Nonlinear Seismic Behavior of Elevated Circular Water Tanks

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Abstract

Elevated water tanks are vital infrastructure components in urban and rural water distribution systems, providing essential storage and pressure regulation. However, their elevated position, high center of mass, and susceptibility to lateral forces make them vulnerable to seismic events. This study investigates the nonlinear seismic behavior of reinforced concrete (RC) elevated circular water tanks supported on frame-type staging. The study focuses on evaluating the impact of different bracing configurations, staging heights, and tank geometries on the seismic performance of these structures. Nonlinear time-history analysis was conducted using real earthquake ground motion records to simulate the dynamic response of the tanks. The results demonstrate that the inclusion of bracing systems significantly improves the seismic performance, with single bracing providing the most effective reduction in displacement, velocity, and base shear. Tanks without bracing exhibited the highest lateral displacements and base shear values, indicating the importance of bracing in enhancing structural resilience. The study also highlights the role of staging height and tank geometry in influencing seismic response. The findings underscore the importance of considering nonlinear behavior and fluid-structure interaction for a comprehensive understanding of the dynamic performance of elevated water tanks under seismic loading. This research provides valuable insights for the design and seismic evaluation of elevated water tanks, particularly in seismic-prone regions, and contributes to the development of improved design practices that ensure continued functionality and safety during and after seismic events.

Keywords: Nonlinear Seismic Behavior, Elevated Water Tanks, Bracing Systems, Frame-Type Staging, Time-History Analysis, Fluid-Structure Interaction

1. Introduction

Elevated water tanks are critical infrastructure in urban and rural water distribution systems, providing both storage and pressure regulation to ensure a consistent water supply. As essential lifeline structures, their structural integrity and post-earthquake functionality are of paramount importance. Seismic events pose a significant threat to these structures due to their elevated nature, high center of mass, and susceptibility to lateral forces. Failure of water tanks during earthquakes not only disrupts water supply but can also result in substantial economic losses and safety hazards. Consequently, understanding the seismic behavior of elevated water tanks is essential for designing resilient and reliable water storage systems. Reinforced concrete (RC) elevated water tanks typically comprise a water container supported by a staging system, which may be a solid shaft or a frame composed of columns and braces. The frame-type staging system offers distinct advantages in seismic regions due to its three-dimensional structural behavior, which allows effective redistribution of lateral loads and enhanced energy dissipation. Unlike shaft-type staging, which primarily resists forces through axial compression, frame staging utilizes flexural and shear resistance in columns and braces, resulting in improved ductility and reduced likelihood of catastrophic failure. The seismic performance of such systems is influenced by several factors, including tank geometry, staging height, bracing configuration, and soil conditions.

Fig. 1: RC Frame Staging of an Elevated Water Tank

Circular tanks are widely preferred over rectangular tanks due to their inherent geometric advantages. For a given storage capacity, circular tanks have the smallest surface area, reducing material usage and construction costs. Their symmetrical geometry also minimizes torsional irregularities, which can amplify seismic effects in rectangular tanks. Furthermore, circular tanks provide uniform stress distribution along the walls, enhancing stability and structural efficiency. However, circular tanks present complex dynamic interactions between the contained water and the structure, particularly under seismic loading. The sloshing of water during an earthquake generates impulsive and convective hydrodynamic forces, which contribute to additional lateral loads on the tank walls and staging. Accurate assessment of these forces is crucial for predicting realistic structural responses. Traditional linear static and response spectrum methods are commonly employed for preliminary design and seismic evaluation. While these methods provide insights into elastic behavior and initial yielding, they often fail to capture the full extent of post-elastic deformations, ductility requirements, and energy dissipation characteristics. Nonlinear time-history analysis offers a more robust approach by simulating the structure's response to actual earthquake records over time increments. This method accounts for material inelasticity, geometric nonlinearity, and fluid-structure interaction, providing a comprehensive understanding of the tank's dynamic response. Parameters such as lateral displacement, base shear, acceleration, and velocity can be tracked throughout the event, enabling identification of critical regions and potential failure modes.

Bracing systems, such as cross-bracing, diagonal bracing, and knee bracing, are widely adopted to enhance the seismic performance of elevated water tanks. They provide additional lateral stiffness, reduce displacements, and improve energy dissipation. The height of the staging system further influences the dynamic characteristics of the tank, affecting natural periods, mode shapes, and amplification of seismic forces. Despite extensive research on elevated water tanks, there remains a need for detailed studies that integrate nonlinear time-history analysis with various bracing configurations and realistic water-structure interaction modeling, particularly for circular tanks in seismic-prone regions.

The present study aims to address this gap by investigating the nonlinear seismic behavior of RC elevated circular water tanks supported on frame-type staging. Using real earthquake ground motion records, the study evaluates the dynamic responses of braced and unbraced tanks, focusing on displacements, velocities, accelerations, and base shear. The research examines the effectiveness of different bracing systems and staging heights in mitigating seismic effects, providing valuable insights for the design of safe and resilient water storage infrastructure. The outcomes are expected to enhance earthquake-resistant design practices for elevated water tanks, ensuring continued functionality and public safety during and after seismic events.

2. Related work

Mr. Rohit Kiran Chaudhari et al. (2021) investigates the seismic performance of reinforced concrete (RC) elevated water tanks with frame staging compared to shaft staging. The research highlights that frame staging enhances seismic resistance due to its ability to absorb seismic energy. Circular water tanks were chosen for their minimal surface area and reduced material requirements. Seismic analysis of elevated RC circular water tanks was performed following the IITK-GSDMA guidelines, with the analysis considering factors like seismic zone, soil conditions, and staging heights. SAP 2000 was used to evaluate modal characteristics, including mode shapes and modal participation mass ratio. **Manali Ugemuge et al. (2023)** examines the seismic performance of elevated circular water tanks, focusing on the influence of the height-to-diameter (H/D) ratio and different bracing patterns. Using finite element analysis (FEA) software, the study investigates the dynamic response of these tanks under various seismic loading conditions. Different H/D ratios are analyzed to determine their impact on the tank's behavior during seismic events. Additionally, the research evaluates the effectiveness of various bracing patterns—radial, circumferential, and combined—on improving seismic resistance. The goal is to identify the most efficient design approach for enhancing the structural integrity of elevated circular water tanks and mitigating the effects of seismic forces, ultimately ensuring their safety and stability. **P. Kodanda Rama Rao et al. (2022)** investigates the influence of Soil-Structure Interaction (SSI) on the seismic response of elevated RC circular water tanks. Two tanks, each with a 4.0 lakh liter capacity, were analyzed with different foundation types: one on a circular ring raft supported by sandy soil, and the other on a raft supported by piles in black cotton soil. The results highlight that SSI significantly impacts seismic behavior, particularly displacements, which are higher for tanks on loose soils. The study underscores the importance of considering SSI effects in seismic analysis, as per IS 1893 (Part-1) 2016 guidelines.

Maryam Rafieeraad et al. (2021) investigates the seismic behavior of concrete tanks, focusing on the impact of various parameters using finite element methods with pushover and time-history analysis. The research evaluates the response modification factor (R), a crucial parameter in seismic design, based on nonlinear static and time-history analyses. It highlights the significant influence of tank size, material non-linearity, base conditions, and earthquake frequency content on seismic performance. The study finds that fixed-based and shallow tanks exhibit higher R values than hinged-based and tall tanks. The results suggest that current R values specified in seismic codes may not be accurate. **Panagiota Katsimpini et al. (2025)** investigates the use of a novel curved steel damper system to reduce the seismic response of elevated steel tanks. It focuses on two tank types—broad and tall—by analyzing their behavior during past earthquakes. Non-linear time history analyses were performed using various ground motion records to evaluate dynamic characteristics and structural responses. The study finds that the curved steel damper, placed between the tank container and its supporting structure, significantly reduces base shear forces and deformations compared to traditional designs. The research demonstrates that the curved damper effectively decreases maximum displacement and base shear during seismic events, offering a cost-efficient solution for enhancing the earthquake resilience of elevated steel tanks.

3.2 Nonlinear Time History Analysis

Nonlinear time history analysis is a detailed, step-by-step procedure that accounts for material and geometric nonlinearity. The structure's response—displacement, velocity, and internal forces—is calculated incrementally at each small time step (Δt), using the conditions (displacements and velocities) from the previous step. This approach allows precise evaluation of inelastic behavior under realistic ground motion conditions.

Properties of ground motions under consideration are tabulated in Table 3.1.

Table 1: Properties of Ground Motion

Earthquake	Year	Magnitude	Record/Component	PGA (g)
El Centro	1940	7.2	El Centro (1940), USA	0.35
Bhuj	2001	7.7	Bhuj (2001), India	0.38
Uttarkashi	2001	6.6	Uttarkashi (2001), India	0.31
Koyna	1967	6.5	Koyna (1967), India	0.31
Chamoli	1999	6.8	Chamoli (1999), India	0.31

2.1 Research gap

Existing studies on elevated water tanks have examined various factors such as staging type, bracing configuration, height-to-diameter ratio, and soil-structure interaction. However, a comprehensive understanding of the combined nonlinear seismic behavior of elevated circular water tanks remains incomplete. Limited research integrates the effects of soil flexibility, tank geometry, and advanced energy dissipation mechanisms under real ground motion data. Furthermore, most analyses rely on simplified or linear approaches, neglecting the complex fluid-structure interaction and dynamic coupling between tank and staging. There is also a lack of standardized design guidelines incorporating nonlinear seismic response parameters. Hence, further research is required to develop integrated models that accurately capture the dynamic performance and improve the seismic resilience of elevated circular water tanks.

3. Methodology

The primary objective of this study is to investigate the nonlinear seismic behavior of an overhead circular reinforced concrete water tank supported on frame staging, considering different modeling configurations. The analysis is performed using SAP2000 software to evaluate the tank's structural response under seismic loading. The models are analyzed using time history analysis for five different real earthquake records to accurately assess their dynamic performance and response characteristics.

3.1 Time History Analysis

Time history analysis evaluates the dynamic response of a structure over time when subjected to specific ground motion records. In this method, the structure is exposed to actual earthquake acceleration data, and its behavior is assessed at discrete time intervals to capture variations in displacement, velocity, and acceleration during seismic excitation.

4. PROBLEM STATEMENT

In the present study water tank is designed for Laxmi Township at Ranjangaon MIDC.

Figure 2: Layout Plan of Laxmi Township, Ranjangaon MIDC

4.1 Design Data -

Total Structure=200

Minimum water capacity required=200 X 5 X 135=135000 lit.

Considering 10% commercial use extra.

Total Capacity=150000 lit. =150m^3

Staging Height=20m

Assume height of tank=4m (Ref.IS 3370)

Thickness of CROSS BRACING wall=180mm

Thickness of base slab=200mm

For rectangular water tank:

CAPACITY=L*B*H

150=L*B*4

Assume Aspect Ratio L/B = 2

Therefore,

L = 9m

B = 4.5m

For circular water tank:

Capacity = 3.14/4*D^2*4

Diameter - 7m

Beam size - 230x600

Column size - 230x650

4.2 SAP-2000 Models

From the problem statement mentioned in above chapter the following models are proposed for time history analysis for earthquake data of Bhuj data.

Table 2: Water Tank Models for Seismic Analysis

Model No.1	Rectangular water tank without bracing
Model No.2	Rectangular water tank with single bracing
Model No.3	Rectangular water tank double bracing
Model No.4	Rectangular water tank knee bracing
Model No.5	Circular water tank without bracing
Model No.6	Circular water tank with single bracing
Model No.7	Circular water tank double bracing
Model No.8	Circular water tank knee bracing

- **Rectangular Water Tank (Plain)**

Fig 3: Rectangular water tank without Bracing

- **Rectangular Water Tank with Single Bracing**

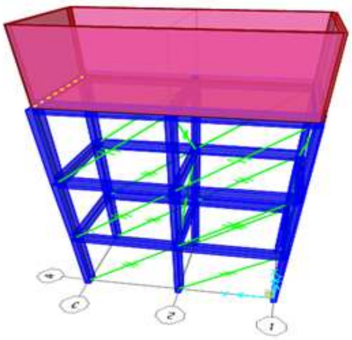

Fig 4: Rectangular water tank with Single Bracing

5. Results and Discussion

5.1 Analysis Parameter for Rectangular Water Tank

Table 3: Rectangular Water Tank

Rectangular Water Tank			
Sr. No.	**Name**	**Type**	**Max Value**
1	Without Bracing	Displacement (Ux)	4.6
		Velocity	45.9
		Acceleration	6.5
		base shear	1.43x102
2	Single Bracing	Displacement (Ux)	2.26
		Velocity	41.31
		Acceleration	5.85
		base shear	6.45x102
3	Knee Bracing	Displacement (Ux)	1.09
		Velocity	26.8515
		Acceleration	3.8025
		base shear	3.36x102
4	Cross Bracing	Displacement (Ux)	1.74
		Velocity	32.2218
		Acceleration	4.563
		base shear	3.74x102

5.2.1 Deformation vs Various Cases

Table 4: Time History Deformation

Sr. No.	Type of Rectangular Tank (RT)	Time History Deformation (X) [mm]
1	RT Without Bracing	4.60
2	RT With Cross Bracing	2.26
3	RT With Single Bracing	1.09
4	RT With Knee Bracing	1.74

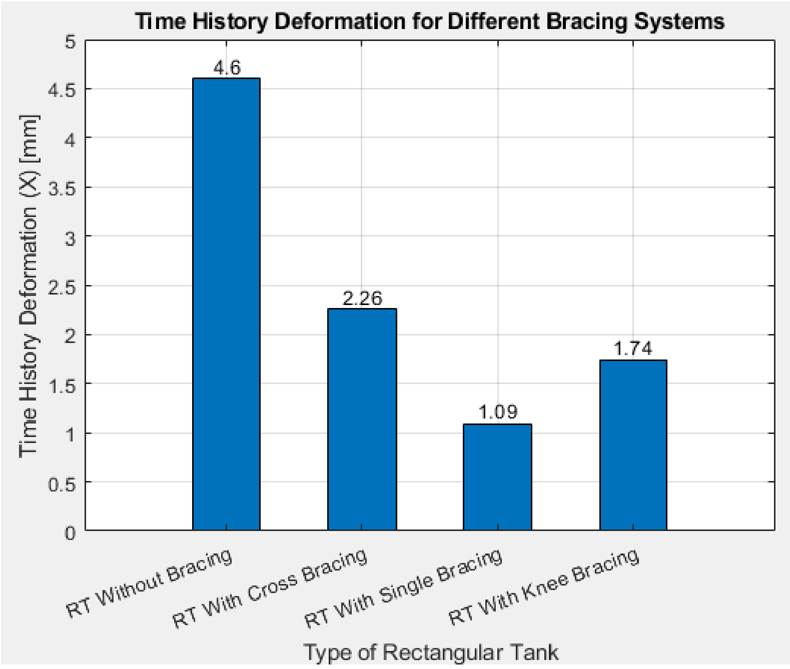

Figure 5: Time History Deformation

In this figure maximum deformation is 4.6 mm rectangular tank without bracing difference between Rectangular Tank without Bracing and rectangular tank with Single Bracing is 30%.

Table 5: Time History Response Parameters for Rectangular Water Tank (Y-Direction)

Rectangular Water Tank			
Sr. No.	**Name**	**Type**	**Max Value**
1	Without Bracing	Displacement (Uy)	4.37
		Velocity	0
		Acceleration	6.175
		base shear	138.567
2	Single Bracing	Displacement (Uy)	2.147
		Velocity	39.2445
		Acceleration	5.5575
		base shear	625.005
3	Knee Bracing	Displacement (Uy)	1.0355
		Velocity	25.508925
		Acceleration	3.612375
		base shear	325.584
4	Cross Bracing	Displacement (Uy)	1.653
		Velocity	30.61071

		Acceleration	4.33485
		base shear	362.406

Table 6: Time History Deformation in Y-Direction for Rectangular Water Tank

Sr. No.	Type of Rectangular Tank (RT)	Time History Deformation (Y) [mm]
1	RT Without Bracing	4.37
2	RT With Cross Bracing	1.653
3	RT With Single Bracing	2.147
4	RT With Knee Bracing	1.0355

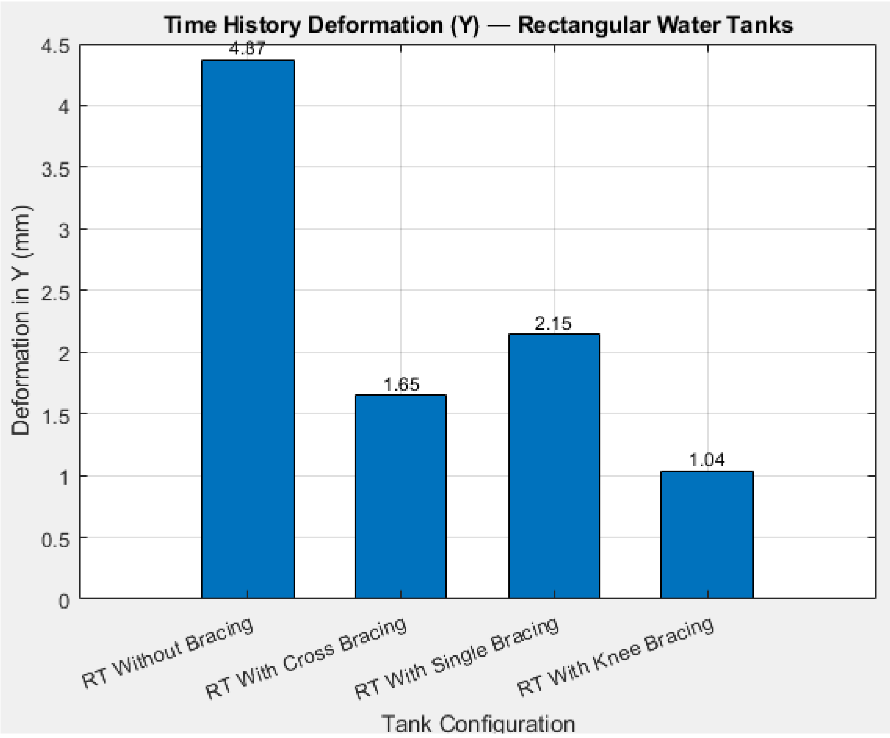

Figure 6: Time History Deformation in Y-Direction for Rectangular Water Tank

In this figure 6 maximum deformation is 4.37 mm rectangular tank without bracing difference between Rectangular Tank without Bracing and rectangular tank with Single Bracing is 28%.

5.2.2 Base Shear Vs Various Cases

Table 7: Base Shear

Base Shear KN			
RT Without Bracing	**RT With Cross Bracing**	**RT With Single Bracing**	**RT With Knee Bracings**
$1.43x10^2$	$3.36x10^2$	$6.45x10^2$	3.74e+02

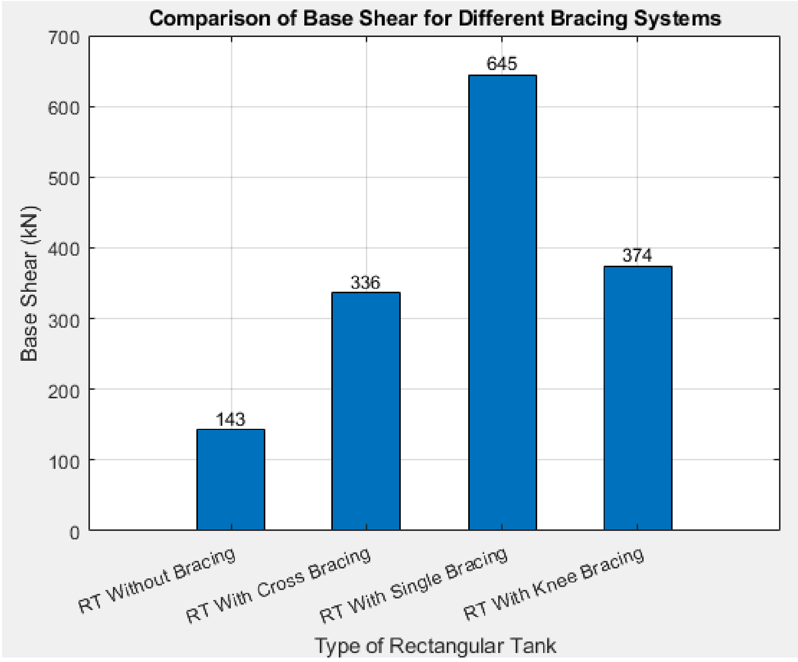

Figure 7: Comparison of Base Shear for Different Bracing Systems

In This Figure 7 Max. Base Shear is 645 KN obtain in single bracing system and Min. in without cross bracing. Using bracing for water tank increase the Base Shear.

6. Conclusion

This study provides a comprehensive evaluation of the nonlinear seismic behavior of elevated circular and rectangular water tanks supported on frame-type staging systems, with a particular focus on the impact of bracing configurations and tank geometry on seismic performance. The research employed nonlinear time-history analysis to simulate the dynamic response of the tanks under actual earthquake ground motion records. The results offer significant insights into how different factors, including bracing systems, staging heights, and tank shapes, influence the overall seismic resilience of water tanks. The findings show that bracing systems—specifically single bracing, cross bracing, and knee bracing—dramatically improve the seismic performance of elevated water tanks. Tanks with single bracing exhibited the highest reduction in both lateral displacement and base shear, making them the most effective in mitigating seismic forces. In contrast, unbraced tanks exhibited the highest displacements and base shear, underlining the critical role of bracing in enhancing the tank's structural stability during seismic events. Additionally, base shear analysis demonstrated that the use of bracing increases the base shear capacity, with the single bracing system resulting in the highest base shear of 645 kN.

The time history deformation analysis highlighted the importance of incorporating bracing to reduce the displacement by approximately 30% in the X-direction and 28% in the Y-direction, compared to unbraced configurations. This illustrates the substantial improvement in the tank's lateral stiffness and overall seismic performance when bracing is implemented. Furthermore, the study confirms that staging height and tank geometry influence the tank's seismic behavior, with taller staging systems amplifying the seismic forces on the tank. The research also identifies key gaps in the existing literature regarding the integration of soil-structure interaction, fluid-structure coupling, and bracing systems in the seismic analysis of elevated water tanks. The findings contribute to the development of more resilient, cost-effective design strategies for elevated water tanks in seismic zones. Future studies should explore advanced bracing systems, fluid-structure interaction, and soil-structure interaction models for optimizing the seismic design of water tanks, ensuring their functionality and public safety during and after seismic events.

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