

Comprehensive study of cost, seismic & wind impacts on circular water tanks with varying cylindrical height-to-diameter ratio

Sukanya Saxena* & Krishna Kant Pathak

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

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This study had systematically assessed the cost and material efficiency of circular water tanks with varying capacities, closely examining the influence of cylindrical height-to-diameter (H/D) ratios within the range of 0.2 to 2.0. The investigation has delved comprehensively into the effects of wind and seismic forces, accounting for both tank-filled and empty conditions across the entire spectrum of H/D ratios. The analysis has specifically focused on water storage capacities of 600, 700, 800, 900, 1000, 1100, and 1200 kiloliters. Employing an in-house Software Program developed for the Design of Elevated Circular Water Tanks and adhering to the guidelines of IS 3370:2021, the study has conducted a thorough parameter comparison to reveal substantial cost savings achievable through strategic H/D ratio selection. Particularly noteworthy is the revelation that the H/D ratio optimizing cost aligns with the configuration that experiences minimal wind and seismic forces. Informed parameter have choices emerged as a driving force behind considerable reductions in material consumption, underscoring the software program's efficacy as a pivotal tool for designing elevated water tanks, particularly in scenarios where conventional analysis and design software lack accessibility.

Keywords: Elevated water tanks, Circular tanks, RCC structures, Staging, Base shear, Seismic loads, Wind loads, Limit state method of design

1 Introduction

Elevated water tank construction holds immense importance in supplying drinking water to communities, especially with initiatives like India's Jal Jeevan Mission. This research centers on enhancing water tank structures through the variation of cylindrical height-to-diameter ratios to attain cost efficiency and sustainable designs. The investigation delves comprehensively into the effects of wind and seismic forces, accounting for both tank-filled and empty conditions across the entire spectrum of H/D ratios. A robust software program, developed in the C++ language, has been created to thoroughly analyze, design, and optimize these structures, incorporating the latest IS Codes. The study adheres to the Limit State Method in line with the updated IS Code 3370, ensuring adherence to crack width limitations. The outcomes vividly illustrate the effectiveness of the software program.

In-depth Literature survey has been done to identify the research gaps. Parametric study on cylindrical water tanks, exploring varying aspect ratios for optimized design was done using IS 3370:2009. The research highlighted that an aspect

ratio (H/D) of 0.60 resulted in the most efficient and cost-effective design, taking into account factors such as structure height, diameter, and material costs¹. Although the study was done on a single capacity tank and earlier standards were used. Few studies investigated the seismic behavior of RC elevated water tanks with varying staging patterns and earthquake characteristics² and also to study the seismic response of elevated circular water tanks with and without base isolators using finite element-based software, highlighting the significance of base isolators in reducing damages from lateral forces during seismic events³. A similar Study is done comparing the seismic analysis of elevated circular water tanks using the Equivalent Static Method and Response Spectrum Method. The study focused on the behavior of these tanks during earthquakes, considering factors like water movement and ground interaction⁴. Minimum weight design study was conducted for the analysis and design of cylindrical concrete water tanks, with a focus on minimum weight design⁵. The study maintained constant internal radius and height while varying the wall thickness to achieve desired stress values. Cost optimization techniques were used in the designing reinforced concrete cylindrical water tanks to

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

minimize material costs, aligning with BS8007 standards. The study encompassed considerations of reinforcement and concrete quantities for accurate cost assessments⁶. Another study focused on achieving the minimum weight design of cylindrical water tanks, adhering to BS5337 specifications. This study employed a combination of finite element analysis and numerical optimization techniques⁷.

While existing studies have contributed to aspects of water tank design, such as wind, seismic loads, staging, and H/D ratios, a comprehensive approach is still needed. This study addresses this gap by considering the combined effects of these factors. A specialized software program for elevated circular Water tank design is introduced, encompassing various parameters. A parametric study explores diverse H/D ratios, offering insights into optimal ratios for cost-effective and resilient water tank structures. The analysis extends to investigating wind and seismic forces for each H/D ratio, unveiling connections between optimal ratios and minimized horizontal forces on the structure. This holistic approach provides valuable insights for the design of efficient and robust water tanks.

2 Materials and Methods

The principal objective of this academic study is to comprehensively investigate the influence of varying height-to-diameter (H/D) ratios on the design of elevated circular water tanks. By examining this parameter alongside critical factors such as wind and seismic loads, staging configurations, Crack Width Check, Latest design standards and provisions using LSM (Limit State Method) of Design, and associated considerations, the research aims to reveal optimal H/D ratios that lead to efficient, resilient, and cost-effective water tank structures. Further analysis extends to comprehensive examinations of wind forces and seismic forces at both empty and full tank conditions for each H/D ratio, aiming to establish relationships between the optimum H/D ratio and

minimal horizontal forces exerted on the structure. The development of a specialized software program developed for this purpose is intended to facilitate precise and efficient design processes. Furthermore, through a parametric study exploring diverse H/D ratios, the study seeks to identify configurations that offer both cost-effectiveness in water tank structures. The overarching aim is to provide valuable insights that inform decision-making in the design and construction of Elevated Circular Water tanks. This study employs custom C++ software based on the Membrane approach to analyze water tanks ranging from 600 kL to 1200 kL. Conforming to IS 3370: 2021 and other codes, seismic, wind, and staging analyses are considered using the Limit State Method. Variations in H/D ratios (0.2-2.0) are explored, impacting cost and design parameters. The software computes member dimensions, steel reinforcement, and more, ensuring precise tank design. Material costs for concrete, steel, and shuttering are calculated using CPWD DAR VOL 1 2021. Optimal H/D ratios and corresponding costs are determined through IS codes, such as IS 875 Part 3: 2015 for wind loads, IS 3370: 2021 for seismic analysis, IS 456-2000, IS 1893 Part 2: 2016 for earthquakes, and IS 11682 for staging design. The investigation delves into wind and seismic forces under varying conditions, aiming to reveal connections between optimal H/D ratios and minimized forces. These findings are crucial for informed decisions in the construction of Elevated Circular Water tanks. The properties of the tanks are mentioned in Table 1.

The C++ software program developed encompasses several features:

- (i) Comprehensive design coverage: Top dome, Ring beams, Circular wall, Main Girder Beam, Columns, Braces, Bottom dome, and more.
- (ii) Inclusion of Crack Width check for elements in contact with water.
- (iii) Adherence to IS 3370: All parts 2021 and Limit State design principles.

Table 1 — Properties of circular water tanks.

Parameter	Value/Name	Parameter	Value/Name
Concrete Mix	M30	No of Braces	4
Steel Grade	Fe500	Earthquake Zone	3
Method	Limit state method	City wind speed	47
Type of tank	Circular tank	Terrain category	2
No of bays/ braces	4	Region Type	Non-Coastal region
Bearing Capacity of soil	250 kN/m ²	Height of Staging	16 m

- (iv) Seismic design for Zone II, III, IV, and V, including Seismic response Time calculation.
- (v) Thorough Wind Load calculations according to IS 875: 2016, accommodating various Indian cities, terrains, and regions.
- (vi) Annular raft footing design integration.
- (vii) Precise estimation of Concrete Volume, Steel Quantity, and Shuttering Area.
- (viii) Utilization of the Latest DAR VOL 1 Updated Dec 2021 CPWD for item rates.

- (ix) Comprehensive design and cost calculations for the entire tank in a single run.

3 Results and Discussion

3.1 Cost versus H/D ratios

Table 2 presents calculated water tank costs for different H/D ratios for circular water tanks ranging from 600 – 1200 kL. H/D ratios range from 0.2 to 2.0. H/D ratios of 0.2-0.5 see steep cost declines, followed by gradual changes as shown in Fig. 1.

Table 2 — Cost of tanks (in lakhs) relative to diverse H/D ratios across distinct tank capacities. h/d ratios.

	Cost for different storage capacities in lakhs						
	600 kL	700 kL	800 kL	900 kL	1000 kL	1100 kL	1200 kL
0.2	69.37	77.2	83.53	91.59	98.79	108.26	116.6
0.3	56.2	62.2	69.97	76.92	82.75	90.28	98.4
0.4	52.25	57.06	65.65	71.18	77.37	85.76	92.24
0.5	50.25	55.59	62.99	71.18	75.93	84.51	91.84
0.6	50.09	55.74	62.01	70.72	75.82	82.83	90.58
0.7	48.81	54.73	63.46	70.54	76.11	83.77	91.7
0.8	49.36	53.64	62.68	71.3	77.3	85.74	94.26
0.9	48.19	54.8	61.87	72.11	78.2	83.94	92.65
1	50.36	55.38	62.8	70.77	77.1	86.2	95.6
1.1	50.13	55.2	65.68	74.23	78.1	87.83	97.88
1.2	51.66	57.2	65.41	74.4	81.7	88.23	99.14
1.3	50.56	58.6	67.77	77.12	81.52	92.2	99.35
1.4	51.51	57.54	66.3	76.04	84.27	95.7	103.2
1.5	52.4	58.6	68	78	86.93	94.1	106.9
1.6	52.95	59.4	69.2	79.68	89.14	96.81	111.06
1.7	53.21	63.58	70.18	81.01	90.92	98.91	112.8
1.8	56.4	63.99	74.7	82.03	92.3	100.6	115.1
1.9	56.34	64.1	75.26	82.65	93.3	101.7	116.93
2	56.16	64.04	75.31	88.02	94.15	108.8	118.4

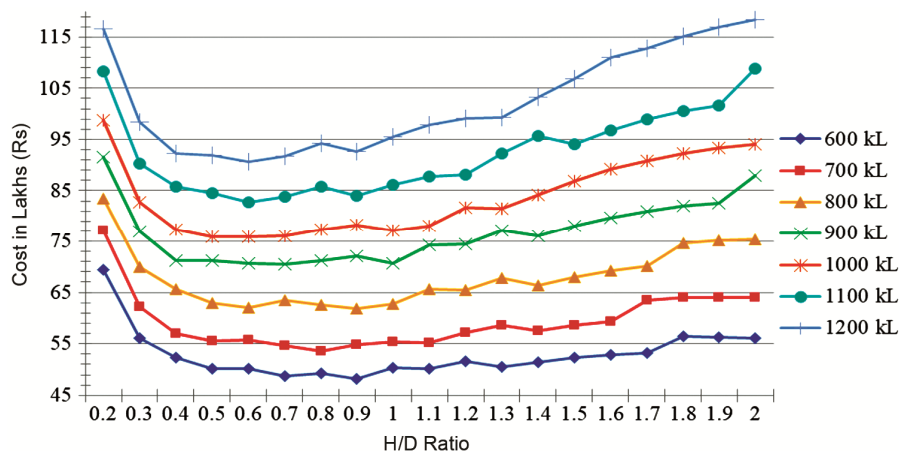


Fig. 1 — Cost versus H/D ratios of circular water tank of capacities ranging 600 kL -1200 kL.

Notably, cost variation across H/D ratios is evident. Cost experiences a significant drop as the H/D ratio shifts from 0.2 to 0.5, followed by gradual changes within the optimal range of 0.6 to 0.9, and rises beyond this range. The optimal cost range is consistently 0.6 to 0.9 for cylindrical tanks as shown in Fig 2. The Savings range from 30.7% to 44% by adjusting the H/D ratio as shown in Fig. 3. Optimal H/D ratio reduces tank weight, and costs, and aligns with structural integrity. Optimizing the H/D ratio reduces water tank weight and costs. H/D values are vital for achieving economic designs with structural integrity.

3.2 Wind-induced shear forces and H/D ratios

As stated earlier, the wind-induced shear forces of all water tanks at various H/D ratios have been calculated and presented in Table 3. Notably, it reveals that there exists an optimum H/D ratio associated with minimized wind-induced shear forces. As the H/D ratio deviates from this optimum point, wind forces generally tend to increase. This underscores the critical interplay between structural design parameters and the impact of wind forces. Wind forces at H/D ratio 0.2: 240.5 kN (600 kL) to 364.4 kN (1200 kL). Wind forces rise with increasing

H/D ratios across all capacities. Maximum Wind forces at H/D ratio 2.0: 333.2 kN (600 kL) to 365.9 kN (1200 kL). Shear forces decrease within the H/D ratio range of 0.5 to 0.9 after an initial rise and beyond this rise again as shown in Fig. 4. Lowest

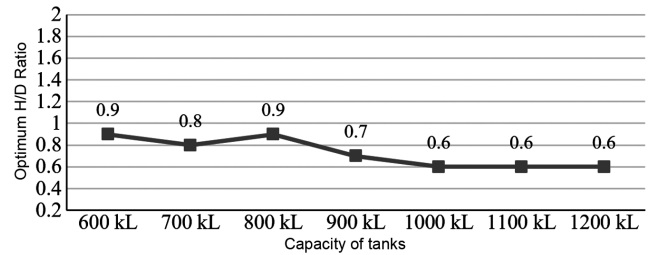


Fig. 2 — Optimum H/D ratio versus storage capacity for different circular water tanks.

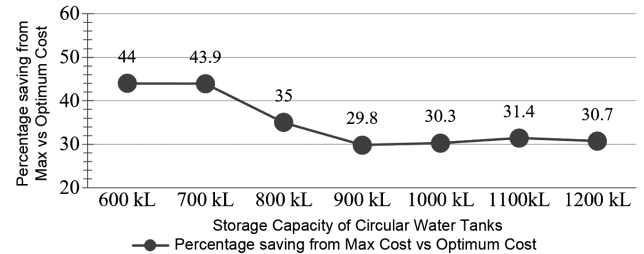


Fig. 3 — Percentage saving w.r.t maximum cost to optimum cost at optimum H/D ratios.

Table 3 — Shear Forces Generated by Wind on Tanks (kN) in relation to Various H/D Ratio

H/D Ratios	Wind-induced shear forces (kN) for different storage capacities						
	600 kL	700 kL	800 kL	900 kL	1000 kL	1100 kL	1200 kL
0.2	240.5	254.7	279.3	304.1	316.9	342.4	364.4
0.3	224.6	237.5	263.9	287.1	297.7	321.8	345.7
0.4	221.16	232.03	260.14	280.6	292.6	317.8	339.2
0.5	220.2	232.3	257.7	283.6	292.4	319	341.4
0.6	222.13	235.4	257.4	284.5	294.18	317.2	340.1
0.7	220.24	234.4	262.3	285	295.84	325.4	343.5
0.8	225	235.2	264.1	287.9	299.2	323.5	348.6
0.9	222.6	238.9	263.1	293.6	305.7	324.9	350.39
1	229	240.95	265.7	290.9	303.6	329.4	356
1.1	229.2	241.2	273.2	299.2	305.8	332.4	359.8
1.2	233.8	246.6	272.7	299.3	313.6	333.8	361.5
1.3	230.9	250.13	278	305.3	312.6	340.6	361.4
1.4	233.7	247.5	274.8	302.6	318.09	346.9	368.1
1.5	235.7	250.1	278	306.4	322.6	343.9	373.3
1.6	237	251.9	280.4	309.5	326.3	347.6	378
1.7	237.7	261.2	282.1	311.7	329.2	350.8	382
1.8	245.7	261.9	291.8	313.3	331.34	353.2	385.04
1.9	245.3	262	292.2	314.08	332.6	355.2	387.2
2	244.4	261.4	292.2	323.7	333.2	365.9	388.2

shear forces consistently within the H/D ratio range- 0.6 to 0.9 for all capacities. The optimal H/D ratio range (0.6 to 0.9) signifies reduced vulnerability to wind-induced shear forces, enhancing potential cost savings.

3.3 Seismic base shear and H/D ratios at full tank and empty tank conditions

Table 4 presents the seismic base shear forces for all water tanks at different H/D ratios have been computed under both full and empty tank states. Empty tank seismic base shear forces follow a similar

trend, increasing with higher H/D ratios for all capacities. For full tank conditions- Base shear forces are consistently higher in Full tank conditions as compared to empty tank conditions across all height-to-diameter (H/D) ratios. Seismic base shear forces rise as H/D ratios increase for full tank conditions. At H/D 0.2, base shear forces range from 326 kN (600 kL) to 607.7 kN (1200 kL). The increasing trend continues, peaking at H/D 2.0 as shown in Fig. 5. Notably, shear forces decrease within H/D range of 0.5 to 0.7. The optimal zone for minimized base shear

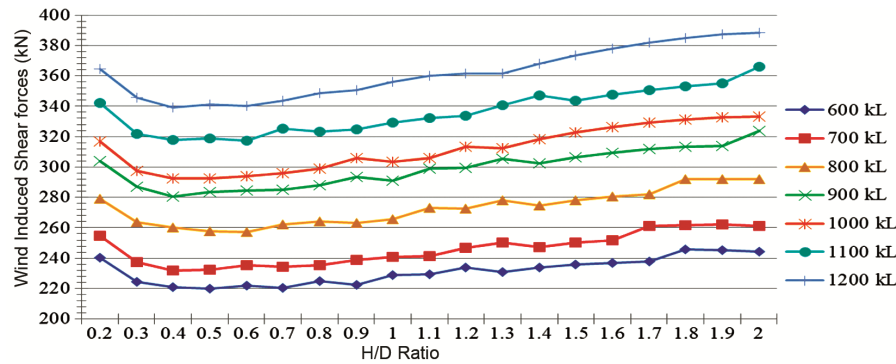


Fig. 4 — Wind-induced shear forces for different circular water tanks.

Table 4 — Base shear forces (for both full and empty tank conditions) of tanks (in kN) across various H/D ratios/h/d ratio seismic base shear forces (kN) at full tank (F.T.) & empty tank (E.T.) conditions for different storage

	600 kL		700 kL		800 kL		900 kL		1000 kL		1100 kL		1200 kL	
	F. T.	E.T.	F. T.	E.T.	F. T.	E.T.	F. T.	E.T.	F. T.	E.T.	F. T.	E.T.	F. T.	E.T.
0.2	326	227.8	351.4	244.1	405.7	280.9	462.2	319.7	485.3	334.2	545	376.4	607.7	415.4
0.3	310.7	205.5	335.5	220.5	389.6	256.9	443.7	292.2	468.2	306.9	521.9	342.3	580.3	382.1
0.4	306.6	199.3	330.2	212.3	385	249.9	436	281.8	462.4	298	520.3	337.6	572.3	369.9
0.5	305.2	197.2	329.6	211.5	382	245.9	437.9	283.3	461.2	296.8	520.2	337.6	577.5	371.8
0.6	306.8	198.5	331.2	214.0	381.9	245.2	438.4	284.8	462.4	298.0	515.2	332.0	575.2	369.5
0.7	304.8	196.5	330.6	212.9	385.5	250.8	439	285.1	463.9	300.4	517.4	335.4	575.2	374.3
0.8	308	201	331.0	213.4	386.8	252.8	441.2	288.4	466.7	304.7	524.2	343.7	580.3	382.1
0.9	306.6	199.3	333.8	218.0	386.3	252	446.1	295.9	472.2	313	522.6	343.2	582.3	385.1
1	311.7	206.6	335.5	222.5	388.7	255.6	444.2	293	471	311.2	530.2	352.4	588.3	394.3
1.1	311.6	206.8	335.9	221.1	394.6	264.5	451.4	303.8	473.2	314.2	533.4	357.6	592.2	400.0
1.2	314.9	211.9	339.9	227.2	394.6	264.6	452.1	304.8	480.1	324.8	532	357	594.7	403.6
1.3	313	209.3	343.4	232.4	399	271.1	457.5	312.8	479.9	324.4	541.8	369.9	595.1	404.2
1.4	315.5	212.7	341.1	229.0	397	268	455.5	310	485.0	322.0	548.2	379.3	602.2	414.7
1.5	317	215	343	232.4	399.8	272.2	459.3	315.4	489.3	338.3	542.7	373.3	611.9	426.6
1.6	318.4	217	345.1	234.9	402.1	275.6	462.5	320	493.2	343.9	550	381.8	617	434.3
1.7	319.2	218.1	352.4	245.4	403.9	278.3	464.8	323.4	496.3	348.3	553.5	387	621.9	440.8
1.8	325.4	227.1	353.1	246.5	412.3	290.2	466.6	325.9	498.6	351.6	556.6	391.0	626.6	445.9
1.9	325.5	227.1	353.5	247.0	413.2	291.5	467.6	327.4	500.2	353.9	555.3	391.2	628.4	449.9
2	325	226	353.4	246.9	413.2	291.5	476.8	340.4	501.2	355.3	569.8	409.9	630.4	452.7

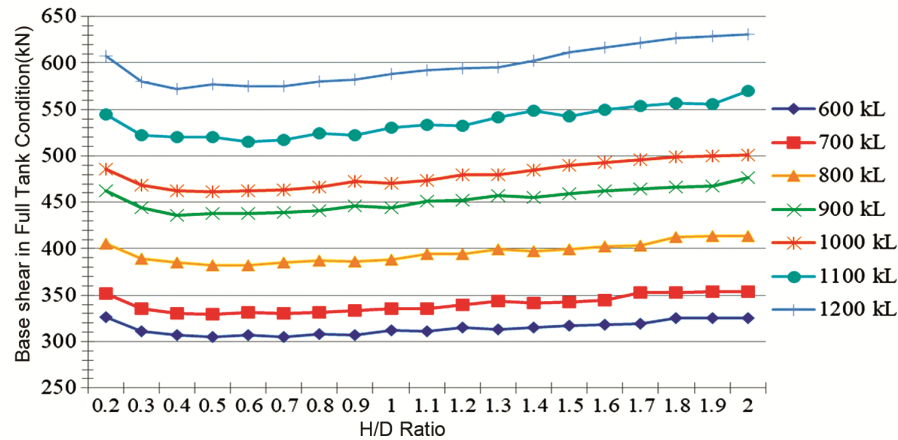


Fig. 5 — Base shear forces in full tank condition versus H/D ratios for different circular water tanks.

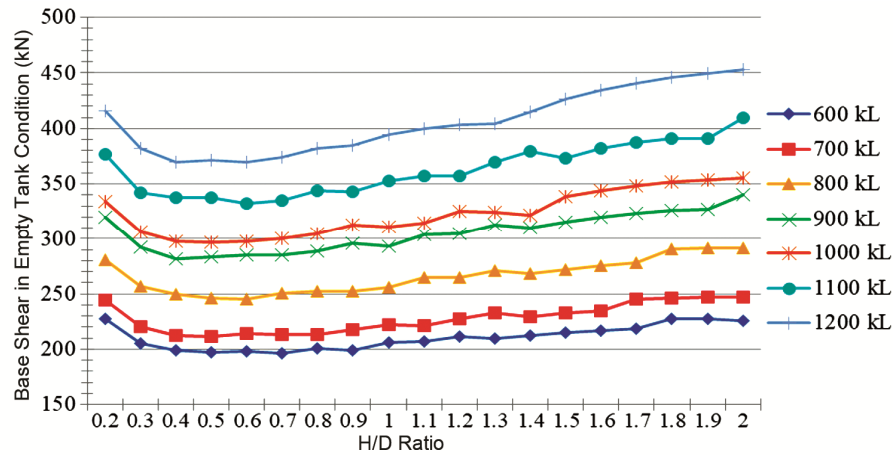


Fig. 6 — Base shear forces in empty tank case versus H/D ratios for different circular water tanks.

forces was observed around H/D 0.6, with shear forces ranging from 306.8 kN (600 kL) to 515.2 kN (1200 kL). Empty tank seismic base shear forces follow a similar trend, increasing with higher H/D ratios for all capacities. At H/D 0.2, base shear forces range from 227.8 kN (600 kL) to 415.44 kN (1200 kL). The optimal design zone for minimized base shear forces remains in the H/D range of 0.5 to 0.7 as shown in Fig. 6. At H/D 0.7, base shear forces range from 196.5 kN (600 kL) to 300.46 kN (1200 kL), emphasizing its importance for structural resilience. Base shear forces are consistently higher in Full tank conditions as compared to empty tank conditions across all height-to-diameter (H/D) ratios.

In summary, the analysis of base shear forces in relation to varying H/D ratios reveals a compelling trend. At lower H/D ratios, circular water tanks experience elevated base shear forces in both full and empty tank conditions. As H/D ratios progress, a critical point emerges within the range of 0.5 to 0.7,

characterized by minimized shear forces, signifying enhanced structural resilience. Beyond this range, shear forces gradually rise again. This intricate U-shaped trend emphasizes the significance of optimal H/D ratio selection for effective seismic performance and structural robustness.

4 Conclusion

The study yields significant insights-

- a **Cost vs H/D ratios:**
 - The optimal cost range is consistently 0.6 to 0.9 for cylindrical tanks.
 - Savings range from 30.7% to 44% by adjusting the H/D ratio.
 - H/D ratios of 0.2-0.5 see steep cost declines, followed by gradual changes.
 - Optimal H/D ratio reduces tank weight, and costs, and aligns with structural integrity.
 - Cost experiences a significant drop as the H/D ratio shifts from 0.2 to 0.5, followed by gradual

changes within the optimal range of 0.6 to 0.9, and rises beyond this range.

- Optimizing the H/D ratio reduces water tank weight and costs. H/D values are vital for achieving economic designs with structural integrity.

b Wind-induced shear forces and H/D ratios

- Wind forces at H/D ratio 0.2: 240.5 kN (600 kL) to 364.4 kN (1200 kL).
- Wind forces rise with increasing H/D ratios across all capacities.
- Maximum Wind forces at H/D ratio 2.0: 333.2 kN (600 kL) to 365.9 kN (1200 kL).
- Shear forces decrease within the H/D ratio range 0.5 to 0.9 after an initial rise and beyond this rises again. Lowest shear forces consistently within H/D ratio range- 0.6 to 0.9 for all capacities.
- Optimal H/D ratio range (0.6 to 0.9) signifies reduced vulnerability to wind-induced shear forces, enhancing potential cost savings.

c Seismic base shear forces and H/D ratios (full tank)

- Seismic base shear forces rise as H/D ratios increase for full tank conditions.
- At H/D 0.2, base shear forces range from 326 kN (600 kL) to 607.7 kN (1200 kL).
- The increasing trend continues, peaking at H/D 2.0.
- Notably, shear forces decrease within H/D range 0.5 to 0.7.
- Optimal zone for minimized base shear forces observed around H/D 0.6, with shear forces ranging from 306.8 kN (600 kL) to 515.2 kN (1200 kL).

d Seismic Base Shear Forces and H/D Ratios (Empty Tank)

- Empty tank seismic base shear forces follow a similar trend, increasing with higher H/D ratios for all capacities.
- At H/D 0.2, base shear forces range from 227.8 kN (600 kL) to 415.44 kN (1200 kL).
- The optimal design zone for minimized base shear forces remains in the H/D range of 0.5 to 0.7.
- At H/D 0.7, base shear forces range from 196.5 kN (600 kL) to 300.46 kN (1200 kL).
- Base shear forces are consistently higher in Full tank conditions as compared to empty tank conditions across all height-to-diameter (H/D) ratios.

e Combined effects of wind induced shear forces and seismic base shear and trend lines

- Trend lines of shear force data reveal a distinct pattern: higher values at lower H/D ratios,

decreasing as the H/D ratio increases, with a minimum at 0.5 to 0.7 range and rising beyond.

- Base shear forces (Full tank) consistently dominate wind shear forces across all capacities & H/D ratios.
- Comparative analysis of wind and base shear forces on empty tanks at different H/D ratios unveils patterns. For tanks of 600-1200 kL, wind shear prevails at low H/D ratios (0.2) but gives way to base shear as H/D ratio increases (≥ 0.3).
- For 900 kL and 1000 kL tanks, wind shear prevails up to H/D ratios ≤ 0.6 and ≤ 0.8 , respectively, then base shear takes over.
- Larger tanks (1100 kL and 1200 kL) are dominated by base shear forces across all H/D ratios.

f Minimum cost and horizontal forces

The data on minimum costs aligns with the range of H/D ratios associated with minimized Horizontal (Wind & seismic) forces. Within the range of 0.6 to 0.9 for the H/D ratio, the costs show a steep decline. This range corresponds to the same range where shear forces are notably reduced. This alignment emphasizes the economic benefits of optimizing the H/D ratio in tandem with achieving enhanced structural resilience.

g Optimal design intersection

An interesting observation emerges at the intersection of these trends. The range of H/D ratios where Horizontal forces are minimized and where costs experience a steep decline coincides, indicating an optimal design zone. Selecting a H/D ratio within this range not only reduces shear forces and enhances structural resilience but also leads to economic benefits in terms of reduced costs.

h About software program

The software program is a very powerful tool for the design of water tanks. Software program compilation time ranges between 0.3-34 seconds. Compared to other software, the program is simple & user-friendly. This can be used for R&D work in water tanks.

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