A Comprehensive Review on the Use of Digital Image Correlation to Assess the Fluid–Structure-Soil Interaction Dynamic Response of Elevated Water Tanks

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Abstract

Elevated water tanks are critical elements of infrastructure, especially in seismic regions where an uninterrupted water supply is a necessity. Their dynamic behavior is controlled primarily by fluid–structure–soil interaction (FSSI), and therefore their seismic response and natural frequencies need to be determined precisely in order to be designed accurately. This review brings together analytical, experimental, and numerical methods for studying FSI, SSI, and combined FSSI of tall water tanks. Simple models such as lumped-mass and spring–mass analogues are compared with advanced methods such as finite element analysis and computational fluid dynamics. The growing application of Digital Image Correlation (DIC), a non-contact high-precision monitoring tool, is also highlighted. Research indicates that simplified models provide conservative but practical estimates, whereas advanced simulations better capture structural deformation, hydrodynamic effects, and sloshing. Integrating DIC with numerical methods shows strong potential to refine frequency prediction and dynamic response assessment. This paper stresses the importance of including FSSI effects in seismic codes and identifies DIC-based experimentation as a promising path toward safer, more reliable water tank structures.

Keywords: *Elevated water tanks, fluid–structure interaction, soil–structure interaction, FSSI, digital image correlation, seismic response*.

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Introduction

The criticality of the function performed by water tanks in providing the water necessary to put out fires that erupt following earthquakes makes them a vital post-disaster infrastructure. Besides, spilling contained fluid during an earthquake can cause environmental issues if a reservoir containing chemicals or oil products fails [1].

Fluid-structure interaction

Fluid-structure interaction (FSI) Modeling techniques will be examined hereinafter. Whenever a liquid in a container of any kind or shape, under the influence of external stimuli, the surface is turbulent as well as the volume. Such turbulence is complex due to several reasons, such as pressure gradients and sloshing. Sloshing simulation within the liquid container is more likely to have structural issues [2].

In the structural design of an elevated water tank to resist seismic forces, the intent is to design it to be resistant to the pressure from a Maximum Expected Earthquake that will produce major structural damage but not failure, and forces from a Design Fundamental Earthquake that will produce minor localized damage [3].

Plane, non-plane, rotating, and irregular beats are a few of the numerous types of motion experienced by the fluid. Depending on the nature of the disturbance and the container shape, the free liquid surface may experience symmetric, asymmetric, quasi-periodic, or chaotic events. The degree of sloshing depends on numerous parameters, including liquid properties, tank geometry, liquid fill level, and tank motion frequency and amplitude. Accordingly, there is a risk to tank safety due to liquid sloshing [2].

Figure 1 shows the dynamic pressure distribution exerted by the fluid on the walls and base of a ground tank. The convective waves created by the liquid mass in the free surface due to lateral acceleration depend on the geometry of the tank; the sloshing vibrations of the tank can last 2 to 6-10 seconds. Fig. 1 shows an antisymmetric wave for the lowest frequency [4].

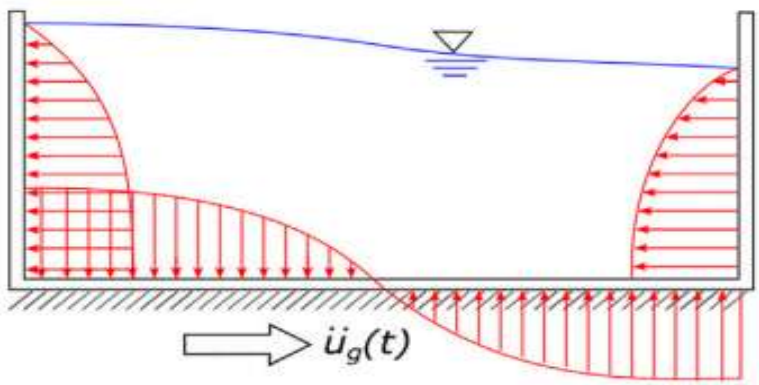

Fig. 1: Dynamic pressure distribution of a liquid in a tank during a ground motion [4].

The water mass alongside the tank base moves with the tank as a unit in the impulsive mode, contributing to the inertial mass of the structure. The liquid mass proportion in the convective mode varies with the proportion of the water level to the tank base dimension in the direction of motion [4]. It would take a huge amount of time and effort to solve the complex mathematical problems that simulate all types of motion and properties of fluid. other approaches have been used to simplify the modeling of this problem, including the spring-mass model, which can be used to study fluid-structure interaction, the single lumped mass, and two lumped mass systems. One of the simplest means of describing the impulsive response of fluid is by using the concept of added mass. these methods have been utilized in designing earthquake-resistant structures for decades [5]. The stiffness of the structural boundary conditions and the incompressibility of water are the keystones of the Added-Mass Approach (AMA). Because it neglects the effect of the stiffness of the fluid, the method usually results in conservative solutions [6]. Compared to other hypotheses, for instance, those used by lumped mass models, research shows that the (AMA) is a superior method in finite element modeling [7].

Chandrasekaran et al. (1954) [8] proposed the single-lumped-mass model based on basic assumptions, such as a single-degree-of-freedom (SDOF) system is a full liquid-filled liquid tank with no vertical motion of water in the water sloshing mechanics. The support structure acts as a cantilever if it is uniformly stiff along its length. ACI 371R states that if the water weight in the system is greater than or equal to 80% of the tank's weight, then this model can be used [9].

Research on lumped-mass models of elevated water tanks has proven that it yields results equivalent to experimental results and other numerical models [7]. The tank's geometric design lessens the effect of convective mass. One of the most basic mechanical models given by **Housner (1963)** [10] was the two-lumped-mass model, founded on the idea of the relative motion of the ground to the contained liquid and the storage reservoir. Three of these considerations are recommended by him to be utilized during the analysis of EWTs. There is minimal sloshing when the tank contains water, and no sloshing water effect when it is initially empty. In this case, the EWT will be treated as a single-mass system or a single-degree-of-freedom (SDOF) system. The effect of sloshing is seen when the tank is filled to some percentage, then an additional degree of freedom is added to the tank, making the system a dual-mass system [10].

Housner (1963) introduced a system that consists of two decoupled (SDOF) systems, the free surface motion of the water, or top mass, or convective mass, indicated by the symbol (m_c), lower mass (m_i) presented as the weight of the storage tank and a portion of the weight of water, as indicated in **Fig. 2** [11].

Lu et al. (2015) [7] proved that the equivalent two-mass model could predict the natural phenomenon of the water sloshing effect with high accuracy, results being comparable to the more advanced fluid Finite Element (FE) method.

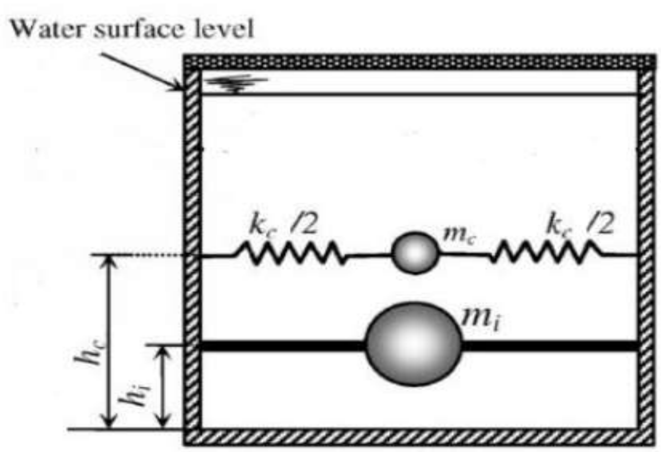

Fig 2 Ground tanks mechanical analog [12].

Housner (1963) [10] also created a dual-mass model for elevated tanks, conceptualizing the system as two distinct single-degree-of-freedom systems: (m_1), the impulsive component of the fluid, and (m_2), the convective component of the fluid. As seen in Fig. 3.

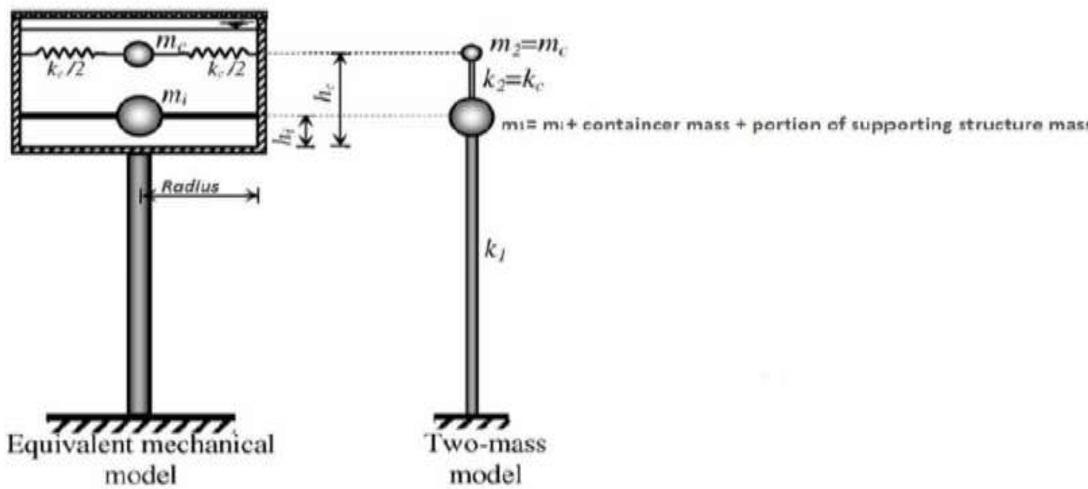

Fig. 3 : Elevated tanks two-mass model [12].

Elevated water tanks (EWTs) may be simplified as separate lumped masses in accordance with American Concrete Institute ACI 350.3 (ACI-350.32006) to evaluate the inherent properties of the convective and impulsive components [13], as shown in Figure 4.

In 2023, **Mansour and Nazri** [14] assessed how fluid-structure interaction affected the dynamic response of EWT. The time periods corresponding to the impulsive and convective components of the EWTs were identified using the equations of the two-mass model by depicting the supporting structure as a vertical cantilever, as shown in Table 1.

Table 1 The vibration period of the significant modes of the EWT system [13].

Equations for the period of vibration		
The impulsive component	$T_i = 2\pi\sqrt{\frac{m_i+m_s}{K_s}}$	(1)
The convective component	$T_c = \frac{2\pi}{\sqrt{3.68\tanh\left(3.68\frac{H_L}{D}\right)}}\sqrt{\frac{D}{g}}$	(2)

**Where: K_s is the horizontal translation stiffness of the EWT's supporting structure, m_s is the lumped structural mass, whivelech includes mass of water tank and two-thirds of staging mass, m_i is the impulsive mass, g is the acceleration due to gravity, equal to 9.81 m/s^2, and HL and D correspond to the tank's geometry, i.e., the height and the diameter.*

As an alternative to more complex and computationally intensive solutions, such as continuous liquid-medium models, researchers have used the spring-mass model as a more straightforward method of assessing the seismic susceptibility of liquid tanks [10, 14, 15]

Ibrahim (2005) [16] states that the aspect ratio and the tank's water height govern the properties of the mechanical spring-mass model. According to the American Concrete Institute (ACI) Standards outlined in ACI-350.3-2006, the formulas in Table 2 are used to evaluate this model's parameters.

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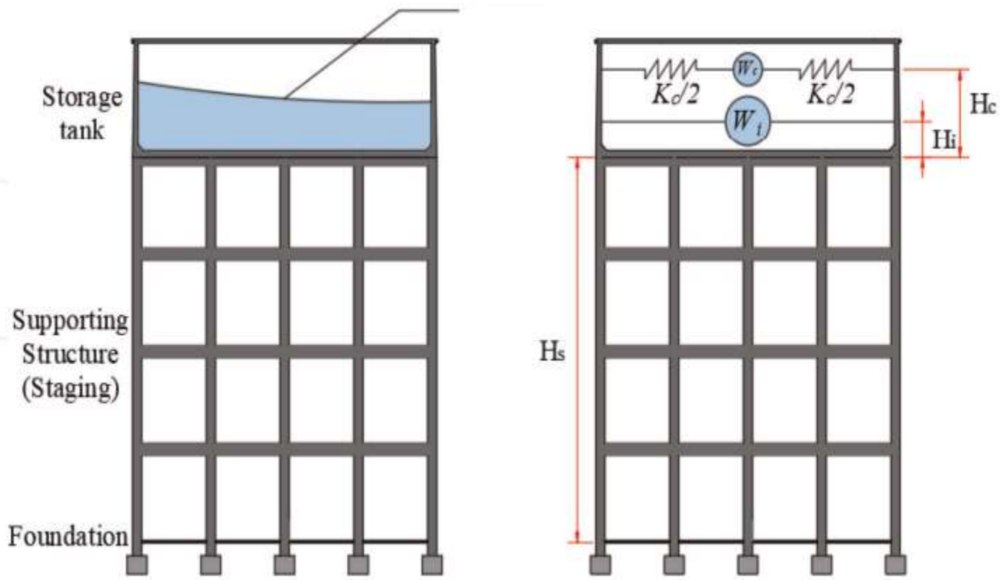


Fig. 4 The spring mass model representation of an EWT [13].

Table 2 The vibration period of the significant modes of the EWT system [13].

Equations for the parameters of the spring-model		
The impulsive and convective weights (W_i and W_c, respectively) can be obtained using Eqs. (3) and (4) where, D is the inside diameter of a circular tank, and H_L is the maximum water level.	$\frac{W_i}{W_l} = \frac{\tanh\left[0.866\left(\frac{D}{H_L}\right)\right]}{0.866\left(\frac{D}{H_L}\right)}$	(3)
	$\frac{W_c}{W_l} = 0.23\left(\frac{D}{H_L}\right)\tanh\left[3.68\left(\frac{H_L}{D}\right)\right]$	(4)
The heights of the impulsive and convective masses from the bottom of the tank wall can be determined from Eqs. (5)–(7) where, H_i is the height of the center of gravity of the impulsive mass measured from above the base of the tank wall, and H_c is the height of the center of gravity of the convective mass measured from above the base of the tank wall.	$\frac{H_i}{H_L} = 0.5 - 0.09375\left(\frac{D}{H_L}\right)$ for $\frac{D}{H_L} < 1.333$	(5)
	$\frac{H_i}{H_L} = 0.375$ for $\frac{D}{H_L} > 1.333$	(6)
	$\frac{H_c}{H_L} = 1 - \frac{\cosh\left[3.68\left(\frac{H_L}{D}\right)\right]-1}{3.68\left(\frac{H_L}{D}\right)\sinh\left[3.68\left(\frac{H_L}{D}\right)\right]}$ for all tanks	(7)
The stiffness of convective mode can be obtained by Eqs. (8)–(10) where λ is the circular frequency coefficient, g is the gravitational acceleration taken as 9.81 m/s^2, ω_c is the circular frequency of oscillation of the first sloshing mode (convective mode), and K_c is the spring stiffness of convective mode.	$\lambda = \sqrt{3.68g\tanh\left[3.68\left(\frac{H_L}{D}\right)\right]}$	(8)
	$\omega_c = \frac{\lambda}{\sqrt{D}}$	(9)
	$K_c = \frac{W_c}{g}\omega_c^2$	(10)
Alternatively, the stiffness of the convective mode can be obtained using the combined Eq. (11)	$K_c = 3.68\frac{W_c}{D}\tanh\left(3.68\frac{H_L}{D}\right)$	(11)

The Egyptian Code of Practice **(ECP201-2012)** [17] also provides charts for calculating convective and impulsive components based on the tank type (circular or rectangular), as illustrated in **Fig. 5**

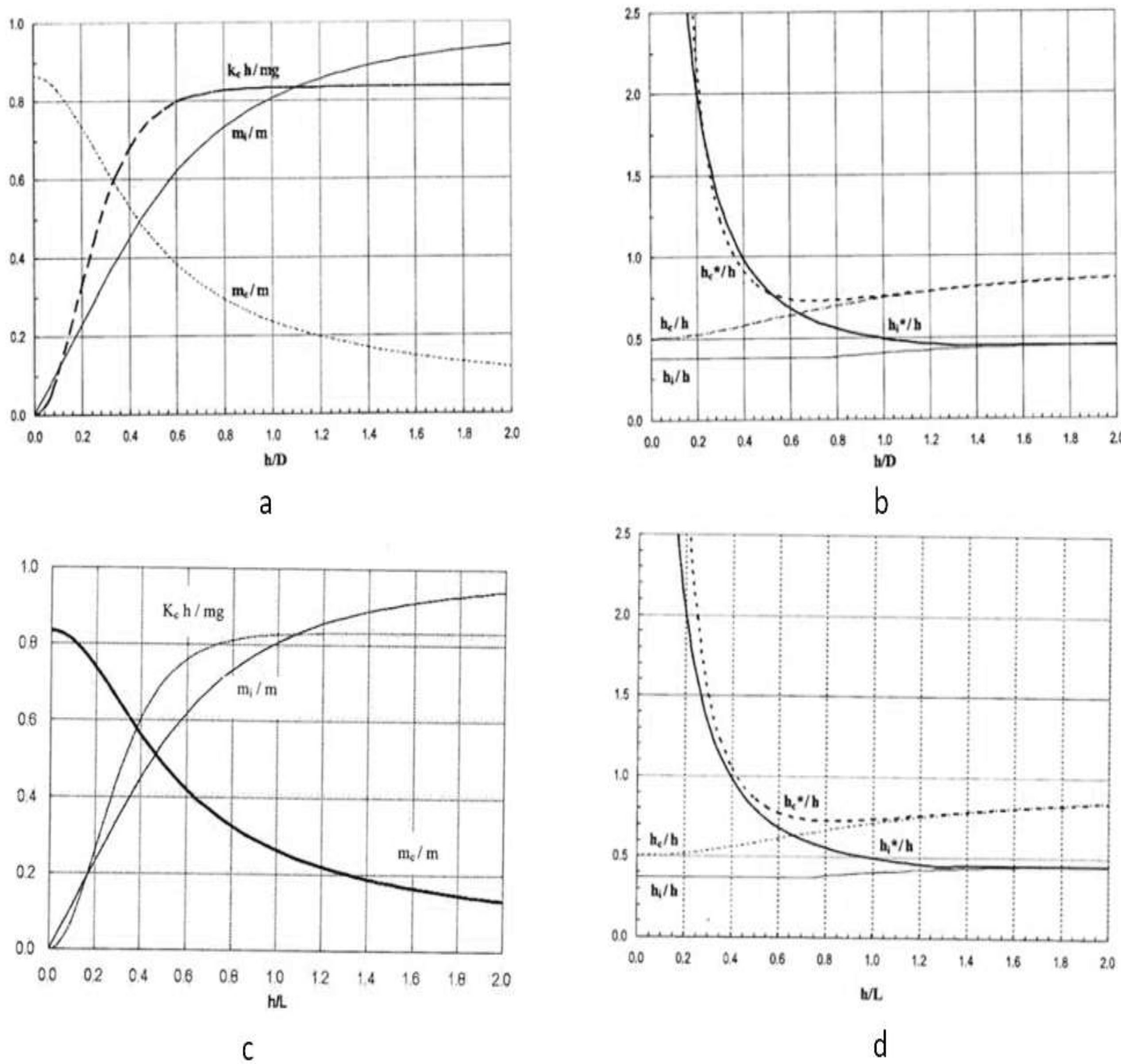


Fig. 5 : ECP charts for dynamic parameters: (a) convective and impulsive mases and convective stiffness for circular tank (b) convective and impulsive height for circular tank (c) convective and impulsive mases and convective stiffness for rectangular tank(d) convective and impulsive mases and heights for rectangular tank [17]

Previous research has focused on the examination of hydrodynamic pressure generated by ground motion data, specifically examining its effects on stiff tank walls [10, 15. 18]. Nonetheless, after a series of notable earthquake events in Japan and the United States, which caused significant damage to liquid storage tanks, it became apparent that the use of the rigid tank model for analytical purposes is inadequate. This is due to the significant distortion that real tanks experience when exposed to seismic forces. Subsequently, numerous investigations were done, which confirmed that accounting for the tank's flexibility and the relationship between the fluid trapped within and the vibrations of the wall can substantially affect the hydrodynamic pressure. and, hence, the impulsive element of the structural response [13].

Haroun and Housner (1981) [19, 20] proposed a three-mass model representation for cylindrical tanks under seismic loading, as seen in Fig. 6

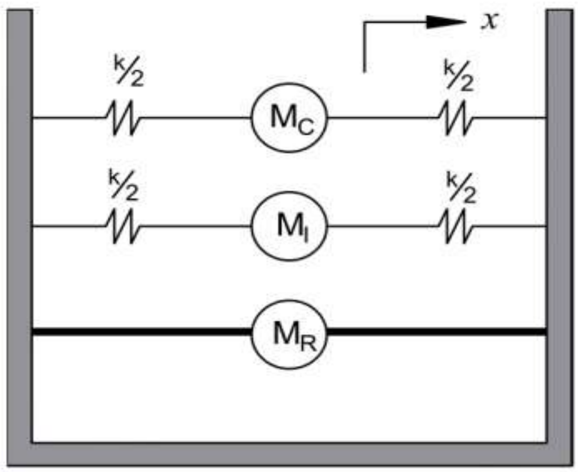


Fig. 6 : Equivalent three mass models, adapted from [19].

The impulsive, convective, and mass stand for the tank wall flexibility constitute the three masses of this mechanical model [19].

In their subsequent work, **Haroun and Ellaithy (1985)** [21] investigated the dynamic behavior of EWTs and analyzed the effect of tank wall flexibility on their dynamic behavior using the three-mass model. Although the structure's natural frequency is close to the natural frequency of the fundamental convective mode, there can be very small influences from higher-order convective modes on the pressure exerted on the vessel. According to a subsequent study by **Jaiswal et al.** [22], the parameters of the similar spring-mass mode produced by rigid and flexible tank walls are not significantly different in EWTs.

Some researchers have studied the hydrodynamic pressure that is generated in flexible cylindrical tanks. **Haroun and Housner (1981)** [19] conducted an analysis of the response of flexible liquid-filled vessels using modal superposition. The finite element method was used to model the tank walls by shell elements, with mathematical boundaries used in the study of the fluid domain. As is proven from previous studies, the flexible tanks produce a rocking along the base and walls and thus create a prolonged impulsive frequency that affects reactions and improves effective damping.

On the other hand, convective mass can be determined disregarding the tank wall and soil elasticity due to the large oscillation period of the convective mode [23].

Ghaemmaghami and Kianoush (2010) [24] studied the seismic behavior of tall and shallow tank designs based on a two-dimensional finite element model, considering the influence of the flexibility of the walls and fluid-structure interaction (FSI). The results indicate that fluid damping properties coupled with wall flexibility can potentially have a significant impact on the dynamic response of liquid tanks.

Simple models, such as those advanced by **Housner (1963)** [10] and **Haroun and Housner (1981)** [19], may have a dynamic response similar to that of a liquid 3D tank model, but could not necessarily reflect entirely on all factors that could impact the analytical results to be less precise. **Erkmen (2017)** [25] analyzed the seismic performance of unanchored liquid storage tanks using a series of diameters and liquid fill levels. Spring-mass systems and coupled Eulerian-Lagrangian were used. The results indicate that the effect of uplift forces on the dynamic properties of unanchored systems is not addressed by the traditional masses and springs used in previous approaches.

Empirical investigations of conical and interconnected conical tanks' dynamic performance by **Sweedan and El Damatty (2003)** [26] and **El Damatty et al. (2005)** [27] suggested that the analytical and numerical models previously established for other tanks can be applied to conical and interconnected conical tanks. Fig. 7 and 8 provide schematics for the respective conical and combination conical tanks.

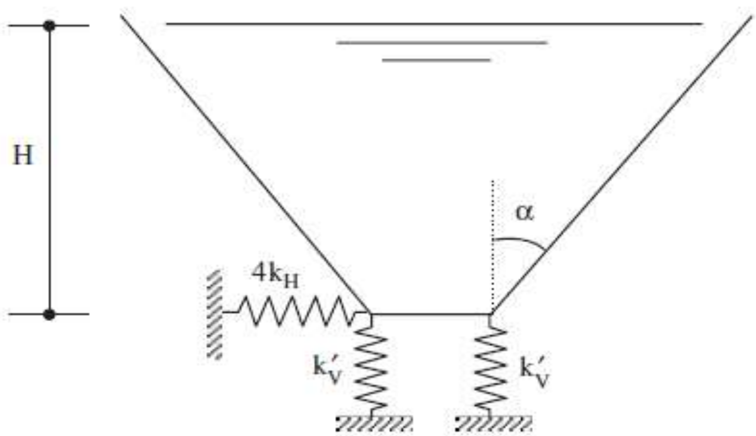


Fig. 7 : Schematic of the equivalent tank–spring system [26]

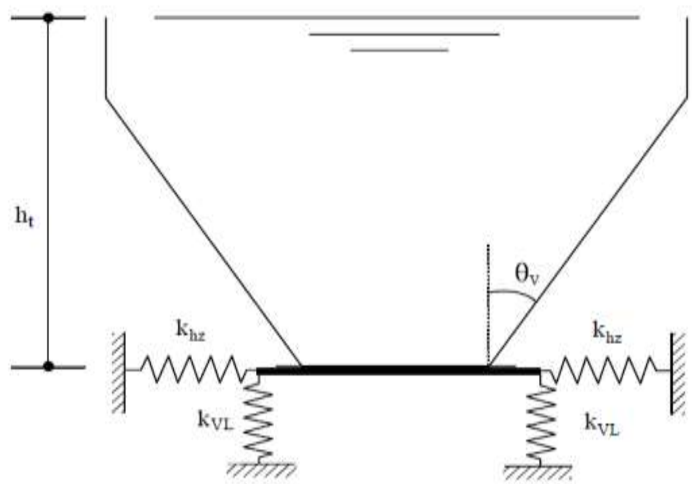


Fig. 8 : Schematic of the equivalent tank-spring system [27]

Rashed et al. (2019) [12] examined the seismic behavior of conical ground and elevated tanks, by comparison to **El Damatty and Sweedan (2006)** and validating their findings against the experimental study by **Maheri et al. (1988)**. The research findings indicate that the seismic sensitivity of conical tanks is underestimated when utilizing approximate approaches. As a result, multiple correction factors have been recommended to alleviate this issue while utilizing the codes.

Sweedan (2009) [28] proposed a mechanical model to simulate the forces generated in EWTs exposed to vertical ground acceleration, hence improving the seismic analysis of EWTs. Fig. 9 illustrates the schematic representation of the idealized configuration.

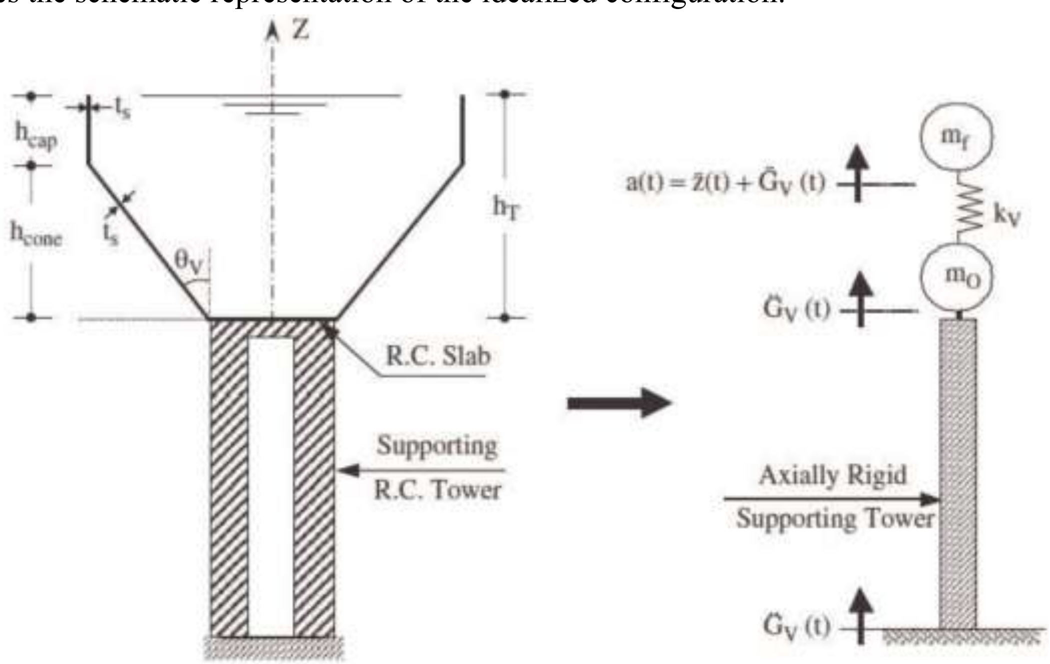


Fig. 9 : Equivalent model for vertically excited combined tanks proposed by Sweedan [28]

Experimental and computational evaluations of liquid sloshing in partly filled prismatic containers exposed to external stimulation were carried out by **Pal and Bhattacharyya (2010)** [29]. They developed a local symmetrical weak form (LSWF) for fluid sloshing that is not linear. Additionally, an experimental framework to study the dynamics of liquid sloshing in a partly filled prismatic container was developed along with a new meshless technique using the LSWF.

Younes and Younes. 2015 [30] studied the sloshing effects in a rectangular tank, half-filled with vertical baffles, stimulated by lateral motion, showing that the damping effect is significantly impacted by the vertical baffles' size and positioning.

Li et al. (2018) [31] studied the nuclear island structure's passive containment cooling system (PCS), proving that the air inlet junction was where the von Mises stress peaked. It was also found that potential-based fluid elements (PBFE) could well predict the fluid-structure interaction (FSI) effects of the nuclear island structure through the analysis of their hydrodynamic pressure and sloshing frequencies. Future projects involving the AP1000 and CAP1400 reactors may benefit from the use of the Finite Element (FE) model in shield structure design.

Pravallika et al. (2021) [32] investigated the effect of porous baffles on sloshing dynamics. The results showed that a porous baffle can be purported to increase damping and decrease sloshing oscillations at natural sloshing frequencies.

Ma et al. (2023) [33] also applied the same mechanical model, experimental test, and numerical calculation to study the dynamic liquid slosh parameters in the bulkhead tanks. According to studies, the liquid depth ratio and fundamental slosh frequency rise simultaneously. But the second slosh frequency reduces when the ratio of the liquid depth rises. Rotational sloshing and symmetrical rotary sloshing phenomena in the CBH tank are shown experimentally. It was discovered that sloshing was unstable due to changes in excitation frequency and amplitude, which led to the development of symmetrical rotary sloshing. This symmetrical rotating sloshing cycle would start and end at regular intervals in a certain manner based on the stimulation frequency, as shown in Fig. 10.

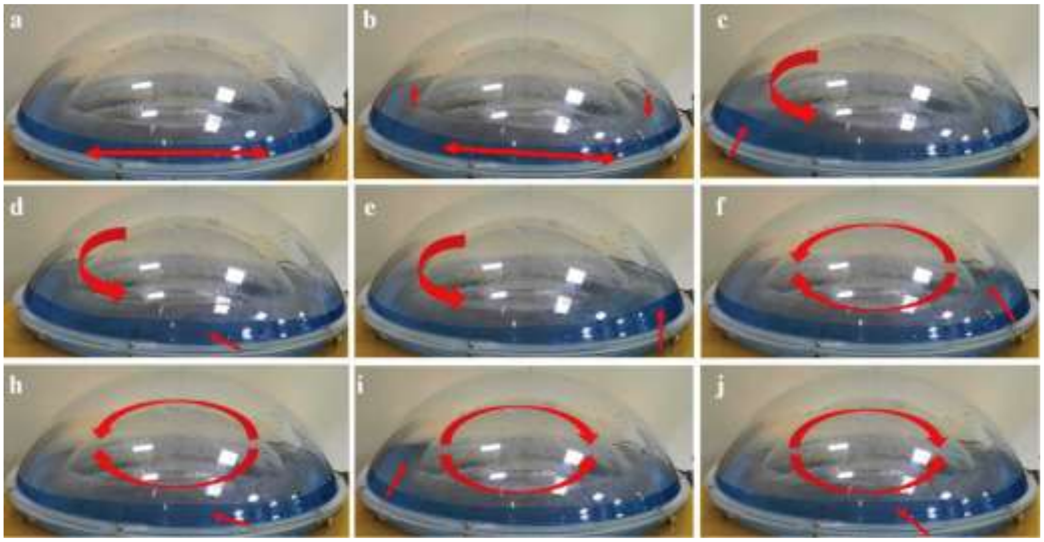


Fig. 10 : Time history of rotary liquid sloshing in CBH tank [33]

The effect of two-way fluid-structure interactions (FSIs) on the dynamic response of flexible liquid tanks was explored by **Tuong (2023)** [34]. Findings showed that flexible tank walls are more common than rigid tank walls, especially if hydrodynamic pressure caused by the motion of the liquid within the tank is taken into account. Hydrodynamic pressure decreases as tank thickness increases. The opposite takes place when the tank loses stiffness.

In 2024, **Xb, F. et al.** [35] investigated liquid sloshing modes in liquid tanks. The result from this research validated the simulation method using acoustic fluid elements against dynamic and time-history approaches in analyzing different water levels in cylindrical tanks filled with liquids. The results indicate that finite element analysis (FEA) with acoustic fluid elements can simulate liquid sloshing modes in liquid-filled containers and their vibration characteristics at different liquid levels. Numerical simulations using acoustic fluid elements provide a good and effective means for the dynamic characterization of liquid-filled containers in less time.

Cylindrical baffled storage tanks sustained by a circular surface foundation were investigated by **Sun, Y. et al. (2024)** [36] under horizontal stimulation. A theoretical model shows how each tank oscillates perpetually. A lumped-mass model showing the coupling, horizontal, and rocking impedance functions using Chebyshev complex polynomials is used to illustrate the effect of soil on upper-tank structures. The sloshing height, frequency, hydrodynamic shear, and moment under hard and soft foundation soils were validated with existing published empirical data and computational solutions to ascertain the proposed model. The maximum difference of sloshing height between the modified model and the numerical solutions was 5.27%. The system dynamics solution of the novel model was 40–50 times more effective than the ADINA model.

Zhao et al. (2016) [37] applied a fluid-structure interaction technique via finite element analysis to investigate the seismic performance of a water tank with an internal baffle. They contrasted multiple shapes of ring baffles and characteristics such as configuration and height. Their research found that one particular design with a vertical ring baffle located near the tank's bottom was most efficient in minimizing the dynamic response of the structure and sloshing during seismic activities. This design provided improved performance via hydrodynamic damping as well as higher interaction effects.

Alembagheri et al. (2020) [38] propose a technique for identifying the structural characteristics of steel EWTs based on ambient vibration testing and calibration of a numerical model. Ambient vibration tests were performed on the tank to identify its natural frequencies, mode shapes, and damping behavior. The results from the ambient vibration tests were used to calibrate a numerical model of the water tank. It increases our insight into the tank's dynamic characteristics and provides precise predictions under different loading conditions.

Al-Khafaji et al. (2021) [39] investigated seismic responses of elevated storage tanks, reporting high correlation between ANSYS models and experimental evidence. It was demonstrated that small internal forces within the tank during earthquakes may result in high tank displacements and instability. Water is essential for maintaining tank stability during an earthquake. The research indicates that tanks with water levels up to 53.3% are more likely to be at risk due to large water displacement.

Anagha et al. (2020) [40] simulated a steel water tank of a square shape using ANSYS 2019 R1. To analyze modal behavior (frequencies, mode shapes) under different fill levels and boundary conditions. They employed a modal acoustic model within ANSYS. It showed that the impulsive frequencies reduce with the reduction of fluid levels, especially when they fall below 50%. Convective frequencies increase with the height of the fluid. And showed the effectiveness of the modal acoustic model as an alternative to time history models.

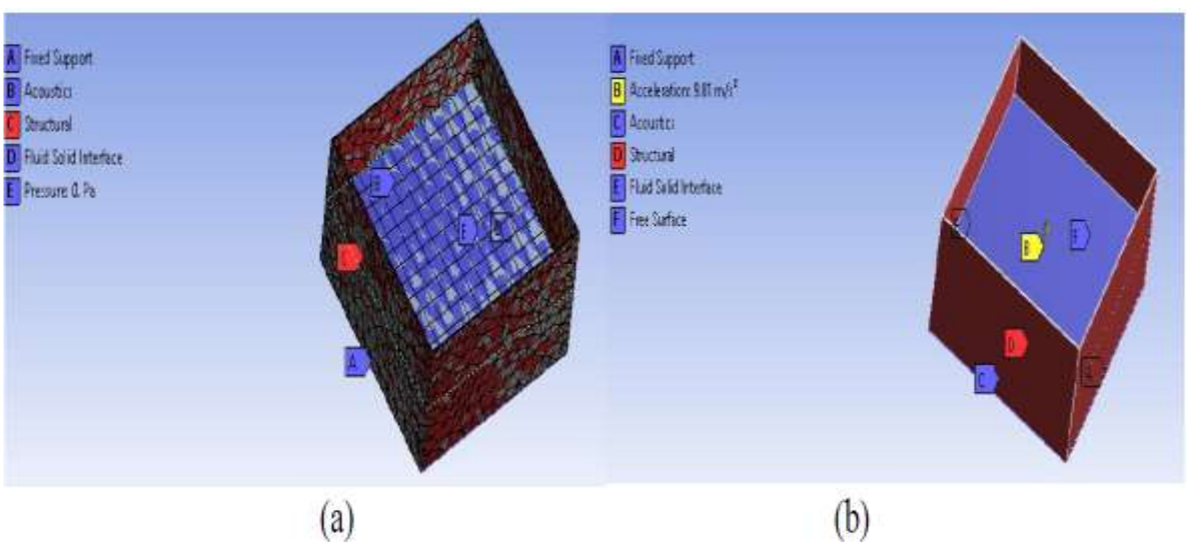


Fig. 11 Modal Acoustics setup. (a) Impulsive and (b) Convective frequencies [40]

Soil structure interaction

Soil-Structure Interaction (SSI) of elevated water tanks (EWTs) is now an important research area to understand the dynamic behavior of structures under various loading conditions. A number of key studies utilized the analytical method to study the complex interaction between EWTs and soil foundation. The findings of the research are presented below:

Soil-structure interaction (SSI) influence on seismic response of elevated water tanks (EWTs) is investigated by **Haroun and Temraz (1992)** [41]. Two-dimensional x-braced EWTs on isolated footing are analyzed for static, dynamic elastic, and dynamic inelastic responses to horizontal ground movement. Member-end activity is found to be reduced because of soil-structure contact, particularly at the tower base. When considering dynamic inelastic response and soil contact, seismic design forces can be safely evaluated through static analysis.

Using a circular plate on an elastic homogeneous half-space model, **Dutta and Mandal (2004)** [42] examined the effect of soil-structure interaction (SSI) on the dynamic response of elevated water tanks (EWTs) with an extremely rigid foundation. By analyzing two dynamic parameters, the impulsive lateral period and impulsive torsional-to-lateral period ratio, the study validated the influence of SSI on EWTs of various staging configurations. By the application of different frame staging configurations, the study gives design engineers mathematical equations and variation curves to quantify the influence of SSI on the dynamic performance of EWTs.

With the help of finite element analysis, **Livaoglu and Dogangun (2007)** [43] examine the seismic response of EWTs on different subsoils. The properties of the subsurface significantly influence the seismic response of the tank, and soil-structure interaction (SSI) influences impulsive modes as well as lateral displacement. Even though a higher Young's modulus increases the base shear and bending moment, tall tanks resting on soils of lower Young's modulus are prone to large displacements. Impulsive modes are influenced by the changes in soil stiffness, while sloshing modes show prolonged periods.

Seismic response of a liquid storage tank supported on soft foundation was examined by **Livaoglu et al. (2012)** [44], who emphasized the dominant role of soil-structure interaction (SSI) in terms of displacement and seismic shear pressure. The significance of including soil-structure interaction (SSI) for reliable estimation of seismic performance of elevated water tanks is shown in Figure 12, which shows SSI increased sloshing responses and a related compression-bending moment failure mechanism.

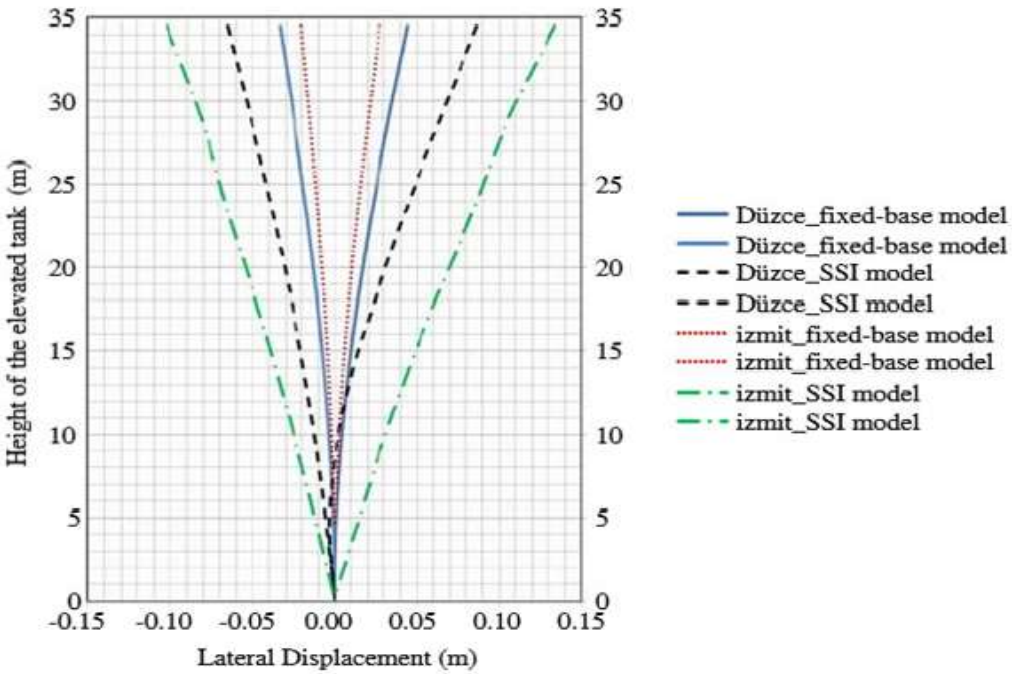


Fig. 12 Time history of rotary liquid sloshing in CBH tank [28]

Livaoglu (2013) [45] examines the influence of SSI on the sloshing response in EWTs. The research utilized transient analysis and finite element modeling with Lagrangian fluid finite element approximation. The relationship between earthquake wave propagation and the soil/foundation system is examined through three-dimensional models with viscous barriers. The findings illustrated the impact of SSI and the characteristics of the supporting system on the fluid's sloshing behavior. The study includes the motion equation governing the fluid-elevated tank-soil/foundation system, enabling the analysis of dynamic behavior.

Swamy et al. (2013) [46] sought to precisely measure structural displacements and pressures, accounting for three-dimensional behavior and nonlinear SSI. A program was developed to compare linear and nonlinear SSI assessments for a three-dimensional frame on a mat base. The study confirmed the efficacy of the hypoelastic model for nonlinear analysis, emphasizing its significance in accurately representing authentic behavior in contrast to linear and non-interactive studies.

The study by **Ghanbari and Ghanbari (2016)** [47] examines the influence of SSI on seismic response. They examine moment frame structures of varying heights on different soil types using direct and analogous spring-dashpot methods. Research demonstrates that the incorporation of SSI can markedly influence displacements, shear forces, and the fundamental period.

Farajian et al. (2017) [48] examine the seismic response of steel liquid storage tanks (LSTs), both wide and slender, on half-space soil subjected to various earthquake ground motions, incorporating soil-structure interaction (SSI). The research adopted a fundamental mass-spring model (Fig. 13) with two discrete masses to replicate liquid behavior (sloshing and impulsive) and incorporated interconnected springs and dashpots to characterize fluid-structure interaction (FSI) and soil-structure interaction (SSI) effects. MATLAB programming is employed to acquire responses. Research indicates that SSI results in a reduction in impulsive displacement. The overturning moment and normalized base shear are adjusted, whereas the sloshing displacement remains unchanged due to its extended period.

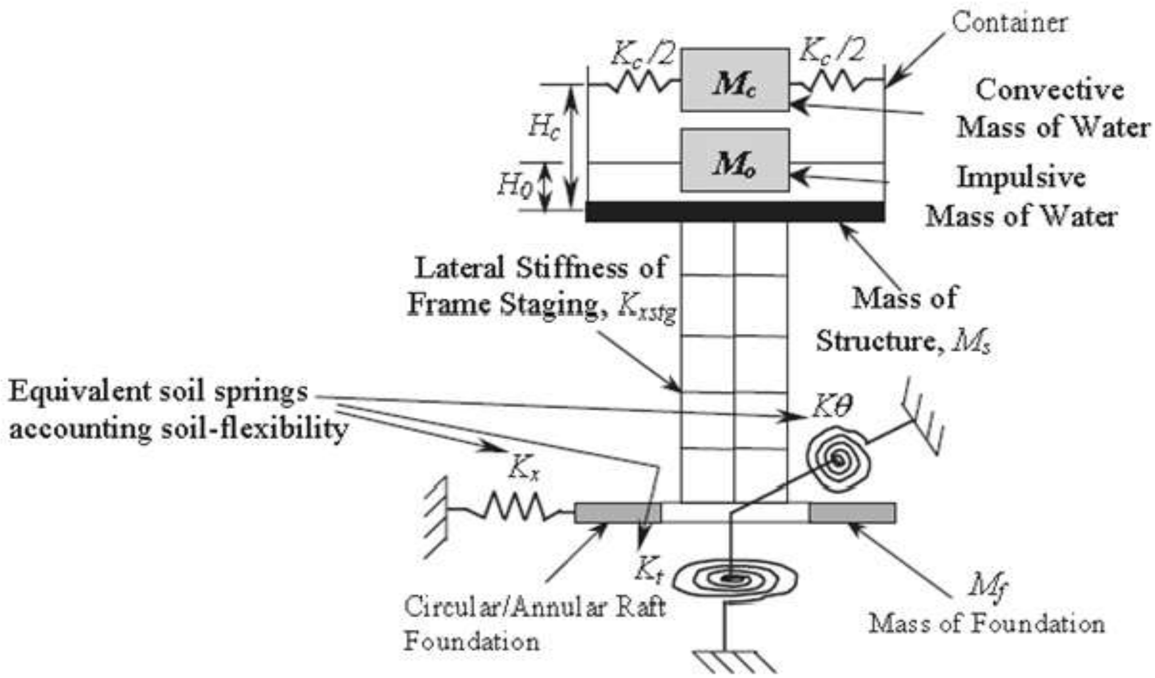


Fig. 13 Simplified mass spring model [48]

Rectangular EWT's SSI system is modeled by **Visuvasam et al. (2017)** [49] using finite element analysis and higher-level computational methods. Modal analysis and time history analysis are used in the study to assess the dynamic performance of tanks. For the purpose of incorporating the effect of seismic performance based on soil parameters, a flexible fundamental approach in terms of spring stiffness is proposed. Linear time history earthquake analysis with different classes of soil is done with the assistance of SAP2000. The response shows that the building period and base shear are directly proportional to the stiffness of the soil.

In seismic design of RC EWTs, **Patel and Amin (2018)** [50] emphasized the criticality of correct R factor values and the need to account for SSI effects. According to the conclusions, the response reduction factor accounts for soil flexibility effects. For improving the safety and robustness of these vital infrastructure elements, this paper offers relevant findings on seismic design of water tanks and leads to future modifications in Indian Standards.

The influence of dynamic soil-structure interaction on the seismic behavior of liquid-storage tanks is investigated by **Tsipianitis et al. (2020)** [51]. The Finite Element Method (FEM) is used for designing and investigating a coupled soil-tank model. Different tank structures, foundation layer types, liquid capacity in volume, and anchoring conditions are all taken into account in nonlinear dynamic analysis. Results reflect the mechanics of base sliding, base uplift, and acceleration amplification. The presence of a soft soil layer leads to increased sliding, significant influence of liquid volume on slender tanks, significant effect of the friction coefficient on base sliding, and increased acceleration amplifications on anchored slender tanks based on key findings.

Ductility demands are examined for steel elevated water tanks by **Assatourians and Fallahi (2020)** [52], who recognize the role of soil-structure interaction on ductility demands. According to different fill levels and seismic demands, two kinds of tanks were evaluated by the researchers. The Spring-Dashpot model is used to simulate the SSI. From the outcomes, there is a rise in the requirement of ductility from rock to clay soil and from dense to loose soil. The design consideration of SSI largely influences the need for ductility, particularly for situations involving both thick and loose kinds of soil.

Nath and Dutta (2021) [53] analyze the effect of SSI on the behavior of EWT under different soils. Three example earthquakes are used in ANSYS Workbench to simulate two EWTs with different staging setups. The design by gravity load that is traditionally practiced is insufficient for seismic areas, according to the time history analysis.

For better LST SSI, **Kumar and Saha (2021)** [54] investigate the seismic performance of base isolation devices. According to numerical analyses, the seismic response of the tank is significantly reduced by base isolation, especially in the presence of soil-structure interaction. Performance of the system depends on seismic parameters and soil properties, which reveal their role in earthquake-resistant tank construction.

Seismic response of tanks is further examined by **Kumar and Saha (2021),** showing that soil-structure interaction increases base shear and sloshing response. Higher slenderness ratio increased overturning moment, whereas soil-structure interaction reduced overturning moment and base shear amplitudes for fixed-base tanks and increased them for base-isolated tanks. Soil stiffness, earthquake characteristics, and tank geometry all play roles in determining how effective base isolation is.

The seismic responses of column-supported tanks are investigated by **Liu et al. (2023)** [55], taking into account uplift effects and soil-structure interaction. They take two structures into account: resilient tanks and anchored tanks. Resilient tanks are better than anchored tanks. Complicated topographical conditions and many classes of soil are incorporated. The results highlight how critical SSI is in seismic design for these tanks.

Seismic response of soil-structure interaction (SSI) LSTs is investigated by **Kumar et al. (2023)** [56]. The paper takes into account how SSI affects parameters such as overturning moments and displacement. It has been determined that regardless of soil type and staging time, soft soil induces greater overturning moments, whereas greater slenderness decreases them. Moreover, SSI varies in affecting the sloshing response based on the tanks' aspect ratio.

Mathematical modeling of the complicated interaction between the foundation, soil, and structure should be carried out to establish how EWTs will respond under different loads.

More research must be done in order to understand how EWTs respond under seismic loading and the interaction between fluid sloshing and structural dynamics. The overall response of EWTs largely depends on the configuration and stiffness of the foundation. For EWT structures to be safe and reliable, efficient design techniques accounting for FSI and SSI effects are crucial. In order to achieve stable, economical EWT structures, nonlinear phenomena, parametric analysis, and experimental testing are significant considerations.

Fluid-Structure-Soil Interaction

FSSI combines the two earlier factors and examines how the fluid mechanics and soil behavior interact to determine the EWT. This section examines how the fluid, structure, and soil interact and how that affects the overall stability and responsiveness of the tank. FSSI is a very important area of research where analytical studies are applied to examine dynamic fluid-structure-soil interactions. The following articles are worthwhile research dedicated to the analytical examination of FSSI:

A framework of evaluation for seismic performance of fluid-filled tank foundation/soil interaction is presented by **Livaoglu et al. (2005)** [57]. Their approach accounts for fluid sloshing effects, frequency-dependent soil behavior, and embedment. In addition to soil-fluid interaction, material damping, and radiation damping, the work employs modal analysis in the frequency domain. They came to the conclusion that although changes to stiff soil and embedment did not influence the sloshing response, the characteristics of soft soil do.

For EWTs, **Livaoglu et al. (2006)** [58] present simplified seismic analysis methods including FSSI. They introduce a mathematical model that takes into account the soil-structure interaction (SSI), the hydrodynamic effect of the fluid, and the dynamic response of the structure. Comparing the model results with the finite element analysis results and illustrating a case study, the validity of the model is ensured.

Livaglue et al. (2007) [59] discuss the effect of embedment of foundations on tank behavior. Using ANSYS and the finite element method, the research discusses soil-structure interaction and fluid sloshing effects. It is noticed that for soft soil, embedment strongly affects tank roof displacements, whereas in stiff soil, its effect is small. Even in the case of soft soil conditions, embedding barely affects sloshing displacement.

Seismic performance of EWTs was investigated by **Algreane et al. (2011)** [60]. Seismic responses were investigated as a function of nonlinear local site characteristics and artificial seismic excitation generation. It detected important influences on base shear, overturning moment, and base axial force using various models from mechanical, SSI, to FSI models.

In their vertical liquid storage tank seismic analysis, **Elkholy et al. (2014)** [61] concentrate on FSSI during earthquakes. They examine full and empty tanks using ANSYS 3D finite element models to establish the best types and number of elements for reliable predictions. The relevance of element selection and meshing for accuracy is suggested by the recommendations, which are SHELL93 for an empty tank and SHELL43 for a full tank.

Experiments using actual steel tanks with scaled properties are suggested by the research **Tiwari and Hora (2015)** [62]. experimented on over-water tanks. Actual tanks rest on elastic soil, but rigid foundations are taken into account in classical analysis. Using ANSYS software, they have conducted a three-dimensional interaction analysis of an Intze-type water tank supported by stratified ground. Significant findings are that they must construct circular columns and girders to withstand seismic pressures, lowered natural frequency in proportion to higher water load, and increased stresses owing to interaction effects. Moreover, transient analysis showed that sloshing effects produced the maximum acceleration when the tank was full and for fill percentages between 40% and 80%.

Mirtaha and Bargi (2016) [63]. research investigates the influence of soil conditions, water depth, and tank height on the response modification coefficient ('R') of EWTs. According to the research findings, FSSI has a serious impact on "R," and higher tank height and water level result in lower values of "R." Soft soils possess lower 'R' values than stiffer soils. The research describes how crucial it is to include FSSI in seismic design so that high concrete tanks can be safely constructed.

New FSSI-based analytical models for calculating natural periods of EWTs are provided by **Maedeh et al. (2016)** [64], elegantly taking into account soil effects and making a differentiation between impulsive and convective periods. Since soil stiffness influences impulsive durations, modeling with tank configuration, liquid level, and ground mass participation is better than alternative approaches. The need for FSSI models is brought out by the fact that current codes provide predictions that are not sufficient for soft soil conditions.

Using the finite element method, **Kotrasováa et al. (2017)** [65] investigate the seismic response of a cylindrical tank considering foundation-soil-structure interaction. The investigation considers the influences of hydrodynamic pressure, fluid-structure interaction (FSI), and soil-structure interaction (SSI) on the dynamic response of the tank under earthquake loading. To illustrate the sophisticated relations between the tank, ground, and fluid, various numerical models and simulations are used by the authors. They also examine how the other parameters, i.e., the tank diameter and height, soil properties, and ground motion, affect the seismic response.

Regarding FSSI, **Maedeh et al. (2017)** [66] analyzed the influence of vessel wall flexibility on the inherent sloshing frequency. They proposed two equations to quantify the effects of soil-structure interaction and wall flexibility on frequency. Wall flexibility has little impact on fixed base conditions but becomes important when soil-structure interaction (SSI) is taken into account, the research discovers. Changes in natural frequency caused by the effects of wall flexibility and soil-structure interaction are shown in Fig. 14.

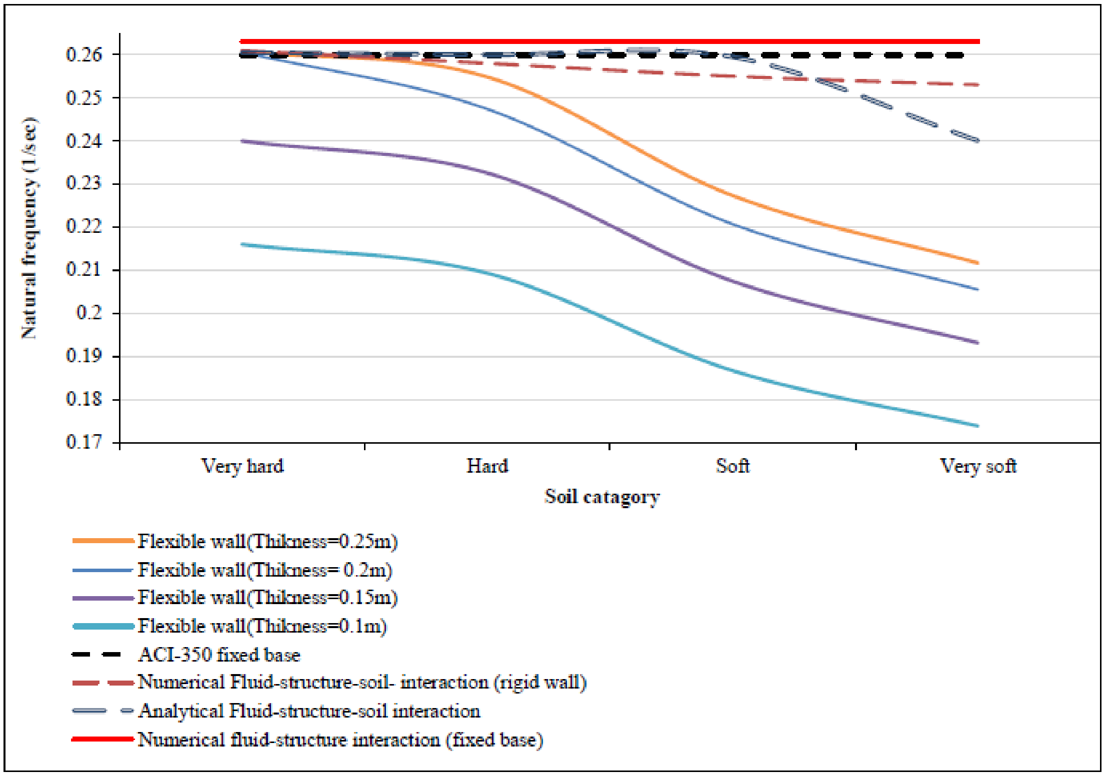


Fig. 14 The natural frequency values of the vessel considering SSI effects and wall condition [66]

Mellati (2018) [67] introduces an innovative pushover methodology for determining the mean incremental dynamic analysis (IDA) curve of EWTs supported by concrete shafts. The methodology encompasses separate evaluations for the linear and nonlinear elements of the curve, incorporating SSI (Fig. 15 (b))—where kh and kθ denote translational and rotational stiffness, Mθ represents the mass of the internal degree of freedom, ch and cθ indicate translational and rotational damping, M refers to the foundation mass, and If signifies the moment of inertia of the foundation mass—and FSI (Fig. 15 (a)), where M denotes the total mass of the tank water, R and h represent the radius and height of the tank, while M0 and M1 indicate the impulsive and convective masses, respectively, and h0 and h1 denote the heights of the impulsive and convective masses from the base, respectively. A parametric study evaluates the performance of these tanks under varying soil types, water levels, and tank sizes. The study demonstrates the significant influence of soil type, tank capacity, shaft rigidity, and water level on structural integrity and failure risk. The proposed pushover method accurately predicts the IDA curve with deviations below 30%.

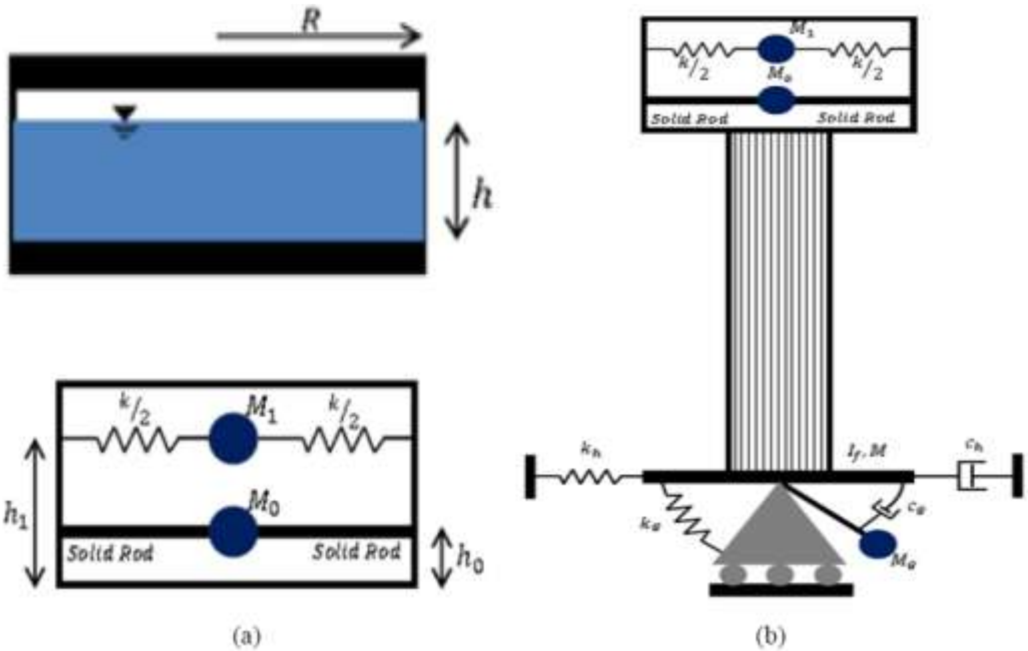


Fig. 15 The natural frequency values of the vessel considering SSI effects and wall condition [67]

In their broad review of studies on liquid storage tanks, **Zhao and Zhou (2018)** [68] recognized base isolation, seismic response, soil-structure interaction, fluid-structure interaction, liquid sloshing, and uplifting effects as the key factors. In order to support greater insight into dynamic performance and seismic safety design criteria, they stressed the need for further research. Stochastic earthquake and probability estimation for structural response, optimal structure to guarantee reliability, replaceable isolation systems to allow quick restoration, increased stress during earthquakes, the influence of liquid sloshing on tank dynamics, and the need for an easy yet efficient liquid model for seismic tank design are all key factors.

In their 2019 study, **Joseph and Joseph** [69] discuss the impact of FSSI on the dynamic performance of circular water tanks. Finite element analysis software is used to analyze the modal and transient analysis of cylindrical tanks on various soils in an attempt to assess the impact of soil properties on dynamic response. Using time history study, the study assesses the impact of earthquake frequency content on the earthquake response of water tanks. The findings determine the significant contribution of seismic parameters, soil properties, and FSSI towards the circular water tank's dynamic response.

The seismic response of reinforced concrete elevated water towers under near-field (NF), near-field no-pulse, and far-field long-period earthquakes was investigated by **Cheng et al. (2020)** [70], taking into account foundation-soil-structure interaction. Using a numerical model, the study accounted for forecasting the seismic response of the tank and investigating the effect of different parameters like tank height, water level, and soil type. There was more response towards near-field pulse seismic waves compared to that of far-field long-period and near-field non-pulse waves, according to findings. The research emphasizes the need to include the effects in seismic design of RC EWTs in consideration of rendering them safe, since FSSI plays an important role in the seismic response of the tank.

Zanni et al. (2020) [71] employ large finite element techniques and discrete approximation models to model the dynamic responses of rigid square or cylindrical tanks having concentric openings. Parametric analysis is employed to generate experimental design curves for various geometrical configurations. The hollow cylindrical tank support system is simulated by research in the dynamic analysis of an old water tower. FSSI effects and fixed base conditions (the conventional design assumption) are used for seismic analysis of the water tower. The simplest frequency-independent mass-spring-damping model for rigid ring foundations is used to account for dynamic soil behavior. The research emphasizes the importance of FSSI on the design of tanks.

Requirement of strong structures that can resist great seismic activities without failure is pointed out by **Chitte et al. (2022)** [72]**.** The study invokes consideration of why earthquake design codes for water tanks fail to provide sufficient information regarding the response reduction factor (R). It is uncertain about viscous dampers and their influence on R. Utilizing the generalized pushover curve provides ease in examining ductility, redundancy, and overstrength features more easily.

Highlighting the base isolation, fluid-structure interaction, and soil-structure interaction aspects, **Chaithra et al.'s paper from 2023** [73] explains earlier modeling techniques for seismic response of LSTs. The research puts across the significance of major factors like soil characteristics, tank flexibility, and fluid behavior while designing under earthquake conditions. Numerical approaches and advanced base isolation systems are explained as means to improve tank strength in seismic conditions.

Rezaiee-Pajand et al. (2023) [74]. suggested an analytical solution to the free vibration of rectangular tanks filled with compressible fluid that are placed in cohesive soil. The method was proven by finite element analysis, and sensitivity analysis was conducted to find the impact of parameters on natural frequencies.

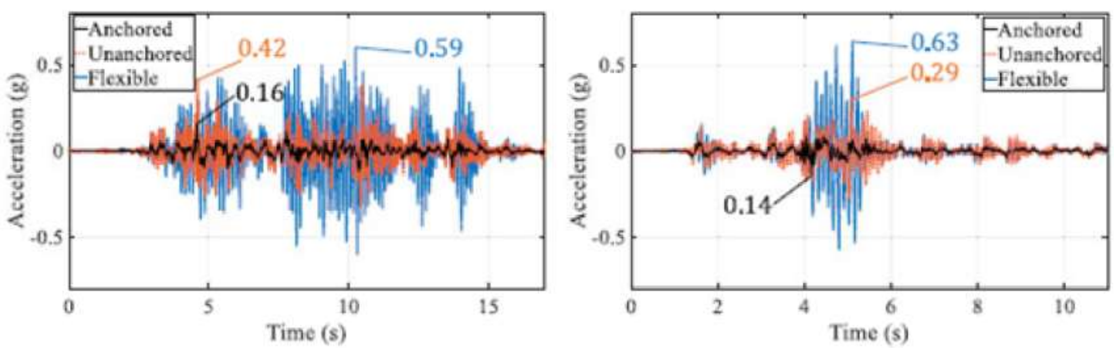
Seismic response of partially filled water tanks is examined in **Baharvanda et al. (2023)** [75], where the impacts of fluid-structure interaction (FSI) and soil-structure interaction (SSI) are emphasized. According to their results, SSI dominates impulsive behavior but has no contribution toward sloshing behavior, especially for shallow tanks. The paper emphasizes the pivotal role flexible foundations have in reducing stress amplitudes and sloshing.

Seismic damage of a reinforced concrete elevated water tank was evaluated by **Bouchala and Seghir (2023)** [76], taking into account the action of soil-structure interaction and water, such as uplift of the foundation. They used impulsive masses and convective masses in computing the inertia of water stored and springs with gap elements for SSI simulation. For the evaluation of the actions of uplift of the foundation and SSI, a global seismic damage index is recommended.

It should be observed that no experimental studies have been mentioned yet that specifically particularize FSSI analysis of EWTs because it is difficult to conduct experimental studies on FSSI in EWTs. These are challenges to measure dynamic response to an accurate degree under changing loads, simulated SSIs in laboratory conditions, simulating actual real-life conditions within laboratory facilities, and creating effective scaling procedures to extrapolate results from scaled models to full-scale tank structures. There are very few publications on experimental studies that have been found, and this study has been able to compare its findings with available experimental data.

The following are the facts of these studies:

Hernandez et al. (2021) [77] conducted a laboratory study in order to investigate the seismic behavior of tanks in terms of the aspect ratio, flexibility, and foundation fixity. The studies show that in designing thin-walled storage tanks subject to seismic stresses, nonlinear soil-structure interaction and fluid-structure interaction effects must be taken into account. For an aspect ratio of h/r = 2.5, the transient acceleration history at the top of the tank is given in Figure 16. This specific aspect ratio was selected due to the fact that it was more sensitive than any other ratio tested for computation without compromising the top plastic cover.



(a) (b)

Fig. 16 Effects of the supporting base flexibility on top acceleration for the tank with h/r = 2.5 ((a) La Union earthquake (b) Tabas earthquake) [77]

Chaduvula et al. (2013) [78] conducted experiments on a scaled model of a cylindrical steel energy wind turbine to investigate its performance during seismic events. They found that impulsive base shear and base moment increased with earthquake acceleration, while convective values increased with acceleration and decreased with angular motion. The rocking motion exerted an insignificant effect on water sloshing. Non-linearity was seen as the impulsive pressure decreased with increasing tank acceleration. The study underscores the importance of considering diverse foundational movements in the design of earthquake-resistant water tanks, especially in seismically active areas.

The analytical assessment of FSSI in EWTs poses numerous challenges. This includes modeling complexity, accurate parameter estimation, addressing nonlinear behavior, validation with empirical data, accounting for soil variability, practical implementation, estimation of impulsive and convective periods, addressing soft soil challenges, resource management, and ensuring practical applicability. Collaboration among experts from many engineering disciplines is crucial for developing robust analytical models and techniques to enhance the seismic safety and performance of EWTs under different soil conditions. The lack of solid design principles and inadequate research on response reduction factors for water tanks necessitates comprehensive investigations. Alleviating uncertainties and executing retrofit measures would enhance the safety and resilience of these structures. Mitigating these challenges will improve earthquake design and safety measures. The experimental and analytical investigation of FSSI in EWTs presents challenges in model scaling, simulating realistic dynamic loads, addressing complex soil-structure and FSI interactions, managing non-linear effects, replicating complex base motions, accounting for fixture influences, obtaining precise material properties, establishing suitable instrumentation, and validating results. Confronting these difficulties requires a multidisciplinary approach and collaboration among researchers, engineers, and industry experts to ensure accurate and reliable earthquake-resistant water tank designs. The lack of current research publications on the experimental examination of FSSI analysis in EWTs hinders the comprehensive knowledge of this crucial element of tank design.

DIC in the system identification

Digital Image Correlation (DIC) has emerged as a robust non-contact global measurement method for structural health monitoring (SHM) and system identification in civil engineering. The DIC approach enables the measurement of displacements, stresses, and dynamic features of systems through high-resolution imaging and sophisticated image processing techniques. The subsequent investigations concentrate on employing DIC for structural identification in systems.

Sutton, M. M., et al. (2017) [79] employed 3D-DIC to investigate wall elements subjected to lateral forces, accurately measuring comprehensive field displacements to ascertain dynamic characteristics and damage. Accurate displacement fields were quantified, and the initiation of damage in wall elements was detected using 3D-DIC. The research demonstrated the benefits of employing 3D digital image correlation (3D-DIC) over two-dimensional digital image correlation (2D-DIC) for intricate geometries in civil engineering applications.

Roettgen et al. (2018) [80] examined DIC for nonlinear system identification in systems featuring bolted joints. Digital Image Correlation (DIC) was utilized to quantify displacements, while nonlinear modal models were implemented to ascertain joint dynamics. DIC effectively captured nonlinear responses, facilitating the precise identification of joint stiffness and damping. The work demonstrated the applicability of DIC to complex, nonlinear structural systems.

Ngeljaratan et al. (2019) [81] conducted dynamic monitoring of three 1/3-scale two-span bridges with target-tracking digital image correlation (DIC). They juxtaposed the outcomes from DIC and conventional sensors to validate its precision for system identification. The DIC results closely aligned with standard sensors, accurately capturing the modal characteristics. The study highlighted DIC's capacity for long-term bridge monitoring due to its non-contact nature and ease of implementation.

Dizaji et al. (2021) [82] used Digital Image Correlation (DIC) to identify subsurface damage in composite civil constructions by comprehensive strain measurement for the detection of internal defects and modal alterations. DIC was utilized for subsurface damage identification by recording localized strain anomalies, which were associated with variations in modal frequency. The research illustrated the capability of DIC for non-destructive assessment in structural health monitoring.

Teng et al. (2022) [83] created a convolutional neural network (CNN) to classify the structural states of a steel frame utilizing vibration data obtained via digital image correlation (DIC). The CNN amalgamated feature extraction and classification to assess structural health based on displacement data. The CNN effectively identified structural states with high precision in damage identification using DIC displacement data. The research suggested potential for the amalgamation of deep learning and DIC for automated structural health monitoring.

Azizi et al. (2023) [84] utilized Digital Image Correlation (DIC) to analyze vibrations of a cantilever beam captured via high-speed video, focusing on structural nodes vulnerable to damage. They employed Digital Image Correlation (DIC) to acquire displacement time histories and utilized blind source separation for the extraction of vibrational frequencies and mode shapes. The study demonstrated the precision of DIC in deriving modal frequencies and mode shapes, notwithstanding the presence of simulated damage and reduced stiffness. The fluctuation in vibration frequencies aligned with damage patterns, establishing DIC as a legitimate technique for non-contact structural health monitoring.

Perera et al. (2023) [85] utilized Digital Image Correlation (DIC) for the assessment of damage in concrete beams, enabling comprehensive displacement and strain measurements to detect fracture start, propagation, and alterations in their modal properties. DIC shown high sensitivity in detecting fracture initiation and growth, correlating modal frequency alterations with damage. This research illustrated the feasibility of Digital Image Correlation for real-time damage assessment in concrete buildings.

Meng et al. (2023) [86] integrated 3D scanning with Digital Image Correlation (DIC) to assess the geometry and deformation of metallic structures, focusing on modal analysis and system identification. The combination of 3D scanning with DIC provided comprehensive geometric and deformation data, hence improving the precision of modal parameter estimates. The technology was effective for metallic structures featuring intricate geometries.

He et al. (2024) [87] delineated the applications of DIC, particularly in ultra-high-temperature environments for civil structures. Digital Image Correlation (DIC) was utilized on concrete specimens subjected to heat stress to assess deformation and modal characteristics. DIC demonstrated accuracy retention under severe temperatures, effectively recording deformations and modal characteristics. Subpixel registration and camera calibration were identified in the review as crucial for precise measurements.

Liu et al. (2024) [88] conducted an experimental study on liquid sloshing in a rectangular tank under pitch excitations, varying frequencies and amplitudes at liquid-carrying rates of 20%, 30%, and 70%. Employed pressure sensors and high-speed cameras to examine impact pressures, waveforms, and spectral properties. Nonlinear sloshing was recorded, exhibiting maximum pressures of up to 31,607 Pa at a 20% liquid-carrying rate at resonance. At 70%, a "soft spring" phenomenon altered resonance, resulting in decreased pressures. At 70%, a "soft spring" effect altered resonance and diminished pressures. They identified four waveforms, including vortex waves at 70% resonance. Spectral analysis revealed predominant frequencies corresponding to stimulation frequencies, facilitating industrial applications.

The papers demonstrate the application of DIC in various facets of civil engineering, including system identification, damage detection, and modal analysis. It offers multiple advantages, including non-contact, high-resolution measurement capabilities suitable for hostile environments and intricate geometries. Future problems include subpixel registration, camera calibration, and the examination of massive structures. There exists significant potential for collaboration and resources using DIC and machine learning to automate damage detection, improve real-time processing efficiency, and facilitate deployment on extensive dynamic infrastructure.

Conclusion

The seismic response of elevated water tanks is governed by the interactive responses of fluid, structure, and ground motions, which should be addressed in seismic design for safety. The traditional analysis models, e.g., lumped-mass and spring–mass analogs, yield simplified but efficient approaches but result in underestimated deformation and hydrodynamic forces. Advanced finite element and numerical methods give more realistic predictions but demand enormous computational time and meticulous parameter adjustment. Experimental evidence indicates that neglecting wall flexibility, sloshing, and soil-structure effects can lead to dangerous design assumptions. Recent developments in Digital Image Correlation (DIC) have introduced a powerful, non-destructive technique for accurately measuring modal properties, monitoring damage, and validating numerical models. The use of DIC together with experimental and numerical testing has the ability to develop more reliable design and monitoring methods. Future research must focus on full-scale experimental verification of FSSI effects, incorporation of DIC-based monitoring into operational use, and development of improved seismic design codes that explicitly encompass fluid–structure–soil coupling. Ultimately, the improvement in the understanding and simulation of these interactions will enhance the robustness of elevated water tanks as important lifeline structures in seismically active areas.

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Consent for publication

Not applicable.

Competing interests
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