International Journal of Recent Research and Review, Vol. XVII, Issue 1, March 2024

ISSN 2277 – 8322

INVESTIGATING THE EFFECT OF SEISMIC ZONE AND LOADING CONDITION ON STABILITY OF WATER TANK

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Abstract: The devastating impact of earthquakes on infrastructure, particularly elevated water tanks, underscores the limitations of static analysis in structural engineering. These tanks, vulnerable due to their height and the concentration of mass at the top, demand a nuanced understanding of their dynamic behaviour, especially considering fluid-structure-soil interactions during seismic events. Failures in historical earthquakes have often been traced back to inadequate structural codes and poor design, highlighting the need for realistic seismic analysis. This study investigates the seismic performance of circular elevated water tanks using STAAD Pro for numerical modelling, focusing on the effects of soil types, water levels, and bracing configurations on seismic resilience. Through experimental design analysis, it reveals significant influences of soil compliance, water content, and bracing systems on key seismic indicators like base shear, displacement, and overturning moment. The research advocates for advanced seismic design strategies, incorporating these factors to enhance the earthquake readiness of water tanks.

Key words: Elevated water tank, Seismic analysis, Fluid-structure interaction, Soil-structure interaction, STAAD

1. Introduction

The critical role of water tanks in ensuring a stable water supply in varied geographical settings, especially in regions like India, where water scarcity becomes pronounced outside the monsoon season, cannot be overstated. Given their importance in storing and distributing water for residential, commercial, and emergency uses, the seismic resilience of these structures, particularly elevated water tanks, is of paramount concern. Elevated water tanks, characterized by their raised design for gravity-fed water supply systems, pose unique challenges in seismic design due to their vulnerability to damage from earthquakes. This vulnerability stems from the combination of a heavy mass concentrated at the top and a relatively slender supporting structure below, along with complex interactions between the tank structure, the water it holds, and the underlying soil.

The devastating earthquake in Nepal in 2015 highlighted the susceptibility of water supply infrastructures, including elevated tanks, to seismic forces, underscoring the imperative for incorporating earthquake-resistant features in their design and construction. The seismic performance of these tanks is crucial not only for maintaining water supply post-disaster but also for preventing significant damage and mitigating health risks associated with the leakage of stored chemicals or water. This introduction provides an overview of water tanks, their classification, structural features, past failures, and the motivation behind focusing on their seismic resilience, setting the stage for a comprehensive analysis aimed at enhancing their design and construction practices to withstand seismic forces.

Water tanks are classified based on their location (ground-level, elevated, underground), shape (circular, rectangular, spherical, Intze), material (reinforced concrete, steel, fiberglass, plastic), and functionality (potable water, fire protection, irrigation, chemical and oil storage). Each category addresses different storage needs and operational requirements, reflecting the versatility of water tanks in various applications.

The structural components critical to the analysis and design of reinforced concrete elevated water tanks include the container or tank itself, the supporting structure or staging, and the foundation. The design complexities of these tanks are further accentuated by their unique shapes, the choice of staging (frame or shaft), and foundation design, which must consider soil conditions and the tank's height. Innovations in materials, computer-aided design, and construction techniques have contributed to the evolution of tank designs that are not only structurally sound but also environmentally sustainable.

Historically, elevated water tanks have suffered from structural issues leading to early distress and failure, often within 10 to 15 years of service. These problems arise from various factors, including non-compliance with ductility provisions, flawed structural designs, substandard materials, and the impact of seismic and wind forces. The Bhuj earthquake in 2001, among others, serves as a stark reminder of the vulnerability of elevated water tanks to seismic events, highlighting the importance of the supporting system in bearing the brunt of such forces.

The seismic behavior of elevated water tanks involves complex interactions, notably soil-structure interaction (SSI) and fluid-structure interaction (FSI), which have significant effects on the tanks' response to seismic forces. The traditional assumption of a fixed base in seismic structural analysis is overly simplistic, as it fails to account for the dynamic properties of soil and the behavior of fluids within tanks during earthquakes.

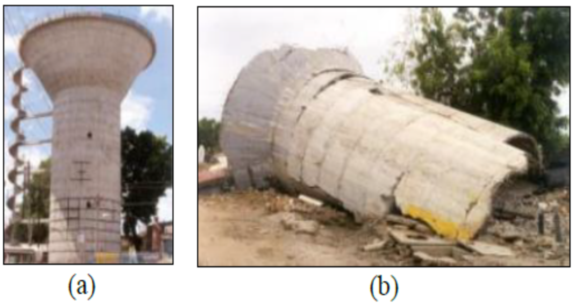
(a) (b)

Figure 1Water tanks affected during Bhuj earthquake in (a) Morbi and (b) Chobari (Source: Rai, 2002)

Current seismic codes, such as IS 1893:2002 in India, offer guidance for the design of structures to withstand earthquake forces. However, these codes often fall short in adequately addressing the unique aspects of elevated water tanks, particularly the effects of FSI, leading to potential underestimation of seismic forces. The necessity for regular updates and revisions to these codes, informed by advances in design practices and lessons learned from past earthquakes, is evident.

Motivated by the geographical necessity for water storage in India, the societal reliance on elevated water tanks, the historical evidence of their vulnerability to seismic forces, and the observed early distresses, this study aims to improve the understanding and enhance the seismic resilience of elevated water tanks. By addressing the gaps in current design and construction practices, this research seeks to contribute to the development of elevated water tanks that can reliably serve communities, even in the aftermath of severe earthquakes.

Table 1Previous Literature

Author(s)	Year	Key Findings and Contributions
Gurkalo et al.	2024	Found that slits in reinforced concrete shafts enhance ductility and seismic behavior, especially in tall, slender tanks.
Holtschoppen and Knoedel	2024	Adapted flat-bottom tank designs for slender tanks, demonstrating reductions in seismic base shear and moment.
Tanmoy Kona	2023	Introduced a dual-purpose slender tuned sloshing damper (STSD) and overhead water tank (OWT) with consistent performance despite liquid depth fluctuations.
Bansode and Datye	2018	Showed that increasing bracing levels increases base shear and moment but reduces lateral displacement and vibration periods in Intze-type tanks.
Chougule et al.	2017	Identified that increases in the height-to-diameter ratio of tanks result in higher base shear, bending moments, and hydrodynamic pressure.
Rai Durgesh C.	2002	Highlighted the vulnerabilities of elevated tanks in seismic regions and documented failures in tank staging post-earthquakes.
Bhadauria and Gupta	2006	Assessed deterioration in water tank structures due to environmental factors like corrosion and provided a damage scale.
Masood Amjad et al.	2008	Examined technological failures in rural water tanks, citing poor concrete quality as a cause of distress.
Dutta et al.	2000	Explored the torsional and lateral stiffness of tank staging and the influence of soil-structure interaction on dynamic characteristics.
Housner	1960	Laid the groundwork for understanding fluid-tank interaction and dynamic behavior under seismic loading.
Livaoğlu and Doğangün	2000	Studied the impact of ground types and the added mass approach on seismic behavior, providing simplified design methods.
Algreane et al.	2011	Investigated elevated tank behavior considering soil and water interactions and dynamic responses under seismic loads.
Omidinasab et al.	2010	Analyzed a concrete water tank using time history analysis for different seismic responses.
Masood Amjad et al.	2008	Examined technological failures in rural water tanks, citing poor concrete quality as a cause of distress.

This study is dedicated to enhancing our understanding of the seismic resilience of circular elevated water tanks, focusing on their behavior under varying conditions. The objectives include examining the effects of different soil types (hard, medium, and soft) and water levels (empty, half-full, and full) on their seismic performance. Key performance metrics such as base shear, maximum resultant displacement, and overturning moment will be quantified to assess the impact of these variables. Through the use of statistical analysis and numerical modeling in STAAD Pro, the research aims to explore the interplay between soil compliance, fluid dynamics, and seismic forces, identifying the critical factors that influence the seismic durability of these essential structures.

2. Modal provision and Output

2.1 Structural Data

This study examines the seismic performance of 1000 cubic meters reinforced concrete circular elevated water tank in Delhi, seismic Zone IV. The tank, with a 14-meter diameter, 7-meter height, and wall thickness of 0.35 meters, features top and bottom domes and a conical dome, all designed with concrete and steel grades of 30 MPa and 415 N/mm^2, respectively. Positioned 16 meters above the foundation, it is supported by eight columns and reinforced with four levels of bracings. Using STAAD Pro, the analysis focuses on the impact of varying water levels (empty, half-full, full) and soil types (soft, medium, hard) on the tank's seismic stability and safety.

Table 2 Structural data of considered water tank

Parameter	Specification
Capacity of the tank	1000 m3
Unit weight of concrete	25 kN/m3
Unit weight of Water	9.81 kN/m3
Grade of concrete fck	30 MPa
Grade of Steel fy	415 N/mm2
Rise of Top Dome	1.7 m
Size of Top Ring Beam	0.35 x 0.35 m
Diameter of tank container	14 m
Height of Cylindrical wall	7 m
Thickness of Cylindrical wall	0.35 m
Size of Middle Ring Beam	1.2 X 0.6 m
Rise of Conical dome	2 m
Thickness of Conical dome	0.5 m
Rise of Bottom dome	1.3 m
Thickness of Bottom dome shell	0.3 m
Size of Bottom Circular girder	0.8 X 1.2 m
Distance between intermediate bracing	4 m
Height of Staging above Foundation	16 m
Number of Columns (circular)	8
Number of Peripheral (Circumferential) Bracings Level	4
Distance between intermediate bracing	4 m
Diameter of Columns	0.75 m
Size of Peripheral Bracing	0.5X0.5 m
Size of Radial, Diagonal and Cross Bracing	0.3X0.3 m

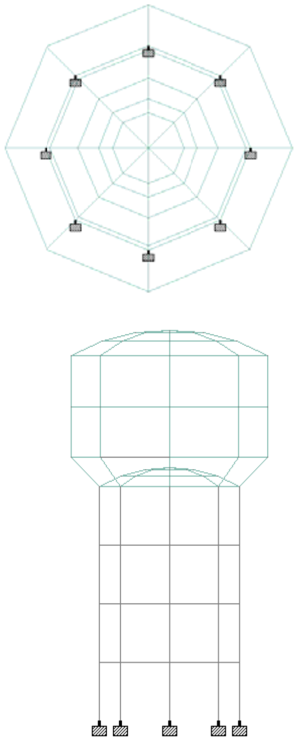

Figure 2 Model (a) top view and (b) elevation

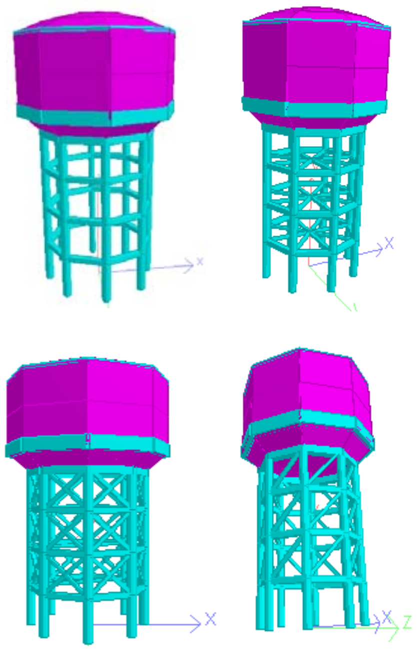

Figure 3 Stagging pattern and 3D view of model a) Peripheral b) Radial c) Cross and (d) Diagonal

3. Output of analysis

The study undertook a detailed seismic analysis of a circular elevated water tank by evaluating its response across twelve scenarios, combining three soil types (hard, medium, soft) with four water levels (empty, quarter-full, half-full, full). Utilizing STAAD Pro, the analysis focused on key metrics: shear forces along the x and z axes for each tank level, nodal displacements in all directions, and forces and moments on each node. This methodical examination aimed to identify the impact of soil conditions and water content on the tank's seismic resilience, facilitating the optimization of design for enhanced safety and stability

Table 3 Combination of each condition for seismic analysis

Condition	**Soil Type**	**Bracing Type**	**Water condition**
Condition 1	Hard	Peripheral	Empty
Condition 2	Hard	Peripheral	Half
Condition 3	Hard	Peripheral	Full
Condition 4	Medium	Peripheral	Empty
Condition 5	Medium	Peripheral	Half
Condition 6	Medium	Peripheral	Full
Condition 7	Soft	Peripheral	Empty
Condition 8	Soft	Peripheral	Half
Condition 9	Soft	Peripheral	Full
Condition 10	Soft	Peripheral + Horizonal Radial	Full
Condition 11	Soft	Peripheral + Vertical Diagonal	Full
Condition 12	Soft	Peripheral + Vertical Cross	Full

Table 4 Maximum outcomes for each condition

Condition	**Bracing Type**	**Soil Type**	**Water condition**	**Base Shear (kN)**	**Overturning Moment (kN-m)**	**Top Displacement (cm)**
Condition 1	**Peripheral**	Hard	Empty	436.65	8979.53	1.83
Condition 2		Hard	Half	653.03	12685.06	2.72
Condition 3		Hard	Full	790.72	15017.31	3.28
Condition 4		Medium	Empty	593.84	12212.16	2.49
Condition 5		Medium	Half	888.12	17251.71	3.70
Condition 6		Medium	Full	1075.38	20423.55	4.46
Condition 7		Soft	Empty	629.21	12939.41	2.64
Condition 8		Soft	Half	1090.55	21184.07	4.54
Condition 9		Soft	Full	1320.51	25078.92	5.48

Table 5Consolidated results for Peripheral. Radial, Diagonal and Cross Bracings

Bracing Type	**Soil Type**	**Water condition**	**Base Shear (kN)**	**Overturning Moment (kN-m)**	**Top Displacement (cm)**
Peripheral	Soft	Full	1320.51	25078.91738	5.4775
Horizontal Radial	Soft	Full	1342.85	25455.45656	5.4614
Vertical Diagonal	Soft	Full	1345.24	25488.72709	1.6472
Vertical Cross	Soft	Full	1371.35	25922.38495	1.2932

4. RESULTS AND DISCUSSION

4.1 Impact of Soil Type and Water Condition:

(a) Hard Soil Conditions

In hard soil, an incremental increase in base shear, displacement, and overturning moment was observed as the tank's water level rose from empty to full. This increment suggests that the presence of water significantly affects the seismic response, primarily through the added mass and the hydrodynamic pressure exerted on the tank walls. Hard soil, with its relatively higher stiffness, transmits seismic energy more efficiently, resulting in clear differences in seismic response based on the tank's fill level.

(b) Medium Soil Conditions

The medium soil conditions exhibited a marked increase in the seismic response parameters as the water level increased, indicating a compounded effect of soil flexibility and fluid mass. Medium soil's lesser stiffness compared to hard soil means more energy is absorbed by the soil itself, leading to larger displacements and forces on the tank structure. The intermediate compliance of medium soil amplifies the seismic effects, highlighting the necessity of considering medium soil's unique characteristics in the seismic design of tanks.

(c) Soft Soil Conditions

Soft soil conditions showcased the most dramatic increases in all measured parameters across the water conditions. The soft soil significantly amplifies the seismic response due to its high compliance, allowing more pronounced movements and stresses on the tank structure. The results from soft soil conditions emphasize the critical impact of soil compliance on seismic behaviour, with soft soils presenting the greatest challenge in terms of seismic design and mitigation.

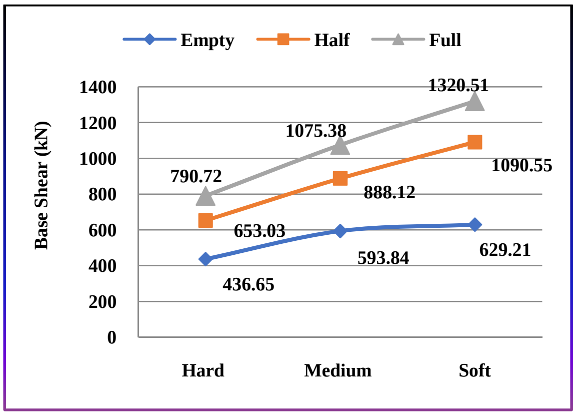

Figure 4 Base Shear for different soil and water level condition

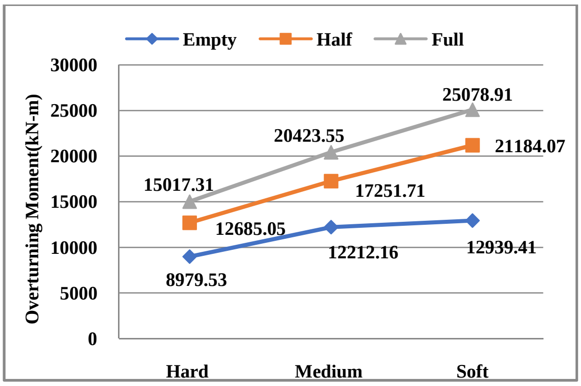

Figure 5 Overturning Moment for different soil and water level condition

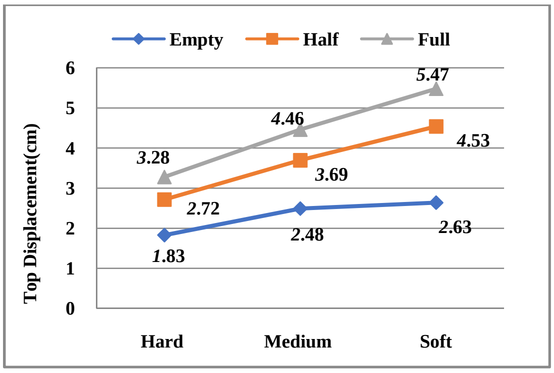

Figure 6 Top Displacement for different soil and water level condition

The analysis reveals a consistent trend across all soil types: as the tank's water level increases, so do the base shear, displacement, and overturning moment. This trend underscores the dual influence of fluid mass and soil compliance on the seismic behaviour of elevated water tanks. The added mass of the water enhances the inertial forces during seismic events, while the soil type determines the extent to which these forces are amplified or mitigated.

Moreover, the maximum resultant displacement observations indicate an increased susceptibility of the tank to seismic-induced movements as the water level rises. This susceptibility is most pronounced in tanks situated on soft soil, underscoring the importance of detailed soil investigation and appropriate seismic design considerations.

In conclusion, this detailed seismic analysis highlights the nuanced interaction between water mass, soil type, and seismic forces. It clearly demonstrates that water tanks, especially those on soft soil and at full capacity, face the highest risk during seismic events. Therefore, understanding these dynamics is crucial for the development of effective seismic design strategies, ensuring the structural integrity and safety of elevated water tanks under diverse seismic conditions.

4.2 Impact of Bracing system for full tank on soft soil:

When evaluating the performance of different bracing types for a full water tank on soft soil, it's essential to consider the implications of higher base shear and overturning moment, as well as lower top displacement.

(a) Peripheral Bracing

Peripheral Bracing represents the reference point for this analysis. It has the lowest base shear and overturning moment, which may be advantageous in seismic situations because it could indicate less force being transferred to the foundation, potentially reducing the risk of foundation failure. However, this bracing type also has the highest top displacement, which is a critical factor to consider. Higher top displacements can lead to increased strain on the structure and potential damage during seismic events, as it indicates more movement and less control over the sway of the tank.

(b) Horizontal Radial Bracing

Horizontal Radial Bracing shows a slight increase in base shear and overturning moment compared to the peripheral bracing. This suggests a small increment in the forces that the foundation must resist during an earthquake, which could be unfavorable if the foundation design cannot accommodate these forces. The top displacement is nearly the same as with peripheral bracing, indicating that this design does not substantially improve the control of sway at the top of the tank.

(c) Vertical Diagonal Bracing

Vertical Diagonal Bracing presents an interesting result with a modest increase in base shear and overturning moment, implying a slight increase in the load on the foundation during seismic events. However, there's a significant decrease in top displacement, which is highly beneficial. This reduction indicates that the vertical diagonal bracing is effective at controlling the movement of the tank's top, likely reducing potential damage during earthquakes.

(d) Vertical Cross Bracing

Vertical Cross Bracing shows the highest base shear and overturning moment, which may not be favorable since it suggests that the foundation is subjected to the highest forces among all bracing types considered. However, the vertical cross bracing has the lowest top displacement, significantly reducing the tank's sway during seismic events. This characteristic is highly desirable as it implies that the bracing is very effective at keeping the tank stable at its top, which is crucial for maintaining the integrity of the tank and connected piping during an earthquake.

In summary, while the base shear and overturning moment are generally unfavorable when they are higher, the significantly reduced top displacement seen with Vertical Diagonal and Vertical Cross bracing types may outweigh these concerns. It suggests that these bracing systems offer improved control over the tank's movement, which is a vital factor in seismic resilience. The choice of bracing should, therefore, balance the need for a stable foundation capable of handling increased forces with the critical requirement to minimize top displacements during seismic activity.

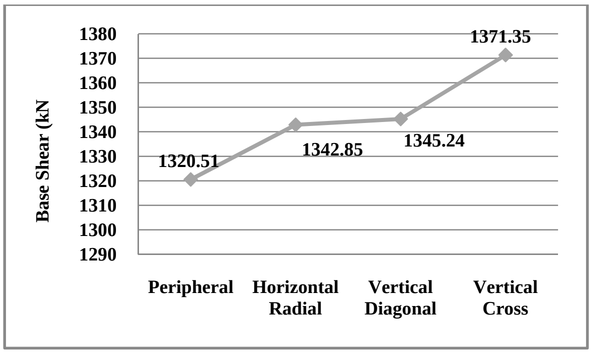

Figure 7 Base shear comparison for different types of Bracing

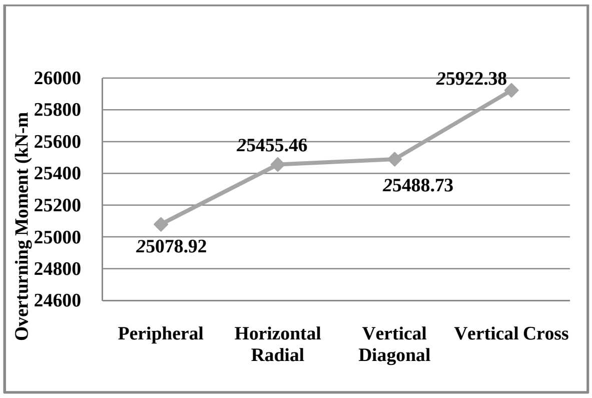

Figure 8 Overturning moment comparison for different types of Bracing

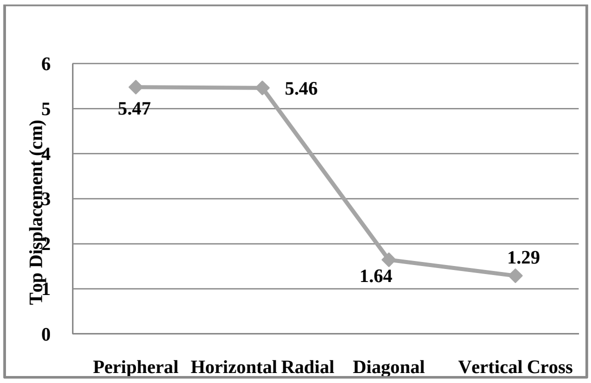

Figure 9 Top Displacement comparison for different types of Bracing

Conclusion

The study's comprehensive analysis, reinforced by ANOVA results, conclusively demonstrates the significant impact of soil type and water condition on the seismic behavior of circular elevated water tanks. The findings articulate a clear statistical significance of these factors in influencing base shear, top displacement, and overturning moment, which are critical parameters in assessing a structure's seismic resilience.

- Water condition (full, half, empty) plays a significant role in influencing the seismic response of the tanks, showing a substantial impact on base shear, overturning moment, and displacement.
- Soil type, despite being statistically insignificant in the ANOVA analysis, still accounts for a notable percentage of variability in seismic response parameters and cannot be ignored in design.
- Different bracing types affect seismic performance variables of water tanks differently. The choice of bracing impacts the base shear, overturning moment, and top displacement in various ways.
- Vertical bracing systems, particularly vertical diagonal and vertical cross, significantly reduce top displacement, which is critical for the stability of the tank during seismic events.
- Higher base shear and overturning moments are observed with more robust bracing types. While they indicate a stronger structure, they also imply more substantial forces acting on the foundation during seismic events.

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