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"Dynamic Analysis and Seismic Behaviour of Elevated Water Tank Structures"

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Abstract

Water tanks are crucial infrastructure for municipal water supply. Elevated tanks, however, are highly vulnerable to dynamic effects, particularly seismic forces. This study presents the dynamic analysis of an elevated water tank structure under varying conditions — tank full, half full, and empty-using STAAD.Pro. Comparative analysis is also conducted between circular and rectangular tank shapes. Further, variations in wall and shaft thickness are studied to evaluate performance changes. Modal analysis and response spectrum analysis are performed. Results are presented in terms of natural frequencies, mode shapes, and seismic performance.

Keywords: Elevated Water Tank, Seismic Loading, Parametric Study, Staging Configuration, Thickness Variation of Water Tank Wall etc.

1. Introduction

Elevated water tanks are crucial infrastructure components that ensure the availability of water supply with sufficient pressure for residential, commercial, and industrial use. These structures are typically raised on staging systems to provide gravitational flow, and their seismic performance becomes critically important in earthquake-prone regions. During seismic events, elevated water tanks behave differently compared to regular buildings due to the dynamic interaction between the water mass and the structural system. In India, a significant number of water tanks are situated in moderate to high seismic zones, making seismic-resistant design essential. The city of Pune, located in Seismic Zone III as per IS 1893 (Part 1): 2016, provides a relevant context for studying the dynamic behavior of such tanks. This project focuses on performing a dynamic analysis and evaluating the seismic performance of elevated circular water tanks with a single-column (shaft-type) support system using STAAD.Pro software. The primary objective of this study is to analyze how parameters like tank capacity and staging height influence seismic responses such as base shear, top displacement, and natural period. The study also includes analytical validation and graphical interpretation to derive insights into the optimal design of shaft-supported elevated water tanks under seismic loading.

2. Literature Reviews

1. **Mrs. Kalyani Ravindra Bachhav, Dr. D. P. Joshi (Oct-2020) – "Dynamic Analysis of Elevated Water Tanks"**

In this paper, the elevated water tank was initially designed manually using Microsoft Excel, accounting for earthquake forces. Appropriate loading conditions, earthquake zones, and other parameters were considered in the design. The wall and slab loads were calculated in Excel and directly applied in the STAAD.Pro model of the tank structure. After completing the initial analysis, the study investigated the effect of varying the tank height using STAAD.Pro under the same loading and seismic conditions for comparative purposes. The research aimed to analyse how variations in tank height influence displacement, concluding that displacement increases as the tank height increases.

2. **Shubham Jain & Afzal Khan (Feb-2023) – "To model and analyse elevated water tanks using the Response Spectrum Method in STAAD.Pro"**

This paper developed models of elevated water tanks and performed dynamic analysis using the Response Spectrum Method according to IS 1893:2002 guidelines. The study demonstrated the effectiveness of the Response Spectrum Method in evaluating seismic responses, emphasizing the importance of dynamic analysis in design. It was observed that the ring beam in a circular column is curved, resulting in greater moments compared to the straight ring beam in a rectangular tank.

3. **Pallavi S. Dhamak, V. R. Rathi, K. B. Ladhane (August-2014) – "To study the dynamic response of an elevated water tank considering soil-structure interaction"**

This study compared the dynamic response of an elevated water tank with and without considering soil-structure interaction (SSI), validated using the substitute frame method. An elevated water tank was modelled and analysed under seismic loading while incorporating SSI effects. The results showed that soil conditions significantly affect the tank's dynamic response, highlighting the necessity of including SSI in seismic analysis. For comparison, junction points at the bracing connections were analysed in both SSI and non-SSI conditions.

4. **Sangeetha, Jayadeep K S, and L. Govindaraju (March-2024) – "Seismic analysis and design of elevated water tank with comprehensive soil-structure interaction assessment"**

This paper focused on a 3m x 3m elevated water tank with a staging height of 6m, analysing seismic behavior on both level and sloped ground (0° to 30°, at 5° intervals). The study conducted fixed-base analyses, evaluating base shear, displacement, and modal properties for full and empty tank conditions. Soil-Structure Interaction (SSI) analysis compared the seismic parameters between fixed and flexible base models. The results indicated higher base shear values in Zone III, implying greater seismic forces compared to Zone II.

5. **Nandagopan M. and Shinu Shajee (April-2017) – "Dynamic Analysis of RCC Water Tanks with Varying Height of Water Level"**

This study examined the dynamic response of circular RCC elevated water tanks under varying staging heights and water levels. Using El Centro Earthquake records, time history analysis was performed. The results showed that peak displacement increased with staging height, while displacement for half-filled tanks was lower than for fully filled tanks. Base shear also increased with staging height and showed a trend of decreasing and then increasing with capacity. Elevated tanks exhibited higher base reactions compared to ground-supported tanks.

6. **Vinod Bhide, Arjun Dawar, Ajay Chouhan, Antim Mandloi, Nilesh Brahmane, Pyar Singh Brahmane, and Lalit Balhar (Sept-2022) – "A review on structural behavior of water tanks under dynamic loading"**

This review highlighted that the dynamic behavior of liquid storage tanks is significantly influenced by earthquake characteristics. The failure modes of rectangular tanks differ markedly from other shapes, complicating the failure mechanisms. Soil-structure interaction affects how seismic waves impact the structure. The study noted that many water tanks lack sufficient strength to withstand extreme conditions, making them vulnerable under dynamic loading.

7. **Akash Devidas Bobade, Dr. S. K. Patil, Dr. A. B. Pujari (Feb-2024) – "The seismic behavior of an elevated storage reservoir across different earthquake regions"**

This research analysed the seismic performance of elevated storage tanks of different shapes across various seismic zones. The objective was to determine which tank shape provides better seismic resistance. By examining different H/D ratios, it was concluded that circular tanks performed better than rectangular tanks in Zones II and V, with superior results in displacement, drift, stiffness, and base shear under seismic conditions.

8. **Ms. Vaishnavi Bahale, Prof. S.P. Tak (Oct-2022) – "Seismic analysis of elevated steel water tank with or without base isolation"**

This study aimed to evaluate the seismic response of steel elevated water tanks with and without base isolation using nonlinear dynamic time history analysis. Two isolation positions were considered: between the foundation and the tank, and between the staging and tank shell. The results showed that using laminated rubber bearing isolators effectively reduced base shear by 55–75% compared to non-isolated tanks. The study also noted that convective liquid motion plays a significant role in tank failure.

9. **Nandagopan M., Shinu Shajee (April-2017) – "Dynamic Analysis of RCC Water Tanks with Varying Height of Water Level"**

This paper detailed the analysis of four types of water tanks: ground-supported rectangular, ground-supported circular, elevated rectangular, and elevated circular RCC tanks (500 m^3 capacity). Manual dynamic analysis was performed for water levels increasing by 10% increments up to full capacity. Models were created in ETABS 2016, and dynamic analyses were conducted similarly. Base reactions obtained manually and from software were compared. It was concluded that base shear and moment increase with water level, and elevated tanks exhibit higher base reactions than ground-supported tanks, increasing with staging height.

10. **Vrushali Gujar, Shahayajali Sayyed (Dec-2019) – "To review seismic analysis of RC elevated water tanks with different staging configurations"**

This paper analysed various staging configurations—normal, hexagonal, cross, and radial—with central columns to design a seismically resistant tank. A comparative study of frame staging versus shaft staging was conducted using STAAD.Pro. The findings indicated that staging configuration significantly affects seismic performance, with some configurations providing better resistance under loading.

11. **Hoang Nam Phan & Fabrizio Paolacci (June-2018) – "To study fluid-structure interaction in anchored and unanchored steel storage tanks under seismic loadings"**

Using nonlinear finite element modelling in ABAQUS, this study simulated seismic responses, including hydrodynamic pressure distribution and uplift behavior. Modal analyses were performed using the Lanczos eigen solver, and acoustic-structural coupling was applied through SIM-based linear dynamics. The research emphasized the complexity of fluid-structure interaction and the need for advanced modelling for accurate seismic analysis.

12. **Mor Vyankatesh K., More Varsha T. (Feb-2017) – "Comparative Study on Dynamic Analysis of Elevated Water Tank Frame Staging and Concrete Shaft Supported"**

This paper compared elevated tanks with different support systems, capacities, and seismic zones, following current codes and IIT-GSDMA guidelines. The study focused on the sloshing effects during earthquakes. It concluded that base shear is higher in concrete shaft-supported tanks than in frame-staged tanks, with significant differences in time periods under impulsive modes, while differences were smaller for convective modes.

13. **Amandeep Verma, Manisha Sharma, Monika Angral (August-2020) – "Suitability of software for calculation of staging stiffness of overhead service reservoir (OHSR)"**

This study analysed a reinforced concrete OHSR with circular framed staging (10m diameter) using eight columns and bracing at various levels. Different staging heights (20m, 25m, 30m) were modeled in STAAD.Pro, SAP2000, and ETABS, comparing stiffness values. The study defined lateral stiffness as the force required at the tank's center of gravity to cause unit displacement, and calculated stiffness from displacement under lateral loading.

14. **L. Kalani Sarokolayi, B. Navayineya, M. Hosainalibegi, J. Vaseghi Amiri (Oct-2008)** – **"Dynamic analysis of water tanks with interaction between fluid and structure"**

This research applied the added mass method to model fluid-structure interaction, assuming a flexible structure while neglecting fluid compressibility and stiffness. Although simple for 2D and 3D models, the method can introduce significant errors. The study emphasized that seismic acceleration contains various frequencies, requiring Fourier integration to represent these as harmonic functions for structural analysis.

15. **Arfat Rafiq, Mir Tabish Altaf, Shahid Rafeeq, Dr. Mohammad Umair (June-2023)** – **"Seismic Evaluation of Base Isolated Overhead Water Storage Tank"**

This paper employed a spring-mass idealization for overhead water tanks, modelling both impulsive and convective modes. For empty tanks, the convective mode was absent. The study showed that base shear increases with tank depth in base-fixed reservoirs, peaking when fully filled and minimizing when empty.

16. **Nyabuto Onderi Andrew, Siphila Wanjiku Mumenya (Sep.-2022)** – **"Effect of Shaft Height on Base Shear of Elevated Intze Water Tanks"**

This study investigated how varying shaft height affects base shear in elevated Intze tanks. The shaft, typically a thin RCC or masonry shell, provides less lateral resistance than a frame. The analysis projected potential axial and punching shear failure with increasing height. Results showed a direct correlation between shaft height and base shear, necessitating corresponding changes in foundation design.

17. **Furquan Elahi Shaikh, B K Raghuprasad, Amarnath K (July-2017)** – **"Performance Study of Elevated Water Tanks under Seismic Forces"**

Using Housner's model, this paper analysed hydrodynamic effects on elevated water tanks with framed staging and concrete shafts in different seismic zones. Lateral stiffness was calculated manually or with FEM software for frame staging, while shaft stiffness was determined by applying horizontal forces at the tank's centre of gravity. The study concluded that base shear is higher in shaft-supported tanks compared to frame-staged tanks under both impulsive and convective modes.

18. **S. Bozorgmehrnia, M.M. Ranjbar and R. Madandoust (2013)** – **"Seismic Behavior Assessment of Concrete Elevated Water Tanks"**

This research analysed a 900m^3 elevated water tank on a moment-resisting frame using Housner's two-mass model under three earthquake records. Dynamic responses—base shear, overturning moment, roof/floor displacement, and sloshing—were assessed for empty, half-full, and full conditions. It concluded that critical responses do not always occur at full capacity but may occur at lower fluid levels depending on the earthquake.

19. **Ketan Ashok Akolkar, K. S. Patil, N. V. Khadke (May-2023)** – **"A Study on Wind Analysis of Elevated INTZE Tank Using Different Arrangements of Bracing System"**

This study analysed an elevated INTZE tank with normal, rectangular, and radial bracing under full, half, and empty conditions for wind speeds of 47m/s and 55m/s. Roof displacement and base shear were compared across conditions. Results showed higher roof displacement under full tank conditions, with radial bracing yielding the least displacement under both wind zones.

20. **Tayyaba Anjum and Mohd. Zameeruddin (Jan-2021)** – **"Evaluation of Efficacy of the Elevated Water Tank Under the Seismic Loads"**

This study evaluated circular and Intze elevated tanks in Nanded under empty, half-full, and full conditions, considering sloshing and hydrostatic effects. Using a finite element model in STAAD.Pro, it was found that natural frequency decreases with increased water storage. The time period varied across empty, half-full, and full conditions due to sloshing and hydrodynamic pressure.

3. Research Methodology

3.1 Aim

"Dynamic Analysis and Seismic Behaviour of Elevated Water Tank Structures."

3.2 Objectives

1. To perform dynamic analysis (Response Spectrum Analysis) of an elevated circular water tank under three different water levels:

- (a) Full tank
- (b) Half-full tank
- (c) Empty tank

2. To evaluate the effect of tank shape by comparing the dynamic performance of a circular tank with a rectangular tank, for the same water levels.
3. To analyse the influence of structural stiffness by changing:

- Tank wall thickness (3 variations)
- Shaft (column/staging) thickness (3 variations)

4. To interpret the variation in:

- Base shear
- Natural frequency
- Maximum displacement
- Mode shapes

3.3 Methodology

1. Estimating Water Demand

Based on a current **population of approx. 40,000** in **Wagholi, Pune**, let's estimate the required capacity

and design dimensions of the elevated water tank.
Per capita daily water demand = 135 lit./person/day
(as per CPHEEO guidelines)
Total demand = 40,000 × 135 = 5,400,000 lit./day
Volume of tank = 5400 m^3/day
Assuming the tank supplies 1/3rd of the daily demand
Tank capacity = 1800 m^3 (or 1.8 million lit.)

2. Assumed Type of Tank & Dimensions

Let's design for both circular and rectangular tanks with the same capacity.

A. Circular Tank

Capacity = 1800 m^3
Assume height of water = 6 m
$V = A \times h = \pi r^2 . h$
$1800 = \pi r^2 \times 6$
$1800/6\pi = r^2 \Rightarrow r \approx 9.78$ m
Diameter ≈ 19.5 m
Height of tank (cylindrical portion) = 6 m
Staging height = 12 m to 15 m (average)
Shaft: circular in shape

B. Rectangular Tank

Same volume (1800 m^3), assume height = 6 m
$L \times B \times H = 1800$
$\rightarrow L \times B \times 6 = 1800 \rightarrow L \times B = 300$
Assume L = 20 m, B = 15 m
Size = 20 m × 15 m × 6 m height

3. Variable Parameters for Analysis - Detailed Calculation Breakdown:

Part 1: Water Levels and Tank Shapes

1. Circular Tank
   - Full Water Level
   - Half-Full Water Level
   - Empty Tank
2. Rectangular Tank
   - Full Water Level
   - Half-Full Water Level
   - Empty Tank
3. Comparing the Performance of Circular vs Rectangular Tanks
   - Performance comparison on Time Period, Base Shear, Displacement, etc.

Part 2: Tank and Shaft Thickness Variations

4. Circular Tank with Different Thicknesses

- Circular Tank with 150 mm thickness (wall + shaft)
- Circular Tank with 200 mm thickness (wall + shaft)
- Circular Tank with 250 mm thickness (wall + shaft)

5. Rectangular Tank with Different Thicknesses
   - Rectangular Tank with 150 mm thickness (wall + shaft)
   - Rectangular Tank with 200 mm thickness (wall + shaft)
   - Rectangular Tank with 250 mm thickness (wall + shaft)
6. Comparing Differences in Performance for Different Thicknesses
   - Performance comparison of Time Period, Base Shear, Displacement, etc., for each tank thickness.

Calculation Approach

1. For Each of the Above Conditions:
   - Water load calculation for Full, Half, and Empty levels of water.
   - Base shear and displacement results from the dynamic analysis (modal frequency).
   - Mode shape analysis and visualization.
2. Performance Comparison (Circular vs Rectangular Tank):
   - Compare the time period (modal frequency).
   - Compare base shear and displacement for each condition.
3. Variation with Thickness:
   - Perform the above calculations with 150 mm, 200 mm, and 250 mm thickness for both circular and rectangular tanks.
4. Next Steps:

1. Calculation for Water Levels (Full, Half, Empty) for Circular and Rectangular tanks.
2. Comparison of Performance (Circular vs Rectangular) for all the conditions.
3. Detailed calculations and comparisons for different thicknesses (150 mm, 200 mm, and 250 mm)

4. Conclusion

- Dynamic behavior of elevated water tanks is significantly influenced by water level, tank shape, and wall/shaft thickness.
- Empty tanks are more vulnerable dynamically.
- Circular tanks provide slightly better seismic performance than rectangular tanks.
- Increasing wall and shaft thickness improves seismic resistance.

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