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Original Article

A Comparative Study on the Seismic Behaviour of Square and Circular Water Tank Considering Soil-Structure Interaction

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Abstract

The seismic performance of elevated water tanks is a major concern due to the large mass of stored water at an elevated level and the flexibility of the supporting staging system. Unlike conventional buildings, the dynamic response of elevated water tanks under seismic loading is complex, depending on tank geometry, staging characteristics, fluid-structure interaction, and soil-structure interaction (SSI). The traditional fixed-base approach assumes a rigid foundation and ignores soil flexibility, potentially leading to inaccurate seismic response predictions, particularly for structures on soft or layered soil. Additionally, water sloshing introduces a dynamic component that further affects tank behaviour. This study presents a comparative numerical investigation of the seismic behaviour of square and circular elevated water tanks, explicitly incorporating SSI. Both tank configurations were analysed under identical geometric, material, loading, and staging conditions to isolate the effect of tank geometry on seismic response. The influence of soil flexibility and water sloshing was considered, and structural responses were compared using natural period, base shear, and displacement. Results show that circular tanks exhibit lower seismic responses than square tanks under both fixed-base and SSI conditions. The influence of SSI becomes more pronounced as soil stiffness decreases, with the fundamental time period increasing by approximately three times under soft-soil conditions relative to the fixed-base case. These findings offer insight into the combined effect of tank geometry and soil-structure interaction on seismic performance, supporting the selection of more suitable and resilient tank configurations for seismic regions.

Keywords: Sloshing Wave, Soil Structure Interaction, Stratified Soil.

1. Introduction

Earthquakes are one of the most damaging of the natural hazards, as they can cause severe damage to infrastructure and lead to the disruption of essential services. The fact that major earthquakes have occurred repeatedly has shown how important it is to design buildings so that they can withstand seismic forces and remain functional after an earthquake. Among the essential infrastructure, elevated water tanks have a vital function in providing water to both urban and rural areas; because of their elevated position, water distribution is made possible by gravity, thus decreasing the need for pumping systems. For this reason, it is very important to ensure that elevated water tanks are safe from seismic activity and will remain functional after an earthquake, especially in areas prone to earthquakes.

Elevated water tanks are different from ordinary building structures because of the large amount of water stored at a high level and the flexible nature of their supporting staging system (Quadri & Sawant, 2016). When an earthquake occurs, the interaction between the tank structure, the water it contains, and the supporting system leads to complicated dynamic effects. The shape of the tank also affects how it responds to seismic activity (Tarwatkar & Bias, 2021). Thus, square and circular tanks differ in their stiffness distribution, structural arrangement, hydrodynamic behaviour, and the way loads are transferred. For this reason, choosing the right tank shape is a key factor in the seismic design of elevated water tanks. The damage and failures that have been seen in elevated water tanks in past earthquakes, such as the 2001 Bhuj earthquake, have shown the results of poor seismic design, an inappropriate staging configuration, and an incorrect estimation of seismic demands (Rai, 2003; Soroushnia et al., 2011).

The seismic behaviour of an elevated water tank is not determined entirely by the characteristics of its superstructure. The interaction between the foundation and the soil it is supported on can have a significant effect on the whole dynamic response of the structure. This is what is generally known as soil-structure interaction (SSI), and it takes into account the flexibility and dynamic properties of the supporting soil and the way these interact with the structural system. In traditional seismic analysis, elevated water tanks are often simplified by assuming a fixed base, that is to say that the foundation is treated as perfectly rigid. Yet this assumption does not reflect the real conditions encountered in the field, where the supporting soil deforms and interacts with the foundation as a result of ground motion (Mylonakis & Gazetas, 2000).

The influence of SSI becomes particularly significant for structures founded on soft and stratified soil deposits (Jayadeep & Govindaraju, 2025). Compared with structures founded on stiff soil or rock, soil flexibility can modify the natural period, damping characteristics, displacement, base shear, and overall seismic demand of the structure. Neglecting these effects may result in an inaccurate estimation of the actual seismic response and consequently lead to unsafe or overly conservative designs (Mylonakis & Gazetas, 2000). Therefore, incorporating SSI into the seismic evaluation of elevated water tanks provides a more realistic representation of their behaviour under earthquake loading.

In addition to soil-structure interaction, the movement of water during an earthquake introduces another important dynamic phenomenon known as sloshing. The seismic excitation causes the water surface to oscillate, resulting in impulsive and convective components of hydrodynamic pressure. These effects influence the overall response of the tank and may increase the demands on the tank wall, staging, and foundation. Sloshing-induced effects have been identified as an important contributor to damage in liquid storage structures during major earthquakes, including the 1960 Chilean earthquake (Housner, 1963). Consequently, an appropriate seismic assessment of elevated water tanks should consider both the structural response and the dynamic behaviour of the stored water. Although the effects of soil-structure interaction and fluid-structure interaction on the seismic response of elevated water tanks have been recognized, the influence of tank geometry on their combined seismic response under varying soil conditions requires further comparative investigation. Such an assessment is particularly important for identifying the tank configuration that provides better seismic performance under realistic soil and fluid interaction effects.

Therefore, the present study focuses on a comparative investigation of the seismic behaviour of square and circular elevated water tanks considering soil-structure interaction. Both tank configurations are evaluated under comparable structural, loading, and staging conditions to determine the influence of tank geometry on their seismic response. The analysis considers the effects of soil flexibility and the dynamic behaviour of stored water, and the responses are compared using parameters such as natural period, displacement, base shear. The findings of the study are expected to provide useful insights into the influence of tank geometry and soil conditions on the seismic performance of elevated water tanks and contribute towards the selection of safer and more resilient tank configurations in seismic regions.

2. Literature Review

2.1. Seismic Behaviour of Elevated Water Tanks

Tank geometry and staging pattern are key variables governing seismic response. Quadri and Sawant (2018) found staging configuration significantly affect base shear and displacement in RC elevated tanks. Tarwatkar and Bias (2021) showed that H/D ratio and tank shape strongly influence natural period and base shear. Rai (2003) documented staging failures during the 2001 Bhuj earthquake, while Soroushnia et al. (2011) linked staging flexibility to observed damage patterns, together confirming geometry and staging stiffness as central to seismic vulnerability.

2.2. Soil-Structure Interaction (SSI)

SSI describes how soil flexibility (stiffness, stratification) modifies a structure's period, damping, and displacement relative to the fixed-base assumption. Mylonakis and Gazetas (2000) showed SSI effects can be beneficial or detrimental depending on soil-structure properties. Jayadeep and Govindaraju (2025) found stratified soil deposits substantially alter period and displacement of elevated tanks, more so as soil stiffness decreases. Livaoğlu and Doğangün (2006) proposed simplified procedures incorporating fluid-structure-soil interaction for practical design.

2.3. Fluid-Structure Interaction and Sloshing

Impulsive mass (water moving with the tank) and convective mass (sloshing water) define hydrodynamic response. Housner (1963) developed the foundational two-mass formulation still used in codes today. This is codified in (Bureau of Indian Standards, 2014) and detailed in IITK-GSDMA (2007) guidelines, with container design governed by Bureau of Indian Standards (2009), Bureau of Indian Standards (2000), and Bureau of Indian Standards (2016).

3. Methods

3.1. Idealization of Elevated Water Tanks

Elevated water tanks are seldom filled to capacity, and this partial filling permits movement of the contained water during seismic excitation, a phenomenon known as sloshing. Housner's formulation, which relates the motion of the contained water to the motion of the tank structure relative to the ground, provides the theoretical basis for accounting for the dynamic forces generated by sloshing (Housner, 1963). Following the idealization prescribed in Bureau of Indian Standards (2014) elevated water tanks in this study were modelled using two representations, selected according to the fill condition under analysis:

A. Single lumped mass model, adopted for the empty tank condition, in which the tank is treated as fully rigid with no free water surface and, consequently, no sloshing effect, as shown in Figure 1.

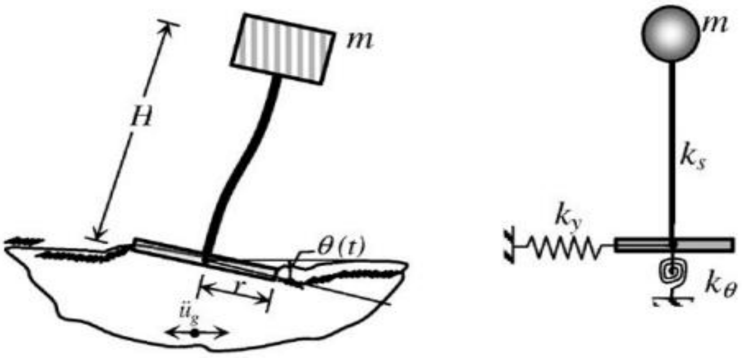

Figure 1. Single lumped mass model of elevated water tanks
Source: Bureau of Indian Standards (2009)

B. Two mass model, adopted for the full tank condition, in which the stored water is represented by an impulsive mass rigidly attached to the tank wall and a convective mass that responds independently of the tank, capturing the sloshing behaviour associated with a free surface, as illustrated in Figure 2. This representation is also referred to as the spring mass model in Bureau of Indian Standards (2014).

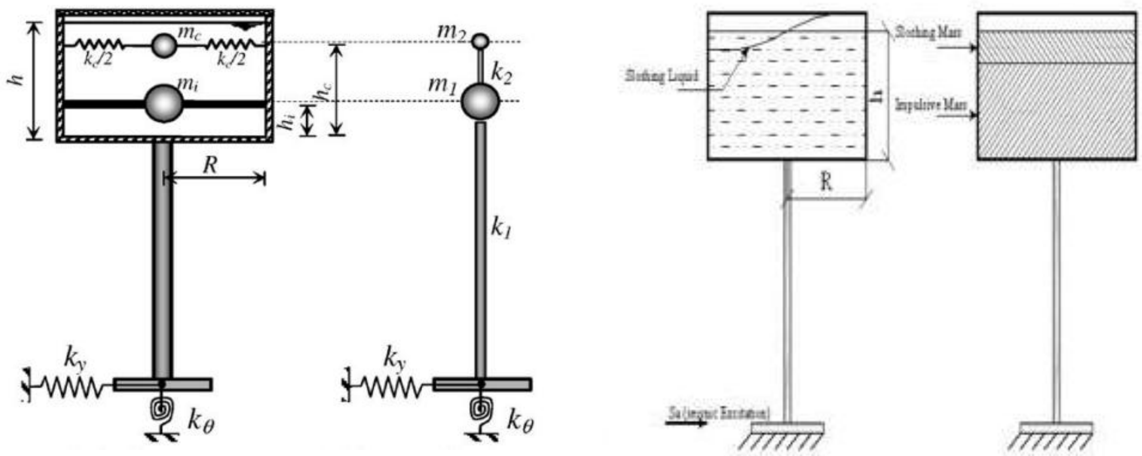

Figure 2. Two mass model of elevated water tank
Source: Bureau of Indian Standards (2016)

3.2. Structural Configuration

Two elevated water tank configurations, square and circular, were designed for comparison, both constructed of reinforced concrete (RC) and supported on a staging approximately 6 m above ground level. The circular tank was assigned a height and diameter of 3 m with a freeboard of 0.3 m, while the square tank was assigned dimensions of 3 m × 3 m × 3 m with an equivalent freeboard of 0.3 m. Both configurations were kept identical in material grade, staging height, and loading conditions to isolate the effect of tank geometry on seismic response. The structural elements common to both tanks, including columns, beams, bracings, slab, and wall thickness, are summarised in Table 1, and the material grades adopted for steel and concrete are given in Table 2.

Table 1. Descriptions of the structure's geometrical characteristics

Sl. No	Structural elements	Dimensions	
		Square Tank	Circular tank
1.	Column	300mm x 300mm	300mm x 300mm
2.	Beam	300mm x 400mm	300mm x 400mm
3.	Bracings	300mm x 300mm	300mm x 300mm
4.	Slab	180mm	180mm
5.	Walls	180mm	180mm

Table 2. Descriptions of the structure's material characteristics

Sl. No	Material type	Grade
1.	Steel	Fe-500
2.	Concrete	M-25

The tanks were designed in accordance with Bureau of Indian Standards (2000) and Bureau of Indian Standards (2009), while the dynamic analysis procedure followed Bureau of Indian Standards (2016) and Bureau of Indian Standards (2014). The dynamic parameters used in the analysis, namely the importance factor, response reduction factor, soil type, and seismic zone, are listed in Table 3.

3.3. Numerical Modelling

Three-dimensional finite element models of both tank configurations were developed in SAP2000 V18.2, with the resulting geometry shown in Figure 3.

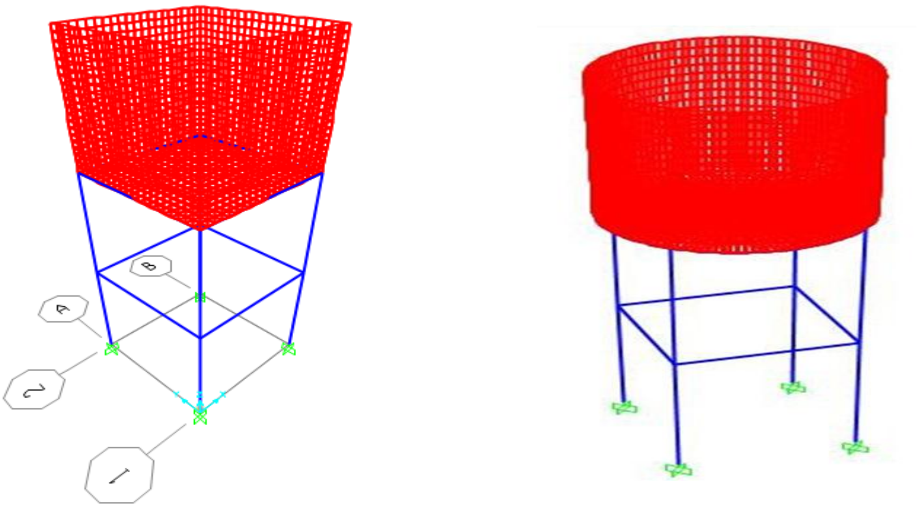

Figure 3. 3D View of square and circular elevated water tank

The response spectrum method was employed to evaluate seismic response in Zones II and III, with the structural system idealized as a special moment resisting frame governed by the dynamic properties listed in Table 3.

Table 3. Descriptions of the structure's dynamic characteristics

Sl. No	Parameters	Description
1.	Importance factor	1.5
2.	Response reduction factor	4
3.	Soil type	I, II, III
4.	Seismic Zone	II & III

Consistent with the idealization described in Section 3.1, each tank was modelled as a single lumped mass system for the empty condition and as a two mass system for the full condition, with impulsive and convective hydrodynamic pressures applied for the latter.

3.4. Fixed Base Analysis

To establish a baseline seismic response, both tank configurations were first analysed assuming a fixed base condition, in which the foundation was treated as fully rigid and fixity was applied at ground level. Response spectrum curves were generated for Zone II and Zone III under three soil types (hard, medium, and soft), following the response spectrum procedure of Bureau of Indian Standards (2014). Base shear, displacement, and modal period and frequency were computed for both empty and full tank conditions under this assumption.

3.5. Soil-Structure Interaction (SSI) Analysis

To account for the flexibility of the supporting soil, which the fixed base assumption does not capture, a second set of models was developed incorporating soil-structure interaction using the Elastic Continuum Approach within the finite element framework, as depicted in Figure 4.

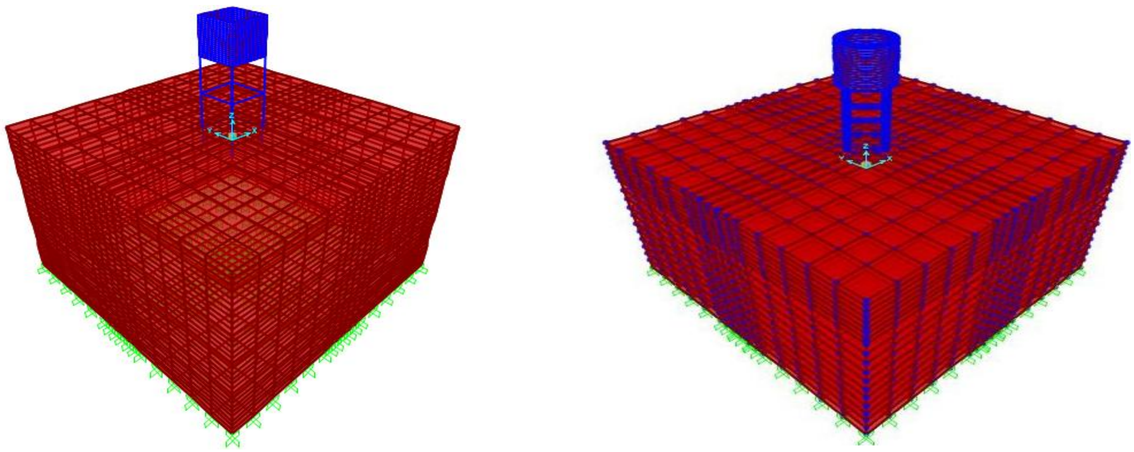

Figure 4. SSI model of square and circular water tanks resting on soft soil

Isolated square footings, sized to carry the maximum load transferred from individual columns, were modelled with plan dimensions of 1.5 m × 1.5 m, a founding depth of 1.5 m below ground level, and a thickness of 500 mm. The soil and substructure were represented as a continuum measuring 50 m in breadth and 30 m in depth, with free field boundary conditions applied at the lateral extents and fixity assigned at the base, beyond which a hard stratum was assumed to exist below 30 m depth. Soil properties, namely unit weight, modulus of elasticity, and Poisson's ratio, were adopted for three soil profiles (soft, medium, and hard) following Bowles (1968), as summarised in Table 8. Both tank configurations were re-analysed under this flexible base condition for empty and full tank conditions across Zones II and III, allowing subsequent comparison of the SSI response against the corresponding fixed base results.

4. Results and Discussion

4.1. Research Results

4.1.1. Fixed Base Analysis

Base shear values obtained under the fixed base assumption are presented in Table 4, with corresponding modal periods and frequencies for the empty and full tank conditions given in Tables 5 and 6, and displacement values summarised in Table 7.

Table 4. Base shear from fixed base analysis

Zone	Soil Type	Empty tank Condition		Full Tank Condition	
		Square tank	Circular tank	Square tank	Circular tank
II	Hard	14.63	13.52	18.07	17.33
	Medium	14.63	13.52	20.43	19.30
	Soft	14.63	13.52	20.43	19.30
III	Hard	23.40	22.36	28.91	25.38
	Medium	23.40	22.36	32.69	31.20
	Soft	23.40	22.36	32.69	31.20

Table 5. Modal period and frequencies in empty tank condition

Mode No	Square tank		Circular tank	
	Time Period (Secs)	Frequency (Cyc/sec)	Time Period (Secs)	Frequency (Cyc/sec)
1.	0.37	2.66	0.31	3.23
2.	0.37	2.66	0.31	3.23
3.	0.26	3.80	0.25	3.82

Table 6. Modal period and frequencies in full tank condition

Mode No	Square tank		Circular tank	
	Time Period (Secs)	Frequency (Cyc/sec)	Time Period (Secs)	Frequency (Cyc/sec)
1.	0.45	2.21	0.39	2.52
2.	0.45	2.21	0.39	2.52
3.	0.29	3.42	0.27	3.70

Table 7. Displacement of water tank

Zone	Soil Type	Empty tank Condition		Full Tank Condition	
		Square tank	Circular tank	Square tank	Circular tank
II	Hard	1.9	1.4	2.3	2
	Medium			2.6	2.2
	Soft			2.6	2.2
III	Hard	2.9	2.2	3.7	3.2
	Medium			4.1	3.4
	Soft			4.1	3.4

The results indicate that seismic responses were consistently higher under full tank conditions than empty tank conditions, attributable to the additional water mass and the associated impulsive and convective pressures. Circular tanks exhibited lower displacement, base shear, and modal response values than square tanks across all cases, indicating reduced seismic vulnerability under the fixed base assumption. Within a given zone, base shear and displacement values were identical across all three soil types, since the average acceleration coefficient (Sa/g) does not vary by soil type under this assumption. Because fixed base outcomes were nearly indistinguishable across soil conditions, this approach was found to be incapable of capturing SSI effects where relevant.

4.1.2. Soil Structure Interaction (SSI) Analysis

The response of the structure evaluated using a fixed base model that ignores the effect of soil-structure interaction (SSI) may affect the structure's behavior in real time, which may be helpful or detrimental to structural performance. So, the current study compares fixed base analysis to flexible base (SSI) analysis. In this study, actual soil conditions are modeled and examined for earthquake circumstances. The displacement, modal period, and frequency are compared. The influence of the SSI is analysed using the Elastic Continuum Approach (FEM Model). Isolated square footings are designed to withstand the maximum load on individual columns. The footing measures 1.5m by 1.5m and is 1.5m below ground level, with a thickness of 500mm.The soil and substructure are modeled as a continuum; the soil mass has dimensions of 50 meters in breadth and 30 meters in depth, and free field motion is addressed; at the base, fixity is attributed to the soil mass, with the soil below 30 meters being a hard stratum. The soil properties are adopted as per Bowles (1968) and three different soil profiles are considered and the responses are evaluated for both circular and square water tanks.

Table 8. Soil properties

Soil Type	Unit weight (kN/m^3)	Modulus of elasticity (kN/m^2)	Poisson's ratio (μ)
Soft soil	16	15000	0.4
Medium soil	16	35000	0.4
Hard soil	18	95000	0.3

Table 9. Displacement of water tank under SSI (Soft Soil)

Zone	Empty tank Condition		Full Tank Condition	
	Square tank	Circular tank	Square tank	Circular tank
II	11.8	8.2	13.9	9.4
III	18.9	11.6	22.2	12.1

Table 10. Displacement of water tank under SSI (Medium Soil)

Zone	Empty tank Condition		Full Tank Condition	
	Square tank	Circular tank	Square tank	Circular tank
II	7.5	6.3	8.9	7.6
III	11.9	10.4	14.2	12.8

Table 11. Displacement of water tank under SSI (Hard Soil)

Zone	Empty tank Condition		Full Tank Condition	
	Square tank	Circular tank	Square tank	Circular tank
II	6.5	5.2	7.9	6.9
III	10.3	8.3	12.1	10.2

Table 12. Modal period and frequencies under full tank condition with SSI (Soft Soil)

Mode No.	Square tank		Circular tank	
	Time Period (Secs)	Frequency (Cyc/sec)	Time Period (Secs)	Frequency (Cyc/sec)
1.	1.27	0.78	1.15	0.87
2.	1.27	0.78	1.15	0.87
3.	1.11	0.89	1.03	0.97

Table 13. Modal period and frequencies under full tank condition with SSI (Medium Soil)

Mode No.	Square tank		Circular tank	
	Time Period (Secs)	Frequency (Cyc/sec)	Time Period (Secs)	Frequency (Cyc/sec)
1.	0.84	1.19	0.72	1.38
2.	0.84	1.19	0.72	1.38
3.	0.73	1.36	0.64	0.64

Table 14. Modal period and frequencies for full tank condition with SSI (Hard Soil)

Mode No.	Square tank		Circular tank	
	Time Period (Secs)	Frequency (Cyc/sec)	Time Period (Secs)	Frequency (Cyc/sec)
1.	0.55	1.82	0.43	2.32
2.	0.55	1.82	0.43	2.32
3.	0.49	2.03	0.40	2.47

Incorporating SSI produced higher displacement and longer time periods than the corresponding fixed base analysis across all cases, reflecting the influence of soil flexibility. Maximum displacement increased with seismic zone intensity, peaking in soft soil under Zone III. Displacement values for hard soil under SSI closely matched fixed base results, indicating that SSI effects are comparatively insignificant for stiff soils, whereas medium and soft soils showed substantial deviation, confirming the necessity of SSI analysis for these conditions. The fundamental time period increased by approximately three times in soft soil relative to the fixed base value. Across all soil types and fill conditions, circular tanks consistently outperformed square tanks, confirming that tank geometry meaningfully influences seismic behaviour under SSI as well as under fixed base conditions.

5. Conclusion

Based on the seismic analysis of square and circular elevated water tanks under fixed-base and soil-structure interaction (SSI) conditions, it is evident that the seismic response of elevated water tanks is governed by the combined influence of tank geometry, stored water, seismic demand, and supporting soil conditions. The presence of water increases the seismic response compared with the empty-tank condition due to the additional mass and associated impulsive and convective effects. Among the two tank configurations considered, circular tanks generally exhibit comparatively lower displacement, base shear, and modal response parameters than square tanks under both fixed-base and SSI conditions, indicating a more favourable seismic performance. The incorporation of SSI introduces additional flexibility into the tank-foundation system, resulting in increased displacement and amplification of the dynamic characteristics, particularly in case of medium and soft soil conditions. In contrast, the seismic responses under hard soil conditions remain relatively close to those obtained from fixed-base analysis, indicating a comparatively lower influence of SSI.

The combined effect of increased seismic demand and reduced soil stiffness leads to more pronounced displacement responses in soft-soil conditions, while the substantial increase in the fundamental time period under SSI, reaching approximately three times the corresponding fixed-base value for soft soil, demonstrates the significant influence of soil flexibility on the dynamic behaviour of the tank system. Overall, the study establishes that tank geometry and soil flexibility are important factors governing the seismic performance of elevated water tanks. Although circular tanks demonstrate comparatively favourable seismic behaviour, the influence of SSI should not be neglected, particularly for tanks founded on medium and soft soils. Therefore, reliable seismic assessment and design of elevated water tanks should account for the interaction between tank configuration, stored water, and supporting soil rather than relying solely on conventional fixed-base analysis.

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