



## Investigate the Impact of Response Reduction Factors and Height-To-Depth Ratio on Seismic Performance Metrics in the Elevated Storage Tank

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**Abstract:** Water tanks are critical structure, and the investigation of seismic activity is now receiving significant attention. This study examines the impact of the revised Indian Standard IS 1893 (Part 2): 2014, which was implemented in March 2022, on the seismic performance of elevated water tanks. The IITK-GSDMA Guidelines (IITK-GSDMA 2007) impacted these improvements, especially those dealing with response reduction factors. The modifications are assessed by contrasting the prior code with base shear, hydrodynamic pressure, base moment, and sloshing wave height calculations. This assessment examines ten models with 50 cubic-meter elevated water tanks. These models have different height-to-diameter ratio (h/D) ratios. The response reduction factor affects deflection, hydrodynamic pressure, moment, and base shear. These parameters usually decrease with higher response reduction factor values. As the h/D ratio increases beyond 0.5, deformation and seismic forces decrease.

**Keywords:** elevated water tank, response reduction factor, hydrodynamic pressure, base shear, moment

### Article Highlights

- Higher RRF values reduce base shear, moment, and pressure, enhancing seismic performance.
- Higher h/D ratios decrease seismic forces and deflection in elevated tanks.
- Recent standards increase base shear and moment values, improving tank resilience.
- Optimizing RRF and h/D ratios crucial for safer water tank designs.

### 1. Introduction

Natural disasters like earthquakes, droughts, floods, and cyclones are incredibly common in India. The most hazardous of them are earthquakes, which can result in significant property and human loss. Poorly designed buildings cause more deaths during earthquakes than actual natural disasters. The elevated water tank is one important structure that needs to be carefully considered in earthquake-prone areas. These tanks' large volume of water and thin support structures make them especially vulnerable to seismic damage. Therefore, in-depth seismic assessments are necessary to determine whether they can endure the forces of an earthquake. This requires assessing the overall stability, ground motion response, and structural integrity.

India's complex water distribution system relies on elevated water storage reservoirs (ESRs). Elevated water tanks consist of a storage container, a staging structure, and a foundation that transfers loads to the ground. Each component needs separate considerations and analyses to meet functional requirements efficiently. An elevated water tank has a foundation, staging, and container. The staging elevates the container, the foundation supports it, and the container holds water. Analyzing and designing each element is necessary to meet functional requirements. The container must withstand wind, earthquakes, and water weight. The staging must be strong and stable to support the container's weight and structure. A foundation with even soil load distribution prevents settlement and instability. Seismic safety is important because elevated water tanks are lifelines. National Institute of Disaster Management (National Institute of Disaster Management, n.d.) published that India's increasing population and unscientific constructions pose a high risk to earthquakes, with over 59% of its land area under moderate to severe seismic hazard, resulting in over 20,000 deaths in the last 15 years.

Following catastrophic seismic events, numerous storage tanks are deemed critical infrastructure for sustaining human life and must remain functional. Earthquakes frequently result in fires, necessitating a substantial



amount of water to extinguish them. The damage assessments of the 1964 Alaska earthquake (Rinne 1967) indicate that liquid storage tanks exhibit intricate dynamics when subjected to seismic activity. The seismic behavior of elevated water tanks with reinforced concrete shaft-type supports during the 2001 Bhuj (Rai 2002) and 1997 Jabalpur (Rai et al. 1997) earthquakes in India were poorly understood. The Bhuj earthquake (Rai 2002) resulted in the total collapse of three elevated water tanks and inflicted extensive damage on numerous others. The Jabalpur earthquake had a comparable impact on the city. Damage estimates from 1964 (National Institute of Disaster Management, n.d.) show that liquid storage tanks have complex behavior during earthquakes. Since then, a significant amount of research has been conducted on the seismic behavior of ground-supported storage tanks. Elevated water tank designs are vulnerable to earthquakes, with frame staging causing damage and collapses. Soroushnia S. (Soroushnia et al. 2011) studies losses in reservoirs during past earthquakes and identifies better seismic behavior for reinforced concrete tanks with frame staging.

D. C. Rai (Rai 2003) conducted a study on the performance of elevated tanks during the devastating 7.7-magnitude Bhuj earthquake in January 2001. He discovered that tanks with capacities ranging from 80 to one thousand kiloliters were significantly affected and that many staging structures exceeded the seismic force requirements specified in IS 1893:1984. D.C. Rai (Rai 2002) highlighted that the IS code lacks provisions for incorporating ductile detailing in thin-shell tanks regarding elevated water tanks.

Standard IS 1893:1984 (Bureau of Indian Standards 1984) seismic design for liquid-retaining structures has been largely based on the Indian Standard IS 1893 (Part 2): 2014 (Bureau of Indian Standards 2014). It is crucial to remember that this standard has changed over time to increase its efficacy and consider the most recent information and scientific discoveries. The study aims to examine the most recent changes made to Indian Standard IS 1893 (Part 2): 2014 (Bureau of Indian Standards 2014) and contrast them with the earlier code version. The objective is to evaluate the effect of these changes on the seismic performance of liquid-retaining structures by utilizing the updated code to analyze the structure. Aware & Mathada (2013) examined IS 1893:2002 Proposed code Part II recommendations. This study calculates seismic design forces for an elevated water tank using draft code Part II of IS 1893:2002 and IS 1893:1984. This study shows that the latest code and IITK-GSDMA (2007) guidelines require higher design base shear for most tanks than the previous code.

The calculation of the response reduction factor (R) for the seismic analysis of water tanks, according to the Indian Standard (IS) code, depends on the particular edition of the code being followed. The value of R may vary depending on the seismic design regulations specified in the relevant IS code that applies to the analysis. The response reduction factor (R) for seismic analysis of structures, including water tanks, varies depending on factors such as the utilized seismic design code. Both the guidelines from the IITK-GSDMA and the Indian Standard IS 1893 (Part 2): 2014 (Bureau of Indian Standards 2014) are being utilized for the analysis. The thoroughness of the IITK-GSDMA guidelines' approach to seismic analysis and design is well known. The study aims to assess the seismic resilience of liquid retaining structures, identify areas for improvement, and evaluate the structural behavior by comparing the most recent and older versions of IS 1893 Part 2 and applying the IITK-GSDMA guidelines.

The main objective of this study is to conduct a comparative analysis of the recently updated regulations regarding liquid storage tanks. The emphasis is on the significance of shifting from obsolete regulations to a more precise and efficient new code. The primary aim of this research is to assess the structural characteristics and seismic response of elevated water tanks with varying height-to-diameter ( $h/D$ ) ratios. The investigation will specifically target water tanks with a volume of 50 cubic meters. The analysis will provide useful insights into the design and performance considerations related to elevated water tanks of different capacities and heights. This study aims to provide significant insights into the impact of the response reduction factor on seismic design forces for elevated water tanks. This study aims to analyze various models of tanks to evaluate their performance under different seismic design codes. The matter is of great significance, especially in the context of the continuous advancement of seismic design standards in India.

When subjected to horizontal ground motion and fully anchored to a rigid foundation, rigid rectangular and cylindrical water tanks would respond liquidly. Housner G. W. (Housner 1963) proposed a helpful idealization for this purpose in the early 1960s. He distinguished between two types of hydrodynamic response of the tank: "impulsive" motion, which involves the fluid moving in tandem with the tank's shell and is assumed to be rigidly attached, and "convective" motion, which involves the vertical movement of the fluid's free surface and is characterized by long-period oscillations. Later studies by El Damatty et al. (El Damatty, Saafan, & Sweedan 2005, El Damatty, Korol, & Mirza 1997) identified experimentally the dynamic properties of liquid-filled combined vessels, which consisted of a conical steel section with a top cylindrical shell superimposed. Sweedan M. I. (Sweedan 2009) suggested an equivalent mechanical model to replicate forces created in combined elevated tanks subjected to vertical ground acceleration to further streamline elevated tanks' seismic analysis. To facilitate the seismic design of liquid storage tanks, numerous existing standards and guides,

including ACI 350 (American Concrete Institute, 2006) and ACI 371R-08 (American Concrete Institute, 2008), have been modified as a result of subsequent research conducted by other researchers.

Lakhade S. O. et al. (Lakhade, Kumar, & Jaiswal 2017) analyzed the seismic regulations of Indian Standard IS 1893:1984 (Bureau of Indian Standards 1984) and IS 1893:2014 (Part 2) (Bureau of Indian Standards 2014). They investigated the fundamental requirements of Indian Standard IS 1893 (Part 2): 2014 (Bureau of Indian Standards 2014), paying particular attention to the seismic analysis effects caused by the response reduction factor. According to the findings, the old code used a modeling technique with only one degree of freedom (DOF). In contrast, the current code uses a modeling approach with two degrees of freedom (DOF), which has resulted in greater design base shear requirements under the revised code.

Jain S. K. et al. (Jain & Jaiswal 2005) identified the shortcomings in IS 1893:1984 and proposed an updated set of principles for the seismic design of liquid storage tanks. Rinne J. E. (Rinne 1967) studied elevated conical steel tank seismicity. The study modeled the tank wall using shell elements and considered the fluid effect using coupled boundary-shell elements. Adding linear springs to the vessel base supported it and prevented rocking. The model considered geometric and material nonlinearities.

The response reduction factor, hydrodynamic force, base shear, base moment, and deflection under dynamic loading must all be examined to comprehend the behavior and structural performance of elevated water tanks in dynamic loading scenarios. The contents of each of these parameters are summarized as follows.

### 1.1. Response reduction factor (R)

This seismic design parameter measures the extent to which the seismic forces acting on a structure are reduced for design intent. It is a crucial component of seismic design that shows how well a structure can resist forces caused by earthquakes without deforming beyond allowable limits. Building structures resistant to severe ground vibrations must not collapse. Structural components can lose damage. To maintain linear elastic properties, a structure must be built to withstand seismic forces much lower than those expected during intense ground shaking. Lowering base shear with the response reduction factor,  $R$ , yields the design lateral force. In other words, " $R$ " represents a structure's predicted ductility and overstrength.

The guidelines provided by the IITK-GSDMA (IITK-GSDMA, 2007) and Indian Standard IS 1893 (Part 2): 2014 (Bureau of Indian Standards 2014) are both being used to conduct the analysis. The study aims to assess the seismic resistance of liquid retaining structures, identify areas for improvement, and evaluate the structural behavior by comparing the most recent and older versions of Indian Standard IS 1893 (Part 2): 2014 (Bureau of Indian Standards 2014) and applying the IITK-GSDMA (IITK-GSDMA, 2007) guidelines. This study compares two important seismic design codes in India: Indian Standard IS 1893:1984 (Bureau of Indian Standards 1984) and Indian Standard IS 1893 (Part 2): 2014 (Bureau of Indian Standards 2014), including the most recent modification from March 2022 (Bureau of Indian Standards 2022). This comparison aims to investigate the seismic design approach for elevated water tanks. Indian Standard IS 1893:1984 (Bureau of Indian Standards 1984) used a modeling technique with one degree of freedom (1 DOF); however, the updated code, Indian Standard IS 1893 (Part 2): 2014 (Bureau of Indian Standards 2014), and the current amendment shifted to a modeling approach with two degrees of freedom (2 DOF), which is more sophisticated.

Different countries recommend different " $R$ " values for water tank seismic design. IBC-2000 (International Code Council, 2000) recommends 2-4, ACI 350 (American Concrete Institute 2006), and AWWA (D-100) (American Water Works Association 1996) 3-4. The " $R$ " factor ranges from 1 to 5 in Eurocode 8 (European Committee for Standardization, 1998). The Indian seismic analysis code, Indian Standard IS 1893 (Part 2): 2014 (Bureau of Indian Standards 2014), has values 2-4. This makes it tempting to examine the " $R$ " factor evaluation. Using Eurocode 8 (European Committee for Standardization 1998), Malhotra P. K. et al. (Malhotra, Wieland, & Wieland 2000) introduced a simplified seismic design method for cylindrical ground-supported liquid storage tanks, using Eurocode 8 as the basis for analysis. They utilized Eurocode 8 to calculate seismic responses, such as overturning moments and base shear, by employing site response spectra and limit state design techniques.

### 1.2. Hydrodynamic pressure

During an earthquake, water sloshing inside the tank creates dynamic loads known as hydrodynamic forces. Understanding how water movements impact the tank structure and how it reacts to dynamic loading requires understanding hydrodynamic forces. In 1960, a pioneering study was conducted by Housner G. W. (Housner 1963) to examine the impact of seismic forces on fluid containers by developing the water tank as a system with two distinct masses and differentiating between impulsive and convective hydrodynamic pressures. Housner G. W. (Housner 1963) conducted a study to analyze the theoretical behavior of rectangular and circular tanks that are fixed to a rigid foundation when subjected to seismic activity. The researcher discovered

a notable decrease in the maximum forces exerted on a tank when it was filled to only 50% capacity compared to when it was filled.

### 1.2.1. Impulsive hydrodynamic pressure

The hydrodynamic pressure resulting from the rapid flow of water is called impulsive hydrodynamic pressure. The force is exerted on both the vertical wall of the container and the base slab. The calculation for the impulsive hydrodynamic pressure on the tank's wall and base is as follows:

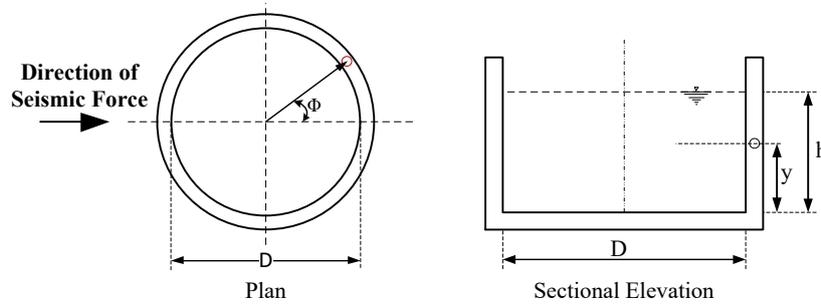
### 1.2.2. Lateral hydrodynamic impulsive pressure on a wall ( $p_{iw}$ )

The lateral hydrodynamic impulsive pressure  $p_{iw}$  (Bureau of Indian Standards 2014), on the wall is calculated as follows:

$$p_{iw}(y) = Q_{iw}(y)(A_h)_i \rho g h \cos \phi$$

Figure 1 demonstrates the plan and sectional elevation of the circular water tank. The lateral hydrodynamic impulsive pressure will be maximum when  $\Phi = 0$ . The symbol  $Q_{iw}(y)$  (Bureau of Indian Standards 2014) denotes the coefficient of impulsive hydrodynamic pressure on a wall, which can be determined using the following formula.

$$Q_{iw}(y) = 0.866 \left[ 1 - \left( \frac{y}{h} \right)^2 \right] \tanh \left( 0.866 \frac{D}{h} \right)$$



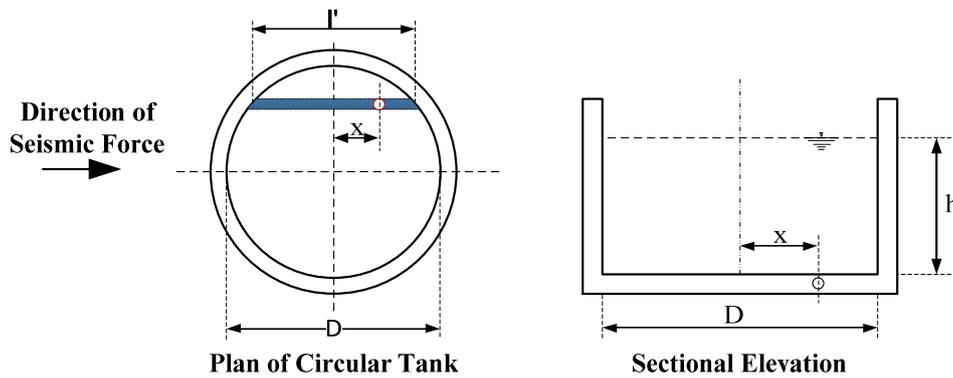
**Fig. 1.** Geometry of Circular Tank for calculation of Hydrodynamic pressure on wall of Circular Water tank

### 1.2.3. Impulsive hydrodynamic pressure on the base slab ( $p_{ib}$ )

Impulsive hydrodynamic pressure ( $p_{ib}$ ) (Bureau of Indian Standards 2014) on the base slab in a vertical direction ( $y = 0$ ) on a strip of length  $l'$  is given by (Refer Figure 2) and can be calculated by using the following formula.

$$p_{ib} = 0.866(A_h)_i \rho g h \frac{\sinh \left( 1.732 \frac{x}{h} \right)}{\cosh \left( 0.866 \frac{l'}{h} \right)}$$

$x$  – horizontal distance of a point on the base of the tank in the direction of seismic force from the center of the tank. The figure demonstrates the plan and sectional elevation of a circular water tank. The impulsive hydrodynamic pressure on the base slab will be maximum when the horizontal distance of a point on the base slab is at  $x = D/2$  and strip length  $l' = D$ .



**Fig. 2.** Geometry of Circular Tank for calculation of Hydrodynamic pressure in a vertical direction of base slab of circular water tank

#### 1.2.4. Convective hydrodynamic pressure

The term "convective hydrodynamic pressure" in the context of a water tank mainly refers to the variations in pressure encountered by the water enclosed within the tank due to its dynamic motion or circulation. The calculation for the convective hydrodynamic pressure on the tank's wall and base is as follows:

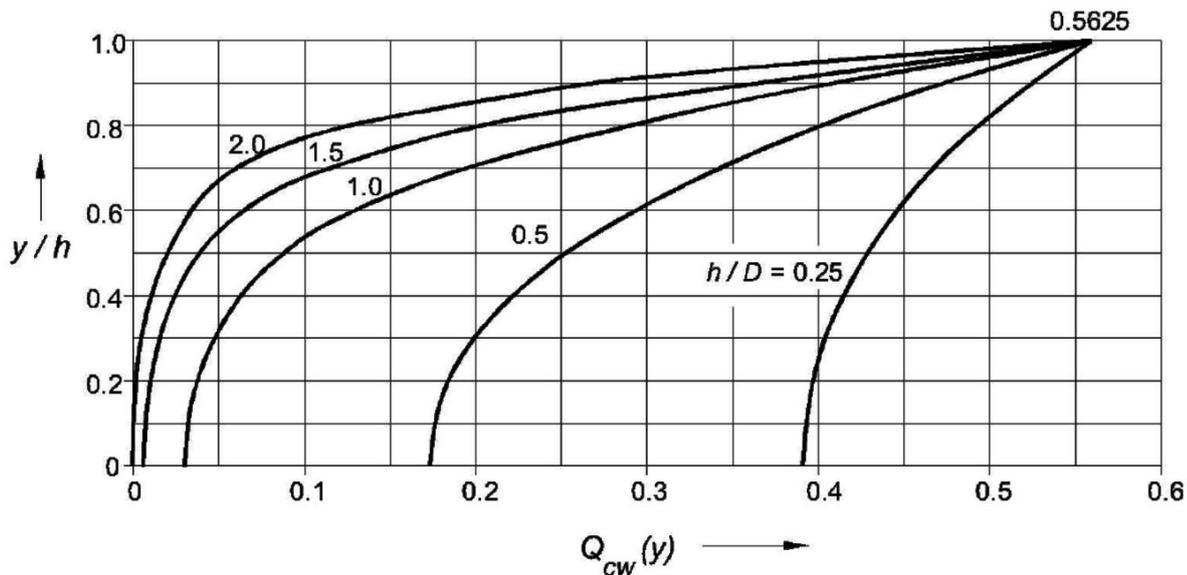
#### 1.2.5. Convective hydrodynamic pressure on a wall ( $p_{cw}$ )

Lateral convective pressure on the wall  $p_{cw}$  (Bureau of Indian Standards 2014) is given by.

$$p_{cw} = Q_{cw}(y)(A_h)_c \rho g D \left[ 1 - \frac{1}{3} \cos^2 \phi \right] \cos \phi$$

$$Q_{cw}(y) = 0.5625 \frac{\cosh\left(3.674 \frac{y}{D}\right)}{\cosh\left(3.674 \frac{h}{D}\right)}$$

Figure 3 (Bureau of Indian Standards 2022) can also be used to get the value  $Q_{cw}$  (Bureau of Indian Standards 2014).



**Fig. 3.** Coefficient  $Q_{cw}$  on wall of rectangular and circular water Tank (Bureau of Indian Standards 2022)

#### 1.2.6. Convective hydrodynamic pressure on the base slab ( $p_{cb}$ )

Convective hydrodynamic pressure ( $p_{cb}$ ) (Bureau of Indian Standards 2014) on the base slab in a vertical direction ( $y = 0$ ) on a strip of length  $l'$  is given by (Refer Fig. 2)

$$p_{cb} = Q_{cb}(x)(A_h)_c \rho g D$$

$$Q_{cb}(x) = 1.125 \left( \frac{x}{D} - \frac{4}{3} \left( \frac{x}{D} \right)^3 \right) \operatorname{sech} \left( 0.3674 \frac{h}{D} \right)$$

### 1.2.7. Pressure due to wall inertia ( $p_{ww}$ ) (4.9.5)

The tank's motion or acceleration causes wall inertia pressure in a water tank. The water and tank's inertia causes this pressure during sudden starts, stops, or tank motion. In water tank design and analysis, wall inertia effects are important, especially when the tank or liquid is subject to dynamic forces.

Pressure ( $p_{ww}$ ) (Bureau of Indian Standards 2014) on the wall due to inertia is given by.

$$p_{ww} = (A_h)_i t \rho_m g$$

$\rho_m$  – mass density of tank wall

### 1.2.8. Pressure due to vertical excitation (vertical ground acceleration) ( $P_v$ )

As per IS 1893 (Part 1): 2016, the effect due to vertical earthquakes shall be considered when the structure rests on soft soil. The effective weight of the liquid increases because of the vertical ground acceleration ( $p_v$ ) (Bureau of Indian Standards 2014); as a result, this causes additional pressure to be induced on the tank wall, the distribution of which is comparable to that of hydrostatic pressure.

$$p_v = (A_v) \left[ \rho g h \left( 1 - \frac{y}{h} \right) \right]$$

The design seismic acceleration spectral value ( $A_v$ ) (Bureau of Indian Standards 2014) or vertical motion shall be taken as:

$$A_v = \frac{2}{3} \left[ \frac{Z}{2} \frac{I}{R} \right] (2.5)$$

### 1.2.9. Maximum hydrodynamic pressure

The hydrodynamic pressure's maximum ( $p$ ) (Bureau of Indian Standards 2014) value can be obtained by combining the pressure resulting from horizontal and vertical excitation using the square root of the sum of squares (ERSS) rule, expressed as:

$$p = \sqrt{(p_{iw} + p_{ww})^2 + p_{cw}^2 + p_v^2}$$

## 1.3. Base shear

Base shear measures the total lateral force that dynamic loading applies to the base of the tank structure. It is an important seismic design parameter that helps determine the structure's overall stability. During an earthquake or other lateral loads, the water and tank structure exert lateral or horizontal force on the tank foundation, known as base shear. The base shear is the total lateral force on a structure's foundation during an earthquake.

Base shear at the bottom of staging, in impulsive mode ( $V_i$ ) (Bureau of Indian Standards 2014) and convective mode ( $V_c$ ) (Bureau of Indian Standards 2014) can be calculated as follows.

$$V_i = (Ah)_i (m_i + m_s) g$$

$$V_c = (Ah)_c (m_c) g$$

$m_s$  – mass of container and one-third mass of staging.

To combine impulsive and convective base shear and get the total base shear ( $V$ ) (Bureau of Indian Standards 2014), use the square root of sum of squares rule (SRSS). This will allow you to calculate the total base shear.

$$V = \sqrt{V_i^2 + V_c^2}$$

## 1.4. Base moment

The base moment measures the rotational or twisting force that dynamic loading applies to the tank structure's base. The base moment in an elevated water tank is the maximum bending moment at the base caused

by lateral loads. It is calculated by considering the distribution of lateral load along the height of the tank and the stiffness of the lateral load-resisting system.

$$M_i^* = (A_h)_i [m_i (h_i^* + h_s) + m_s h_{cg}] g$$

$$M_c^* = (A_h)_c m_c (h_c^* + h_s) g$$

$$M_c^* = (A_h)_c m_c (h_{cg}^* + h_s) g$$

As per Amendment No. 1 March 2022 (Bureau of Indian Standards 2022) to IS 1893 (Part 2): 2014 Criteria for Earthquake Resistant Design of Structures Part 2 Liquid Retaining Tanks.

The total moment (M) (Bureau of Indian Standards 2014) is obtained by combining impulsive and convective moments using the square root of the sum of squares (SRSS) rule.

$$M = \sqrt{M_i^2 + M_c^2}$$

The abbreviations used in formulae are as follows:

- Mi\* Overturning moment in impulsive mode at the base (Bureau of Indian Standards 2014),
- (Ah)i Design horizontal seismic coefficient for impulsive mode (Bureau of Indian Standards 2014),
- (Ah)c Design horizontal seismic coefficient for convective mode (Bureau of Indian Standards 2014),
- mi Impulsive mass of liquid (Bureau of Indian Standards 2014),
- mc Convective mass of liquid (Bureau of Indian Standards 2014),
- hi\* Height of impulsive mass above the bottom of tank wall (considering base pressure) (Bureau of Indian Standards 2014),
- hs Structural height of staging, measured from the top of the foundation to the bottom of the container wall (Bureau of Indian Standards 2014),
- ms Mass of empty container of elevated tank and one-third mass of staging (Bureau of Indian Standards 2014),
- hc Height of convective mass above the bottom of the tank wall (without considering base pressure (Bureau of Indian Standards 2014),
- hc\* Height of convective mass above bottom of tank wall (considering base pressure) (Bureau of Indian Standards 2014),
- hcg Height of the center of gravity of the empty container of the elevated tank, measured from the base of staging (Bureau of Indian Standards 2014),
- g Acceleration due to gravity.

## 1.5. Deflection

Deflection is a term used to describe a tank's structural deformation or displacement when subjected to dynamic loading conditions. Evaluating the tank's structural integrity and serviceability is of utmost importance. The presence of excessive deflection may suggest potential concerns regarding the tank's performance or safety.

## 2. Model and Methodology

### 2.1. Model description

This research analyses elevated water tanks with specific design parameters. Construction features include a stable base, a 50 m<sup>3</sup> capacity, M25 concrete, and Fe500-grade steel reinforcement. The capacity of the tank is selected based on the general construction of ESR in villages in India. The tanks have 300 mm freeboard and 200 mm thick walls and base slabs. Four horizontal beams (250 x 600 mm) and four 500 mm vertical circular columns provide structural support. Additionally, 300 x 450 mm bracing improves stability.

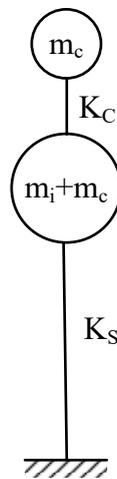
This study compares two important seismic design codes in India: Indian Standard IS 1893:1984 (Bureau of Indian Standards 1984) and Indian Standard IS 1893 (Part 2): 2014 (Bureau of Indian Standards 2014), including the most recent modification from March 2022. This comparison aims to investigate the seismic design approach for elevated water tanks. Indian Standard IS 1893:1984 (Bureau of Indian Standards 1984) used a modeling technique with one degree of freedom (1 DOF); however, the updated code, Indian Standard IS 1893 (Part 2): 2014 (Bureau of Indian Standards 2014), and the current amendment shifted to a modelling approach with two degrees of freedom (2 DOF), which is more sophisticated.

One of the most important aspects to consider is the response reduction factor (R). Regarding water tanks, Indian Standard IS 1893:1984 (Bureau of Indian Standards 1984) utilized a response reduction factor of around 5. Indian Standard IS 1893 (Part 2): 2014 (Bureau of Indian Standards 2014), on the other hand, established a response reduction factor of 4, although the most recent modification to Indian Standard IS 1893 (Part 2): 2014 (Bureau of Indian Standards 2014), which took effect in March 2022, established a factor of 2.5. These values of the response reduction factor are shown in Table 2. The primary objective of this study is to determine how the alterations in the response reduction factor influence the seismic design forces for elevated water tanks.

In order to carry out this evaluation, a total of ten different models are being investigated, each of which has a capacity of 50 cubic meters for the elevated water tank. The height-to-diameter ( $h/D$ ) ratios of these several models are different from one another. All the water tanks feature circular containers installed on frame staging, and they are located in seismic Zone 2 so that there is consistency between them. The container is held in place by a staging structure consisting of 4 columns, and the structure's height is 12 m, regardless of the model. Table 3 compares these 10 different models'  $h/D$  ratios and serves as the basis for methodical organization and presentation of the models.

## 2.2. Spring mass model for seismic analysis

Elevated tanks can be idealized by a two-mass model, as shown in Figure 4. During an earthquake, when a tank is filled with liquid, the response of the liquid can be categorized into impulsive and convective mass. The impulsive liquid mass refers to the lower region of the liquid within the tank. This liquid portion behaves as if it is rigidly connected to the tank wall and accelerates with the tank during the earthquake. It induces impulsive hydrodynamic pressure on the tank wall and base because it moves as a single unit with the tank structure. In a spring-mass model, the impulsive liquid mass as a concentrated mass is located at the tank's center of mass. This mass is connected to the tank's structure through a spring element to account for its dynamic behavior during the earthquake. The convective liquid mass refers to the portion of the liquid in the tank in the upper region and experiences sloshing motion when subjected to an earthquake. This mass generates convective hydrodynamic pressure on the tank wall and base because of its sloshing motion. Modeling the convective liquid mass in a spring-mass model is more complex. It would typically use a series of interconnected spring and mass elements to represent the dynamic behavior of the liquid's sloshing.



**Fig. 4.** Two Mass Idealization of Elevated Tank (Bureau of Indian Standards 2014)

Haroun & Ellaithy (Haroun & Housner 1981) studied deformable liquid storage tanks using modal superposition analysis. This study mathematically treated the fluid domain and finite elements to model the tank's shell using a boundary solution. Haroun & Ellaithy (Haroun & Ellaithy 1985) developed a mechanical model to evaluate elevated water tank dynamics. They examined a cross-braced frame and concrete pedestal tower. This study evaluates concrete shaft-supported elevated tanks using the finite element method (FEM).

Using the finite element method, Ghaemmaghani et al. (Ghaemmaghani, Moslemi, & Kianoush 2010) investigate the seismic behavior of concrete liquid tanks. In his study, two finite element models for rectangular and cylindrical tanks are studied under horizontal and vertical ground motions. According to the findings, incorporating both horizontal and vertical ground motions reduces the significance of vertical acceleration on the dynamic response of liquid tanks.

When liquid vibrates, it exerts a hydrostatic and hydrodynamic force on the tank's walls and floor (impulsive and convective, respectively). It is possible to idealize a tank using an equivalent spring-mass model, which considers hydrodynamic pressure and the interaction between the tank walls and the liquid.

In order to ascertain the deflection behavior of these models, a finite element analysis, commonly referred to as FEA, is implemented. A rigid link is assumed to exist from the top of the staging to the center of gravity of the container due to the rigid characteristics of the container portion. This is done to account for the rigidity that is revealed by the floor slab. An analysis is necessary to determine the stiffness of the staging in the X-direction. The deflection is determined by assuming a load of 10 kilonewtons in the X-direction. A deflection study was conducted using the Finite Element Method (FEM) software, Staad Pro after the parameters of the elevated water tank were established. This load was introduced to determine the X-direction stiffness of the staging structure. The structured Table 1 shows the specific value of the deflection that changes with the h/D ratio, together with the matching staging stiffness (Ks) values:

**Table 1.** Deflection and stiffness of staging (Ks) for different h/D ratio

SN	h/D ratio	Deflection (m)	Ks (kN-m)
1	0.1	0.00386	5181.34
2	0.2	0.00340	5882.35
3	0.3	0.00321	6230.52
4	0.4	0.00311	6430.86
5	0.5	0.00305	6557.37
6	0.6	0.00302	6622.51
7	0.7	0.00301	6644.51
8	0.8	0.00299	6688.96
9	0.9	0.00303	6600.66
10	1	0.00320	6250.00

**Table 2.** Response Reduction Factor (R)

SN	Staging of Water Tank	Response Reduction factor (R)		
		IS 1893 (Part 1): 2002 and 2016	IS 1893:2014 (Part 2)	IITK-GSDMA guidelines
1	Tank supported on RCC Special Moment Resisting Frame (SMRF) Frame conforming to ductile detailing as per IS13920, i.e., special moment resisting frame (SMRF)	5	4	2.5

After finding the stiffness of staging, the next step is to determine the necessary parameters for the spring-mass model, like period, and design horizontal seismic coefficient ( $A_h$ ) for impulsive and convective mode. The newly amended provisions in Indian Standard IS 1893 (Part 2): 2014 (Bureau of Indian Standards 2014) give formulas for a more straightforward and systematic calculation of the spring-mass model. It is crucial to note that while these parameters are represented in IS 1893:2014 (Part 2) through graphical representations, the new provisions in IS 1893:2014 (Part 2) provide these formulas. To facilitate a full knowledge of the spring-mass model and its application in the seismic design process, Table 3 below gives all the essential parameters. These parameters include the overturning moment in impulsive mode ( $M_i$ ), overturning moment in convective mode ( $M_c$ ), height of impulsive mode ( $h_i$ ), height of impulsive mass above bottom of tank wall with base pressure ( $h_i^*$ ), height of convective mode ( $h_c$ ), height of convective mass above bottom of tank wall with base pressure ( $h_c^*$ ), and stiffness of staging ( $k_s$ ).

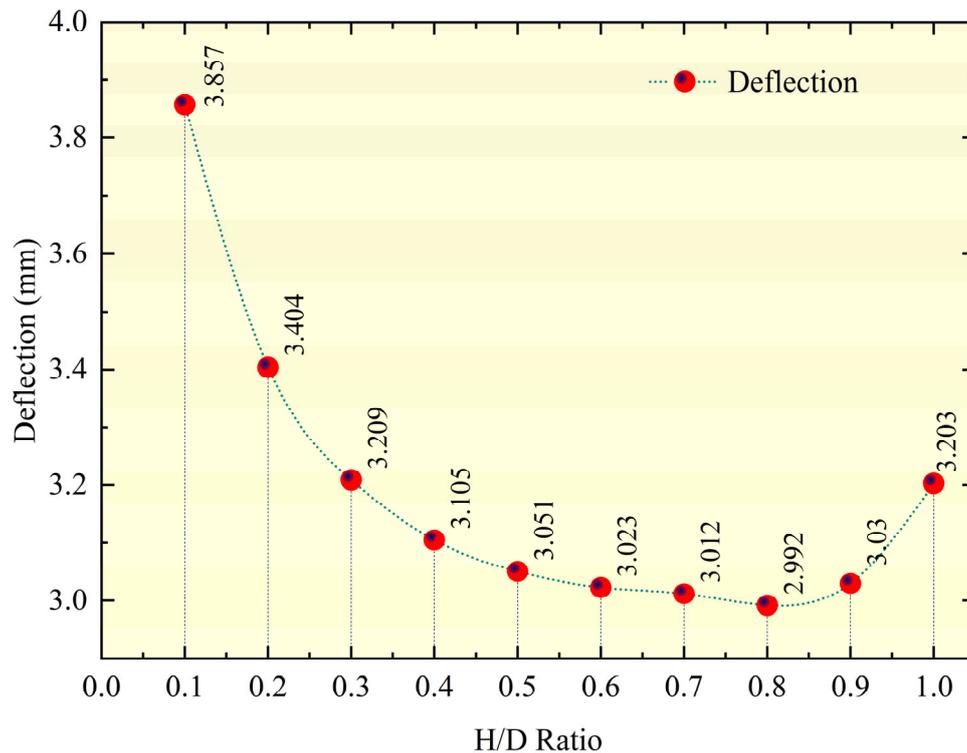
**Table 3.** Parameters of spring-mass model with different h/D ratio

Dia. of Tank (D) m	Depth of Water (h) m	h/D	$M_i$ (kN)	$M_c$ (kN)	$h_i$ (m)	$h_i^*$ (m)	$h_c$ (m)	$h_c^*$ (m)
8.60	0.86	0.1	57.70	409.79	0.33	3.63	0.439	6.71
6.83	1.37	0.2	115.37	364.82	0.52	2.80	0.724	3.05
5.96	1.79	0.3	172.05	309.84	0.68	2.38	0.984	2.20
5.42	2.17	0.4	224.83	259.87	0.82	2.15	1.257	1.97
5.03	2.52	0.5	271.02	219.89	0.96	2.02	1.534	1.99
4.73	2.84	0.6	309.67	189.90	1.08	1.96	1.818	2.10
4.50	3.15	0.7	341.19	164.91	1.20	1.93	2.109	2.30
4.30	3.44	0.8	366.62	144.92	1.48	1.93	2.400	2.55
4.14	3.72	0.9	387.07	129.93	1.56	1.98	2.680	2.79
3.99	3.99	1	403.57	114.94	1.64	2.00	2.995	3.03

Table 3 shows the various parameters of the spring-mass model with different h/D ratios. As the h/D ratio increases, all the parameters ( $M_i$ ,  $M_c$ ,  $h_i$ ,  $h_i^*$ ,  $h_c$ ,  $h_c^*$ ) tend to increase. This suggests a correlation between the water depth relative to the tank diameter and the behaviors of the spring-mass system. The major contribution of hydrodynamic pressure at the base is responsible for the values of  $h_i^*$  and  $h_c^*$  being greater than h in the case of a shallow tank with a h/D ratio of 0.1, 0.2, and 0.3.

### 3. Results and Discussion

Below is a graphical representation of the various results of deflection, hydrodynamic pressure, moment at base, and base shear with varying h/D ratios. These results are discussed in detail.

**Fig. 5.** Variation in deflection with H/D ratio

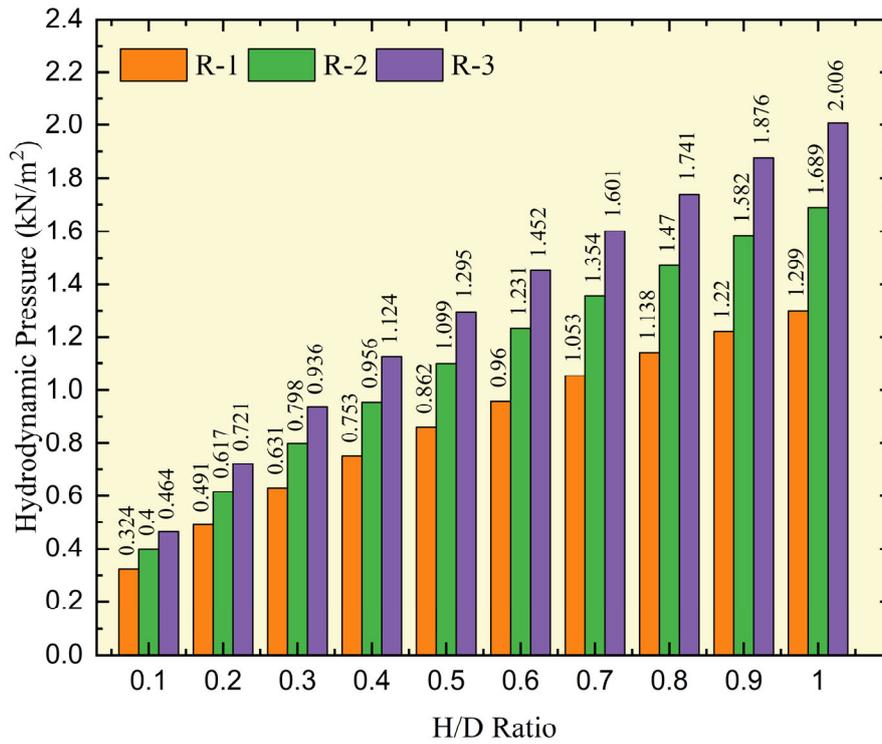


Fig. 6. Variation in hydrodynamic pressure with H/D ratio

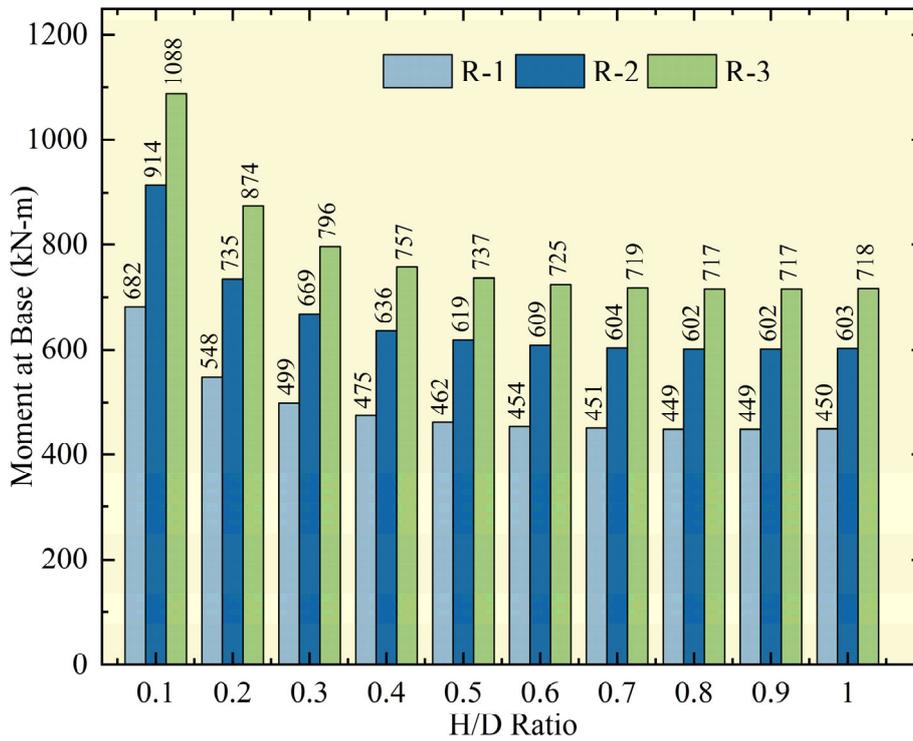
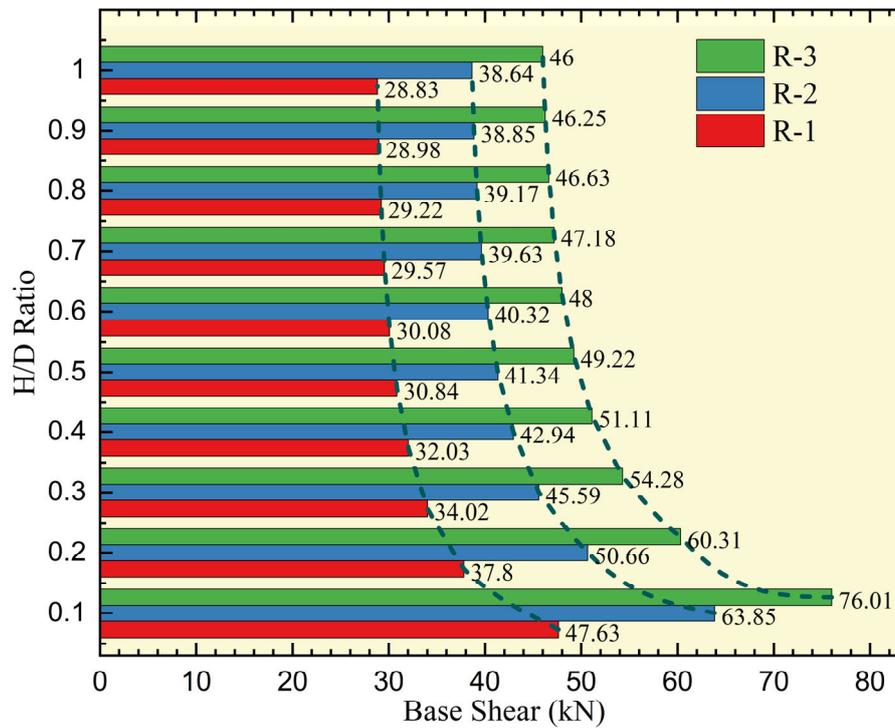


Fig. 7. Variation in moment at base with H/D ratio



**Fig. 8.** Variation in base shear with H/D ratio

**Deflection:** Fig. 5 illustrates the relationship between the deflection of the water tank and variations in the H/D (height-to-diameter) ratio. As the height-to-depth (H/D) ratio increases, there is a tendency for the deflection to decrease. The deflection values offer valuable insights into the structural response of the tank under varying conditions, thereby facilitating design and analysis.

**Hydrodynamic pressure:** Fig. 6 illustrates the hydrodynamic pressure values for various h/D ratios under different response reduction factors as per the IITK-GSDMA Guidelines (IITK-GSDMA 2007), IS 1893 (Part 2): 2014, and IS 1893 (Part 2): 2014, March 2022. It illustrates how the chosen seismic design provisions and the h/D ratio affect the hydrodynamic pressure.

The hydrodynamic pressure for various h/D ratios and response reduction factors (R) in seismic design provisions leads to the following highlights:

- (i) Response Reduction Factors (R): Response reduction factor changes significantly affect hydrodynamic pressure. A higher R reduces hydrodynamic pressure. This is important because R is a key seismic design factor that reduces structural seismic forces.
- (ii) Impact of h/D ratio: Hydrodynamic pressure also depends on h/D ratio. An increased h/D ratio decreases hydrodynamic pressure. This suggests that taller tanks with smaller diameters have lower hydrodynamic pressure, which can help design tanks.

Comparison of Seismic Design Provisions: IS 1893 (Part 2): 2014, IS 1893 (Part 2): 2014, March 2022, and IITK-GSDMA Guidelines show hydrodynamic pressure differences. Changes in design provisions and code amendments may cause these variations. The code version and provisions must be considered for accurate design and analysis.

Seismic Design Implications: Hydrodynamic pressure differences emphasize the need for appropriate seismic design provisions based on project location and needs. Making informed code and response reduction factor choices during design can greatly affect the structural response to seismic forces.

Finally, the data shows how response reduction factors and h/D ratios affect hydrodynamic pressure in water tanks, emphasizing the need for careful seismic design to ensure structure safety and stability.

**The moment at the base of the wall:** Fig. 7 presents the moment values for various h/D ratios under different response reduction factors as per the IITK-GSDMA Guidelines, IS 1893 (Part 2): 2014, and IS 1893 (Part 2): 2014, March 2022. It illustrates how the moment changes concerning the chosen seismic design provisions and the h/D ratio.

Based on the given values for different h/D ratios and response reduction factors (R) in line with different seismic design rules, it can draw the following conclusions:

**Response Reduction Factors (R):** When the response reduction factor (R) varies, there are noticeable changes in the moment values. Moment values decrease with increasing R values. This observation is crucial because lower moments denote fewer structural demands, and R significantly reduces seismic forces on the structure.

**Impact of h/D ratio:** There is a discernible relationship between the moment values and the h/D ratio, or height-to-diameter ratio. The moment tends to decrease as the h/D ratio rises. This suggests that moments are lower in taller tanks with smaller diameters. This can be useful information for designing tanks.

**Base shear:** According to various seismic design provisions, Fig. 8 compares base shear values for various h/D ratios and response reduction factors (R).

Based on the information given about comparing base shear values for different response reduction factors (R) and h/D ratios in line with different seismic design requirements, it can draw the following conclusions:

(i) **Response Reduction Factors (R):** Changes in the response reduction factor (R) cause notable variations in the base shear values. Base shear values decrease with increasing R values. This observation is important because lower base shears indicate lower structural demands, and R is a key factor in reducing seismic forces acting on the structure.

(ii) **Effect of h/D ratio:** A discernible relationship exists between the base shear values and the h/D ratio, or height-to-diameter ratio. The base shear tends to decrease as the h/D ratio rises. Tank design can benefit greatly from knowing that taller tanks with smaller diameters have lower base shears.

#### 4. Conclusion

Following various seismic design provisions, the following general conclusions are drawn based on the results for deflection, hydrodynamic pressure, moment, and base shear values for different h/D ratios and response reduction factors (R):

- The deflection, hydrodynamic pressure, moment, and base shear are all greatly influenced by the response reduction factor (R). Lower values for these parameters are typically the consequence of higher R values. This emphasizes the importance of choosing a suitable R-value following the seismic design guidelines to lessen structural demands and increase safety.
- The values of deflection, hydrodynamic pressure, moment, and base shear are all significantly influenced by the h/D ratio or height-to-diameter ratio. These values tend to decrease with increasing h/D ratios, indicating that taller tanks with smaller diameters undergo less deformation and seismic forces.
- Differences in deflection, hydrodynamic pressure, moment, and base shear values are visible when contrasting various seismic design provisions, such as IS 1893 (Part 2): 2014, IS 1893 (Part 2): 2014 March 2022, and IITK-GSDMA Guidelines. The alterations in the seismic codes and modifications to the design guidelines are responsible for these discrepancies. The provisions of the code version have a substantial effect on how the structure reacts to seismic forces.
- The data emphasizes the importance of choosing the right seismic design provisions, such as the particular code version and related response reduction factor.
- The data presented in this research provides insightful information about how response reduction factors and h/D ratios affect important structural parameters. It highlights the necessity of carefully choosing seismic design requirements to guarantee secure and economical water tank designs; lower values signify fewer structural demands and better seismic performance.

#### 5. Future Recommendations

The correlation between the height-to-diameter (h/D) ratio and the response reduction factor (R) plays a crucial role in understanding the seismic behavior of elevated water tanks. It can provide valuable insights for future studies. Increasing the h/D ratio generally reduces seismic parameters like the moment at base, base shear, hydrodynamic pressure, and deflection. Taller tanks (higher h/D ratios) experience less lateral force due to their narrower profiles, which reduces overall seismic demands. Considering these effects in future studies on the nonlinear behavior of structures.

Further research can be conducted by considering the effect of soil structure interactions and the effect of variation in response reduction factor and h/D ratio, as the base shear and moment at the base will be affected by the soil stiffness, damping, and lateral displacement.

## Statements and Declarations

### Data Availability

This manuscript does not report data generation or analysis

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