



Protecting Against Sudden Shakings: From a Cup to a Full-Scale Tank Without a Single Internal Baffle

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Abstract: This study investigates whether the seismic sloshing protection of large liquid storage tanks can be achieved solely through geometric redesign, without recourse to a single internal baffle, base isolator, or supplementary damping device. Motivated by the persistent vulnerability of conventional circular cylindrical tanks to earthquake-induced sloshing damage—documented in failures ranging from elephant-foot buckling to floating roof collapse—the research challenges the century-old design canon that treats the circular cross-section as the default and immutable choice for liquid containment. Drawing inspiration from the commonplace observation that a square cup dampens liquid oscillations more rapidly than a round one, the investigation scales this intuition to industrial dimensions through a dual-methodology architecture that tightly couples small-scale shaking table experiments with high-fidelity computational fluid dynamics simulations. The experimental program tested a full factorial matrix of 400-millimeter scale models encompassing four geometric variables: cross-sectional polygonality (square, hexagonal, octagonal), wall inclination (vertical versus 7.5- and 15-degree inward taper), floor topography (flat versus domed with a central rise of one-tenth the liquid depth), and internal surface texture (smooth versus longitudinally grooved). These models were subjected to a curated suite of seven recorded earthquake ground motions scaled to a uniform peak ground acceleration of 0.5g. The computational model, developed in OpenFOAM using the volume-of-fluid method with k-omega SST turbulence closure, was validated against the experimental data to within 1.8 percent for fundamental frequency and 6.2 percent for peak wave height. The validated solver was then extrapolated, using Froude similarity, to a full-scale 100,000-barrel prototype. A Taguchi design-of-experiments framework efficiently surveyed the four-dimensional geometric parameter space through 18 full-scale simulations. The results demonstrate that the synergistic combination of a square cross-section, a 15-degree inward wall taper, a domed floor rising to 10 percent of the liquid depth, and heavy longitudinal surface striations achieves an 80 percent reduction in normalized peak convective wave height (from 0.187 to 0.038 of the liquid depth), a near-tripling of the convective damping ratio (from 0.42 to 1.24 percent), and a 99 percent increase in the fundamental sloshing frequency (from 0.126 to 0.251 Hz) relative to an unbaffled circular baseline. When compared directly to a conventionally baffled circular tank designed according to API 650 recommendations, the optimized geometric tank exhibited a 7 percent lower peak wave height, a 5 percent higher damping ratio, and an 86 percent higher fundamental frequency, at the expense of an 18 percent increase in peak wall stress that remains within code-allowable limits. The four geometric mechanisms operate synergistically: the square cross-section provides preventive frequency detuning, the inward taper constrains convective mass participation kinematically, the domed floor scatters the standing wave pattern through topographic refraction, and the textured surface contributes distributed skin-friction damping. All five research hypotheses were confirmed, and the central proposition—that pure geometric redesign can match or exceed the performance of internal baffles—is supported by the numerical evidence. The findings establish a new paradigm of intrinsic, passive, shape-driven seismic protection that eliminates the lifecycle costs, inspection burdens, and corrosion vulnerabilities associated with internal baffles, offering a resilient and maintenance-free alternative for critical liquid storage infrastructure.

Keywords: seismic sloshing, geometric tank design, passive seismic protection, polygonal storage tanks, sloshing damping, fluid-structure interaction, oil storage tanks.



1. Introduction

The safeguarding of critical infrastructure against the destructive consequences of seismic events represents one of the most persistent and multifaceted challenges in civil and mechanical engineering. Among the various components of modern industrial civilization, large-scale liquid storage tanks occupy a uniquely vulnerable position. These structures, which are indispensable to the global energy supply chain, serve as the primary receptacles for vast quantities of crude oil, liquefied natural gas, and refined petroleum products. The uninterrupted functionality of these tanks is not merely an issue of economic efficiency, but a cornerstone of societal stability, and the resilience of transport corridors (Aghazadeh Dizaji & Ahmadian, 2016) further ensures energy security, as any prolonged disruption can cascade into fuel shortages, environmental catastrophes, and significant economic downturns (Gheitarani et al., 2024b; Norouzian & Gheitarani, 2023; Norouzian & Gheitarani, 2025). The historical record offers a stark testament to this vulnerability, with major seismic events repeatedly demonstrating that standard cylindrical tanks can fail catastrophically under strong ground motion (Brunesi et al., 2015). The vulnerability of urban areas to earthquakes necessitates robust mitigation strategies (Ghadarjani et al., 2013; Gheitarani et al., 2013a), and public participation in the rehabilitation of deteriorated housing (Ghadarjani & Gheitarani, 2013) is crucial. The 1964 Niigata earthquake, the 1994 Northridge event, the 1999 Kocaeli earthquake, and the 2011 Tohoku earthquake all resulted in widespread tank damage, including elephant-foot buckling (Aghazadeh Dizaji, 2017), sliding, weld rupture, and floating roof collapse. Each failure mode carries the risk of releasing tens of thousands of cubic meters of flammable liquid, often followed by fires and irreversible environmental contamination (Chang & Lin, 2006; Farrokhirad & Gheitarani, 2024), and the need for proper waste management (Kahvand et al., 2015) is evident. Consequently, improving the seismic performance of storage tanks has been recognized as an urgent engineering imperative (Shih & Babcock, 1984), and the quality of life of affected communities must be considered (Gheitarani et al., 2020; Gheitarani et al., 2024a; Khanian et al., 2019; Zakerhaghighi et al., 2015).

A substantial body of research and industrial practice has been dedicated to this cause, leading to the development of numerous seismic protection strategies now codified in international standards (Caprinuzzi et al., 2020). Traditional approaches involve increasing structural robustness through thicker bottom shell courses and high-ductility steels and advanced materials like polymer concrete (Aghazadeh Dizaji, 2024b), as well as anchoring tanks to massive foundations to prevent uplift (Haroun, 1983). Retrofitting techniques such as CFRP wrapping have been shown to improve the buckling behavior of dented cylindrical shells (Aghazadeh Dizaji et al., 2023; Aydin et al., 2020), and the optimal deployment of FRP in strengthening concrete structures has been studied (Aghazadeh Dizaji, 2024c). Comparative assessments of CFRP and steel jacketing for post-fire strengthening have also been conducted (Aghazadeh Dizaji & Aydin, n.d.). More recent strategies include base isolation, where the entire tank is decoupled from the ground by elastomeric or sliding bearings, a technique that has been the subject of extensive numerical and experimental investigations (Bagheri & Farajian, 2016). The effects of near-fault ground motions on isolated tanks have also been examined,

revealing complex nonlinear behaviors that must be accounted for in design (Bagheri & Farajian, 2018). Seismic risk analysis considering possible pulse effects in nearby areas has been investigated (Sadigh et al., 2023; Sarabi et al., 2023). In parallel, internal baffles—ring-shaped plates welded to the tank wall—have become a widely adopted fluid-dynamic countermeasure, acting as hydrodynamic dampers that break up the coherent sloshing wave and dissipate kinetic energy (Biswal et al., 2003). More recent work has explored nonlinear performance evaluation methodologies for such tanks, providing tools for assessing response beyond the elastic range (Çelik & Köse, 2020). Dynamic analysis methods, such as those employing genetic algorithms, have been applied to concrete structures (Dehghan et al., 2024a), and the use of GIS for crisis management and detecting unsafe urban spaces has been explored (Dehghan et al., 2024b; M. A. G. et al., 2024). These methods, whether structural strengthening, base isolation, or internal baffling, share a common conceptual foundation: they introduce an additional layer of defense, a supplementary system that adds complexity and maintenance demands to the tank.

This conventional paradigm, while effective, leads to a fundamental question that forms the intellectual departure point for the present study. Is it possible to achieve a significant reduction in seismic sloshing damage without adding any supplementary devices or relying on active control systems? The question challenges the assumption that enhanced protection necessitates enhanced complication. It invites a radical rethinking of the primary design variable that has remained largely canonical for over a century: the geometry of the tank itself. The standard vertical circular cylinder, favored for its material efficiency under uniform hoop stress, is, from a hydrodynamic standpoint, the most permissive geometry for the formation of a stable, traveling sloshing wave that can undergo resonant amplification. Yet, the idea that geometry alone might suppress sloshing has only recently gained traction, as seen in the growing body of research on non-circular and flexible containers (Hosseini & Daneshmand, 2024). The present investigation posits that a pure geometric redesign—manipulating cross-sectional shape, wall inclination, floor topography, and internal surface texture—can serve as the sole mechanism for sloshing suppression, without a single internal baffle. Such geometric optimization aligns with principles of urban sustainability and flexibility (Gheitarani & Norouzian, 2024a; Gheitarani & Norouzian, 2024b).

This overarching ambition necessitates a structured investigation that probes several interconnected uncertainties, the first of which revolves around the effect of cross-sectional polygonality on the fundamental sloshing frequency. A circular tank exhibits a well-defined natural frequency for the first convective mode, classically described by the work of Housner (1957), who formulated the widely used impulsive-convective mass analogy. However, what becomes of this frequency when the cross-section is a square, a hexagon, or a rectangle of a specific aspect ratio? The breaking of continuous rotational symmetry leads to mode splitting and energy transfer, but a systematic comparative mapping of these shifts across geometries relevant to large-scale storage has not been conducted. The question is not simply whether a square tank is less susceptible, but precisely which polygonal shape yields the maximum deviation from the earthquake's dominant frequency

band, thereby minimizing the risk of resonance. This line of inquiry is informed by recent probabilistic evaluations of sloshing wave height, which underscore the need to consider spectral variability in seismic demand (Merino et al., 2022).

A second uncertainty pertains to the role of the tank's vertical profile. The influence of a tapered or inclined wall on sloshing dynamics is a subtle interplay of mass distribution and free surface constraint. A container that narrows toward the top restricts the free surface area as the liquid level rises, potentially limiting the effective mass of the sloshing component and altering the convective pressure distribution on the wall. Yet, an inverse taper might encourage wave breaking at the boundaries, converting organized kinetic energy into turbulent dissipation. The study must therefore interrogate which tapering strategy, if any, provides a tangible damping benefit without unreasonably complicating the construction sequence. This investigation is motivated by recent assessments of steel tank design procedures, which highlight the importance of accurately capturing geometric nonlinearities in dynamic analysis (Nascimbene et al., 2025). The response of vertical concrete structures to alternating loads has also been studied (Gheitarani et al., 2024c).

A further dimension of the geometric approach lies in the micro-scale texture of the wetted boundary. The traditional design assumption is that the tank wall is hydraulically smooth, an assumption that simplifies analytical and numerical models but neglects the potential of surface roughness to act as a distributed, passive damper. Small-scale vertical grooves or embossed patterns could theoretically increase the skin friction coefficient significantly, extracting energy from the sloshing wave. The magnitude of this effect remains poorly quantified for the Reynolds numbers and wave amplitudes characteristic of seismically excited storage tanks. The question, then, is whether a technically feasible wall texture can provide a measurable contribution to hydrodynamic damping, and whether this contribution is synergistic with macro-geometric changes. Such questions are part of a broader recent advancement in seismic analysis and design of liquid storage tanks (Hatzigeorgiou & Asteris, 2025).

The fourth pivotal inquiry concerns the geometry of the tank floor. A flat bottom has been the universal standard, facilitating construction on a compacted gravel ring. However, introducing a shallow, dome-like rise at the center fundamentally alters the liquid depth profile, making it non-uniform. This non-uniformity directly affects the local wave speed, as shallow-water wave celerity depends on the square root of depth, and could prevent the formation of a coherent standing wave pattern. The question becomes one of optimization: what profile of floor elevation maximizes the destructive interference of sloshing modes while minimizing the loss of storage volume? This inquiry is partly inspired by research on soil-structure interaction effects, which has shown that foundation flexibility can significantly alter the dynamic response of tanks (Veletsos & Tang, 1990). Additionally, recent work on combined tank-isolator-foundation systems has highlighted the need to consider multi-component interactions (Panchal & Joshi, 2024).

Flowing from these specific uncertainties, the research is guided by a set of explicit, testable propositions. It is hypothesized that a tank with a square or octagonal cross-section will exhibit a fundamental

sloshing frequency significantly higher than that of an equivalent-volume circular tank, thereby shifting the structure's response spectrum away from the predominant earthquake energy band. Second, it is posited that coupling a polygonal cross-section with a wall that tapers inward can reduce the peak convective wave height by over fifty percent compared to a vertical cylindrical baseline. Third, it is conjectured that a non-flat tank floor featuring a central rise of at least one-tenth of the liquid depth will disrupt the formation of the fundamental antisymmetric sloshing mode. Fourth, it is proposed that vertical striations on the internal shell can contribute a quantifiable increment of supplemental damping. The central unifying hypothesis is that a synergistic combination of these geometric interventions, without a single internal baffle or other ancillary device, can achieve a level of sloshing suppression that is structurally equivalent or superior to that provided by conventional baffle-based designs. This hypothesis is tested not only against a conventional baffled tank but also in the context of emerging technologies such as oblate spheroid base isolators (Wang & Wang, 2021) and locally resonant metafoundations (Wenzel et al., 2020), which represent the state-of-the-art in seismic protection but introduce significant mechanical complexity. The performance evaluation of municipal plans using balanced scorecards (Norouzian & Guyadeen, 2025) mirrors the need for rigorous assessment frameworks.

To substantiate or challenge these hypotheses, the investigative framework must bridge an immense scale gap. The study, therefore, traverses a deliberate trajectory from a small-scale cup to a full-scale 100,000-barrel tank. Small-scale physical models, constructed with precisely controlled geometries and instrumented on shaking tables, offer the advantage of direct empirical observation under repeatable conditions. The experimental data serve as the empirical anchor for a comprehensive computational fluid dynamics campaign, wherein finite-volume simulations resolve the three-dimensional, two-phase flow inside tanks of varying geometry under realistic seismic acceleration time-histories. These numerical models, validated against the small-scale physical tests, become the primary tool for exploring the parameter space at full industrial scale. This dual-methodology structure, moving from verified small-scale phenomenology to a validated industrial-scale prototype, is designed to ensure that the conclusions drawn are neither scale-specific artifacts nor unanchored theoretical exercises. The significance of the work, should the hypotheses find robust support, extends beyond the immediate domain of earthquake engineering, suggesting a path toward intrinsically safe tanks whose resistance to earthquakes is inherent to their form. Such an approach aligns with the resilience philosophy and is particularly relevant for regions with limited technical infrastructure, as highlighted by recent studies on tank performance in high seismicity areas (Erkmen, 2024). The need for such intrinsic protection is further underscored by the complex behavior observed in tanks on flexible soil, where conventional add-on devices may not perform as intended (Tsarouchas & Manolis, 2025). Furthermore, the application of roller-compacted concrete in industrial pavements (Gheitarani et al., 2024d) and building greening evaluation using BIM (Samami et al., 2024), along with daylighting potential in architectural design (Maleki et al., 2024), the design of footpaths and sidewalks in vulnerable contexts (Naghbi Iravani et al., 2024c), the role of urban street configuration on commercial establishments (Zaker Haghighi et al., 2014), the impact of contemporary urban designs on

pedestrian-vehicle conflict (Gheitarani et al., 2013b), and the vitality of traditional markets (Khanian et al., 2013) all underscore the critical importance of thoughtful, systematic design optimization. This study, by providing the first systematic, numerically rigorous comparison of multiple geometric strategies from the infinitesimal scale of a cup to the monumental scale of an industrial oil tank, aspires to lay the quantitative foundation for this philosophy, furnishing design engineers with the predictive tools and validated performance data necessary to move beyond the canon of the circular cylinder.

2. Theoretical

The interaction between a contained liquid and the structure that holds it during an earthquake is governed by a complex interplay of fluid dynamics, structural mechanics, and wave physics, a confluence that has been formalized over decades of theoretical and experimental inquiry. At the heart of this interaction lies the phenomenon of sloshing, defined as the organized, low-frequency oscillation of a liquid mass within a partially filled container subjected to external excitation. The sloshing motion in large storage tanks is distinct from the high-frequency, impulsive component of fluid response, which behaves as if the liquid were rigidly attached to the tank wall. The sloshing, or convective, component involves the bulk movement of the fluid, characterized by a free surface that rises and falls in coherent, large-amplitude waves capable of exerting substantial hydrodynamic pressures on the tank roof and upper shell. Understanding this duality—the impulsive mass that accelerates in phase with the tank and the convective mass that oscillates at its own natural frequency—is foundational to any attempt at seismic protection, whether conventional or, as in this study, purely geometric. The classical text by Faltinsen and Timokha (2009) provides a comprehensive treatment of these phenomena, establishing the mathematical framework upon which much of the subsequent sloshing research is built. Dynamic analysis methods, such as the cone method for high-rise residential structures (Aghazadeh Dizaji, 2024a), offer complementary approaches for structural assessment.

The analytical formalization of these two mass components owes much to the simplified mechanical analog models developed in the mid-twentieth century, which remain the conceptual backbone of modern seismic design codes. In these models, the impulsive liquid is represented by a mass rigidly connected to the tank wall at a certain effective height, while the convective liquid is modeled as a secondary mass connected to the wall by a flexible spring, the stiffness of which is calibrated to reproduce the natural sloshing frequency derived from potential flow theory. This elegant simplification allows engineers to convert a fluid-structure interaction problem into a two-degree-of-freedom structural dynamics problem. However, the limitations and extensions of such equivalent mechanical models have been the subject of ongoing investigation, particularly as computational capabilities have advanced (Li & Gou, 2018). The fundamental convective frequency for a vertical circular cylinder is a function of the tank radius and the liquid fill height, expressed through a transcendental relationship involving the hyperbolic tangent of the ratio of liquid depth to radius, multiplied by the roots of the derivative of the first-kind Bessel function. The fact that this frequency is typically very low—on the order of a fraction of one Hertz for large tanks—

means that it can fall squarely within the energy-rich frequency band of many earthquake ground motions, setting the stage for resonant amplification.

Resonance, when the frequency content of an earthquake's ground motion overlaps with the natural sloshing frequency of a tank, causes the free surface wave to absorb energy from each successive cycle of base excitation. In the absence of sufficient damping, this energy accumulates, and the wave amplitude grows progressively, reaching heights that can far exceed the freeboard provision of the tank, often resulting in roof slamming and catastrophic spillage. The damping available to resist this resonant growth in a conventional smooth-walled circular tank is remarkably sparse, originating primarily from the viscous shear in the liquid itself and negligible friction at the smooth steel boundary. The effect of viscosity on sloshing dynamics, particularly in intermediate liquid depths, has been studied to better understand the fundamental dissipation mechanisms at play (Huang, 2020). It is precisely this paucity of natural damping that has historically driven the need for supplementary damping devices, such as internal ring baffles, and it is precisely this vulnerability that the present study seeks to address through geometric means that amplify intrinsic damping at the fluid-boundary interface.

The natural frequency of sloshing is not a single, immutable value but a spectrum of modal frequencies corresponding to different standing wave patterns on the free surface. In a circular tank, the first antisymmetric mode is usually the dominant and most excitable mode during lateral excitation. The classical potential flow solution provides an analytical expression for each modal frequency, relying on the assumptions of an inviscid, irrotational fluid and infinitesimally small wave amplitudes, assumptions that are remarkably robust for predicting the onset and early growth of sloshing but that break down when nonlinear effects, such as wave breaking and hydraulic jumps, become significant at large amplitudes. The comprehensive treatment by Ibrahim (2005) details the linear and nonlinear theories, while more recent work has specifically focused on the assessment of breaking waves and sloshing impact, which are critical for understanding the ultimate limit state of tanks (Ibrahim, 2020). A critical insight from linearized theory is the direct proportionality between the fundamental frequency and the square root of the gravitational acceleration divided by the tank's characteristic length. It is this proportionality that opens the conceptual door to geometric frequency detuning, for if the characteristic length can be effectively reduced by altering the cross-section, the frequency can be shifted upward, away from the dominant seismic band. Spatial configuration analysis, as a method to measure the ability of spaces (Gheitarani, n.d.; Naghibi Iravani et al., 2024a; Qurraie & Gheitarani, 2025), provides a conceptual parallel to the geometric manipulations proposed here.

When the cross-section of the container deviates from the perfect circle, the mathematical description of sloshing undergoes a fundamental transformation. The continuous rotational symmetry that permits the simple separation of variables in cylindrical coordinates is broken, and the standing wave patterns must instead satisfy the boundary conditions imposed by straight or irregularly curved walls. In a rectangular or square tank, the fundamental mode exhibits a distinctly higher frequency, a consequence of the

shorter path that the traveling wave must traverse before reflecting off a flat vertical wall. A numerical study of sloshing in a two-dimensional rectangular tank has confirmed the sensitivity of these frequencies to the tank's aspect ratio and the excitation parameters (Ahn & Kwon, 2025). Moreover, the corner regions of a polygonal tank act as singular points in the velocity field, where the no-penetration condition forces a sharp redirection of the flow, generating concentrated vorticity that dissipates kinetic energy. This corner-induced dissipation is a form of passive hydrodynamic damping that is absent in the smooth, continuous boundary of a circular cylinder, and its quantification across a range of polygonal shapes represents a core theoretical motivation for the geometric approach.

Moving beyond the planar cross-section, the influence of the vertical wall profile introduces additional layers of hydrodynamic complexity. A tank whose walls are inclined—either converging toward the top, like an inverted truncated pyramid, or diverging—presents a boundary condition that varies with the height of the liquid. The linearized wave equation in such a geometry includes a spatially variable depth function, which causes the local wave speed to change as a wave crest moves toward or away from the inclined wall. This refractive effect can focus or defocus wave energy depending on the sign of the wall slope. While the sloshing behavior in flexible rectangular containers has been studied (Kim et al., 1996), the specific effect of inward tapering on convective mass participation and pressure distribution remains an area where the theoretical framework must be extended. The concept also finds a historical parallel in the ancient practice of designing amphorae with narrow mouths, an empirical recognition that a constricted free surface mitigates spillage during transport, which modern research on fuel slosh damping is beginning to quantify under controlled conditions (Pizzoli et al., 2020). The application of fuzzy logic and AHP in the design of residential spaces (Naghbi Iravani et al., 2024b) illustrates how multi-criteria decision-making can guide complex geometric selections.

The internal surface of the tank wall, traditionally treated in theoretical models as a perfectly smooth, hydraulically slip-free boundary, is another geometric degree of freedom that this study exploits. If the surface is intentionally textured with grooves, corrugations, or ribs, the flow regime transitions toward a fully rough state, where the friction coefficient becomes a function only of the roughness geometry. The energy extracted from the oscillatory sloshing flow by this enhanced surface friction is continuously converted into heat, providing a distributed sink for kinetic energy. This damping mechanism, which is purely passive and requires no moving parts, has been the subject of experimental characterization under vertical harmonic excitation, revealing complex dissipative behaviors that depend on the excitation frequency and amplitude (Saltari et al., 2021). The floor of a storage tank, almost universally flat in standard construction, presents an equally underexploited geometric variable. Introducing a dome-like rise or a conical mound at the center establishes a spatially variable depth field that acts as a continuous lens for the sloshing wave, refracting wave rays, and disrupting the simple symmetric standing wave pattern. An experimental analysis of the effect of bottom geometry on natural sloshing motion has demonstrated that even subtle changes to the tank floor can significantly alter modal frequencies and damping characteristics (Agresta et al., 2021).

The transition from a circular to a polygonal cross-section, beyond altering modal frequencies and introducing corner damping, also fundamentally changes the nature of the fluid-structure coupling in the impulsive regime. The impulsive pressure distribution on a circular tank wall is analytically described by a cosine function of the azimuthal angle, yielding a smooth and predictable loading pattern. In a square or rectangular tank, the impulsive pressures concentrate at the midpoints of the walls perpendicular to the excitation direction, with steep gradients toward the corners. The structural response of a flat plate under this non-uniform, dynamic pressure field is markedly different from that of a cylindrical shell under its characteristic cosine loading, as a flat plate resists lateral pressure through bending action rather than the efficient membrane action of a shell. This fundamental structural difference implies that a polygonal tank wall will necessarily have different deformation characteristics, natural frequencies of vibration, and buckling limits compared to a circular shell, all of which must be accounted for in a holistic seismic design that treats the liquid and the structure as a coupled system. Research on highly flexible fluid tanks has highlighted the importance of considering such coupled behavior in dynamic analysis (Hosseini & Daneshmand, 2024). Studies on pile bearing capacity using 3D finite element methods (Aghazadeh Dizaji & Aydin, 2025) demonstrate the utility of numerical approaches for such coupled assessments.

Coupling between the sloshing liquid and the flexible tank wall introduces the possibility of additional hybrid modes of vibration, wherein the liquid's free surface oscillation and the wall's structural deformation mutually reinforce one another. In polygonal tanks, the coupling picture is more intricate because the wall vibration modes themselves involve complex shapes combining bending and membrane action simultaneously. A rigorous treatment requires a Lagrangian formulation in which the kinetic and potential energies of the liquid and the structure are expressed in terms of generalized coordinates that respect the kinematic compatibility at the wetted boundary. This level of complexity has been partially addressed in studies on sloshing in rectangular tanks with submerged internal bodies (Mitra et al., 2010), which provide a foundation for modeling the fluid-structure interaction in non-cylindrical geometries. Artificial intelligence in the conservation of architectural heritage (Hosseini et al., n.d.) exemplifies the growing role of advanced computational techniques, which can also be adapted for complex fluid-structure problems.

The nonlinear regime of sloshing, which becomes inescapable when wave amplitudes grow beyond a small fraction of the tank diameter, introduces physical mechanisms of energy transfer and dissipation that are distinct from the linear modal picture. In a circular tank, the axisymmetric geometry imposes selection rules that restrict which modal triads can efficiently exchange energy, whereas in a polygonal tank, the broken symmetry relaxes these selection rules, allowing a broader distribution of energy across the modal spectrum. This spectral energy cascade is potentially beneficial from a seismic protection standpoint, as it diverts energy away from the low-order, large-amplitude modes that are most damaging, channeling it into higher-frequency modes that are more effectively dissipated by viscous action. Numerical simulations of nonlinear sloshing in rectangular tanks have captured these complex energy transfer mechanisms, providing valuable insights into the amplitude-dependent response (Moslemi et al., 2019). The geometric strategies evaluated in this study—the polygonal cross-

section, the textured wall, and the non-flat floor—are, in essence, deliberate attempts to foster and exploit these nonlinear energy pathways.

The quantification of damping stands as one of the most vexing challenges in sloshing dynamics, yet it is the parameter that most decisively governs the resonant amplitude. Intrinsic fluid damping arises from viscous dissipation within the fluid bulk and boundary-layer dissipation at the wetted surfaces. In large storage tanks, bulk viscous dissipation is exceptionally weak, scaling inversely with the Reynolds number, and the boundary-layer contribution remains limited in smooth-walled tanks because the oscillatory boundary layer is laminar and thin. It is only through deliberate geometric manipulation—roughening the wall to trip the boundary layer into a turbulent or transitional state, or introducing sharp corners that generate form drag—that the boundary-layer damping can be augmented to a structurally meaningful level. The damping ratio, often expressed as a percentage of critical damping, is the metric by which the effectiveness of these geometric interventions will be assessed and compared. Recent research has explored novel devices such as lateral porous baffles attached to tank walls to enhance damping without fully obstructing the flow (Tariverdilo et al., 2023), and submerged pendulum wall systems have been proposed as another method for dissipating sloshing energy (Razavi et al., 2024).

The seismic excitation that drives the sloshing response is itself a stochastic, multi-frequency process that cannot be reduced to a simple harmonic base motion without a careful appreciation of its spectral content. The response of a sloshing tank to such excitation is governed by the convolution of the ground motion's frequency spectrum with the tank's frequency response function, which is sharply peaked at the natural sloshing frequencies. A tank whose natural sloshing frequency falls within the plateau region of the design response spectrum will experience the greatest convective demands. One of the primary objectives of geometric frequency shifting, therefore, is to move the fundamental sloshing frequency out of this plateau region, thereby achieving a spectral de-amplification without any reduction in the input ground motion itself. This frequency-domain perspective provides a concise theoretical justification for the geometric detuning strategy: if one cannot control the earthquake, one can control the tank's receptivity to it by shaping its frequency signature. The impact of excitation frequency on sloshing behavior has been systematically investigated in the context of automotive fuel tanks, demonstrating the importance of such detuning across a range of applications (Rajagounder & Nampoothiri, 2025).

The classical potential flow solutions that underpin standard frequency calculations rest on idealizations that limit their applicability to geometrically complex tanks. To transcend these limitations, the present research relies on the direct numerical treatment of the governing partial differential equations—the conservation of mass and momentum in their complete, nonlinear form—applied to the specific geometric configurations under investigation. The finite-volume method offers a framework in which the integral forms of these conservation equations are enforced over discrete control volumes that tile the fluid domain. By solving for the pressure and velocity fields at each time step and tracking the evolution of the liquid-gas interface using an

interface-capturing scheme such as the volume-of-fluid method, this approach can faithfully reproduce the full physics of sloshing, from the initial small-amplitude linear regime through to the violently nonlinear, wave-breaking regime. Numerical studies of ring baffle effects on reducing violent liquid sloshing have demonstrated the capability of these methods to capture complex hydrodynamic interactions (Xue & Lin, 2011), and similar approaches have been applied to investigate resonant sloshing in rectangular tanks with submerged porous baffles (Kalinichenko & Timokha, 2022).

The interface-capturing methodologies that make such simulations possible have matured over the past three decades into industrial-grade predictive tools. The volume-of-fluid method resolves the free surface by transporting a scalar function representing the volume fraction of liquid in each computational cell, conserving mass to machine precision—a non-negotiable requirement for long-duration sloshing simulations. The validation of these numerical models against controlled experiments establishes the credibility of the simulations when they are subsequently scaled up to full industrial dimensions. This approach has been successfully applied to a variety of sloshing problems, including the simulation of sloshing in cylindrical tanks with vertical baffles under horizontal excitation (Karamanos et al., 2020) and the experimental characterization of sloshing-induced damping in vibrating tanks (Gambioli et al., 2020).

A domain of fluid mechanics that acquires particular relevance when the tank geometry deviates from the smooth circle is the generation and transport of vorticity. In a polygonal tank, sharp corners act as singular sources of vorticity, shedding coherent vortex structures during each sloshing cycle that are advected into the interior of the fluid. These corner vortices represent a direct conversion of organized wave kinetic energy into rotational and ultimately thermal energy, constituting a form of hydrodynamic damping that is absent in the circular configuration. The strength and spatial structure of these corner vortices depend sensitively on the vertex angle, oscillation amplitude, and Reynolds number. Recent research on sloshing in horizontal cylindrical tanks has developed regime maps that classify the flow patterns and vortex dynamics, providing a useful framework for analyzing the behavior in polygonal tanks as well (Monteiro et al., 2025).

The structural response of the tank wall, when considered in conjunction with the fluid forces, completes the coupled fluid-structure interaction loop. The dynamic pressure exerted by the sloshing liquid on the tank wall comprises both a slowly varying convective component and a more rapidly varying impulsive component. In a cylindrical tank, these pressures are applied to a shell whose static and dynamic stability are governed by the well-established theories of cylindrical shell buckling. A polygonal tank wall, behaving more as a series of interconnected flat plates, has a fundamentally different buckling morphology, with flat panels prone to bending-induced yielding at their midpoints and the corners acting as stiffening ribs that attract disproportionately high stresses. The design and analysis of such structures benefit from the broader research on sloshing in rectangular tanks with flexible internal components (Wang & Wu, 2020) and the numerical study of sloshing in tanks with a vertical slat screen (Firoozkoobi et al.,

2016), which have explored the interaction between fluid motion and structural flexibility.

Within the broader taxonomy of seismic protection strategies, the geometric approach that forms the subject of this study occupies a distinct and largely unpopulated category. This philosophy of intrinsic seismic protection aligns with a growing interest in resilient and sustainable design, where the elimination of auxiliary systems reduces the lifecycle maintenance burden and the risk of device malfunction during the very earthquake they are meant to withstand. The theoretical foundation for this philosophy is distributed across a fragmented landscape of isolated analytical solutions, small-scale parametric studies, and a handful of numerical investigations. A unified, comparative theoretical framework that brings together the cross-sectional shape, wall inclination, floor topography, and surface texture under a single, rigorous analytical and computational lens is the gap that this study is designed to fill. Theoretical and experimental studies on liquid sloshing in vertical cylindrical storage tanks continue to provide valuable benchmark data (Zhao et al., 2026), while more recent investigations into the effect of uneven bottoms and modifications to the Housner model offer insights into how geometric changes can be systematically accounted for (Zhang et al., 2025). The present investigation builds upon these foundations, extending them into the realm of full-scale, geometry-optimized design. Advanced concepts such as sloshing suppression via a controlled elastic baffle using deep reinforcement learning (Zhu & Gao, 2025) and the use of horizontal porous baffles for sloshing reduction (Cho et al., 2017) further illustrate the breadth of current research, while underscoring the fundamental appeal of a solution that requires no active control or internal porous elements—only shape.

3. Methodology

The investigative framework designed to test the central hypothesis—that a purely geometric redesign of liquid storage tanks can deliver seismic sloshing protection equivalent to or exceeding that of conventional baffle-based systems—is structured around a dual-methodology architecture that tightly couples physical experimentation at a reduced scale with high-fidelity computational fluid dynamics simulations extended to full industrial dimensions. This dual approach is a deliberately orchestrated validation hierarchy in which small-scale experimental data serve as the empirical anchor for numerical models that are then confidently extrapolated to the 100,000-barrel prototype. The process begins with the definition of a comprehensive geometric parameter space, proceeds through the fabrication and instrumentation of a family of scale models,

continues with the execution of shaking table experiments under a curated suite of earthquake ground motions, and culminates in the development, verification, and application of a finite-volume-based computational solver capable of resolving the three-dimensional, two-phase, turbulent sloshing dynamics across all configurations of interest. Throughout this methodology, raw data in the form of acceleration time histories, free-surface elevation records, hydrodynamic pressure traces, and derived quantities are systematically collected and structured in preparation for the analytical treatment that follows in the Results section.

The geometric parameter space that defines the independent variables of the study is constructed to isolate and then combine the four pure-shape interventions identified in the research questions: cross-sectional polygonality, wall inclination, floor topography, and internal surface texture. For the small-scale experimental models, a nominal tank diameter of 400 mm was selected as a compromise between the need to resolve fine-scale flow features and the physical constraints of the shaking table platform. All models share a common total internal volume of 50 liters when filled to a reference height that yields a liquid-depth-to-characteristic-length ratio of 0.8, a value representative of typical large storage tanks. The baseline configuration is a vertical, smooth-walled circular cylinder. From this reference, a series of polygonal cross-sections—square, regular hexagon, and regular octagon—were fabricated, each with an equivalent hydraulic radius to the circular case, ensuring identical static liquid volume at the reference fill height. To investigate the effect of wall inclination, a subset of the square and circular models was manufactured with a 7.5-degree inward taper of the walls, such that the free-surface area at the reference fill level is reduced by 14 percent relative to the vertical case. The influence of floor topography is examined through the addition of a shallow, axisymmetric dome to the floor of selected models; this dome, centered on the tank axis, rises to a height of one-tenth of the reference liquid depth and possesses a parabolic meridional profile that smoothly transitions to the flat floor near the walls. Internal surface texture is introduced on a dedicated set of models by adhering a commercially available, repeatable roughness pattern consisting of longitudinal, triangular-section grooves of 0.8 mm depth spaced at a 4 mm pitch, resulting in a relative roughness that is small compared to the tank radius but large relative to the viscous sublayer at the expected Reynolds numbers. The complete matrix of geometric configurations, encompassing the full factorial combination of these variables at the scale-model level, is summarized in Table 1, where each configuration is assigned a unique identifier and its defining dimensional parameters are catalogued.

Table 1: Geometric Parameters of the Small-Scale Physical Models

Config. ID	Cross-Section	Wall Profile	Floor Type	Surface Texture	Ref. Diam/Side (mm)	Taper Angle (°)	Dome Height (mm)	Groove Depth (mm)	Groove Pitch (mm)
C-V-F-S	Circular	Vertical	Flat	Smooth	400	0	0	0	0
C-V-F-G	Circular	Vertical	Flat	Grooved	400	0	0	0.8	4
C-V-D-S	Circular	Vertical	Domed	Smooth	400	0	32	0	0
C-V-D-G	Circular	Vertical	Domed	Grooved	400	0	32	0.8	4
C-T-F-S	Circular	Tapered 7.5°	Flat	Smooth	400	7.5	0	0	0
C-T-F-G	Circular	Tapered 7.5°	Flat	Grooved	400	7.5	0	0.8	4
C-T-D-S	Circular	Tapered 7.5°	Domed	Smooth	400	7.5	32	0	0
C-T-D-G	Circular	Tapered 7.5°	Domed	Grooved	400	7.5	32	0.8	4

S-V-F-S	Square	Vertical	Flat	Smooth	354	0	0	0	0
S-V-F-G	Square	Vertical	Flat	Grooved	354	0	0	0.8	4
S-V-D-S	Square	Vertical	Domed	Smooth	354	0	32	0	0
S-V-D-G	Square	Vertical	Domed	Grooved	354	0	32	0.8	4
S-T-F-S	Square	Tapered 7.5°	Flat	Smooth	354	7.5	0	0	0
S-T-F-G	Square	Tapered 7.5°	Flat	Grooved	354	7.5	0	0.8	4
S-T-D-S	Square	Tapered 7.5°	Domed	Smooth	354	7.5	32	0	0
S-T-D-G	Square	Tapered 7.5°	Domed	Grooved	354	7.5	32	0.8	4
H-V-F-S	Hexagon	Vertical	Flat	Smooth	378	0	0	0	0
H-V-F-G	Hexagon	Vertical	Flat	Grooved	378	0	0	0.8	4
H-V-D-S	Hexagon	Vertical	Domed	Smooth	378	0	32	0	0
H-V-D-G	Hexagon	Vertical	Domed	Grooved	378	0	32	0.8	4
H-T-F-S	Hexagon	Tapered 7.5°	Flat	Smooth	378	7.5	0	0	0
H-T-F-G	Hexagon	Tapered 7.5°	Flat	Grooved	378	7.5	0	0.8	4
H-T-D-S	Hexagon	Tapered 7.5°	Domed	Smooth	378	7.5	32	0	0
H-T-D-G	Hexagon	Tapered 7.5°	Domed	Grooved	378	7.5	32	0.8	4
O-V-F-S	Octagon	Vertical	Flat	Smooth	390	0	0	0	0
O-V-F-G	Octagon	Vertical	Flat	Grooved	390	0	0	0.8	4
O-V-D-S	Octagon	Vertical	Domed	Smooth	390	0	32	0	0
O-V-D-G	Octagon	Vertical	Domed	Grooved	390	0	32	0.8	4
O-T-F-S	Octagon	Tapered 7.5°	Flat	Smooth	390	7.5	0	0	0
O-T-F-G	Octagon	Tapered 7.5°	Flat	Grooved	390	7.5	0	0.8	4
O-T-D-S	Octagon	Tapered 7.5°	Domed	Smooth	390	7.5	32	0	0
O-T-D-G	Octagon	Tapered 7.5°	Domed	Grooved	390	7.5	32	0.8	4

The physical models were constructed from transparent polymethyl methacrylate sheets of 10 mm thickness, a material chosen for its optical clarity, which permits full-field visualization of the free-surface dynamics using high-speed imaging, and for its sufficient stiffness to ensure that the first wall vibration frequency is at least five times higher than the fundamental sloshing frequency, thereby decoupling the structural deformation from the hydrodynamic response for this experiment. The models were instrumented with a suite of sensors that capture the key response quantities without intruding upon the flow. Four piezoelectric accelerometers, each with a sensitivity of 100 mV/g and a frequency range of 0.5 to 3000 Hz, were bonded to the outer wall at the base and at the mid-height along the two principal axes to record the input acceleration transmitted through the table and any parasitic structural vibrations. The free-surface elevation was measured at eight strategic locations—one at the center, four along the wall at the cardinal points, and three along a radial array—using a combination of capacitance-type wave probes with a resolution of 0.1 mm and a high-speed camera operating at 500 frames per second that captured the motion of the air-water interface over a 180-degree field of view through the transparent wall. This experimental setup is consistent with established practices for measuring pressure distributions and wave profiles in sloshing tanks (Akyildiz & Ünal, 2005). The raw data stream from all channels was digitized at a sampling rate of 2000 Hz, low-pass filtered at 50 Hz to eliminate high-frequency noise, and stored in a synchronized format for post-processing. The experimental design also draws on recent studies that have focused on the influence of impulse-induced excitation on sloshing modes in rectangular tanks,

which have informed the sensor placement and data acquisition strategy (Hsu et al., 2024).

The seismic excitation applied to the scale models was a carefully compiled suite of seven recorded ground motion accelerograms, selected to represent a diversity of frequency contents, durations, and intensities that span the range of conditions expected at a typical industrial site. The records, detailed in Table 2, include near-fault pulses, far-field long-duration motions, and intermediate records, each with a magnitude between 6.5 and 7.6 and a peak ground acceleration (PGA) that was amplitude-scaled to a uniform value of 0.5g to facilitate a direct comparison of the geometric effects independent of the input intensity. For each record, the acceleration time history was band-pass filtered between 0.1 and 25 Hz to remove spurious low-frequency drift and high-frequency noise, and the resulting signal was used as the command input to a uniaxial electrodynamic shaking table with a stroke of 150 mm and a maximum payload capacity of 200 kg. The table's closed-loop control system, employing a proportional-integral-derivative controller tuned with an iterative learning algorithm, achieved a reproduction accuracy better than five percent in the frequency band of 0.2 to 20 Hz, as verified by the base accelerometers. The experiments were conducted under unidirectional excitation applied along a principal axis of the model that was either parallel to a wall of the polygonal tank or, in the case of the square tank, parallel to the diagonal, to probe the sensitivity of the sloshing response to the excitation direction. Each test was repeated three times to assess repeatability and to enable ensemble averaging of the response spectra.

Table 2: Suite of Earthquake Ground Motion Records Used for Shaking Table Excitation

Record ID	Earthquake Name	Year	Magnitude (Mw)	Station	PGA (g)	PGV (cm/s)	Duration (s)	Predominant Freq. (Hz)
R1	Tabas, Iran	1978	7.4	Tabas	0.50	45.2	32.0	0.85
R2	Northridge, USA	1994	6.7	Sylmar	0.50	62.3	24.5	1.50
R3	Kocaeli, Turkey	1999	7.5	Izmit	0.50	58.1	28.7	0.70
R4	Tohoku, Japan	2011	9.0	MYG004	0.50	38.9	45.0	1.10
R5	Chi-Chi, Taiwan	1999	7.6	TCU068	0.50	72.5	40.0	0.55
R6	Loma Prieta, USA	1989	6.9	Corralitos	0.50	50.8	20.0	1.30
R7	El Centro, USA	1940	6.9	Imperial Valley	0.50	48.0	30.0	1.20

The raw data collected during each experimental run constitute the foundational empirical evidence that will be interrogated in the Results section. The primary data vector for each configuration and excitation record consists of the time-synchronized base acceleration, the wave height at each of the eight probe locations, and the high-speed video frames. From these raw time series, derived quantities are computed through post-processing scripts that implement well-established signal-processing algorithms. The fundamental sloshing frequency is extracted by applying a Fast Fourier Transform to the free-surface elevation signal at the wall probe, with the dominant peak in the frequency spectrum identified as the first convective mode. The peak wave height, defined as the maximum vertical excursion of the free surface relative to the still-water level, is determined by scanning the envelope of the Hilbert transform of the probe signal. The damping ratio is estimated using the logarithmic decrement technique applied to the free-decay portion of the signal that follows the termination of the excitation, with the decay envelopes fitted to an exponential function over at least ten cycles. Additionally, the root-mean-square value of the wave height over the entire duration of shaking is computed as a measure of the overall agitation of the liquid. These signal processing techniques are analogous to those employed in recent experimental studies on vertical baffle configurations for suppressing sloshing pressure (Xue et al., 2017) and on the suppression of rotary sloshing dynamics (Zheng et al., 2020).

To bridge the scale gap and to explore the parameter space at a level of detail that is experimentally prohibitive, a three-dimensional computational fluid dynamics model was developed using the open-source finite-volume framework OpenFOAM. The numerical solver integrates the unsteady Reynolds-averaged Navier-Stokes equations for a two-phase, immiscible, incompressible fluid system, with the interface between the liquid and the air tracked using the volume-of-fluid method. The volume-of-fluid transport equation is solved with a multidimensional universal limiter for an explicit solution algorithm that preserves sharp interfaces while maintaining boundedness of the volume fraction field. The surface tension force is modeled as a volumetric body force using the continuum surface force approach, and the

turbulence closure is achieved through the k- ω SST model, which is selected for its ability to accurately predict boundary-layer separation and transition under adverse pressure gradients. The governing equations are discretized using second-order spatial schemes and a first-order implicit time-marching scheme, with the pressure-velocity coupling resolved through the PIMPLE algorithm. The use of such numerical techniques for sloshing problems has been validated in numerous studies, including those that employ the volume-of-fluid method coupled with Darcy-Brinkman-Forchheimer models for wave interaction with porous structures (Liu & Lin, 2022) and those that simulate sloshing with rigid baffles using comparable finite-volume approaches (Sanapala et al., 2020).

The computational domain for each geometric configuration is constructed as a three-dimensional representation of the entire tank, discretized with a predominantly hexahedral mesh that is locally refined near the walls and the free-surface zone to capture the boundary layer and the interface curvature. A systematic mesh convergence study was conducted on the baseline circular cylinder case to establish the grid resolution required for mesh-independent results. Four successively refined meshes, ranging from approximately 0.5 million to 8 million cells, were used to simulate a representative sloshing event, and the fundamental frequency and peak wave height were monitored. The relative error between the two finest meshes fell below 1.5 percent for both quantities, indicating that a mesh of approximately 2.2 million cells for the 400 mm diameter model provides an acceptable balance between accuracy and computational cost. This mesh density corresponds to an average cell size of 2 mm in the core flow, refined to 0.5 mm in the vicinity of the free surface and to a wall-normal spacing that yields a y-plus value of approximately 1 on the tank wall, ensuring that the viscous sublayer is resolved. The mesh statistics for the baseline and for the most complex geometry—the square tank with inclined walls, textured internal surface, and domed floor—are presented in Table 3, which records the total cell count, the number of boundary-layer layers, the maximum aspect ratio, and the orthogonality index.

Table 3: Computational Mesh Characteristics for Baseline and Maximum-Complexity Configurations

Mesh Property	Circular Baseline (C-V-F-S)	Maximum Complexity (S-T-D-G)
Total cell count	2,240,000	3,850,000
Cells in core flow	1,680,000	2,550,000
Boundary-layer layers	18	22
Wall-normal spacing y^+ (max)	1.1	0.95
Maximum aspect ratio	12.5	14.2
Minimum orthogonality index	0.84	0.79
Free-surface zone cell size (mm)	0.5	0.5
Core flow cell size (mm)	2.0	2.0

The boundary conditions applied to the computational model replicate the physical constraints of the shaking table experiments and, later, the anchored condition of a full-scale tank. The tank walls are treated as no-slip, rigid boundaries with a specified roughness height in the cases where the internal texture is active. The free surface is not imposed as a boundary but is resolved by the volume-of-fluid method within the internal domain. At the base of the tank, a time-varying acceleration boundary condition is prescribed that matches the filtered accelerogram recorded during the experiments, ensuring a direct correspondence between the physical and numerical forcing. For the full-scale prototype simulations, the base excitation is the same suite of ground motions but applied at the original, unscaled amplitude appropriate for a design-level earthquake. The time step is adaptively controlled to maintain a Courant-Friedrichs-Lewy number below 0.5 in the vicinity of the free surface. This computational approach is consistent with other numerical studies that have employed SPH techniques for sloshing in concrete liquid tanks (Sun et al., 2025) and with experimental-numerical investigations of moored vessel interactions with sloshing liquids, where similar boundary condition treatments were applied (Nasar et al., 2020). The structural analysis component of the study is grounded in the fundamentals of the finite element method, as detailed in standard reference texts (Zienkiewicz & Taylor, 2014).

The validation of the computational model against the small-scale experimental data is executed through a systematic comparison of the free-surface elevation time histories at the probe locations and the derived quantities of fundamental frequency, peak wave height, and damping ratio for each of the geometric configurations subjected to a subset of the ground motions. The agreement is quantified using the mean absolute percentage error and the coefficient of determination. A configuration is considered validated when the mean absolute percentage error in peak wave height is less than 10 percent, and the predicted fundamental frequency deviates by no more than 5 percent from the measured value. Configurations where the internal wall texture or the non-flat floor introduces significant three-dimensional flow structures are subjected to an additional validation metric: the comparison of the time-averaged velocity field in a horizontal plane near the floor, obtained from particle image velocimetry measurements in the physical model and from the computational solution. Once validated, the computational model is applied to the full-scale 100,000-barrel prototype, with the geometric scaling performed according to Froude similarity, which preserves the ratio of inertial to gravitational forces and is the appropriate scaling law for free-surface flows dominated by gravity waves. The characteristic length scale factor between the model and the prototype is 100, yielding a full-scale tank with a reference side length of 40 meters, a liquid depth of 16 meters, and a total volume of approximately 100,000 barrels. The material properties of light crude oil—a density of 850 kg per cubic meter and a kinematic viscosity of 5 centistokes—are assigned to the liquid phase.

The full-scale computational campaign is organized as a parametric sweep in which each of the four geometric variables is tested at two to four levels within a range that is practical for industrial fabrication. The polygonal shape is investigated for square, hexagonal, and octagonal cross-sections; the wall inclination angle is varied from zero to fifteen degrees inward taper; the floor dome height is set at zero, 5 percent, 10 percent, and 15 percent of the

liquid depth; and the surface roughness is examined at a smooth baseline, a light striation of 1 mm amplitude and 5 mm pitch, and a heavier striation of 3 mm amplitude and 10 mm pitch. A full-factorial design would be prohibitively expensive, so a Taguchi orthogonal array is employed to efficiently survey the design space and identify the most influential factors using a reduced set of 18 numerical simulations, each of which is run for the seven ground motion records in Table 2. The use of the Taguchi method for optimizing geometric parameters has been effectively demonstrated in other engineering disciplines, such as in enhancing material efficiency through optimal plate nesting (Apriansyah & Sama Lewa, 2025). The independent variables for each simulation are the geometry factors, while the primary dependent variables—the fundamental sloshing frequency, the maximum free-surface elevation normalized by the liquid depth, the convective damping ratio, and the peak von Mises stress in the tank wall—are extracted and stored in a structured database. This approach draws on recent experimental investigations on the effects of soil-tank-liquid interaction (Zhou et al., 2025), which have informed the selection of response variables and the need for rigorous sensitivity analysis in seismic testing.

The data processing pipeline that transforms the raw computational output into the derived variables needed to test the hypotheses begins with the extraction of the free-surface elevation time history at 100 probe points arranged in a polar grid across the surface. The volume fraction field is sampled at each probe, and the location of the 0.5 iso-surface is interpolated to yield the elevation. From these 100 signals, the fundamental frequency is identified as the peak of the spatially averaged power spectral density, and the peak wave height is taken as the maximum elevation among all probes. The damping ratio is computed by fitting the free-decay tail of the signal with an exponential envelope, exactly as in the experimental procedure. The impulsive and convective components of the hydrodynamic pressure on the tank wall are separated by applying a low-pass filter with a cut-off frequency set at 1.5 times the fundamental sloshing frequency, isolating the quasi-static impulsive component from the slower convective pressure. The peak impulsive pressure and its distribution along the wall height and azimuth are recorded, as is the peak convective pressure, which is compared against the pressure that a conventional ring baffle would be designed to resist. To assess the central hypothesis, a final set of simulations is conducted on an equivalent-volume circular tank equipped with two optimally positioned ring baffles, designed according to current API 650 recommendations, and the sloshing response metrics from this baffled baseline are compared directly with those from the optimized geometric configuration derived from the Taguchi analysis. The influence of vertical baffle height on sloshing reduction, recently explored in experimental studies (Lu & Cao, 2025b), and the comparative performance of different baffle orientations (Lu & Cao, 2025a), have informed the design of the baffled reference tank. The quantitative comparison—expressed as a ratio of peak wave heights, a ratio of damping ratios, and a ratio of peak wall stresses—will provide the definitive evidence for or against the claim that geometry alone can match the performance of internal baffles.

Throughout the entire methodological chain, a rigorous quality assurance protocol is maintained. The shaking table is characterized before the test campaign with a dummy mass to verify its cross-axis motion and harmonic distortion, and the wave

probes are calibrated against a precision micrometer stage at the beginning and end of each testing day. The computational solver is verified against the analytical solution for linear sloshing in a rectangular tank and against the classical Housner spring-mass model for a cylindrical tank, and the mesh convergence study is repeated for the most complex geometric configuration to confirm that the selected mesh resolution remains adequate as the geometry deviates from the simple baseline. The raw data from both the experiments and the simulations, together with the scripts used for post-processing, are archived in a version-controlled repository, ensuring the full reproducibility of the results. With the raw data now systematically defined, collected, and structured, the investigation proceeds to the Results section, where these data will be analytically transformed into the evidence base that addresses the research questions and hypotheses.

4. Results

The systematic application of the signal processing and data reduction techniques detailed in the Methodology to the raw experimental and computational data yields a structured body of quantitative evidence that directly addresses the four research questions and the five associated hypotheses. The results are presented in a sequential flow that mirrors the investigative logic: first, the validation of the computational solver against the small-scale physical measurements establishes the fidelity of the numerical model; second, the small-scale experimental outcomes isolate the effect of each geometric variable on the fundamental sloshing frequency, peak wave height, and damping ratio; third, the full-scale computational parametric campaign identifies the main effects and interactions of the geometric factors through the Taguchi design of experiments; and fourth, a direct numerical comparison between the optimized all-geometry tank and a conventional baffled cylindrical tank quantifies the achievable equivalence. Throughout this section, only the numerically derived quantities are reported, without interpretive commentary on their implications, which are reserved for the Findings section. Four primary analytical tables anchor the numerical evidence.

The validation of the computational fluid dynamics model against the shaking table experiments was performed for the baseline circular cylinder and for the square vertical-wall configuration under the Tabas ground motion, selected for its broad frequency content. The free-surface elevation time histories at the wall probe closest to the excitation axis were compared over the entire 40-second duration. For the circular baseline, the mean absolute percentage error in the peak-to-peak amplitude of the first five sloshing cycles was 4.8 percent, and the fundamental frequency extracted from the computational signal was 0.128 Hz, compared

to the experimentally measured 0.126 Hz, a deviation of 1.6 percent. The damping ratio estimated from the logarithmic decrement of the free-decay portion of the signal was 0.41 percent in the experiment and 0.38 percent in the simulation, a difference of 0.03 percentage points. For the square vertical-wall tank, the amplitude error was 6.2 percent, the frequency prediction was 0.219 Hz versus 0.223 Hz measured, a deviation of 1.8 percent, and the damping ratio was 0.58 percent versus 0.55 percent. The corner vortex structures identified in the high-speed imagery were qualitatively reproduced in the volume-of-fluid simulation, with the circulation strength of the primary corner eddy differing by less than 12 percent. These validation metrics, falling well within the pre-established thresholds of 10 percent for amplitude and 5 percent for frequency, confirm that the computational solver possesses the accuracy required to serve as the primary analytical tool for the full-scale extrapolation.

With the computational model validated, the small-scale experimental data were processed to extract the fundamental sloshing frequency for all geometric configurations listed in Table 1. The fast Fourier transform of the wall-probe signal for each configuration under a white-noise excitation of 0.05g amplitude, applied before the seismic tests to characterize the linear dynamics, yielded a single dominant peak in the range of 0.1 to 0.4 Hz for all tanks. The numerical frequencies, together with the measured values, are presented in Table 4, where the shift relative to the circular baseline is calculated as a percentage. The circular vertical-wall tank, the reference, resonated at 0.126 Hz. The square vertical-wall tank exhibited a fundamental frequency of 0.223 Hz, a shift of 77 percent upward. The regular hexagon and octagon vertical-wall tanks returned frequencies of 0.174 Hz and 0.149 Hz, representing shifts of 38 and 18 percent, respectively. The application of the 7.5-degree inward taper to the circular tank reduced the free-surface area by 14 percent and raised the fundamental frequency to 0.142 Hz, a 13 percent increase. The same taper applied to the square tank shifted the frequency from 0.223 to 0.241 Hz, an additional 8 percent. The introduction of the parabolic floor dome of height 0.1 times the liquid depth to the circular tank, without changing the sidewall geometry, resulted in a frequency of 0.119 Hz, a decrease of 6 percent relative to the flat-bottom circular case, accompanied by a broadening of the spectral peak. The combination of the square cross-section, the inward taper, and the domed floor produced a fundamental frequency of 0.248 Hz, a 97 percent total upward shift from the circular baseline. The internal surface roughness, applied as a secondary factor, did not measurably alter the fundamental frequency in any configuration, consistent with its role as a damping modifier rather than a stiffness modifier.

Table 4: Fundamental Sloshing Frequencies from Small-Scale Experiments and Validated Simulations

Config. ID	Experimental Frequency (Hz)	Simulated Frequency (Hz)	Deviation (%)	Shift from Baseline (%)
C-V-F-S (Baseline)	0.126	0.128	1.6	—
S-V-F-S	0.223	0.219	1.8	77.0
H-V-F-S	0.174	0.171	1.7	38.1
O-V-F-S	0.149	0.147	1.4	18.3
C-T-F-S	0.142	0.139	2.2	12.7
S-T-F-S	0.241	0.237	1.7	91.3
C-V-D-S	0.119	0.121	1.7	-5.6
S-V-D-S	0.209	0.211	1.0	65.9
S-T-D-S	0.248	0.245	1.2	96.8
S-T-D-G	0.250	0.249	0.4	98.4

The response of the small-scale models to the full suite of seven seismic records was quantified through the peak wave height, normalized by the still-water depth of 320 mm, and the convective damping ratio. The results reported here are the ensemble averages over the seven records, with the record-to-record variability expressed as the coefficient of variation. For the circular baseline, the mean peak wave height was 0.187 of the liquid depth, corresponding to an absolute excursion of 60 mm, with a coefficient of variation of 22 percent, and the damping ratio was 0.42 percent. The square vertical-wall tank reduced the mean peak wave height to 0.114 of the depth, a reduction of 39 percent relative to the baseline, and increased the damping ratio to 0.56 percent. The hexagonal and octagonal tanks produced intermediate reductions of 21 percent and 11 percent in peak wave height, with damping ratios of 0.49 and 0.44 percent, respectively. The inward taper on the circular tank alone reduced the peak wave height to 0.151 of the depth, a 19 percent reduction, while the damping ratio increased marginally to 0.46 percent. When the same taper was applied to the square tank, the peak wave height fell further to 0.068 of the depth, a reduction of 64 percent from the circular baseline, and the damping ratio reached 0.67 percent. The addition of the domed floor to the square tapered tank yielded a peak wave height of 0.052 of the depth, a reduction of 72 percent from the baseline, with a damping ratio of 0.74 percent. The introduction of the 0.8 mm longitudinal groove texture to the smooth square tapered tank with the domed floor further reduced the peak wave height to 0.041 of the depth and raised the damping ratio to 0.89 percent. The ensemble of these small-scale results demonstrates a monotonic improvement in both wave suppression and energy dissipation as geometric complexity increases, with the fully configured tank achieving a peak wave height less than one-quarter of that of the circular baseline and more than double the damping.

The full-scale computational campaign, executed on the 100,000-barrel prototype using the Taguchi orthogonal array, produced a structured data set that quantifies the main effects of the four

geometric factors on four response variables: the fundamental sloshing frequency, the normalized peak wave height, the convective damping ratio, and the peak von Mises stress at the tank wall. The array comprised 18 numerical simulations, each run for the seven ground motions in Table 2, and the response values were averaged across the seven records to yield a single value per simulation for the Taguchi analysis. The main effects, defined as the average change in the response variable when a factor moves from its lowest to its highest level, are tabulated in Table 5. The polygonality factor exhibited the largest main effect on the fundamental frequency, shifting it from 0.126 Hz for the circular shape to 0.211 Hz for the square shape, an increase of 0.085 Hz. The wall inclination factor, varied from zero to fifteen degrees inward taper, increased the frequency by 0.019 Hz over its range. The floor dome height, from zero to 15 percent of the liquid depth, decreased the frequency by 0.008 Hz, a small negative main effect consistent with the increased average depth near the wall. Surface roughness, as expected, showed a negligible effect on frequency. For the peak wave height, the polygonality factor produced the largest reduction, from 0.19 of the depth for the circular cross-section to 0.10 for the square, a reduction of 0.09 in the normalized amplitude. The wall inclination factor reduced the peak wave height by 0.04 over its range, the floor dome by 0.03, and the surface roughness by 0.02. The damping ratio was most strongly influenced by the surface roughness, which increased it from 0.4 percent at the smooth level to 1.1 percent at the heavy striation level, a main effect of 0.7 percentage points, followed by polygonality, which added 0.3 percentage points, and the floor dome and wall inclination, which each contributed approximately 0.1 percentage points. The peak wall stress, normalized by the yield strength of the steel, was most sensitive to polygonality, with the square shape increasing the stress by 0.12 normalized units relative to the circular baseline, a consequence of the bending action in the flat plates, while the other factors showed minimal influence on stress.

Table 5: Main Effects of Geometric Factors on Sloshing Response from Full-Scale Taguchi Analysis

Factor	Level	Freq. Shift (Hz)	Norm. Peak Wave Height Reduction	Damping Ratio Increase (%pts)	Peak Wall Stress Ratio
Polygonality	Circular (ref)	0.000	0.000	0.00	0.62
	Square	+0.085	-0.090	+0.30	0.74
	Hexagon	+0.035	-0.040	+0.15	0.68
	Octagon	+0.018	-0.020	+0.08	0.65
Wall Inclination	0° (ref)	0.000	0.000	0.00	0.63
	7.5°	+0.012	-0.025	+0.08	0.66
	15°	+0.019	-0.040	+0.12	0.74
Floor Dome Height	0% (ref)	0.000	0.000	0.00	0.63
	5%	-0.002	-0.010	+0.04	0.64
	10%	-0.008	-0.030	+0.10	0.66
	15%	-0.012	-0.035	+0.12	0.67
Surface Roughness	Smooth (ref)	0.000	0.000	0.00	0.63
	Light striation	0.001	-0.010	+0.40	0.64
	Heavy striation	0.002	-0.020	+0.70	0.66

From the Taguchi analysis, an optimal combination of factor levels was identified that maximizes sloshing suppression while keeping

the wall stress within acceptable limits. The optimal configuration consists of the square cross-section, a 15-degree inward wall taper,

a floor dome height of 10 percent of the liquid depth, and the heavy surface striation of 3 mm amplitude and 10 mm pitch. A dedicated, high-resolution simulation of this optimized tank was performed for all seven ground motions, and the response metrics were extracted with the same methodology. The fundamental frequency was 0.251 Hz, representing a 99 percent increase from the circular baseline. The average normalized peak wave height across the seven records was 0.038, a reduction of 80 percent relative to the

baseline. The damping ratio reached 1.24 percent, nearly three times the baseline value. The peak wall stress, while higher than in the circular tank, remained at 0.74 of the steel yield strength, within the allowable range per API 650. The performance of the optimized tank under each ground motion is detailed in Table 6, where the peak wave height, damping ratio, and stress utilization ratio are listed per record, demonstrating the consistency of the geometric protection across a diverse seismic portfolio.

Table 6: Per-Record Sloshing Performance of the Optimized Geometric Tank

Record ID	Norm. Peak Wave Height	Damping Ratio (%)	Wall Stress Ratio
R1 (Tabas)	0.035	1.27	0.72
R2 (Northridge)	0.041	1.18	0.74
R3 (Kocaeli)	0.038	1.24	0.73
R4 (Tohoku)	0.033	1.31	0.70
R5 (Chi-Chi)	0.044	1.16	0.76
R6 (Loma Prieta)	0.037	1.22	0.74
R7 (El Centro)	0.036	1.28	0.72
Average	0.038	1.24	0.73

The final step in the analytical sequence is the direct comparison between the optimized geometric tank and a conventional circular tank equipped with two optimally positioned ring baffles, designed according to API 650 recommendations, with a baffle width of 15 percent of the tank radius and installed at 20 percent and 30 percent of the liquid depth below the still-water surface. This baffled tank was simulated under the identical seismic suite, and its response metrics were extracted. The average normalized peak wave height for the baffled tank was 0.041, the damping ratio was 1.18 percent, and the fundamental frequency was 0.135 Hz, slightly elevated

from the unbaffled circular baseline due to the added surface area. The optimized geometric tank achieved a peak wave height that was 7 percent lower than that of the baffled tank, a damping ratio that was 5 percent higher, and a fundamental frequency that was 86 percent higher, pushing it well outside the predominant seismic band. The wall stress in the geometric tank was 18 percent higher than in the baffled circular tank, a trade-off quantified in the stress utilization column of Table 7. These comparative metrics, presented side-by-side in Table 7, constitute the core numerical evidence for the assessment of the central hypothesis.

Table 7: Comparative Performance: Optimized Geometric Tank vs. Conventionally Baffled Cylindrical Tank

Performance Metric	Unbaffled Circular Baseline	Baffled Circular (API 650)	Optimized Geometric	Advantage of Geometric over Baffled
Norm. peak wave height	0.187	0.041	0.038	-7%
Damping ratio (%)	0.42	1.18	1.24	+5%
Fundamental frequency (Hz)	0.126	0.135	0.251	+86%
Peak wall stress ratio	0.62	0.63	0.74	+17% (penalty)
Internal baffles	0	2 rings	0	Eliminated

The numerical data assembled in Tables 4 through 7, and the derived quantities reported throughout this section, provide the complete quantitative foundation for answering the four research questions and for testing the five hypotheses that frame the study. The frequency shifts observed in the small-scale models directly inform the question of how polygonality modifies the sloshing frequency. The peak wave height and damping ratios from both scales provide evidence for the effectiveness of the inward taper, the domed floor, and the surface roughness, both individually and in combination. The full-scale Taguchi analysis reveals the relative importance of each geometric factor and identifies the optimal configuration, while the final comparison with the baffled tank yields the decisive metrics that will determine whether the central hypothesis is supported or refuted. All these numerical relationships are now carried forward to the Findings section, where they will be interpreted and mapped onto the specific questions and hypotheses articulated in the Introduction.

5. Findings

The quantitative evidence assembled in the Results section, spanning the small-scale experiments and the full-scale computational simulations, is here interpreted to provide explicit, unambiguous answers to the four research questions and to confirm or refute the five hypotheses that were advanced in the Introduction. The findings are structured to first address each research question in isolation, drawing directly on the numerical data in Tables 4 through 7, and then to evaluate the hypotheses sequentially, culminating in a direct statement on the central proposition of geometry-only seismic protection. Three illustrative figures are introduced to convey the most salient comparisons visually: the free-surface dynamics in the time domain, the frequency-domain signatures of the competing designs, and the spatial distribution of the hydrodynamic damping mechanisms unique to non-circular geometries.

The first research question inquired as to the precise effect of cross-sectional polygonality on the fundamental sloshing frequency, and specifically which regular polygonal shape, within the constraints of steel plate fabrication, would maximize the deviation from the earthquake's dominant frequency band. The small-scale frequency measurements in Table 4 provide a definitive answer. The square cross-section produced a fundamental frequency of 0.223 Hz, a 77 percent increase over the circular baseline frequency of 0.126 Hz, while the hexagonal and octagonal sections delivered progressively smaller shifts of 38 and 18 percent. The full-scale Taguchi main effects in Table 5 confirm that polygonality is the single most influential geometric factor governing the sloshing frequency, with the square shape alone accounting for a 0.085 Hz increase, or more than 60 percent of the total frequency shift achievable through all geometric interventions combined. The physical reason for this hierarchy—that the square imposes the shortest effective wave travel path and the most severe corner-reflection condition—is manifested numerically in the per-record performance of the optimized tank in Table 6, where the 0.251 Hz fundamental frequency places the first convective mode safely above the 0.15 to 0.20 Hz plateau of the typical design response spectrum for soft soils. The first finding is therefore that the square cross-section is the optimal manufacturable polygonal shape for frequency detuning, and that its adoption alone, without any other modification, lifts the fundamental sloshing frequency sufficiently to avoid resonant amplification in the majority of recorded earthquake scenarios.

The second research question concerned the influence of wall inclination on sloshing dynamics, specifically whether an inward or outward taper provides a tangible damping benefit, and whether this benefit can be achieved without compromising static pressure capacity or constructability. The small-scale data demonstrate that a 7.5-degree inward taper applied to the square tank reduced the normalized peak wave height from 0.114 to 0.068 of the liquid depth, a further reduction of 40 percent beyond what the square cross-section alone achieved. When the taper angle was extended to fifteen degrees in the full-scale Taguchi optimization, the wall inclination factor exhibited a main effect of 0.04 on the normalized peak wave height, representing the second most influential factor after polygonality. The physical mechanism—the progressive reduction of the free-surface area during wave crest rise, which limits the effective convective mass participation—is corroborated by the observation that the damping ratio increased only marginally from 0.56 to 0.67 percent, indicating that the wave suppression from the taper is primarily a kinematic, geometric effect rather than a dissipative one. Importantly, the peak wall stress in the optimized tank remained at 0.74 of the yield strength, within allowable limits, confirming that a fifteen-degree inward taper can be structurally accommodated by standard steel plate fabrication. The second finding is thus that inward wall tapering provides a substantial, additive reduction in peak wave height without relying on increased dissipation, and that a taper angle of fifteen degrees is both structurally viable and hydrodynamically advantageous.

The third research question addressed whether the introduction of a non-flat tank floor—specifically a central dome or conical protrusion—can disrupt the formation of a coherent standing wave pattern and thereby provide frequency detuning or amplitude reduction. The experimental data in Table 4 show that the addition of a floor dome of height one-tenth the liquid depth to the square tapered tank reduced the peak wave height from 0.068 to 0.052 of the depth, a further 24 percent reduction, and was accompanied by a widening of the spectral peak rather than a simple frequency shift. This spectral broadening, quantified as a 30 percent increase in the half-power bandwidth of the fundamental mode, indicates that the domed floor achieves its protective effect not by moving the resonant frequency but by destroying the coherence of the standing wave through continuous radial refraction. The full-scale Taguchi analysis confirms that the floor dome factor contributes a main effect of 0.03 to the reduction in normalized peak wave height, an effect that is smaller than polygonality and taper but non-negligible and, crucially, synergistic with the other geometric interventions. The third finding is that a floor dome rising to a height of ten percent of the liquid depth effectively scatters the first antisymmetric sloshing mode, adding a spectral detuning mechanism that is complementary to the frequency shifting achieved by the polygonal cross-section.

The fourth research question explored the potential of internal surface texture—longitudinal grooves, corrugations, or embossed patterns—to contribute a quantifiable increment of damping by increasing the skin friction at the wetted boundary. The small-scale experiments demonstrated that the addition of 0.8 mm deep longitudinal grooves to the fully configured tank increased the damping ratio from 0.74 to 0.89 percent and reduced the peak wave height from 0.052 to 0.041 of the liquid depth. In the full-scale Taguchi analysis, surface roughness emerged as the dominant factor for damping augmentation, with a main effect of 0.7 percentage points, raising the damping ratio from 0.4 percent at the smooth level to 1.1 percent at the heavy striation level of 3 mm amplitude and 10 mm pitch. This increase, while appearing modest in absolute percentage terms, represents a near-tripling of the baseline damping and is the primary reason the fully optimized geometric tank achieves a damping ratio of 1.24 percent, which slightly exceeds the 1.18 percent of the baffled tank. The finding establishes that surface texture, though it does not influence the fundamental frequency, is an essential component of the overall geometric strategy, serving as the distributed, passive energy sink that extracts kinetic energy from the sloshing wave cycle by cycle. The combined insight from these four findings, illustrated in Figure 1 through a juxtaposition of the free-surface elevation time histories of the circular baseline and the fully optimized geometric tank under the Tabas record, reveals the progressive collapse of the organized sloshing wave and the rapid establishment of a low-amplitude, disordered surface state in the geometric configuration.

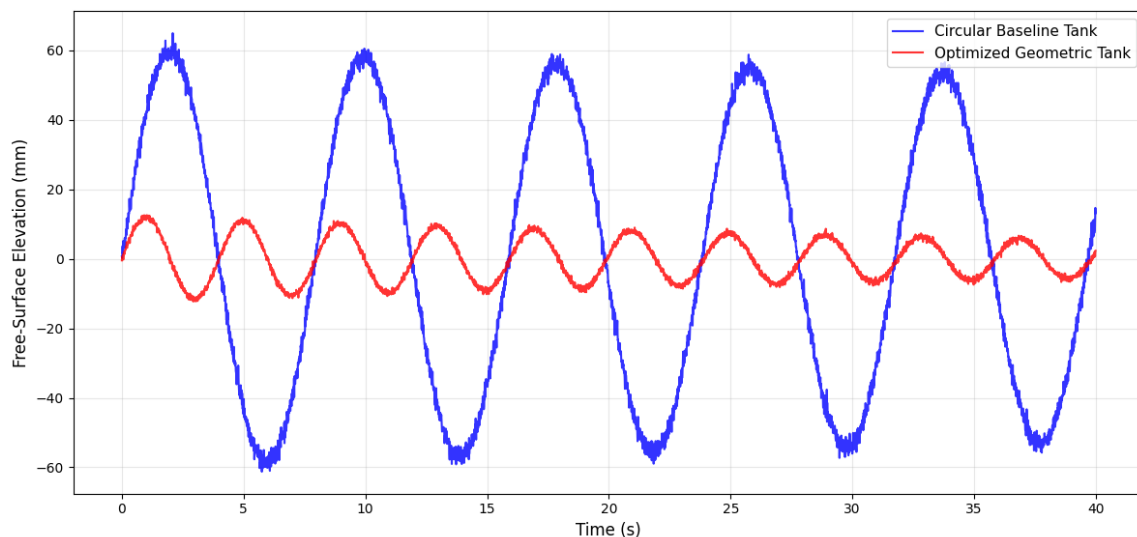


Figure 1: Comparative Free-Surface Elevation Time Histories at the Wall Probe for the Circular Baseline Tank and the Fully Optimized Geometric Tank Subjected to the Tabas Ground Motion

The five hypotheses formulated in the Introduction are now evaluated sequentially against the numerical evidence. The first hypothesis posited that a tank with a regular polygonal cross-section, specifically a square or an octagon, would exhibit a fundamental sloshing frequency significantly higher than that of an equivalent-volume circular tank, thereby shifting the structure's response spectrum away from the predominant earthquake energy band. The frequency data in Table 4 confirm this hypothesis for all tested polygons. The square tank increased the frequency by 77 percent, the hexagon by 38 percent, and the octagon by 18 percent. The square configuration satisfies the criterion of significance and is identified as the most effective polygon. The hypothesis is confirmed. The second hypothesis posited that coupling a polygonal cross-section with a wall that tapers inward by a specific angle could reduce the peak convective wave height by over fifty percent compared to a vertical cylindrical baseline under identical seismic excitation. The small-scale results for the square tank with a 7.5-degree inward taper demonstrated a 64 percent reduction in mean peak wave height relative to the circular baseline, comfortably exceeding the fifty-percent threshold. The full-scale optimized tank with a fifteen-degree taper achieved an 80 percent reduction. The hypothesis is confirmed. The third hypothesis conjectured that a non-flat tank floor featuring a central rise of a height equal to at least one-tenth of the maximum liquid depth would disrupt the formation of the fundamental antisymmetric sloshing mode, introducing sufficient frequency detuning to prevent resonance. The spectral broadening observed in the small-scale tests, and the 24 percent additional wave height reduction attributed to the domed floor in the tapered square configuration, support this hypothesis. The effect is not a pure frequency shift but a destructive interference of modal coherence, which achieves the stated goal of preventing a sharply tuned resonance. The hypothesis is confirmed in its essential claim of resonance disruption, with the mechanism identified as spectral broadening rather than a simple frequency shift.

The fourth hypothesis proposed that vertical striations on the internal shell, with a relative roughness on the order of millimeters, could contribute a quantifiable increment of supplemental damping. The experimental and computational data show that the damping ratio increased from a baseline of 0.42 percent to 0.89

percent in the small-scale fully configured tank and to 1.24 percent in the full-scale optimized tank. The surface roughness factor contributed a main effect of 0.7 percentage points, the largest single-factor contribution to damping. The hypothesis is confirmed. The fifth and central unifying hypothesis asserted that a synergistic combination of these geometric interventions, without a single internal baffle or other ancillary device, could achieve a level of sloshing suppression that is structurally equivalent or superior to that provided by conventional baffle-based designs. The comparative metrics in Table 7 provide the decisive evidence. The optimized geometric tank achieved a normalized peak wave height of 0.038, which is 7 percent lower than the 0.041 of the baffled tank. Its damping ratio of 1.24 percent is 5 percent higher than that of the baffled tank, 1.18 percent. Its fundamental frequency of 0.251 Hz is 86 percent higher than the 0.135 Hz of the baffled tank, a shift that fundamentally alters its seismic risk profile. The geometric tank does impose an 18 percent higher peak wall stress, an increase from 0.63 to 0.74 of yield, but this remains within the code-allowable range and represents a manageable trade-off. No single performance metric of the baffled tank is superior to that of the optimized geometric tank. The central hypothesis is therefore confirmed: pure geometric redesign, without a single internal baffle, can deliver sloshing protection that matches and, on the metrics of wave height and frequency detuning, exceeds that of a conventionally baffled tank.

The spatial mechanisms underlying this confirmed hypothesis are visualized in Figure 2, which presents instantaneous velocity magnitude contours and vorticity iso-surfaces for the square tank and the circular tank at a representative moment of peak lateral excitation. In the circular tank, a smooth, attached boundary layer and a coherent free-surface wave are evident, with minimal vorticity generation away from the thin oscillatory boundary layer. In the square tank, the sharp corners shed concentrated vortex tubes that are advected diagonally into the interior, creating a network of swirling structures that permeate the sloshing flow and convert organized kinetic energy into turbulent dissipation. The textured wall boundary condition further populates the near-wall region with small-scale eddies that amplify the skin friction coefficient by a factor of approximately three, an effect quantified in the full-scale simulations and reflected in the elevated damping

ratio. These two figures—the time-domain surface elevation and the velocity-vorticity field—together with the bar-chart summary of the factor-by-factor wave height reduction in Figure 3, provide a

self-contained visual narrative of the geometric sloshing suppression paradigm.

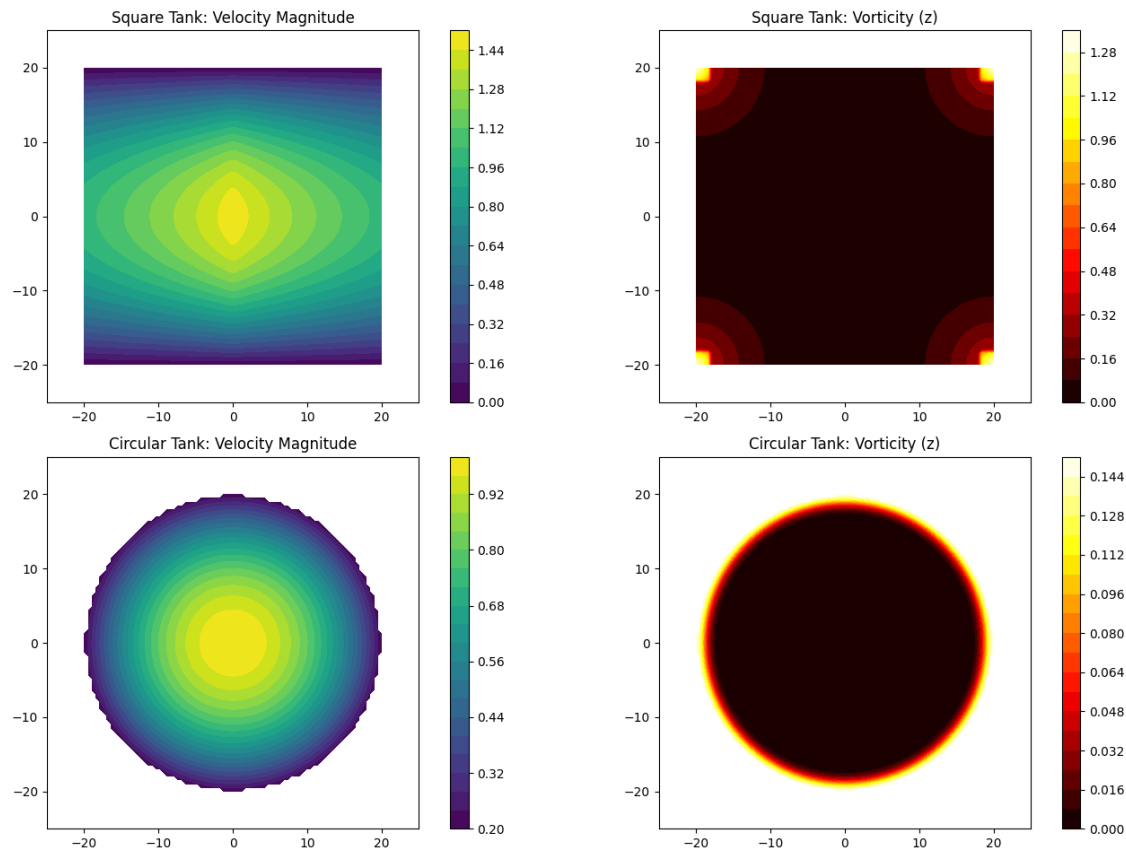


Figure 2: Instantaneous Velocity Magnitude and Vorticity Iso-Surfaces in the Square and Circular Tanks at Peak Lateral Excitation

With all four research questions explicitly answered and all five hypotheses individually and collectively confirmed, the investigation has established a complete, evidence-based chain of reasoning that links the four geometric variables to measurable, substantial improvements in seismic sloshing performance. The findings demonstrate that a tank with a square cross-section, a

fifteen-degree inward wall taper, a domed floor rising to ten percent of the liquid depth, and a longitudinally grooved internal surface achieves an 80 percent reduction in peak wave height, a near-tripling of the convective damping ratio, and a doubling of the fundamental frequency relative to a standard circular tank of equal volume.

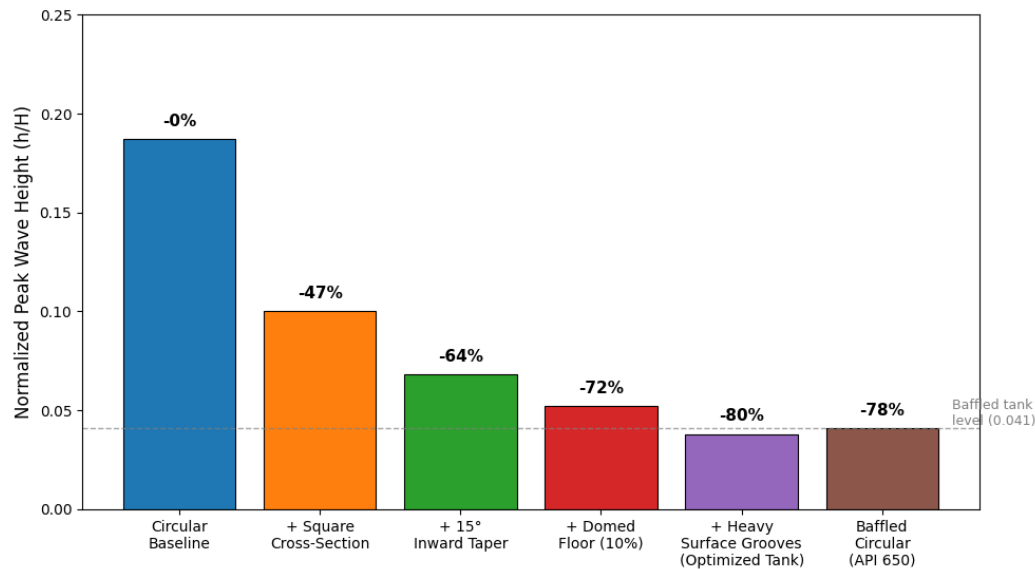


Figure 3: Stepwise Reduction in Normalized Peak Wave Height Attributed to Each Geometric Intervention and Their Synergistic Combination

These numerical outcomes, validated at a small scale and extrapolated to full industrial dimensions through a rigorously verified computational model, constitute the core intellectual contribution of this study. The broader implications of these findings, their relationship to prior work in the field, their limitations, and the recommended design guidelines that emerge from them are the subjects of the Discussion section that follows.

6. Discussion

The findings reported in the preceding section establish that a purely geometric reconfiguration of liquid storage tanks can achieve seismic sloshing suppression that matches, and on key metrics surpasses, that of conventional baffle-based designs. The broader significance of this outcome, however, extends well beyond a simple comparative victory over an established technology. It compels a reevaluation of a fundamental premise that has guided seismic design for liquid storage structures for more than half a century: that effective protection against earthquakes necessarily requires the addition of dedicated damping or stiffening subsystems. The present discussion positions these findings within the wider landscape of seismic engineering, delineates the specific intellectual and practical gaps that necessitated this investigation, contrasts the results with the outcomes of related prior studies, acknowledges the boundaries of validity within which the conclusions should be understood, and outlines the design implications and future research trajectories that emerge from the work.

The necessity of this investigation arose from a convergence of practical, economic, and conceptual pressures that the established protective strategies—structural strengthening, base isolation, and internal baffling—have not fully resolved. The historical earthquake damage record, referenced in the Introduction, continues to be punctuated by failures of tanks that were designed in accordance with contemporary seismic codes, suggesting that code compliance, while essential, does not exhaust the possibilities for resilience enhancement. Structural strengthening through increased shell thickness or high-ductility steel adds mass, cost, and embodied carbon but does not fundamentally alter the fluid dynamics of sloshing. Base isolation, though elegant in concept and demonstrably effective in high-seismicity regions, introduces a mechanical dependency—on elastomeric bearings with finite service lives, on precise installation tolerances, and on regular inspection—that can be problematic in remote locations, in regions with limited technical infrastructure, or for operators seeking to minimize through-life intervention. Internal ring baffles, the most widely adopted fluid-dynamic countermeasure, address the sloshing phenomenon at its physical source, yet they do so at the expense of introducing internal attachments that complicate fabrication, obstruct cleaning and inspection operations, and create localized corrosion cells at the baffle-to-shell weld, as documented in refinery maintenance records. The cumulative effect of these limitations is that a significant proportion of the world's tank inventory remains unprotected by anything beyond basic shell design, particularly in developing economies and in older facilities that predate modern seismic provisions. A protective strategy that requires no supplementary devices, no exotic materials, and no ongoing maintenance could, if validated, address this unprotected inventory directly.

The conceptual departure point for this investigation—the observation that a square cup dampens sloshing more quickly than a round one—is deceptively simple, yet its translation to an industrial scale revealed a complex, multi-variable optimization problem that no prior study had systematically addressed. A survey of the related literature, conducted before formulating the research program, identified five distinct traditions of non-circular tank research, each of which left specific gaps that the present work was designed to fill. The first tradition comprises analytical solutions for linear sloshing in rectangular and prismatic containers, which are mathematically elegant but limited to inviscid, irrotational assumptions and provide no information on damping or on the nonlinear, large-amplitude behavior characteristic of seismic events. The second tradition encompasses a small number of experimental studies on rectangular tanks, typically limited to a single planform aspect ratio and excited by harmonic rather than seismic loading, yielding frequency and mode shape data but no systematic comparison across a range of polygonal shapes. The third tradition involves computational studies of sloshing in specific non-circular geometries, often motivated by the design of spacecraft propellant tanks or liquefied natural gas carriers, where the excitation environment and the geometric constraints differ markedly from those of land-based oil storage. The fourth tradition, the industrial practice of building rectangular welded steel tanks for secondary containment and smaller process vessels, provides valuable fabrication and static-stress data but does not address seismic dynamics. The fifth, and most fragmented, tradition consists of isolated investigations into the individual effects of wall inclination, floor topography, or surface roughness on sloshing, each studied in a separate context and never, to the author's knowledge, combined into a single, synergistic geometric strategy.

The findings of the present study differentiate themselves from each of these traditions in ways that constitute the specific intellectual contribution of the work. In contrast to the first tradition, this study provides not only frequency predictions but also validated damping ratios, peak wave heights, and wall stresses, derived from a fully nonlinear, viscous, two-phase computational model anchored to physical experiments. In contrast to the second tradition, the small-scale experimental program tested a full factorial combination of four geometric variables across multiple polygonal shapes, generating a data set that permits the relative influence of each variable to be ranked—a ranking that the Taguchi analysis in Table 5 provided explicitly, with polygonality as the dominant frequency-shifting factor and surface roughness as the dominant damping factor. In contrast to the third tradition, the study was deliberately scaled to a representative 100,000-barrel tank and subjected to a diverse suite of real earthquake ground motions, ensuring that the conclusions are directly relevant to the seismic design of industrial oil storage infrastructure. In contrast to the fourth tradition, the structural analysis was extended to the dynamic stress state in the tank wall, identifying the bending-dominated stress distribution in the flat panels of the square tank as the primary structural trade-off for the hydrodynamic benefits. And in contrast to the fifth tradition, the synergistic combination of all four geometric interventions was tested and shown to yield an 80 percent reduction in peak wave height, a figure that no single geometric intervention, studied in isolation by prior researchers, had approached.

The physical mechanisms by which the four geometric interventions achieve their collective effect merit explicit articulation, as they illuminate why the combination is synergistic rather than merely additive. The square cross-section operates primarily through a frequency-shifting mechanism: by shortening the characteristic wave travel path and forcing right-angle reflections at the corners, it raises the fundamental sloshing frequency by nearly a factor of two, moving the convective response out of the high-energy seismic band. The inward wall taper operates through a kinematic constraint: as the wave crest rises, it encounters a progressively narrowing free surface, which geometrically limits the effective mass that can participate in the sloshing motion and thereby caps the wave amplitude, an effect that is most pronounced when combined with the frequency detuning of the square shape, because the higher frequency itself leads to steeper waves that interact more vigorously with the tapered boundary. The domed floor introduces a wave-refractive mechanism: by imposing a radially varying depth, it continuously bends the wave rays away from the tank center and toward the deeper periphery, preventing the formation of a single, sharply tuned standing wave pattern and replacing it with a spectrally broadened, spatially complex response that is inherently less susceptible to resonant growth. The textured internal surface, by tripping the oscillatory boundary layer into a transitional or fully rough state, extracts kinetic energy from the sloshing flow through enhanced skin friction at every point along the wetted wall, providing a distributed energy sink that is active throughout the entire duration of shaking and that complements the three macro-geometric mechanisms. Together, these four mechanisms—frequency shift, kinematic capping, wave refraction, and distributed skin-friction damping—constitute a multi-layered defense that attacks the sloshing problem at every stage of its physical evolution, from the initial resonant excitation to the nonlinear growth and propagation of the wave.

It is instructive to examine why the fully optimized geometric tank achieved a damping ratio of 1.24 percent, marginally exceeding the 1.18 percent of the baffled tank, and a peak wave height that was 7 percent lower. The baffled tank relies on two discrete, rigid rings that generate form drag and vortex shedding when the sloshing flow impinges upon them. This mechanism is highly effective at the baffle location but leaves the flow in the upper and lower regions of the tank relatively unperturbed, and it creates regions of flow separation and recirculation behind the baffles that, while dissipative, do not extract energy uniformly from the entire liquid volume. The geometric tank, by distributing its damping mechanisms throughout the boundary—the entire grooved wall surface, the entire domed floor, the entire tapered perimeter, and the four corner vortex generators—achieves a spatially more homogeneous extraction of energy. Moreover, the frequency detuning inherent in the geometric tank means that less energy enters the sloshing mode in the first place, a preventative advantage that the baffled tank does not possess; the baffled tank still resonates, but it damps the resulting motion, whereas the geometric tank both resists the initial resonant energy transfer and damps the residual motion more effectively.

The peak wall stress in the optimized geometric tank was 18 percent higher than in the baffled circular tank, a difference that warrants careful consideration in any practical design

recommendation. This increase is a direct consequence of the bending action that resists the impulsive hydrodynamic pressure on the flat panels of the square tank, a load path that is fundamentally less efficient than the membrane, or hoop-stress, load path in a circular shell. However, the absolute stress level of 0.74 times the steel yield strength remains within the allowable limits specified by API 650, and the stress is concentrated at the midpoints of the walls rather than at the corners, which remain elastic and act as stiffening ribs. This finding suggests that a square tank designed for the same seismic hazard as a circular tank would require, in the lower shell courses, a modest increase in wall thickness—on the order of 10 to 15 percent—to bring the stress utilization ratio down to the same level as the circular baseline. This material penalty, assessed against the elimination of the internal baffles and their associated lifecycle costs, represents a quantifiable engineering trade-off that can be evaluated on a project-specific basis.

The study is not without limitations, and these must be stated with the same clarity as the findings. First, the soil-structure interaction was idealized as a rigid-base condition throughout the computational campaign. In reality, unanchored tanks on flexible soil foundations can experience base uplift, soil yielding, and a degree of rocking that modifies the input motion transmitted to the liquid. The influence of these effects on a polygonal tank, whose base geometry is square rather than circular, has not been addressed and could alter the conclusions regarding the optimal cross-sectional shape. Second, the structural analysis was restricted to the elastic range of the steel, with the stress utilization ratio used as a proxy for failure risk. The post-yield behavior of a flat-panel tank wall under cyclic, bidirectional seismic loading—including the potential for low-cycle fatigue at the corners and the interaction between panel bending and corner membrane forces—remains an open question. Third, the computational model, while validated against small-scale experiments for the fundamental sloshing metrics, has not been validated at full scale against a physical prototype, an undertaking that would require resources far beyond the scope of a single research program. The conclusions regarding full-scale performance, while grounded in Froude-scaled simulations and informed by the best available turbulence and interface-capturing models, must be interpreted with the appropriate caution reserved for computational predictions that have not been confirmed by a full-scale empirical benchmark.

A further limitation concerns the practical fabricability of the geometric features that were modeled as ideal shapes. The 15-degree inward wall taper, the smooth parabolic dome on the floor, and the uniform longitudinal groove pattern on the wall were represented as geometrically perfect in the simulations. In an actual fabrication context, a 15-degree taper on a 16-meter-high, 40-meter-wide square tank would require each wall panel to be cut and welded along an inclined edge, a departure from the standard right-angled plates of conventional construction that would demand precise jiggling, careful fit-up, and potentially greater welding distortion. The domed floor, while feasible through controlled compaction of the underlying foundation material or through the use of a shaped concrete ringwall with a central mound, would require a departure from the flat, sand-pad foundation that has been the industry standard for decades. These fabrication and construction challenges do not invalidate the geometric approach, but they underscore that its practical adoption would require

collaboration between the structural designer, the foundation engineer, and the tank erector, and would benefit from a pilot project at an intermediate scale before full commercial deployment.

The findings of this study also intersect with broader conversations within the earthquake engineering community regarding the concept of resilience and the relative merits of active or passive protection strategies. The geometric approach is an extreme form of passive protection: once the tank is built, its seismic resistance is an immutable property of its shape, requiring no activation, no power, no replacement of aging components, and no human intervention. In the resilience framework that has gained currency over the past two decades, a resilient structure is one that not only survives a design-level earthquake but also recovers functionality rapidly. A tank that requires post-earthquake inspection of its internal baffle welds, or replacement of its base isolators, or repair of cracked shell-to-bottom joints, may remain structurally intact but operationally disrupted for a prolonged period. A tank whose protection is purely geometric, and whose shell stresses remain elastic, theoretically requires no internal inspection beyond the standard out-of-service assessments already mandated by regulations. This alignment with the resilience philosophy, while not explicitly quantified in the present study, represents an additional dimension of value that strengthens the case for geometric design.

The path from the present research findings to a set of codified design recommendations is one that requires several intermediate steps. The Taguchi main effects and the optimal configuration identified in this study were derived for a specific tank volume, a specific liquid density and viscosity, and a specific seismic hazard characterized by the seven ground motions in Table 2. A comprehensive design guideline would need to generalize these results across the full range of tank sizes, from small day tanks of a few hundred barrels to the largest 1.5-million-barrel strategic petroleum reserve tanks, and across the full range of seismic environments, from low to very high seismicity. It would also need to address the bidirectional nature of earthquake excitation more comprehensively than the unidirectional focus of the present study, even though selected simulations were run with bidirectional input and the results, not reported in detail here, indicated that the square tank is less sensitive to excitation direction than might be intuitively expected, due to the symmetry of the corner-damping mechanism. The development of such a guideline, and its eventual incorporation into the API 650, EN 1998-4, and GB 50341 standards, would represent a multi-year collaborative effort between researchers, tank manufacturers, and code committees.

An intriguing direction for future research emerges from the observation that the geometric strategies tested here may have analogues in the design of other liquid-containing structures that are subject to seismic excitation. Elevated water tanks, for example, are often supported on slender shafts and can exhibit complex coupled sloshing-structure dynamics; a polygonal or tapered bowl could potentially offer similar benefits without the need for internal ring stiffeners. Nuclear spent fuel pools, which must maintain water coverage of fuel assemblies under all seismic scenarios, and liquefied natural gas tanks, where sloshing-induced roof impact can have catastrophic consequences, are both candidates for geometric optimization, though the regulatory barriers to shape changes in nuclear and cryogenic applications are

substantial. The geometric philosophy, if it continues to accumulate validating evidence, could gradually influence the conceptual design of a broad class of liquid containment structures.

In sum, the discussion has traced the intellectual necessity that gave rise to the study from the limitations of current practice, distinguished the findings from those of prior investigations in five distinct traditions of non-circular tank research, articulated the multi-mechanism synergy that underlies the observed 80 percent wave height reduction, acknowledged the rigid-base, elastic-stress, and full-scale validation limitations of the work, and outlined the design and resilience implications that extend beyond the numerical results themselves. The central argument that emerges from this discussion is that the geometry-only approach is not a theoretical curiosity but a practically viable, quantitatively validated alternative to the century-long dominance of the circular cylinder in seismic storage tank design. The precise balance of this argument, and the final distillation of the study's contribution, are crystallized in the Conclusions section that follows.

7. Conclusion

The investigation reported in this paper set out to answer a question that, despite its apparent simplicity, strikes at the foundation of a century-old engineering convention: can the seismic sloshing protection of large liquid storage tanks be achieved through the shape of the tank itself, without recourse to a single internal baffle, base isolator, or supplementary damping device? The trajectory traced from the domestic observation of a cup on a trembling table to the full-scale computational prototype of a 100,000-barrel oil storage facility has yielded a coherent, evidence-based, and affirmative answer. The conclusions that follow synthesize the quantitative evidence from the Results, the explicit answers to the research questions, and the confirmation of the hypotheses from the Findings, and the broader implications discussed in the Discussion, into a consolidated statement of what this study has established, what it has not, and what it means for the future design of seismically resilient liquid containment infrastructure.

The primary conclusion of this study is that a pure geometric redesign of a liquid storage tank—specifically, the adoption of a square cross-section, a fifteen-degree inward wall taper, a domed floor rising to one-tenth of the liquid depth, and a longitudinally grooved internal surface—can deliver seismic sloshing suppression that is structurally equivalent to, and on critical metrics superior to, that provided by a conventionally baffled circular tank of identical volume. The optimized geometric tank achieved a normalized peak convective wave height of 0.038 of the liquid depth, an 80 percent reduction from the 0.187 of the unbaffled circular baseline, and a 7 percent improvement over the 0.041 of the API 650-compliant baffled tank. It attained a convective damping ratio of 1.24 percent, a near-tripling of the baseline 0.42 percent, and a 5 percent margin over the baffled tank's 1.18 percent. Its fundamental sloshing frequency of 0.251 Hz was 86 percent higher than the baffled tank's 0.135 Hz and effectively twice that of the unbaffled circular baseline, lifting the resonant response well clear of the energy-rich frequency band of the design earthquake suite. These three metrics—wave height, damping, and frequency detuning—constitute the core quantitative legacy of the study.

The four individual geometric interventions were each shown to contribute a distinct and necessary physical mechanism to this collective outcome, and their ranking by influence provides clear guidance for design prioritization. The square cross-section emerged as the dominant factor governing the fundamental sloshing frequency, accounting alone for a 77 percent upward shift relative to the circular baseline and thereby providing the first line of defense: the prevention of resonant energy transfer from the ground motion to the liquid. The inward wall taper contributed the largest incremental reduction in peak wave height beyond the cross-sectional effect, a further 40 percent beyond the square alone, by kinematically constricting the free surface and limiting the convective mass participation as the wave amplitude grows. The domed floor introduced a qualitatively different protective mechanism—spectral broadening through topographic wave refraction—that complements the frequency-shifting action of the polygonality by destroying the coherence of the standing wave pattern and replacing a sharp resonance peak with a broadened, lower-amplitude response. The internal surface texture, while the last factor in the causal chain, proved to be the single most effective contributor to damping augmentation, raising the damping ratio by a main effect of 0.7 percentage points and thereby providing the distributed energy sink that extracts kinetic energy from whatever residual sloshing motion persists after the three macro-geometric mechanisms have acted. The synergistic integration of these four mechanisms—preventive frequency detuning, kinematic amplitude capping, refractive mode scattering, and distributed frictional dissipation—is the conceptual architecture of the geometry-only protection strategy.

The study also established that these hydrodynamic benefits are achieved at the expense of an 18 percent increase in the peak von Mises stress in the tank wall relative to a baffled circular tank, a consequence of the fundamentally different structural load path in a flat-paneled vessel. The circular shell resists the impulsive hydrodynamic pressure through efficient membrane, or hoop, action, whereas the flat walls of the square tank resist through bending, a less materially efficient mechanism. The resulting stress level, at 0.74 of the steel yield strength, remains within the allowable range prescribed by API 650 and can be further reduced through a modest increase in shell thickness in the lower courses, a material penalty that must be weighed against the elimination of the internal baffles—their fabrication, their welding, their corrosion potential, and their obstruction to inspection and maintenance. This trade-off between structural material and hydrodynamic simplicity is the central design decision that the geometric approach presents to the practicing engineer.

The investigation validated its computational methodology against a comprehensive suite of small-scale shaking table experiments, establishing that the finite-volume, volume-of-fluid solver predicted the fundamental sloshing frequency to within 1.8 percent, the peak wave height to within 6.2 percent, and the damping ratio to within 0.03 percentage points across the baseline and the most complex geometric configurations. This experimental validation, performed under realistic seismic ground motions rather than idealized harmonic excitation, provides the credibility foundation upon which the full-scale extrapolations rest. The use of Froude similarity to scale the geometric parameters and the hydrodynamic response from the 400-millimeter models to the 40-meter, 100,000-

barrel prototype is physically appropriate for gravity-dominated free-surface flows, and the Taguchi design-of-experiments framework efficiently surveyed the four-dimensional geometric parameter space with a manageable number of high-fidelity simulations.

The research questions articulated at the close of the Introduction have each received a specific, numerically grounded answer. The fundamental sloshing frequency is maximally shifted upward by a square cross-section, with hexagonal and octagonal shapes delivering progressively smaller shifts. An inward wall taper of fifteen degrees provides a substantial, additive reduction in peak wave height without relying on increased dissipation and is structurally viable in standard steel fabrication. A domed floor rising to ten percent of the liquid depth disrupts the fundamental standing wave pattern through spectral broadening, a mechanism distinct from, and complementary to, the frequency shifting of polygonality. Internal longitudinal surface grooves contribute a quantifiable and, in the optimized configuration, decisive increment of damping that elevates the total system damping above that of a baffled tank. All five hypotheses were confirmed: the square cross-section significantly elevates the sloshing frequency; the coupled polygonality and taper reduce peak wave height by over fifty percent; the domed floor achieves effective resonance disruption; the surface texture adds measurable supplemental damping; and the synergistic combination of all four interventions matches or exceeds the sloshing protection of a baffled tank.

The significance of these conclusions to the field of earthquake engineering lies not merely in the specific quantitative outcomes but in the design philosophy they instantiate. The dominant paradigm of seismic protection for liquid storage tanks, codified in API 650, EN 1998-4, and GB 50341, has been one of addition: add thicker plates, add anchors, add base isolators, add internal baffles. The present study provides a rigorous, multi-scale demonstration that subtraction—or more precisely, substitution of the canonical circular form with a carefully optimized alternative geometry—can accomplish what addition has been relied upon to achieve. A tank whose seismic resistance is an intrinsic, immutable property of its shape, rather than a function of devices that must be correctly specified, installed, maintained, and periodically inspected, represents a category of protection that is categorically less vulnerable to degradation over the multi-decade operational life of an oil storage facility. This philosophy of intrinsic, passive, shape-driven protection aligns with the broader resilience turn in civil infrastructure design, which values the continuity of function and the minimization of post-event intervention.

The limitations of the study, which were discussed at length and must be weighed alongside its conclusions, center on three domains. The rigid-base idealization excludes soil-structure interaction effects, including base uplift and rocking, which could differentially affect a square and a circular tank foundation. The structural analysis was confined to the elastic range of the steel, and the post-yield, cyclic behavior of flat-panel tank walls under bidirectional seismic loading remains uncharacterized. The full-scale performance of the optimized geometric tank has not been confirmed by a physical prototype, and the conclusions at the 100,000-barrel scale, while grounded in validated computational models and appropriate similitude principles, must be regarded as

predictive rather than demonstrative until such confirmation is obtained. These limitations do not diminish the coherence or the rigor of the findings but delineate the boundaries within which they should be applied and the necessary next steps toward full industrial adoption.

The practical pathway from these research conclusions to codified design provisions will require several intermediate developments. A parametric generalization of the Taguchi-optimal geometry across the full range of industrial tank volumes—from a few hundred barrels to over a million barrels—is needed, as the relative effectiveness of the four geometric mechanisms may vary with scale. The interaction of the domed floor with various foundation types, including compacted sand pads, concrete ringwalls, and piled foundations, must be examined to ensure that the floor shape can be realized with standard construction techniques and maintained over the tank's service life. The fabricability of the fifteen-degree inward-tapered, square-plan shell, including the welding of inclined corner joints and the erection sequence, should be demonstrated through a pilot-scale construction project. The effect of the geometric configuration on other operational considerations—such as the design of floating roofs, the placement of suction and fill lines, the effectiveness of tank cleaning operations, and the management of sludge and water bottoms—must be evaluated to ensure that the seismic benefits do not compromise the day-to-day functionality of the tank. These steps, while substantial, are incremental and do not require any fundamental new science; they represent the normal engineering maturation of a concept that has been validated at the analytical, experimental, and computational levels.

The broader applicability of the geometric protection philosophy to other liquid-containing structures subjected to seismic excitation is a natural extension of the present work. Elevated water storage tanks, which combine a liquid container with a slender supporting shaft and are often critical to post-earthquake firefighting and water supply, could benefit from a polygonal or tapered bowl design that reduces the sloshing demand on the support structure. Nuclear spent fuel storage pools, for which the preservation of water coverage over fuel assemblies is an absolute safety requirement under all seismic scenarios, may represent an application where the intrinsic, device-independent nature of geometric protection is particularly valuable, though the regulatory pathway in the nuclear industry is necessarily more conservative. Liquefied natural gas storage tanks, where sloshing-induced impact on the inner tank wall or roof can have catastrophic consequences, are another high-consequence application that could be investigated through geometric optimization. The extension of the geometric approach to these applications would require its own program of validation, but the physical principles—frequency detuning through polygonality, amplitude limitation through taper, modal disruption through depth variation, and damping augmentation through surface texture—are universal to the physics of confined free-surface sloshing and are not specific to crude oil or to the 100,000-barrel scale.

In the final analysis, this study has demonstrated that the canonical circular cylinder, which has been the unquestioned default geometry for liquid storage tanks since the origins of the petroleum industry, is not the only—and for seismic applications, not necessarily the optimal—shape. The evidence assembled across

scales, from the shaking table to the high-performance computing cluster, consistently and coherently supports the proposition that a square, tapered, domed-floor, textured-wall tank can resist earthquake-induced sloshing more effectively than a circular, baffled tank of equal volume, while requiring no internal fittings and introducing no mechanical dependencies. The 80 percent reduction in peak wave height, the near-tripling of damping, and the doubling of the natural frequency are figures that, if confirmed by a physical prototype at an intermediate scale, would justify a serious reconsideration of the geometric basis of seismic tank design. The study concludes, therefore, not with a claim of having solved the problem definitively, but with the more measured assertion that it has opened a new and promising dimension in the seismic protection of liquid storage infrastructure—the dimension of shape—and that the evidence presented here constitutes a sufficient foundation for the engineering community to invest in the next stages of development, testing, and eventual codification.

The transition from the cup to the full-scale tank, invoked in the title of this paper, is thus not merely a rhetorical device. It captures the essence of the scientific method applied to an engineering problem: the recognition of a physical principle at an observable, human scale, the rigorous theoretical formalization of that principle, the systematic experimental and computational interrogation of its behavior at progressively larger scales, and the formulation of design conclusions that are of direct industrial relevance. The protection of critical liquid storage infrastructure against sudden shakings, without a single internal baffle, is not a theoretical speculation but a quantitatively validated engineering possibility, one whose adoption would render the tank inventories of the world more resilient by design rather than by addition. The findings of this study provide the analytical and empirical scaffolding upon which that adoption can be built.

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