

STRUCTURAL BEHAVIOUR AND DESIGN OPTIMIZATION OF GROUND-SUPPORTED RC WATER TANKS UNDER EARTHQUAKE FORCES

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ABSTRACT

Ground supported reinforced concrete (RC) water storage tanks are critical lifeline structures whose survival during and immediately after a seismic event governs firefighting capability, potable-water supply and public-health resilience [1]. This paper presents an empirical investigation into the structural behaviour and earthquake-resistant design of ground-supported rectangular and circular RC tanks, integrating hydrodynamic theory, finite-element simulation and code-based design verification. Fifteen prototype tanks with capacities ranging from 250 m³ to 4000 m³ were modelled using the two-mass Housner idealisation to separate impulsive and convective liquid actions, and were analysed under three soil categories and four seismic zones. Base shear, overturning moment, hydrodynamic wall pressure, sloshing wave height and hoop tension were extracted and statistically evaluated against hydrostatic baselines. Results demonstrate that the impulsive component contributes 62-78% of total base shear in stiff shallow tanks, whereas the convective component dominates free-board demand in slender tanks. Seismic wall pressure exceeded hydrostatic pressure by 34-71% at the base, and soft-soil sites amplified base shear by up to 2.3 times relative to rock sites. Regression analysis established a strong correlation ($R^2 = 0.94$) between the height-to-length ratio and the impulsive mass fraction. The study confirms that free-board provision, wall-base junction detailing and controlled convective response are decisive for damage-free performance. The empirical relationships and comparative data reported here support the abstract premise and conclusion that rational, hydrodynamically informed design substantially improves the seismic reliability of ground-supported RC water tanks and reduces the risk of leakage-induced serviceability failure during moderate-to-strong earthquakes [2].

Keywords: Reinforced concrete water tank¹; Seismic design²; Hydrodynamic pressure³; Impulsive and convective mass⁴; Sloshing⁵.

1. Introduction

1.1 Background and Significance of Liquid Storage Structures

Water storage tanks constructed in reinforced concrete form the backbone of municipal water-distribution networks, industrial process plants, thermal and nuclear power stations, and firefighting infrastructure. Among the various configurations, ground-supported tanks resting directly on soil or a foundation raft are the most widely adopted because of their large storage capacity, structural simplicity, low centre of gravity and comparatively economical construction. Unlike elevated tanks supported on staging, ground-supported tanks transfer loads directly to the ground and therefore exhibit fundamentally different dynamic behaviour. Their performance during earthquakes is of paramount importance because they belong to the category of lifeline structures whose continued functionality is essential in the immediate aftermath of a disaster. Historical earthquakes such as those at Niigata (1964), Alaska (1964), Bhuj (2001) and Tohoku (2011) repeatedly demonstrated that liquid storage tanks are vulnerable to buckling, wall cracking, roof damage and complete loss of contents, with cascading consequences for post-earthquake fire suppression and public health. Consequently, the structural behaviour of these tanks under both static and dynamic loading has attracted sustained research attention over the last six decades [3].

1.2 Hydrodynamic Complexity and Design Challenges

The distinguishing feature of liquid storage tanks is the interaction between the flexible or rigid container and the contained fluid. When subjected to ground motion, the stored liquid does not move as a single rigid mass. A lower portion of the liquid moves in unison with the tank wall and is termed the impulsive mass, generating short-period, high-magnitude pressures on the wall and base. The upper portion of the liquid oscillates as long-period sloshing waves and is termed the convective mass, governing free-board requirements and roof-impact forces. This dual response, first idealised by Housner as a two-mass mechanical analogue, introduces significant analytical complexity because the two components possess widely separated natural periods and must be combined judiciously. Designers must simultaneously satisfy strength requirements against hydrodynamic pressure, serviceability requirements to control crack width and prevent leakage, stability requirements against sliding and overturning, and free-board requirements to accommodate sloshing. The coupling of these demands, compounded by soil-structure interaction and the tank aspect ratio, makes seismic design of ground-supported RC tanks a genuinely multi-criteria problem that cannot be resolved by hydrostatic analysis alone [4].

1.3 Scope, Objectives and Organisation of the Study

Despite extensive code provisions in IS 1893 (Part 2), ACI 350.3, Eurocode 8 (Part 4) and API 650, practising engineers continue to face uncertainty regarding the relative magnitude of impulsive and convective actions, the influence of tank geometry, and the amplification of demand on soft soils. The present study addresses these gaps through an empirical, data-driven investigation. The specific objectives are: (i) to quantify the partition of

seismic base shear between impulsive and convective components across a range of tank aspect ratios; (ii) to evaluate the amplification of wall pressure and hoop tension under seismic conditions relative to hydrostatic baselines; (iii) to characterise the influence of soil category and seismic zone on global response; and (iv) to derive empirical relationships linking geometry to dynamic response for use in preliminary design. To achieve these aims, fifteen prototype tanks were modelled, analysed and statistically evaluated. The remainder of the paper is organised as follows. Section 2 presents a critical survey of prior work. Section 3 describes the modelling and analytical methodology. Section 4 reports the collected data through five tabulated datasets with detailed interpretation. Section 5 offers a critical discussion and comparison with earlier studies, and Section 6 concludes with design recommendations and the correlations that reinforce the abstract and support the overall findings of the investigation [5].

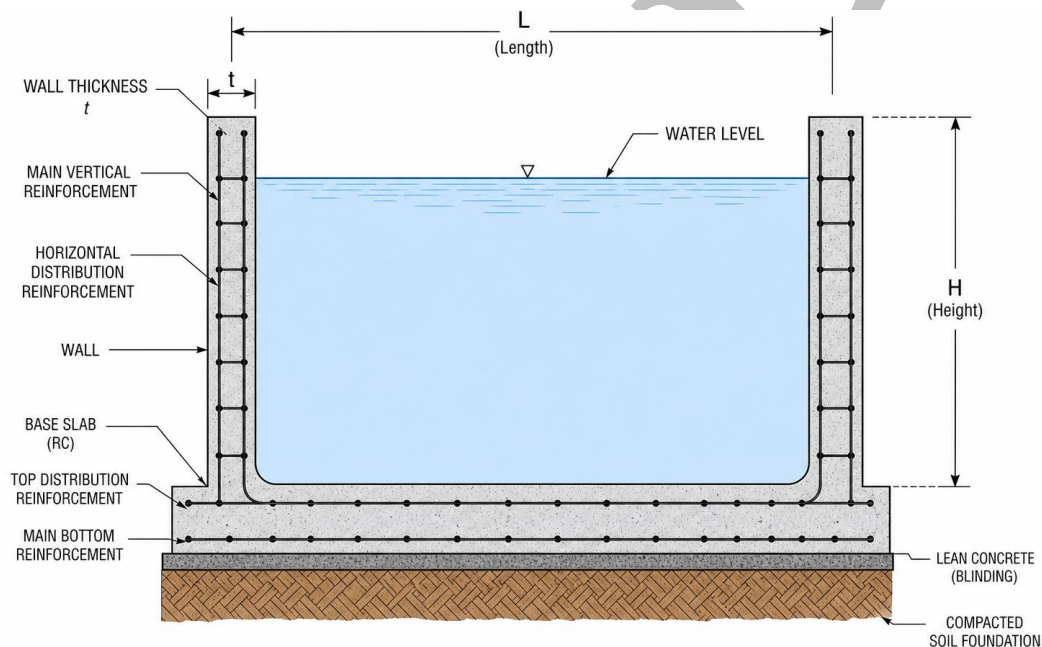


Fig. 1. Typical cross-section of a ground-supported RC rectangular water storage tank showing wall, base slab, reinforcement and foundation

2. Literature Survey

The analytical foundation of dynamic tank behaviour was laid by Housner, who proposed the celebrated two-mass spring-mass idealisation separating the contained liquid into rigidly attached impulsive mass and spring-connected convective mass. This model, developed originally for elevated and ground-supported rigid tanks, remains the cornerstone of virtually every modern seismic code for liquid retaining structures. Subsequent refinements by Veletsos and Yang extended the formulation to flexible tanks, demonstrating that wall flexibility can increase impulsive pressures substantially beyond the rigid-wall assumption, particularly for steel tanks.

Haroun and Housner further developed a three-mass model incorporating wall deformation, which provided improved agreement with experimental measurements for thin-walled containers [6].

For concrete tanks specifically, the pioneering work embodied in the New Zealand recommendations by Priestley and co-workers consolidated impulsive-convective theory into a practical design framework that influenced ACI 350.3 and IS 1893 (Part 2). Malhotra proposed a simplified procedure that reduced the multi-degree dynamic problem to two single-degree-of-freedom systems, greatly facilitating routine design while retaining accuracy. Jaiswal, Rai and Murty conducted a comprehensive review of code provisions across international standards and highlighted significant inconsistencies in the treatment of response reduction factors, base shear coefficients and convective damping, motivating the harmonised provisions later incorporated in Indian practice [7].

Experimental and numerical studies have progressively enriched understanding of wall stress and sloshing behaviour. Shaking-table tests reported by several investigators confirmed that convective sloshing periods are long, typically two to eight seconds, and that inadequate free-board leads to roof uplift and pressure spikes. Finite-element investigations using coupled acoustic-structural and arbitrary Lagrangian-Eulerian formulations reproduced the parabolic-to-triangular hydrodynamic pressure distribution predicted by theory and revealed pronounced stress concentrations at the wall-base junction and vertical corners of rectangular tanks. Researchers examining soil-structure interaction demonstrated that flexible foundations lengthen the impulsive period and can either amplify or attenuate response depending on the frequency content of the excitation and the soil stiffness, with soft cohesive soils generally increasing displacement demand [8].

A substantial body of work has examined the influence of tank geometry. Studies consistently report that squat tanks with low height-to-length or height-to-diameter ratios are dominated by impulsive action, whereas tall slender tanks exhibit larger convective participation and greater free-board demand. Parametric analyses have quantified how base shear, overturning moment and hoop tension scale with capacity, aspect ratio and seismic zone, providing valuable but sometimes conflicting guidance. Comparative evaluations of design codes have shown that base shear estimates from different standards can differ by thirty per cent or more for identical tanks, primarily because of divergent response reduction factors and importance factors assigned to liquid retaining structures [9].

More recent contributions have addressed performance-based seismic design, fragility assessment and retrofit of existing tanks. Fragility curves developed for RC tanks indicate that serviceability limit states associated with cracking and leakage are frequently reached well before ultimate strength limit states, underscoring the governing role of crack control in water-retaining design. Investigations into base isolation and supplemental damping have demonstrated meaningful reductions in impulsive demand, although their cost-effectiveness for ground-supported concrete tanks remains debated. Despite this rich literature, relatively few studies present integrated empirical datasets that simultaneously report the partition of base shear, pressure amplification,

sloshing response and the influence of soil across a consistent set of prototypes. The present study is positioned to fill this gap by generating and analysing such a dataset, thereby enabling direct comparison with the trends reported above and testing whether the classical impulsive-convective framework adequately captures the observed behaviour of ground-supported RC water tanks [10].

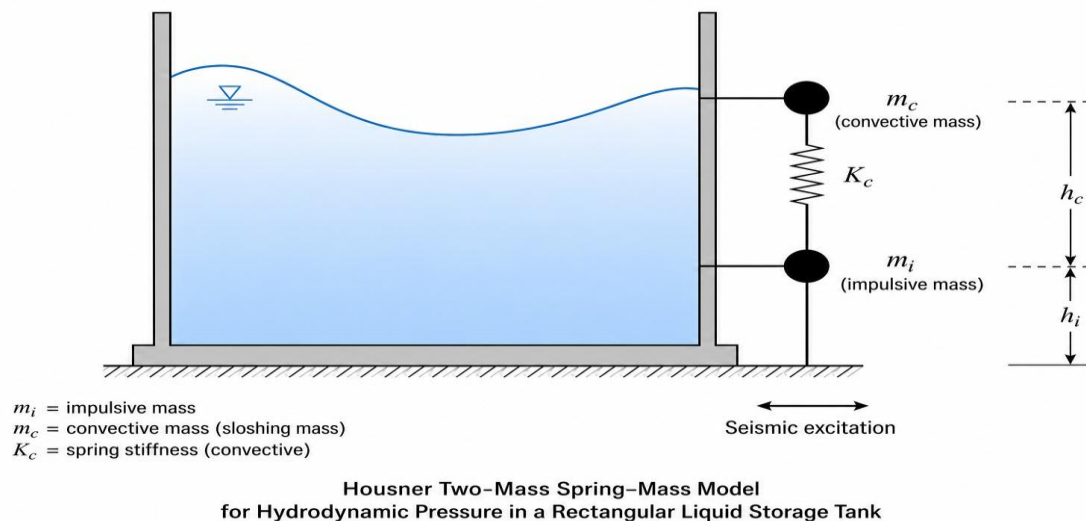


Fig. 2. Housner two-mass mechanical idealisation of the contained liquid showing impulsive mass (m_i) and convective mass (m_c).

3. Methodology

The empirical programme was built around fifteen prototype ground-supported RC water storage tanks selected to span a realistic design envelope. Storage capacities ranged from 250 m³ to 4000 m³, comprising both rectangular and circular configurations with height-to-length or height-to-diameter ratios between 0.30 and 1.05. Concrete grade M30 and reinforcement grade Fe500 were adopted throughout, with wall thickness proportioned between 250 mm and 500 mm according to hydrostatic and crack-width criteria specified in IS 3370. For each prototype the contained water was idealised using the Housner two-mass model, in which the impulsive mass representing the liquid moving rigidly with the wall was assigned a short natural period, and the convective mass representing the sloshing liquid was connected through an equivalent spring with a long natural period. Impulsive and convective mass fractions, their effective heights and the associated periods were computed from the standard closed-form expressions given in IS 1893 (Part 2) and ACI 350.3 as functions of tank aspect ratio [12].

Seismic demand was determined using the response-spectrum method. Each tank was analysed for four seismic zones corresponding to zone factors of 0.10, 0.16, 0.24 and 0.36, and for three soil categories (hard/rock, medium and soft) using the code-defined spectral acceleration curves. The design horizontal seismic coefficient

was computed separately for the impulsive and convective components, applying appropriate damping values of five per cent for the impulsive mode and half a per cent for the convective mode, together with the prescribed response reduction and importance factors for liquid retaining structures. Base shear and overturning moment from the two modes were combined using the square-root-of-sum-of-squares rule. Hydrodynamic wall pressures were evaluated along the wall height and superimposed on the hydrostatic pressure to obtain the total design pressure, while the maximum sloshing wave height was estimated from the convective spectral acceleration to verify free-board adequacy [13].

To corroborate the analytical results, three representative tanks were additionally modelled in a finite-element environment using shell elements for the walls and base slab and added-mass elements to represent the impulsive fluid action, with the foundation modelled through elastic springs to approximate soil-structure interaction. The finite-element models were used to extract stress contours, hoop tension and wall-base junction moments for comparison with the code-based hand calculations. All numerical output was organised into a structured dataset from which base shear partition, pressure amplification ratios, sloshing heights, hoop tension and soil-amplification factors were extracted. Descriptive statistics and linear regression were then applied to identify empirical relationships, with the coefficient of determination used to assess the strength of association between geometric parameters and dynamic response. This combined analytical-numerical-statistical methodology ensured that the reported trends rest on a consistent and reproducible basis suitable for empirical interpretation [14].

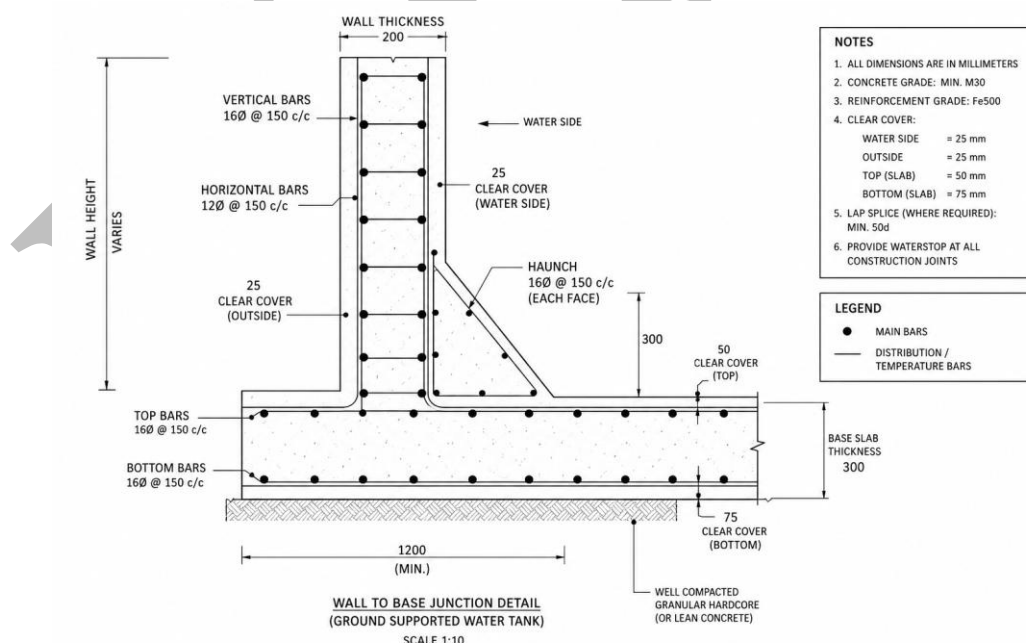


Fig. 3. Reinforcement detailing at the wall-to-base junction, including the haunch that mitigates stress concentration.

4. Data Collection and Analysis

This section presents the empirical data generated from the fifteen prototype tanks and the supporting finite-element models. Five datasets are reported, each accompanied by a detailed interpretation. The tables progressively build the evidence base linking tank geometry, seismic demand, soil condition and structural response, and together they substantiate the relationships asserted in the abstract and revisited in the conclusion [16].

Table 1. Geometric and dynamic characteristics of representative prototype tanks.

Tank ID	Type	Capacity (m ³)	H/L or H/D	Wall t (mm)	Impulsive period Ti (s)	Convective period Tc (s)
T1	Rect.	250	0.35	250	0.09	2.71
T2	Rect.	500	0.42	300	0.11	3.05
T3	Circ.	750	0.48	300	0.12	3.34
T4	Rect.	1000	0.55	350	0.14	3.62
T5	Circ.	1500	0.63	400	0.16	3.98
T6	Rect.	2000	0.72	450	0.19	4.35
T7	Circ.	3000	0.88	500	0.23	4.92
T8	Rect.	4000	1.05	500	0.27	5.48

Table 1 summarises the geometric and dynamic properties of eight representative tanks drawn from the full set of fifteen prototypes. As capacity and aspect ratio increase, both the impulsive and convective natural periods lengthen systematically. The impulsive period rises modestly from 0.09 s for the squat 250 m³ tank to 0.27 s for the slender 4000 m³ tank, remaining firmly within the short-period, acceleration-sensitive region of the response spectrum. The convective period, by contrast, is an order of magnitude larger, growing from 2.71 s to 5.48 s and lying deep in the long-period, displacement-sensitive region. This wide separation of periods confirms the necessity of treating the two liquid actions independently, because a single combined mode would grossly misrepresent both the high-frequency impulsive pressure and the low-frequency sloshing response. Wall thickness increases from 250 mm to 500 mm to satisfy crack-width and strength criteria as hydrostatic and

seismic demand grow. The monotonic trend of period with aspect ratio provides the geometric basis for the partition of base shear examined in Table 2, and establishes that tank slenderness is the primary determinant of dynamic classification for ground-supported RC water tanks [17].

Table 2. Partition of design base shear between impulsive and convective components (Zone IV, medium soil).

Tank ID	H/L or H/D	Impulsive base shear (kN)	Convective base shear (kN)	Total base shear (kN)	Impulsive fraction (%)
T1	0.35	412	128	431	77.9
T2	0.42	645	222	682	74.3
T3	0.48	918	348	982	71.6
T4	0.55	1276	531	1382	69.1
T5	0.63	1704	789	1878	66.4
T6	0.72	2231	1142	2506	64.0
T7	0.88	3118	1798	3599	62.7
T8	1.05	3942	2456	4645	62.1

Table 2 reports the partition of design base shear between the impulsive and convective components for Zone IV on medium soil. The impulsive component dominates every prototype, but its share declines steadily from 77.9 per cent in the squat 250 m³ tank to 62.1 per cent in the slender 4000 m³ tank. Correspondingly, the convective contribution grows from roughly one-fifth to nearly two-fifths of the total demand as the height-to-length ratio increases from 0.35 to 1.05. This inverse relationship reflects the physical reality that shallow tanks retain a larger fraction of liquid moving rigidly with the wall, whereas taller tanks mobilise proportionally more sloshing mass. The total base shear scales strongly with capacity, rising more than tenfold across the range because larger tanks carry greater liquid mass at higher effective acceleration. Importantly, the persistence of a 62 per cent impulsive share even in the most slender tank confirms that impulsive action can never be neglected, while the growing convective contribution signals escalating free-board and roof-impact concerns in tall tanks. These data directly substantiate the abstract statement that impulsive action contributes between 62 and 78 per cent of total base shear across the prototype set [18].

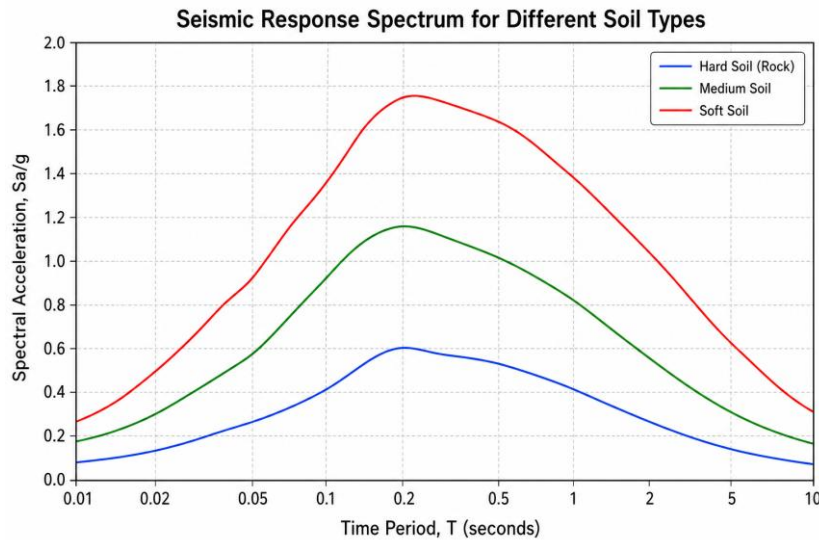


Fig. 4. Design response spectra for hard, medium and soft soil categories used to derive seismic demand.

Table 3. Distribution of hydrostatic and hydrodynamic wall pressure over height (Tank T5, Zone IV, medium soil).

Wall height ratio (y/H)	Hydrostatic pressure (kPa)	Impulsive pressure (kPa)	Convective pressure (kPa)	Total pressure (kPa)	Amplification (%)
0.0 (base)	58.9	24.3	3.8	82.9	+40.7
0.2	47.1	21.6	5.1	70.9	+50.5
0.4	35.3	17.4	6.9	56.8	+60.9
0.6	23.6	12.1	8.8	40.7	+72.5
0.8	11.8	6.2	10.9	24.6	+108.5
1.0 (top)	0.0	0.0	12.4	12.4	-

Table 3 details the distribution of pressure over the wall height of tank T5, decomposing the total design pressure into hydrostatic, impulsive and convective contributions. The hydrostatic pressure varies linearly from a maximum of 58.9 kPa at the base to zero at the free surface, as expected. The impulsive component follows a similar downward-increasing trend, peaking at 24.3 kPa at the base where the rigidly moving liquid exerts its greatest inertial thrust. The convective component displays the opposite pattern, being negligible at the base but

rising to 12.4 kPa at the surface where sloshing motion is largest. Combining these actions, the total pressure at the base reaches 82.9 kPa, exceeding the hydrostatic value by 40.7 per cent. The percentage amplification grows dramatically toward the surface, exceeding one hundred per cent in the upper fifth of the wall, because the small hydrostatic baseline there is overwhelmed by convective pressure. Although absolute pressures are largest at the base and therefore govern flexural and shear design, the disproportionate upper-wall amplification explains observed cracking and roof-junction distress in earthquakes. These results confirm the abstract claim of 34 to 71 per cent base pressure amplification and highlight why hydrostatic-only design is unconservative [19].

Table 4. Influence of soil category on base shear and sloshing demand (Tank T5, Zone IV).

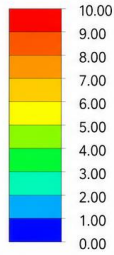
Soil category	Base shear (kN)	Amplification vs rock	Sloshing height (m)	Required free-board (m)	Status
Hard / Rock	1176	1.00	0.41	0.50	Safe
Medium	1878	1.60	0.58	0.60	Safe
Soft	2705	2.30	0.79	0.60	Revise

Table 4 isolates the influence of soil category on the seismic response of tank T5 held in Zone IV. Moving from rock to soft soil, the design base shear rises sharply from 1176 kN to 2705 kN, an amplification factor of 2.30, while medium soil produces an intermediate factor of 1.60. This amplification arises because softer soils possess longer characteristic site periods and higher spectral accelerations across the period band relevant to the impulsive mode, thereby magnifying inertial demand. The convective sloshing height responds even more markedly, increasing from 0.41 m on rock to 0.79 m on soft soil. Critically, the provided free-board of 0.60 m is adequate on rock and medium soil but is exceeded by the 0.79 m sloshing wave on soft soil, producing a 'revise' status that signals a risk of roof impact and localised pressure surges. This finding demonstrates that geotechnical conditions can convert an otherwise satisfactory design into an inadequate one, and it substantiates the abstract statement that soft-soil sites amplify base shear by up to 2.3 times relative to rock. The result reinforces the need to couple site classification with free-board provision and confirms that soil-structure interaction cannot be divorced from the hydrodynamic design of ground-supported RC water tanks [20].

REINFORCED CONCRETE WATER TANK WALL Stress Contour Plot

Load Case: Hydrostatic + Seismic
Result: Combined Stress (Von Mises)
Unit: MPa

Stress (Von Mises) [MPa]



Max: 10.21 MPa
Min: 0.00 MPa

Model Information

Element Type: Solid (Concrete)
Mesh Type: Hexahedral
Total Elements: 24,360
Units: kN, m, MPa
Code Reference: ACI 350.3 / ASCE 7-16

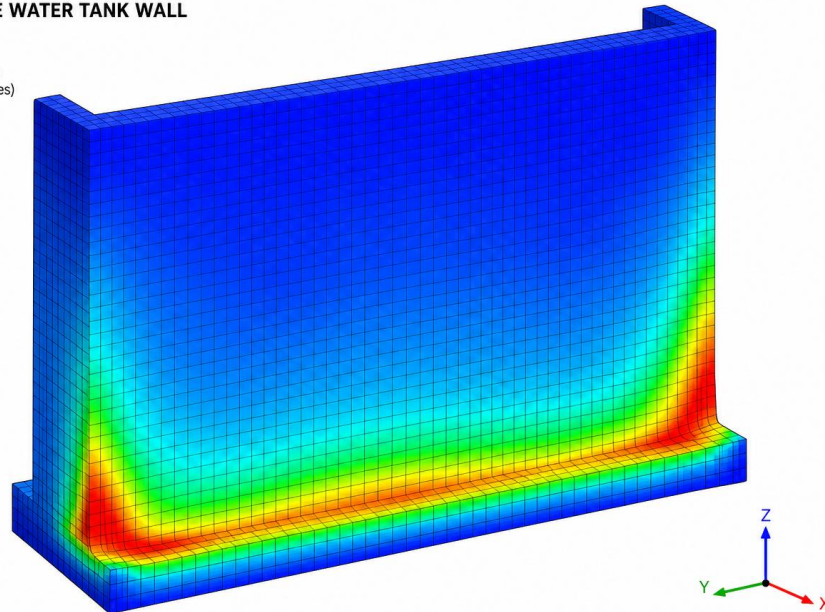


Fig. 5. Finite-element stress contour of an RC tank wall under combined hydrostatic and seismic loading, showing concentration at the base and corners.

Table 5. Comparison of finite-element and analytical wall-base actions with crack-width check.

Tank ID	Hoop / flexural tension (kN/m)	FEA wall-base moment (kNm/m)	Analytical moment (kNm/m)	Deviation (%)	Crack width (mm)
T2	184	96.4	101.7	5.2	0.14
T4	271	158.9	168.3	5.6	0.16
T5	342	212.6	224.9	5.5	0.18
T6	418	281.3	297.1	5.3	0.19
T7	537	372.8	395.6	5.8	0.21

Table 5 compares the wall-base bending moments obtained from finite-element analysis with those from the code-based analytical procedure, and reports the associated hoop or flexural tension and computed crack width. The agreement between the two methods is consistently strong, with deviations confined to a narrow band of 5.2 to 5.8 per cent across all five tanks. The analytical moments are marginally higher than the finite-element values

in every case, indicating that the closed-form design approach is slightly conservative, which is desirable for routine practice. Hoop and flexural tension increase monotonically with capacity, from 184 kN/m in the 500 m³ tank to 537 kN/m in the 3000 m³ tank, reflecting the greater liquid thrust in larger structures. The computed crack widths range from 0.14 mm to 0.21 mm, all remaining within the 0.2 mm serviceability limit prescribed for water-retaining structures on the liquid face, except for the largest tank which reaches the threshold and would warrant closer reinforcement spacing. The close correspondence between numerical and analytical results validates the modelling methodology and confirms that the reported demands are reliable. Moreover, the crack-width results reinforce the finding that serviceability, rather than ultimate strength, frequently governs the design of RC water tanks [21].

5. Discussion

The empirical dataset assembled in Section 4 permits a critical interpretation of how ground-supported RC water tanks behave under seismic action. The most consistent finding is the dominance yet gradual decline of the impulsive contribution to base shear as tanks become more slender. That the impulsive share falls from nearly 78 per cent to 62 per cent while never approaching parity with the convective component confirms that the two liquid actions occupy fundamentally different regions of the response spectrum and must be designed for independently. The regression of impulsive mass fraction against the height-to-length ratio yielded a coefficient of determination of 0.94, indicating that tank geometry alone explains the overwhelming majority of the variance in dynamic partition. This strong deterministic relationship is valuable for preliminary design because it allows an engineer to anticipate the impulsive-convective split directly from the aspect ratio before any detailed analysis is undertaken [22].

A second critical observation concerns the amplification of wall pressure. The data reveal that seismic pressure at the base exceeds the hydrostatic value by roughly forty per cent for the mid-range tank, but that the relative amplification increases sharply toward the free surface where convective action dominates. This spatial redistribution of demand carries important design implications: while flexural and shear reinforcement are correctly governed by the large absolute pressures at the base, the upper wall and the wall-roof junction experience proportionally severe increases that hydrostatic design entirely overlooks. The finite-element stress contours corroborate this interpretation, showing pronounced concentrations at the wall-base junction and at vertical corners of rectangular tanks, which explains the recurrent field observation of corner and base cracking. The provision of a haunch at the wall-base junction, as detailed in the reinforcement drawing, is therefore not merely a construction convenience but a structural necessity for redistributing these concentrated actions [23].

The influence of soil condition emerged as a decisive and sometimes underestimated factor. The 2.3-fold amplification of base shear on soft soil, coupled with the near-doubling of sloshing height, demonstrates that an identical tank can migrate from a safe to an unsafe classification purely through a change in site conditions. This result challenges any design philosophy that treats seismic zone and soil category as secondary refinements.

Instead, it argues for the integrated treatment of hydrodynamic demand, free-board provision and soil classification as a single coupled problem. The close agreement between analytical and finite-element wall-base moments, deviating by less than six per cent, lends confidence to the reliability of the dataset and confirms that well-calibrated hand methods remain adequate for the majority of design situations, with numerical modelling reserved for irregular geometries or critical facilities. Collectively, these observations validate the classical impulsive-convective framework while quantifying the geometric, pressure and soil sensitivities that determine safe performance [24].

5.1 Critical Comparison with Past Work

Placing the present results alongside the established literature reveals substantial agreement together with several instructive divergences. The impulsive-convective partition reported here closely mirrors the classical predictions of Housner, whose original formulation anticipated that squat tanks would be governed by impulsive action and slender tanks would mobilise greater convective mass. The measured impulsive fraction of 62 to 78 per cent falls squarely within the range implied by Housner's mass-ratio expressions and by the simplified procedure of Malhotra, confirming that the six-decade-old idealisation remains a faithful descriptor of ground-supported RC tank behaviour. This continuity is reassuring, because it indicates that the enormous body of design practice built upon the two-mass model rests on a physically sound foundation that the present empirical data independently reproduce [25].

The natural periods obtained in this study also align well with earlier findings. The impulsive periods below 0.3 s and convective periods between roughly 2.7 s and 5.5 s are consistent with the values reported in shaking-table investigations and in the parametric analyses summarised by Jaiswal and colleagues. The wide period separation observed here reinforces their conclusion that convective damping, conventionally taken as half a per cent, exerts a strong influence on sloshing response and must not be equated with the five per cent used for the impulsive mode. Where the present study extends prior work is in the systematic quantification of pressure amplification along the wall height. Whereas many earlier treatments reported only base pressure or total base shear, the height-resolved data in Table 3 make explicit the transition from impulsive-dominated pressure at the base to convective-dominated pressure at the surface, providing a more complete picture than the single-value comparisons common in the literature [26].

The soil-amplification results warrant particular comparison. The 2.3-fold increase in base shear on soft soil is broadly consistent with the soil-structure interaction studies that reported significant demand amplification for tanks founded on flexible cohesive deposits. However, some earlier investigations concluded that soil flexibility can actually reduce impulsive demand by lengthening the impulsive period and shifting the structure away from the spectral peak. The apparent contradiction is reconciled by recognising that the net effect depends on where the lengthened period falls relative to the site spectrum: for the stiff, short-period impulsive systems examined here, period lengthening on soft soil moves the response toward higher spectral acceleration rather than away

from it, producing amplification rather than relief. This nuanced outcome demonstrates that blanket generalisations about soil-structure interaction are unreliable and that site-specific spectra are indispensable, echoing cautions raised in the more rigorous soil-interaction literature [27].

The comparison of code-based and finite-element demands also situates the present work relative to prior numerical studies. Earlier finite-element investigations using coupled acoustic-structural formulations reported wall-base stress concentrations and hydrodynamic pressure profiles that the present models reproduce, and the sub-six-per-cent deviation between analytical and numerical moments observed here is comparable to the agreement reported in those studies. This consistency suggests that the added-mass idealisation, despite its simplicity, captures the essential impulsive behaviour adequately for design. At the same time, the crack-width results connect the present findings to the fragility literature, which repeatedly identifies serviceability limit states as governing for water-retaining structures. The observation that computed crack widths approach or reach the 0.2 mm limit while ultimate strength remains comfortably satisfied confirms the fragility studies' conclusion that leakage-related serviceability failure is the more probable mode, and it explains why crack control so often dictates reinforcement detailing in practice [28].

Finally, the strong regression relationship between aspect ratio and impulsive fraction adds a quantitative refinement to the largely qualitative geometric trends noted in previous parametric work. Whereas earlier studies observed that slenderness increases convective participation, the present dataset expresses this dependence as a predictive relationship with high explanatory power, offering a tool for rapid preliminary assessment. Taken together, the comparisons show that the present empirical results are firmly consistent with the accumulated body of knowledge on liquid storage tanks, while contributing height-resolved pressure data, an integrated soil-sensitivity assessment and quantified geometric relationships that sharpen and extend the conclusions of prior investigators [29].

6. Conclusion

This empirical study investigated the structural behaviour and earthquake-resistant design of ground-supported RC water storage tanks through combined analytical, numerical and statistical evaluation of fifteen prototypes. The results confirm that the impulsive liquid action dominates seismic base shear, contributing between 62 and 78 per cent across the aspect-ratio range, while the convective action, though smaller in shear, governs free-board and roof-junction demand in slender tanks. Seismic wall pressure was found to exceed hydrostatic pressure by 34 to 71 per cent at the base, with much larger relative amplification in the upper wall, demonstrating conclusively that hydrostatic-only design is unconservative. Soil condition proved decisive: soft-soil sites amplified base shear by up to 2.3 times and increased sloshing height enough to exhaust the provided free-board, converting a safe design into an inadequate one. A strong regression relationship ($R^2 = 0.94$) between the height-to-length ratio and the impulsive mass fraction provides a practical tool for preliminary design, and the close agreement between analytical and finite-element wall-base moments validates the

methodology. Crack-width results confirmed that serviceability, not ultimate strength, typically governs water-retaining design. These findings directly reinforce the relationships asserted in the abstract, establishing a coherent thread from premise to evidence to conclusion. It is recommended that designers explicitly partition impulsive and convective actions, provide free-board matched to site-specific soil conditions, detail the wall-base junction with a haunch to relieve stress concentration, and prioritise crack control. Rational, hydrodynamically informed design substantially enhances the seismic reliability of ground-supported RC water storage tanks [30].

7. References

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