An Investigation of the Design of Elevated Water Tanks using SAP

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Abstract:
Elevated water tanks are integral parts of lifeline facilities in any town or city. They are used to store water for various purposes such as drinking, and they are vulnerable to resisting earthquake forces due to the presence of a large mass on slender staging. This study primarily focuses on understanding the seismic behavior and vulnerability of elevated reinforced concrete water tanks and supporting structures under various seismic intensities, soil conditions, and staging heights, in accordance with the provisions of IS1893 Part 2 and guidelines proposed by IITK-GSDMA. Finite element modeling and dynamic analysis of elevated water tanks have been performed using SAP2000. Furthermore, nonlinear static analysis has been conducted to assess the ductility characteristics of the water tank for varying staging heights, considering both empty and full water level conditions. Circular water tanks have been chosen as a case study and analyzed for staging heights at intervals of 3 meters (5, 8, 11, 14, 17, 20, 23, and 26).
Keywords: Elevated water tanks, seismic behavior, reinforced concrete, staging patterns, SAP2000 analysis.

Introduction:
An elevated RC intze tank is a large water storage container constructed to hold water supply at a certain height to pressurize the water distribution system. Various innovations have been made for the storage of water and other liquid materials in different forms. Liquid storage tanks are extensively used by municipalities and industries for storing water, inflammable liquids, and other chemicals, making water tanks crucial for public utility and industrial infrastructure. Elevated water tanks with large diameters and conical domes at the bottom, known as intze tanks, consist of a huge water mass atop slender staging, making them susceptible to failure during earthquakes. A large number of elevated water tanks damaged during past earthquakes were found to be supported on shaft staging. Seismic analysis of these tanks has been carried out using different methods, primarily based on the Indian standard code 1893 (part 1), adopting the lumped mass modal method, and secondarily based on IS 1893 (part 2) draft code and IITK-GSDMA guidelines, considering the two-mass modal method (convective and impulsive mode). Reinforced concrete elevated water tanks with frame staging have shown better seismic resistance than those with shaft staging, attributed to the seismic energy absorption capacity of the staging patterns. This study primarily focuses on understanding the seismic behavior and performance characteristics of elevated RC intze tanks with different staging patterns in Warangal city. Dynamic analysis of RC intze tanks and evaluation of ductility characteristics of different staging, namely frame staging and shaft staging, have also been conducted. The SAP2000 software package has been used for modeling and analyzing the elevated water tank supported on frame and shaft staging.

Malhotra PK [1] used the Finite Element Method to model the elevated tank, where columns and beams in the support system are modeled as frame elements. Different water conditions such as empty, full, and half-full cases were studied, and parameters like time period and modal participation mass ratio were calculated. Various aspects including base shear, overturning moment, roof displacement, and sloshing displacement were investigated. It was concluded that the maximum displacement of the elevated tank occurs at the joint between the support system and the container, rather than in the roof. The occurrence time of maximum roof and sloshing displacements differs due to variations in impulsive and convective mass time periods, as well as differences in the frequency contents and properties of earthquake records used. Responses such as base shear force, overturning moment, and impulsive displacement (roof and floor displacement) depend more on the tank's impulsive mode, while sloshing displacement depends more on the tank's convective mode.

Manish N. Gandhi [2] explained the frame staging type of elevated water tanks, which consist of a huge water mass at the top of a slender staging and are critical considerations for tank failure during earthquakes. Many water tanks that failed due to earthquake forces were found to be shaft-supported, highlighting the need to avoid such tanks in seismic zones. It was also noted that for higher seismic zones, general frame staging is insufficient, and special staging with bracings is required. The study concluded that the slender staging resulting from low design forces is unfavorable for seismic areas. The current designs of RC shaft-type circular staging for elevated water tanks are extremely vulnerable to lateral loads caused by earthquakes, as evidenced by damages sustained to staging up to 125 km away from the epicenter of the Bhuj earthquake. Supporting structures of elevated water tanks are extremely vulnerable to lateral forces during earthquakes.

Housner [3] proposed a two-mass model for elevated tanks, which is more appropriate and commonly used in international codes, including the draft code for IS 1893 (Part-II). The pressure generated within the fluid due to the tank's dynamic motion can be separated into impulsive and convective parts. When a tank containing liquid with a free surface is subjected to horizontal earthquake ground motion, the tank wall and liquid undergo horizontal acceleration. The liquid in the lower region of the tank behaves like a mass rigidly connected to the tank wall, termed as impulsive liquid mass, inducing impulsive hydrodynamic pressure on the tank wall and base. The liquid mass in the upper region of the tank undergoes sloshing motion, termed as convective liquid mass, exerting convective hydrodynamic pressure on the tank wall and base. A spring mass model is adopted for the two-mass model to represent these two masses and include the effect of their hydrodynamic pressure in the analysis.

Dutta [4] studied the torsional response of RC elevated water tanks supported on axisymmetric frame-type staging. Elevated water tanks have failed during past earthquakes due to large torsional response, especially if the uncoupled torsional and lateral natural periods of the tanks are closely spaced.

Research Significance:

The study focuses on the seismic-resistant design of elevated water tanks in accordance with IS 1893 (part 1) and IITK-GSDMA guidelines. It involves finite element modeling and dynamic analysis of elevated RC intze water tanks with different staging patterns, employing lumped mass modal method as per IS 1893 (part 1) and two mass modal method as per IS 1893 (part 2) and IITK-GSDMA guidelines, respectively. Due to the unavailability of earthquake data for Warangal city, response spectrum analysis has been conducted for elevated RC intze water tanks supported with different staging patterns using SAP2000 software. The study aims to analyze the influence of staging patterns on the base shear and ductility characteristics of elevated intze water tanks through nonlinear static analysis using SAP2000.

Seismic Analysis of Elevated RC Intze Tank with Different Staging Patterns:
Analytical studies address the hydrodynamics of liquids in rigid tanks resting on rigid foundations. It is observed that a portion of the liquid undergoes long-period sloshing motion, while the remainder moves rigidly with the tank wall, known as the impulsive liquid. The impulsive liquid experiences the same acceleration as the ground, contributing predominantly to the base shear and overturning moment. The sloshing liquid determines the height of the free-surface waves and, consequently, the freeboard requirement. The flexibility of the tank wall may result in the impulsive liquid experiencing accelerations several times greater than the peak ground acceleration. Tanks supported on flexible foundations, via rigid base mats, exhibit base translation and rocking, leading to longer impulsive periods and generally greater effective damping. These changes may significantly affect the impulsive response. The convective (sloshing) response is practically insensitive to both the tank wall and foundation flexibility due to its long period of oscillation. For this analysis, elevated tanks are considered as single degrees of freedom with their mass concentrated at their center of gravity.

Lumped Mass Modal Method:
For this analysis, elevated tanks are considered as systems with a single degree of freedom, with their mass concentrated at their center of gravity. The damping in the system may be assumed as 5 percent of the critical for concrete.

Two Mass Modal Method:
Since most elevated tanks are never completely filled with liquid, a two-mass idealization of the tank is more appropriate compared to a one-mass idealization. Failures of tanks during the Chilean earthquake of 1960 and the Alaska earthquake of 1964 prompted investigations on the seismic analysis of liquid storage tanks. It became evident that consideration should be given to the sloshing (convective) effect of the liquid and the flexibility of the container wall when evaluating the seismic force of the tank.

NONLINEAR STATIC ANALYSIS

MODELLING OF ELEVATED WATER TANK IN SAP2000

The following steps were followed for modeling the staging and tank container using SAP2000:

1. Define element type: Frame/cable type element is used for the ring beam, bracing, column, and area element (shell) is used for the top dome, bottom dome, cylindrical wall, and shaft type staging.
2. Define Material properties: Material properties such as elastic modulus, shear modulus, Poisson's ratio, weight density, etc., are provided for the beam and shell.
3. Define sections: Frame sections define the width and depth for line element, and area sections define the thickness for shell element.
4. Modelling geometry: The water tank geometry is modeled using a grid system.

5. Apply loads and boundary condition: Boundary conditions and loads are specified using the Define menu.
6. Deflection results: The solution is obtained using the display option in the main menu.

EVALUATION OF DUCTILITY

Nonlinear static analysis capabilities are provided in the nonlinear version of SAP2000. Default hinges are assigned based on flexure (M3) for beams, the interaction of axial force and bending moment (P-M2-M3) for columns, and flexure (M3) for bracing. After assigning hinge properties, structural analysis is carried out to obtain the pushover curve.

RESULTS AND DISCUSSION

The current study investigates two different configurations of staging for elevated water storage tanks: intze tanks supported on frame staging and shaft staging. Seismic analysis of these tanks was conducted using two methods: lumped mass modal and two mass modal methods. Additionally, the ductility of frame and shaft staging was evaluated. The findings of this study can be summarized as follows:

Comparison of Seismic Analysis Parameters: Tables 5 and 6 present a comparison of different seismic analysis parameters for intze tanks supported on frame staging and shaft staging. These tables summarize all parameters for both single mass modal and two mass modal methods for frame and shaft staging.

Time Period and Hydrodynamic Pressure: The time period of water tanks supported on frame staging is higher compared to those supported on shaft staging, attributable to the higher lateral stiffness of shaft staging. Additionally, the hydrodynamic pressure is higher in shaft staging compared to frame staging. Graphical representations of hydrodynamic pressure on the cylindrical wall and bottom of the tank for both lumped mass modal and two mass modal methods are provided in Figures 2 to 5.

CONCLUSIONS

This study presents the seismic analysis and performance of elevated RC intze water tanks with different staging patterns. Using SAP2000 software, modeling, dynamic analysis, and nonlinear static analysis were performed. The behavior of elevated water tanks with various staging patterns was analyzed using single mass modal and two mass modal methods. The key conclusions drawn from the analyses are as follows:

1. Time Period: Tanks supported on frame staging exhibit a higher time period compared to those supported on shaft staging due to the latter's higher lateral stiffness.
2. Lateral Forces: Shaft staging results in higher lateral forces compared to frame staging, leading to higher base shear in tanks supported by shaft staging.
3. Hydrodynamic Pressure: Impulsive hydrodynamic pressure is higher in shaft staging than in frame staging, while convective hydrodynamic pressure remains similar in both staging types.
4. Ductility: Nonlinear static analysis reveals that the ductility of shaft staging is lower than that of frame staging. Specifically, the ductility of RC intze tanks with frame staging is 6.65, while that of shaft staging is 3.12.

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Figures

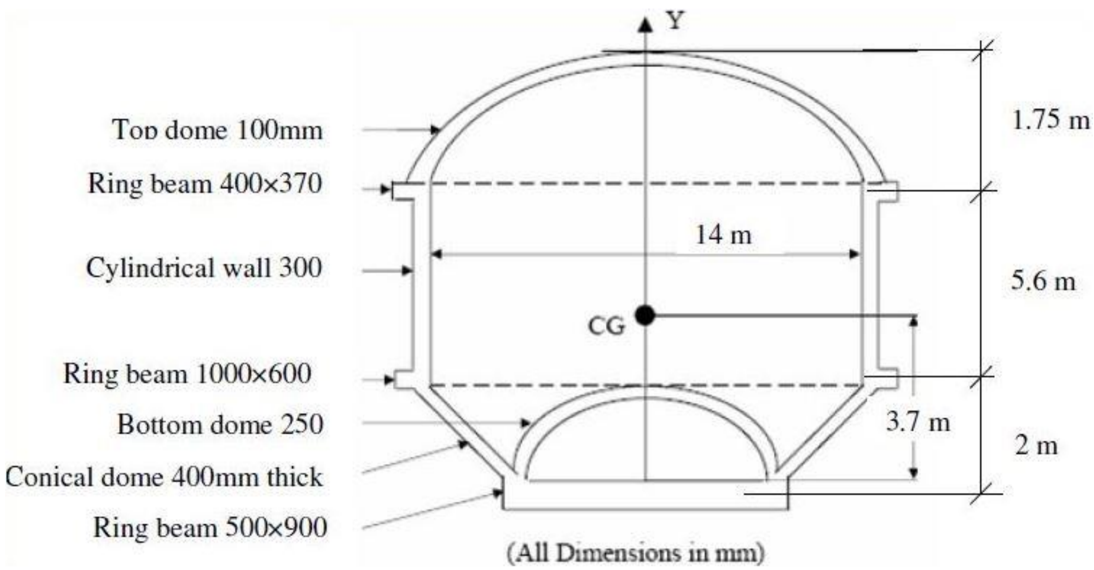

Figure 1 Container parameters in frame staging tank

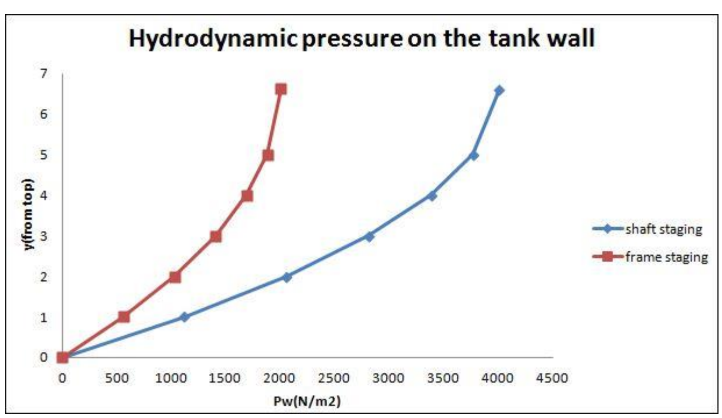

Figure 2 Hydrodynamic pressures on the tank wall (Lumped Mass Modal)

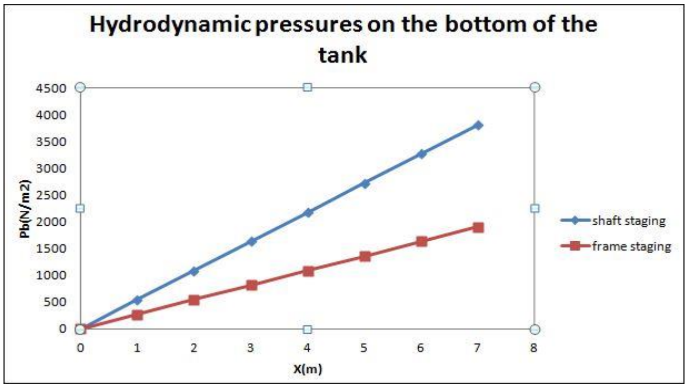

Figure 3 Hydrodynamic pressures on the bottom of tank (Lumped Mass Modal)

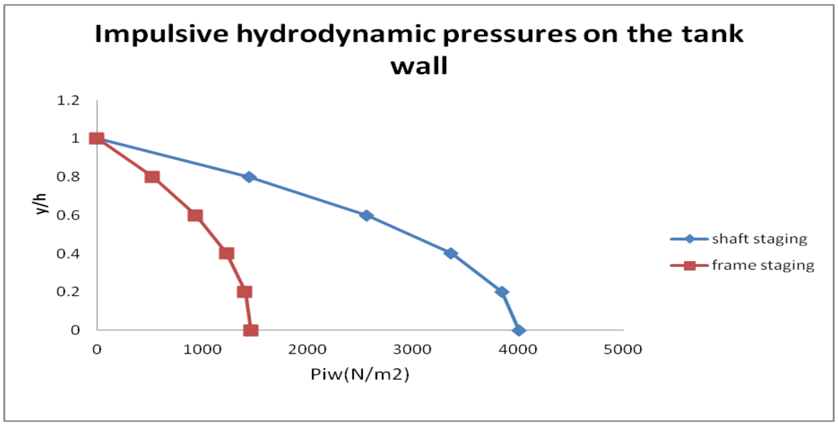

Figure 4 Impulsive Hydrodynamic pressures on the tank wall (Two Mass Modal)

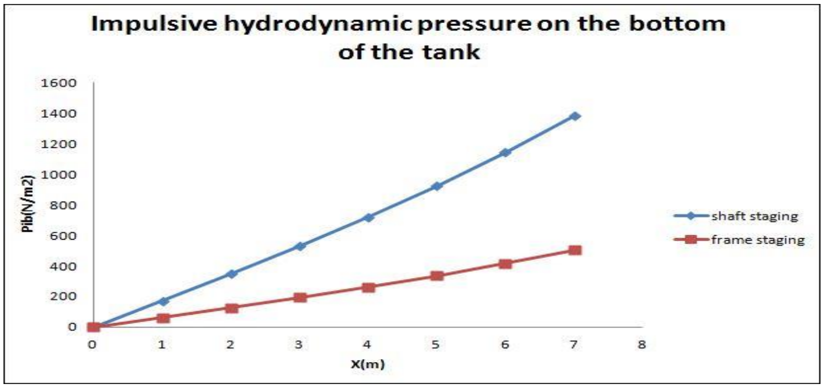

Figure 5 Impulsive Hydrodynamic pressures on the bottom of tank (Two Mass Modal)

Table 1 Preliminary Data

Component		Size (mm)
Top Dome	-	100 thick
Top Ring Beam B1	-	370×400
Cylindrical Wall	-	300 thick
Bottom Ring Beam B3	-	1000×600
Conical dome	-	400 thick
Bottom dome	-	250 thick
Circular Ring Beam B2	-	500×900
Column	-	800mm dia
Bracing	-	300×600

Table 2 Weight calculation frame staging tank

Component	Calculation	Weight kN
Top Dome	$2\pi R_1 \times h_1 \times t \times 25$ 2π×14.875×1.75×0.1×25	408.690625
Top Ring Beam B1	π ×(14+0.4) ×0.4×0.37×25	167.2992
Cylindrical Wall	π ×14.3×0.3×5.6×25	1885.884
Bottom Ring Beam B3	π ×(14+1)×1×0.6×25	706.5
Conical dome	π×[(14+10)/2] ×2.8×0.4×25	1055.04
Bottom Dome	2 × π × 8.02×1.75 × 0.25×25	550.87375
Circular Ring Beam B2	π ×10 ×0.9 ×0.5 ×25	353.25
Column	$\pi/4 \times (0.8)^2 \times 16 \times 12 \times 25$	2411.52
Bracing	0.3×0.6×2.588×12×4×25	559.0008

Table 3 Preliminary Data

Component	Size (mm)
Top Dome	- 100 thick
Top Ring Beam B1	- 370×400
Cylindrical Wall	- 300 thick
Bottom Ring Beam B3	- 1000×600
Conical dome	- 400 thick
Bottom dome	- 250 thick
Circular Ring Beam B2	- 400×600
Shaft Staging	- 220 thick.

Table 4 Weight calculation shaft staging tank

Component	Calculation	Weight KN
Top Dome	$2\pi R_1 \times h_1 \times t \times 25$ $2\pi \times 14.875 \times 1.75 \times 0.1 \times 2$	408.690
Top Ring Beam B1	$\pi \times (14+0.4) \times 0.4 \times 0.37 \times 25$	167.2992
Cylindrical Wall	$\pi \times 14.3 \times 0.3 \times 5.6 \times 25$	1885.884
Bottom Ring Beam B3	$\pi \times (14+1) \times 1 \times 0.6 \times 25$	706.50
Conical dome	$\pi \times [(14+10)/2] \times 2.8 \times 0.4 \times 25$	1055.04
Bottom Dome	$2 \times \pi \times 8.02 \times 1.75 \times$	550.8737
Circular Ring Beam B2	$\pi \times 10 \times 0.6 \times 0.4 \times 25$	188.4
Shaft Staging	$\pi \times 10 \times 0.22 \times 16 \times 25$	2763.2

Table 5 Comparison of Seismic Analysis Parameter of Intze Tank Supported On Frame Staging and Shaft Staging

S.No	Component	Frame staging	Shaft staging
A	Lateral Stiffness (K_S)	50787.202 kN/m	1.41×10^6 kN/m
B	**lumped mass modal**		

1	Time period (a) tank is empty (b) tank is full	0.695 sec 1.129 sec	0.129 sec 0.212 sec.
2	Base shear (a) tank is empty (b) tank is full	321.17 kN 604.01 kN	441.28 kN 1190.47 kN
3	Hydrodynamics pressure on the wall	2003.5 N/m^2	4007.78 N/m^2
4	Hydrodynamics pressure on the base	1905.19 N/m^2	3810.38 N/m^2

Table 6 Comparison of Seismic Analysis Parameter of Intze Tank Supported On Frame Staging and Shaft Staging in Two mass modal.

S.No	**Two mass modal**		
1	Time period (a) impulsive mode (b) convective mode	1.095 sec 4.0 sec.	0.208 sec 4.0 sec
2	Base shear (a) impulsive mode (b) convective mode (c)total base shear	415.3 kN 59.11 kN 419.48kN	1580.17 Kn 82.10 kN 1582.30kN
3	Overturning moment (a) impulsive mode (b) convective mode	8631.17 kN-m 1288.21 kN-m	32840.72 kN-m 1789.18 kN-m
4	Hydrodynamics pressure on the wall (a) impulsive mode (b) convective mode	0 (Top) 1462.31 N/m^2 (Bottom) 666.26 N/m^2 (Top) 227.57 N/m^2 (Bottom)	0 (Top) 4006.06 N/m^2 (Bottom) 666.26 N/m^2 (Top) 227.57 N/m^2 (Bottom)
5	Hydrodynamics pressure on the base (a) impulsive mode (b) convective mode	0 (at centre) 504.36 N/m^2 (at wall) 0 (at centre) 226.56 N/m^2 (at wall)	0 (at centre) 1381.73 (at wall) 0 (at centre) 226.56 N/m^2 (at wall)
6	Pressure due to wall Inertia	205.32 N/m^2	562.5 N/m^2

7	Pressure due to vertical excitation	0 (Top) 3246.22N/m^2 (Bottom)	0 (Top) 3246.22N/m^2 (Bottom)

Table 7 Ductility of frame staging and shaft staging

S.No	Staging type	Ductility
1	Frame	6.65
2	Shaft	3.12