Seismic Soil-Structure Interaction Analysis and Design of Overhead Liquid Storage Tanks in Kathmandu Valley, Nepal

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Abstract: This research investigates the soil-structure interaction (SSI) effects on the analysis and design of overhead liquid storage tanks located in Kathmandu Valley, Nepal; a region characterized by deep alluvial deposits and high seismic vulnerability. Recognizing the limitations of conventional fixed-base assumptions, the research integrates dynamic SSI effects to more accurately capture the tank–foundation–soil system response under earthquake loading. The geological complexity of the valley, characterized by deep alluvial deposits and variable stiffness profiles, necessitates a site-specific approach to modeling soil flexibility and damping. To address this, the study integrates SSI into the dynamic analysis using Midas Gen and GTS Nx software platforms, modelling a reinforced concrete overhead tank with a capacity of 75,000 litres. Time history analysis under EL Centro earthquake loading reveals that SSI significantly influences structural response parameters, including displacement, shear force, bending moment, and natural period. Comparative results show increases of up to 55% in shear force, 52% in bending moment, and substantial elongation of natural periods across varying water levels. These findings underscore the necessity of SSI-inclusive design for critical infrastructure in seismic zones. The study concludes with design recommendations aligned with Indian Standards (IS 1893:2016, IS 3370:2009), advocating for performance-based seismic resilience in municipal water systems.

Keywords: ***Soil–structure interaction, Overhead tank, Seismic design, Kathmandu valley, Time history analysis.***

Introduction

Overhead liquid tanks are critical infrastructure for urban water supply, fire protection, and emergency response. Their elevated configuration, with substantial mass concentrated at height, makes them particularly vulnerable to seismic excitation. In regions like Kathmandu Valley, characterized by deep alluvial deposits and high seismicity (Zone V), the dynamic response of such tanks is significantly influenced by soil–structure interaction (SSI) effects (Livaoglu and Dogangun, 2008; Karabalis and Mohammadi, 2010, Gautam et al., 2024).

SSI refers to the dynamic interplay between a structure and the supporting soil during seismic events. Unlike fixed-base assumptions, SSI recognizes that the foundation and surrounding soil deform under earthquake loading, altering the motion transmitted to the superstructure. This interaction comprises two components:

- Kinematic interaction, where the foundation motion differs from free-field ground motion due to embedment and stiffness contrast.
- Inertial interaction, where the structure's mass induces additional forces on the soil, modifying its response (Wolf, 1985; Mylonakis and Gazetas, 2000).

Neglecting SSI can lead to unsafe underestimations of displacement, base shear, and bending moments; especially in soft or layered soil profiles. Elevated tanks, with slender supports and high center of gravity, are particularly sensitive to these effects. Goyal and Dhingra (2017) demonstrated that SSI significantly increases seismic demands in elevated tanks, especially under varying soil stiffness conditions.

To address these challenges, this study incorporates SSI into the seismic analysis and design of a reinforced concrete overhead water tank located in Duwakot, Kathmandu. The tank is modeled using Midas Gen for structural analysis and GTS Nx for geotechnical simulation, with dynamic loading applied via the El Centro earthquake record. The 1940 El Centro earthquake, recorded in Imperial Valley, California, is widely used in engineering due to its well-documented strong-motion data and complex energy release (Trifunac and Brady, 1975). Its use enables realistic time history analysis, capturing nonlinear structural behavior under seismic excitation.

This research aims to quantify the impact of SSI on key structural parameters: displacement, shear force, and bending moment, under varying water levels. The findings contribute to performance-based design strategies and support the integration of SSI provisions in seismic codes for critical infrastructure in Nepal and similar geotechnical settings.

Methodology

A reinforced concrete overhead tank with a capacity of 75,000 liters was designed based on population demand and codal provisions. The tank was modeled in Midas Gen 2018, and SSI analysis was performed using GTS Nx 2018. The soil profile was represented as a two-layer system with medium stiffness. Dynamic loading was applied using El Centro time history data, recorded during the 1940 Imperial Valley earthquake, the first major event captured by a strong-motion seismograph (Trifunac and Brady, 1975). Structural components such as ring beams, columns, and bracings were analyzed under varying water levels (full, half, empty) to assess the impact of SSI.

Results and Conclusion

The analysis revealed that SSI significantly affects structural behavior:

• Shear Force: Increased by 40–55% in flexible base conditions (Table 1).

Table 1, Maximum shear force values.

Member	Shear force values for different levels of water in the tank								
	Full(kN)			Half(kN)			Empty(kN)		
	Without SSI	With SSI	Percent increase	With out SSI	With SSI	Percent increase	With out SSI	With SSI	Percent increase
Top ring beam	58.69	131.35	55.32%	50.38	101.24	50.24%	12.36	21.46	42.42%
Bottom ring beam	50.32	91.71	45.13%	45.15	68.80	35.32%	9.42	13.57	30.62%
Column	14.59	19.22	24.12%	12.30	15.02	18.13%	3.08	3.59	14.26%

• Bending Moment: Increased by 28–52% depending on water level (Table 2).

Table 2, Maximum bending moment values.

Member	Bending moment values for different levels of water in the tank								
	Full(kN)			Half(kN)			Empty(kN)		
	With out SSI	With SSI	Percent increase	With out SSI	With SSI	Percent increase	With out SSI	With SSI	Percent increase
Top ring beam	95.50	200.2	52.30%	80.38	158	49.14%	11.36	19.69	42.32%
Bottom ring beam	47.50	80.10	40.70%	34.19	52.72	35.15%	6.39	8.88	28.12%
Column	15.10	18.25	17.30%	12.45	14.70	15.32%	5.95	6.81	12.65%

• Displacement: Increased by up to 67% when SSI was considered (Table 3).

Table 3, Displacement of tanks.

Water level in the tank	Node number	Displacement of nodes(mm)	
		Without soil structure interaction	With soil structure interaction
Full	2	22	28.3
Half	2	17	24
Empty	2	12	20.1

These changes are attributed to increased flexibility and longer natural periods induced by soil compliance. Similar findings were reported by Goyal and Dhingra (2017), who observed amplified seismic response in elevated tanks with flexible foundations. The results emphasize the need for SSI-inclusive design, especially in seismic zones with soft or layered soils.

Incorporating SSI into the seismic design of overhead water tanks leads to more realistic and safer structural performance predictions. The study demonstrates that ignoring SSI can underestimate seismic demands, potentially compromising structural integrity. Adopting SSI-based design practices, aligned with IS 1893 (2016) and IS 3370 (2009), is essential for resilient infrastructure planning in Kathmandu Valley and similar geotechnical settings.

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