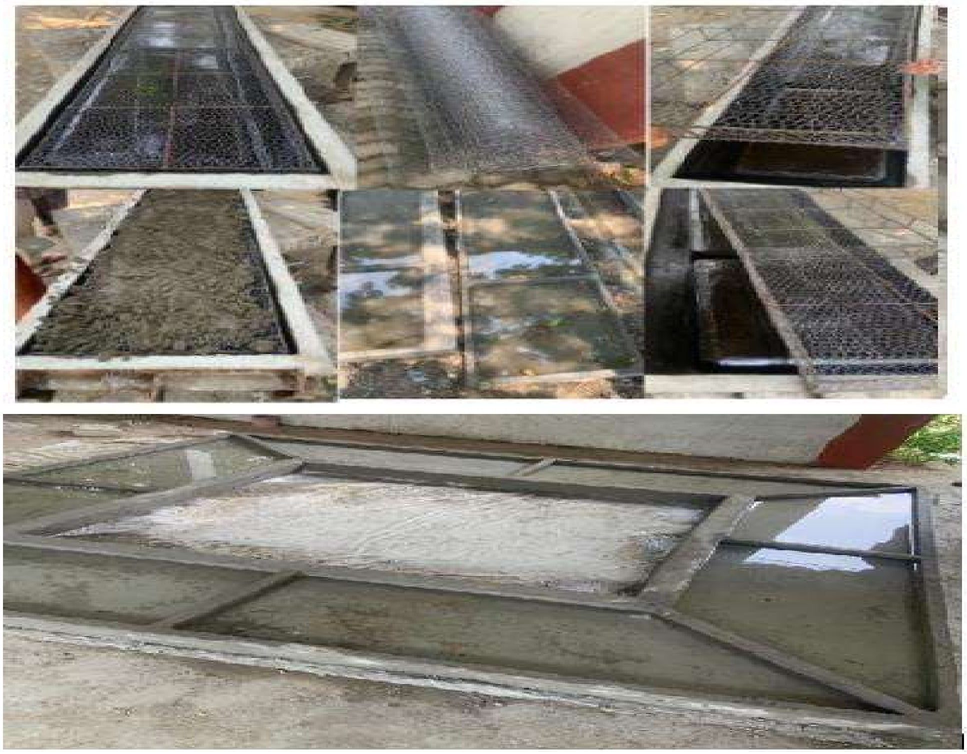


Fig. 1.15: Pictures of Casting of ferrocement at T.M.M Building Centre and ferrocement Factory Tilothu Rohtas Bihar India

Field Rates and Information related Cast in Situ process is obtained from TMM Building Centre and Ferrocement Factory visit Tilothu, Rohtas Bihar as shown in Figure 1.15. Figure explains the Casting process of ferrocement

## 1.15. Aims and objectives

This research introduces an innovative concept of Hybrid Water Tanks, which integrate ferrocement lining with conventional Reinforced Cement Concrete tank structures to overcome the common challenges of cost, bulkiness, and leakage in conventional water tanks. The study aims to develop a comprehensive hybrid design methodology, supported by software tools, and perform a comparative analysis with standard RCC tanks to assess structural and economic benefits. The detailed aims, objectives, and scope of the study are presented in Section 2.7, following the discussion on research gaps.

## 1.16. Layout of the thesis

The present thesis constitutes of seven chapters-

**Chapter 1** presents an overview of the significance and evolution of water tanks, highlighting their historical importance and development into modern elevated storage systems. It explores iconic elevated water tanks around the world and their crucial role in water supply infrastructure. This chapter also classifies water tanks based on location, material, shape, and capacity, providing a comprehensive understanding of their diversity. The components of Intze and circular water tanks are detailed, alongside an explanation of structural members. Indian standards for water tank design, as outlined by the Bureau of Indian Standards, are reviewed, covering IS 3370:1967, IS 3370:2009, and IS 3370:2021. Various loads acting on water tanks and the methods of analysis, including membrane and continuity analysis, are discussed. The chapter addresses CWT, their design criteria, common issues, and failure analysis, emphasizing post-construction leakage concerns. Finally, it introduces HWTs, differentiating them from conventional designs, and explores the properties and applications of ferrocement, especially its use as a lining for RCC tanks. The chapter concludes with the scope and objectives of the study.

**Chapter 2** conducts an extensive literature survey, examining the comprehensive design aspects of RCC tanks and the integration of ferrocement. It begins by reviewing cost optimization studies, analysis and design methodologies, failure investigations, soil-structure interaction (SSI) studies, and seismic assessments in RCC tank design. The chapter then delves into understanding the properties of ferrocement and its versatile applications. It explores how ferrocement enhances RCC structures, providing insights into its integration to improve structural performance. Additionally, the chapter identifies research gaps within the existing literature, laying the groundwork for the study's novel contributions in addressing these gaps and advancing the field of water tank design.

**Chapter 3** of the thesis focuses on the "Material and Methods" employed in the research. It begins with a general overview, followed by the detailed development of software programs for the design and analysis of various types of water tanks. This includes Conventional Intze water tanks, Hybrid Intze tanks, and Conventional and Hybrid Circular water tanks. Chapter provides a detailed concept note on the hybrid design, including the design of RCC elements, ferrocement lining, staging, and foundation. The chapter elaborates on multiple Modules within these programs: Input and dimensioning, analysis of RCC tank bodies, design of tank body (Container) Members, Staging configurations & Lateral analysis, Staging design, foundation design, and Estimation and costing . An additional Module for the design of ferrocement lining in Case of Hybrid Intze and Circular tanks. Finally, the chapter addresses the validation of the developed software programs to ensure their accuracy and reliability.

**Chapter 4** presents a comprehensive comparative study of Hybrid Intze tanks versus Conventional type I and type II Intze tanks, focusing on cost efficiency and structural performance. 200 kL, 600 kL and 1000 kL capacity tanks are specifically chosen for the study. The chapter begins with an introduction and outlines the application and comparison criteria used in the study. It includes detailed cost comparisons, covering the tank body, steel, concrete, and ferrocement lining, as well as analyses of material consumption, deflection, seismic and wind resistance, crack width, and annular raft footing. The study demonstrates that HWT offer significant cost savings and superior structural integrity compared to both conventional designs. The chapter concludes by summarizing the findings and highlighting the overall benefits of Hybrid Intze tanks in terms of cost-effectiveness, material savings, and enhanced performance.

**Chapter 5** presents a comprehensive analysis of Elevated Hybrid Circular tanks versus conventional circular water tanks, focusing on tanks with capacities ranging from 100, 150, 200, 250 and 300 kL. The chapter integrates a parametric study of HWT (100 kL to 300 kL) and compares them with conventional type I and type II tanks. Further Chapter examines cost efficiency, material consumption, deflection, seismic and wind performance, crack width, and annular raft footing designs. The findings highlight the significant cost savings, material efficiency, and superior structural integrity of hybrid designs over conventional RCC structures, emphasizing their overall advantages in terms of cost-effectiveness and performance.

**Chapter 6** presents a comprehensive comparative analysis of the cost-effectiveness and structural integrity of Hybrid versus Conventional RCC water tanks across 16 major urban centers in India. This chapter is divided into several Sections that explore the application and comparison criteria for the study, focusing on both 600 kL Intze tanks and 150 kL Circular tanks. The analysis covers various parameters such as cost comparisons, material utilization, deflection and crack widths, and structural performance under wind and seismic loadings. The goal is to highlight the advantages and potential cost savings of hybrid designs over traditional RCC structures in different urban contexts.

**Chapter 7** provides a comprehensive summary and conclusions of the comparative studies conducted in this thesis. It consolidates the findings from the analysis of Hybrid and Conventional (type I and II) Intze and Circular water tanks. It also includes major findings and recommendations based on the comparative analysis across different types of water tanks and their application in various urban centers in India.

The thesis has Six Annexures, each dealing with specific aspects of the study. **Annexure A** details the design process, material specifications, and construction methodology for the ferrocement lining used in HWTs. **Annexure B** provides a step-by-step manual design procedure for a 600 kL hybrid Intze tank, including detailed calculations and design considerations. **Annexure C** covers the manual design process for a 200 kL hybrid circular tank with similar comprehensive details. **Annexure D** presents the software output for the 600 kL hybrid Intze tank, showcasing the automated design and analysis results. **Annexure E** includes the software output for the 200 kL hybrid circular tank, highlighting the design and analysis facilitated by the developed software program. **Annexure F** includes Detailed Drawings of 600 kL Intze and 200 kL Circular HWT.

In conclusion, this study gives a Novel approach of designing water tanks considering RCC and ferrocement lining. This study endeavors to present a comprehensive methodology, detailed design, equations used, technicalities, and guiding principles for the design of HWT. The study develops user friendly Software program for Hybrid Intze and Hybrid Circular tanks. Subsequently, a comparative evaluation with designed Conventional tanks is also conducted. Furthermore the study systematically compared

Hybrid Intze and Hybrid Circular tanks with Conventional Intze and Circular tanks respectively in 16 different State Capitals/ Major urban centres of India comprising of different Seismic Zones (II, III, IV and V) and different Wind Speeds (39, 44, 47 ad 50 m/s) including 4 Coastal cities also to assess the validity and performance of HWT vs Conventional tanks India wide.

Through a detailed examination of cost-efficiency, structural integrity, and performance under seismic and wind loads, the study highlights the advantages of Hybrid designs in enhancing both economic viability and structural robustness compared to Conventional RCC tanks. The findings underscore the potential of HWTs to meet future water storage (Both urban and rural) demands more effectively, offering valuable insights for engineers, policymakers, and stakeholders involved in infrastructure development. As urban centers continue to expand, integrating HWT designs could play a pivotal role in ensuring sustainable and resilient water supply systems.