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Research Article

Seismic Performance Evaluation of Reinforced Concrete Elevated Intze Tank Using Non Linear Time History Analysis

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Abstract

Elevated Reinforced Concrete Intze tanks play a crucial role in water supply infrastructure and are expected to run effectively during and after seismic events. The observations from pervious earthquakes indicate that these structures are highly vulnerable to damage due to flexibility of their staging systems, the substantial mass of stored water, and the complex interaction between fluid and the structure. This thesis investigates the seismic response of an RC elevated Intze tank through non linear time history analysis (NLTHA). A detailed three-dimensional finite element model is developed using SAP 2000, in which the impulsive and convective components of liquid masses are also modeled. Appropriate earthquake ground motion records are selected, scaled and applied to evaluate the dynamic response of Intze tanks with different capacity (300 cum, 600 cum and 1000 cum) for three tank fill conditions (empty, half filled and full filled). The performance of the tank is assessed based on parameter displacement response. The vulnerability of the tank is assessed through fragility curves obtained from the data of incremental non linear time history analysis. The study concludes that the seismic vulnerability of RC Elevated Intze tanks increases with increase in storage capacity and volume of water stored in the tank at the time of seismic event.

Keywords: intze tank, vulnerability, fragility curves, seismic performance

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Introduction

Nepal, lying along the boundary of Indian and Eurasian tectonic plates, is located in one of the most earthquake-prone areas in the world Mishra and Thing (2019). Because of this geological condition, Nepal is highly vulnerable to moderate and large earthquakes (Bilham, 2004). Historical records and geological studies clearly show that Nepal has experienced many destructive earthquakes in the past. These earthquakes have caused huge loss of life, serious damage to buildings and infrastructure, and long-term social and economic problems across the country (Pandey et al., 1995; Aryal & Mishra, 2021).

Among all types of infrastructure, water supply systems are the most important because they directly affect public health, sanitation, firefighting activities, and recovery after disasters. When water supply systems fail during earthquakes, the overall impact of the disaster worsens. The scarcity of clean water can lead to epidemics, make rescue and emergency operations more difficult, and delays rehabilitation and reconstruction work (United Nations Office for Disaster Risk Reduction [UNDRR], 2022). In Nepal, where many urban and semi-urban areas already face serious water shortages, ensuring the seismic safety and reliability of water supply systems becomes even more critical (Bhattarai & Mishra, 2017).

Elevated water tanks play a vital role in water distribution systems by storing water and maintaining pressure within the network. They allow water to be supplied by gravity, which is especially useful during emergencies when electricity-dependent pumping systems may stop working (Jain & Sameer, 1990). Therefore, the seismic performance of elevated water tanks directly affects the responses of communities to earthquakes and recover after the earthquakes.

Elevated water tanks are key components of municipal water supply systems. Their main functions are to store treated water, maintain sufficient pressure in the distribution network and ensure a continuous water supply during times of high demand. As many parts of Nepal have difficult terrain and have unreliable electricity supply, these tanks are very useful in such areas. Structurally, an elevated water tank consists of a water storage container supported by a staging system made up of columns, beams, and bracing members. The container can be constructed in different shapes, such as cylindrical, rectangular, spherical, conical, or Intze types, depending on storage needs, design preferences, and construction practices. The dynamic response of an elevated tank during an earthquake is greatly affected by the height and arrangement of the staging system (Jain & Sameer, 1990; Mishra and Jha, 2019).

The elevated water tanks are classified as lifeline structures (Bureau of Indian Standards, 2014). Unlike ordinary buildings, which are mainly designed to prevent collapse and protect human life, lifeline structures are expected to remain operational even after strong earthquakes. During and after an earthquake, the elevated water tanks should suffer very little damage, avoid water leakage and maintain their structural strength for uninterrupted water supply. However, evidences from past earthquakes around the world show that elevated water tanks are highly vulnerable to earthquake damage. Observed failures range from minor cracking and water leakage to complete collapse, causing serious disruption to water supply systems (Rai, 2002). These observations suggest that there is a need for careful seismic analysis and specialized design methods for elevated water tanks.

The Intze type tank is a modified form of a circular tank that was developed to reduce hoop tension and bending moments in the structure. It consists of a top dome, a cylindrical wall, a conical shell, and a bottom spherical dome, all supported on a ring beam. Intze tanks are economical and efficient for large storage capacities. They are widely used in many parts of the world. Their structural configuration allows effective load transfer and reduced internal stresses (Punmia et al., 2017). However, due to the elevated mass of water, Intze tanks are highly sensitive to seismic forces and require careful design of the staging system. In addition, their complex geometry, detailing requirements, and need for skilled construction practices increase both the difficulty and cost of construction. The major structural components of an Intze tank include top dome, cylindrical wall, conical shell, top and bottom ring beams, bottom spherical dome and staging system.

Seismic analysis of elevated water tanks is more complex than that of normal buildings because of their special loading conditions and dynamic behavior. In normal buildings, the dead loads remain constant and live loads change only slightly. However, in water tanks, there is a large variation in gravity loads depending upon the quantity of water stored in the tank. Tanks may be empty, partially filled, or fully filled at different times during operation. Each water level changes the total weight, mass distribution, center of gravity and stiffness of the structure, resulting in changes in seismic responses (Chopra, 2017). In addition, the fluid – structure interaction makes the analysis more complicated. During an earthquake, not all the water moves together with the tank. Instead, the water motion is classified into two parts: impulsive and convective components (Housner, 1963). The impulsive part moves with the tank walls, while the convective part represents the sloshing motion of water. For accurately assessing seismic response of the tank, these fluid-structure interaction effects shall be precisely and rationally considered (Bureau of Indian Standards, 2014).

There are various factors affecting the seismic performance of elevated water tanks. The most important factors are structural configuration and supporting system. Other factors include tank shape, storage capacity, height of staging, column layout, bracing pattern, material properties, and foundation conditions (Jain & Sameer, 1990). Taller staging systems usually increases the flexibility of the structure and increase its natural period of vibration, which can lead to larger horizontal displacements during earthquakes. The arrangement of columns and bracing elements is critical for providing enough lateral stiffness and properly distributing seismic forces. Twisting effects and stress concentration may arise due to poor bracing or irregular column layouts, increasing the risk of structural failure. Foundation conditions, such as soil type, bearing capacity, and soil–structure interaction, also have a major influence on the seismic response of elevated water tanks. (Chopra, 2017)

Problem Statement

Despite their importance, very limited level of research attention has been given to elevated RCC Intze tanks as compared to conventional building structures, particularly under nonlinear seismic loading conditions. In many existing design practices, simplified methods such as equivalent static force method or linear response spectrum methods are still used to perform the seismic analysis of water tanks. Although these methods are useful at the preliminary design stage, they are based on linear assumptions and simplified models of structural behavior. As a result, the actual response of Intze tanks may not be represented accurately during strong earthquakes. These simplified methods often fail to assess nonlinear material behavior, loss of stiffness, energy dissipation, and the time-dependent fluid - structure interaction.

Nonlinear time history analysis is the most effective method to realistically assess the seismic behavior of elevated Intze tanks. This method allows consideration of nonlinear material behavior, flexibility of the staging system, and dynamic fluid–structure interaction using real or simulated earthquake ground motion records. A more realistic and accurate evaluation of seismic demand and structural performance can be achieved by using nonlinear time history analysis.

Therefore, the present study is important for properly assessing the seismic response of an elevated Intze tank. The analysis and design process may lead to uneconomical solutions or increased risk of damage and collapse without accurately predicting the true behavior of the tank during earthquake events. Hence, the use of nonlinear time history analysis is essential for achieving safe, reliable, and cost-effective designs of elevated RCC Intze tanks.

Research Objective

The objective of this research is to evaluate the seismic performance and vulnerability of elevated RC Intze tanks having different storage capacities for different tank fill conditions.

Methodology

The methodology adopted for this study consisted of several sequential steps similar to (Mishra & Magar, 2017). First, an extensive survey and review of relevant literature, research articles, and applicable codal provisions related to elevated Intze water tanks were carried out to establish the theoretical background and identify research gaps. Subsequently, the Intze water tank models were developed and modeled using SAP2000 software based on the selected geometric and structural parameters. After modeling, nonlinear time history analyses were performed in SAP2000 to evaluate the dynamic response and seismic behavior of the tanks under different earthquake ground motions. Finally, fragility curves were developed from the analytical results to assess the seismic vulnerability and probability of damage of the Intze tanks under varying levels of seismic intensity.

Literature Review

Patel and Dashore (2017) investigated the seismic behavior of elevated RCC water tanks with square and circular shapes and different storage capacities. They compared lateral displacement and base shear for various staging heights and seismic zone factors. The study found that circular water tanks show greater flexibility under seismic loading compared to square tanks. It was also observed that response parameters such as deflection and base shear increase as the seismic zone changes from lower to higher intensity zones, because earthquake forces are stronger in higher seismic zones.

More and Mor (2017) carried out a dynamic analysis of elevated water tanks based on (Bureau of Indian Standards, 2014). They compared tanks with different supporting systems, storage capacities, and seismic zones and observed that these factors significantly influence the seismic response of water tanks. The base shear of tanks supported on concrete shafts was found to be higher than that of tanks supported on framed staging systems. Due to this higher base shear, shaft-supported tanks were considered more vulnerable than frame-supported tanks in regions with high seismic intensity. The time period in the impulsive mode showed noticeable differences between shaft-supported and frame-supported tanks, whereas the difference in the convective mode time period was relatively small. The study also showed that staging deflection decreases as tank capacity increases and as the staging configuration changes, resulting in increased stiffness. Sloshing wave height was found to be nearly the same for different support systems but increased as tank capacity increased.

Bhojani et al. (2016) compared the seismic performance of elevated square and circular water tanks with the same storage capacity. The study also examined the effect of providing diagonal bracing to stiffen the staging system. Seismic performance was evaluated using various analysis methods, including linear static analysis, modal analysis, response spectrum analysis, nonlinear time history analysis, and pushover analysis. The results showed that lateral displacement was significantly reduced when bracing was provided in the staging system. This reduction indicated that braced structures are safer, as they undergo less deformation under the same earthquake loading. Similarly, bending moments in structural members were found to decrease considerably due to the addition of bracing. Based on these results, the study concluded that braced staging systems perform better and are more economical than unbraced staging systems.

Harsha et al. (2015) designed an Intze-type water tank according to (Bureau of Indian Standards, 2014) using a two-mass model that includes both impulsive and convective vibration modes. By comparing the results of impulsive and convective modes, they observed that the time period, base shear, and base moment obtained from the convective mode were greater than those from the impulsive mode. The total base shear and base moment were higher when the tank was full than when it was empty, and therefore the full tank condition was considered critical for seismic analysis. The study also found that base shear and overturning moment values obtained from the two-mass model were higher than those obtained from the lumped mass model. Based on these findings, the authors concluded that elevated water tanks should be analyzed using a two-degree-of-freedom model instead of a single-degree-of-freedom model when convective effects are considered.

Hirde et al. (2011) studied the effect of staging height on the seismic behavior of elevated water tanks supported on framed staging systems. Their analysis included modeling of both impulsive and convective water masses for different seismic zones and soil conditions. The results showed that the lateral stiffness of the staging system decreases as the height of the staging increases. As staging height increases, the natural time period also increases. For the full tank condition, base shear was found to decrease with increasing staging height, while base moment increased with increasing staging height for both full and empty tank conditions.

Patil and Bhalchandra (2014) examined the seismic performance of elevated water tanks across different seismic zones in India by varying staging height and staging configuration. They noted that most earthquake-related damage to water tanks occurs due to limited understanding of staging behavior and improper selection and design of the supporting system. A total of 27 different tank configurations were analyzed using the Response Spectrum Method in SAP2000 software, considering a two-mass idealization. Tank responses such as base shear, overturning moment, and roof displacement were studied. The results showed that radial staging configurations provide greater stiffness than cross and normal configurations. Although base shear was higher in radial configurations, roof displacement was lower for all seismic zones. Based on these findings, the authors concluded that radial staging configurations provide better overall seismic performance.

Jain and Sameer (1990) investigated the seismic response of reinforced concrete elevated water tanks with different staging patterns and earthquake characteristics. Tanks with square, circular, and rectangular staging layouts were analyzed under various seismic excitations. The study evaluated parameters such as base shear, overturning moment, lateral displacement, and bending stress at critical locations. The results showed that the staging pattern has a strong influence on seismic performance, with circular and square staging providing better lateral stability and more uniform stress distribution than rectangular staging. Tanks with taller and more slender staging experienced larger displacements and higher bending moments, indicating greater vulnerability. The study also showed that earthquake characteristics such as peak ground acceleration, frequency content, and duration significantly affect tank response, especially impulsive forces. Convective effects were found to have less influence on base shear but affected dynamic properties such as the natural time period.

Moslemi et al. (2011) studied the seismic behavior of liquid-filled elevated tanks by focusing on both the structural response of the staging system and fluid–structure interaction effects. Finite element modeling and modal analysis were used to analyze RC elevated tanks under different earthquake excitations, considering both impulsive and convective liquid modes. The results showed that the staging system controls the overall seismic response, with taller and more flexible staging systems experiencing larger lateral displacements, higher bending moments, and increased base shear. The impulsive liquid component mainly contributed to base shear and overturning moments, while the convective component influenced long-period vibrations and caused additional dynamic pressures on tank walls. The interaction between the liquid and tank structure was found to significantly change the natural frequencies, especially in slender tanks, affecting resonance behavior. Tanks with insufficient bracing or poor ductile detailing were found to be highly vulnerable to seismic damage.

Hirde et al. (2011) analyzed the seismic performance of elevated RCC water tanks using analytical procedures based on IS 1893. The study adopted a two-mass idealization to represent impulsive and convective liquid components and examined the effects of staging height, staging configuration, and seismic zone. The results showed that the staging system largely governs the seismic response, with taller and more flexible staging systems leading to increased lateral displacement and higher stresses at column bases and beam–column joints. The impulsive mass was identified as the main contributor to seismic forces, while convective effects mainly influenced vibration periods. The authors concluded that many existing water tanks are vulnerable to earthquakes due to inadequate stiffness, bracing, and detailing. They also found that earthquake forces increase with higher zone factors for all soil types and tank conditions. Soft soil conditions produced the highest earthquake forces, while hard soil produced the lowest, with soft soil forces being about 40–41% higher than those for hard soil.

The dynamic analysis of elevated water tanks was first proposed by Housner (1963), who developed one of the earliest models that emphasized the need to consider the tank and the stored water as one complete structural system. His study highlighted that the mass of water inside the tank has a major influence on how the structure responds during earthquakes. Housner demonstrated that when tanks have flexible containers and staging systems, relying on simplified static analysis methods can give unsafe results, especially when the structure is subjected to seismic forces.

Finite element studies carried out by Dutta et al. (2000) further supported the use of shell models by showing that they provide a better representation of both membrane stresses and bending stresses, especially in the conical shell and bottom dome regions. These regions experience significant stress variations during lateral dynamic loading caused by earthquakes. Their findings challenged the common assumption that tank containers behave as rigid bodies, particularly in medium to large capacity tanks where the shell structure is relatively flexible.

Livaoglu and Dogangun (2006) performed finite element analyses in which shell elements were used to model the tank container and beam elements were used to model the staging system. Their research showed that accurately modeling staging columns and bracing members with appropriate element types leads to better prediction of overall structural response parameters, such as base shear and overturning moment.

Spring Mass Model for Seismic Analysis (IS 1893 Part 2, 2014)

When a tank containing liquid with a free surface is subjected to horizontal earthquake ground motion, tank wall and liquid are subjected to horizontal acceleration. The liquid in the lower region of tank behaves like a mass that is rigidly connected to tank wall. This mass is termed as impulsive mass which accelerated along with the wall and induces impulsive hydrodynamic pressure on tank wall and similarly on base. Liquid mass in upper region of tank undergoes sloshing motion. This mass is termed as convective liquid mass and it exerts convective hydrodynamic pressure on tank all and base. Thus, the total liquid mass gets divided into two parts i.e. impulsive mass and convective mass. In spring mass model of tank-liquid system, these two liquid masses are to be suitably represented. The parameters of spring mass model depend on geometry of the tank. The representation of impulsive and convective liquid masses is explained by (Bureau of Indian Standards, 2014).

Limit States of Performance (Prestandard and Commentary for the Seismic Rehabilitation of Buildings, FEMA, 2000)

Performance-based seismic design (PBSD) is now widely used around the world to evaluate how buildings and structures behave during earthquakes. Instead of just following fixed code equations like traditional force-based design, PBSD lets engineers decide in advance how well a structure should perform under different levels of earthquake shaking.

This approach measures expected damage and links it to clear performance goals, called performance levels. Common levels include Immediate Occupancy, Life Safety and Collapse Prevention.

These ideas first became popular through seismic guidelines such as FEMA 356: Prestandard and Commentary for the Seismic Rehabilitation of Buildings, published by Federal Emergency Management Agency (FEMA) , and have continued to develop and improve over time.

FEMA 356 defines discrete performance levels for structural and non structural systems based on observed or predicted damage. At the core are three major limit states:

- **Immediate Occupancy (IO) :** This level of performance represents minor structural damage and little to no interruption after an earthquake. The acceptable drift limit is 1% transient and negligible permanent. This implies the structure remains essentially operational, with minor localized cracking or serviceability issues.

- **Life Safety (LS):** This level of performance represents permissible significant structural and non structural damages, but overall structural stability is preserved. Repairs may be needed before reuse. The acceptable drift limit is 2% transient and 1% permanent.
- **Collapse Prevention (CP):** This level of performance represents threshold before catastrophic collapse. It is often characterized by extensive cracking and hinge formation in ductile elements, limited cracking in some non ductile columns, severe damage in short columns, extensive spalling in columns and beams, severe joint damage and buckling of some reinforcement. The acceptable drift limit is 4% transient or permanent.

Fragility Curve

A fragility curve is a probabilistic tool used in earthquake engineering to express the likelihood that a structure will reach or exceed a specific damage or performance limit state under a given level of seismic intensity. In simple terms, it relates earthquake severity to structural damage probability. For reinforced concrete elevated Intze tanks, fragility curve represents the probability of exceeding different performance limit states such as Immediate Occupancy, Life Safety or Collapse prevention, as a function of an intensity measure, which can typically be Peak Ground Acceleration (PGA), Spectral Acceleration (Sa) or Peak Ground Velocity (PGV) (Lallemant et al., 2015). Intze tanks being liquid containing structures, their seismic response is strongly influenced by fluid structure interaction, convective and impulsive water masses, staging flexibility and tank fill conditions. Fragility curves capture these uncertainties in a quantitative and probabilistic manner, rather than relying solely on deterministic code checks (Mai et al., 2014).

Fragility curves are most commonly modelled using a lognormal cumulative distribution function (CDF). In the present study, the intensity measure of earthquake is taken as Peak Ground Acceleration (PGA). Hence, for the present study, the fragility curve is modeled as a lognormal cumulative distribution function as follows:

$$P\,(DS > dsi|PGA) = \varnothing \; \frac{\text{In}\,(PGA) - \text{In}\,(\mu_{PGA,i})}{\beta_i}$$

Where,

- $\varnothing(.)$ is standard normal cumulative distribution function
- μ_(PGA,i) is median value of PGA at which structure reaches limit state ds_i
- β_i is logarithmic standard deviation (dispersion) representing uncertainty.

The relationship between drift and PGA can be derived using log-linear relationship as

$$\text{In}\,(Drift) = a \ln\,(PGA) + b$$

Where,

- a and b are correlation constants
- Comparing the above equation with y=ax+b,

The values of a and b are calculated as follows:

$$a = \frac{(n\Sigma xy - (\Sigma x)\,(\Sigma y)}{n\Sigma x^2 - ((\Sigma x)^2)}$$

$$a = \frac{((\Sigma y)(\Sigma x^2) - (\Sigma x)\,(\Sigma xy))}{n\Sigma x^2 - ((\Sigma x)^2)}$$

RC Intze Tank Description

For the study, Reinforced Concrete Intze tanks of three different capacities viz. 300 cum, 600 cum and 1000 cum are considered. The design data is collected through Department of Water Supply and Sewerage Management, Panipokhari, Kathmandu, referring to the project, " Type Design and Optimization of RCC Elevated Water Tanks for Nepal", and the same data is used for the dynamic non linear seismic analyses. data obtained are tabulated below.

Table 1

Design Data of Intze Tank

S.No.	Description	300 cum	600 cum	1000 cum
1	Capacity of tank	300 cum	600 cum	1000 cum
2	Orientation of columns	On edges of a regular hexagon with side 2760 mm	On edges of a regular hexagon with side 3435 mm	On edges of a regular hexagon with side 4110 mm
3	Column size	500 mm X 500 mm	600 mm X 600 mm	750 mm X 750 mm
4	Bracing beam size	400mmx500mm	400mmx500mm	400mmx500mm
5	Bottom ring beam size	500mmX600mm	600mmX800mm	800mmX800mm
6	Bottom dome thickness	300mm	450mm	650mm
7	Bottom dome rise	1000 mm	1200 mm	1700 mm
8	Conical shell thickness	300 mm	450mm	650mm
9	Conical shell height	1840 mm	2300 mm	2800 mm
10	Middle ring beam size	500mm X 300 mm	500mm X 300 mm	700mm X 300 mm
11	Cylindrical shell thickness	200 mm	350 mm	500 mm
12	Cylinder diameter	9200 mm	11450 mm	13700 mm
13	Cylinder height (including 500mm Free Board)	4200 mm	5350 mm	6200 mm
14	Top ring beam size	300mm x 300 mm	400mm x 300 mm	600mm x 300 mm
15	Top dome thickness	100 mm	100 mm	100 mm
16	Top dome rise	2300 mm	2500 mm	2800 mm

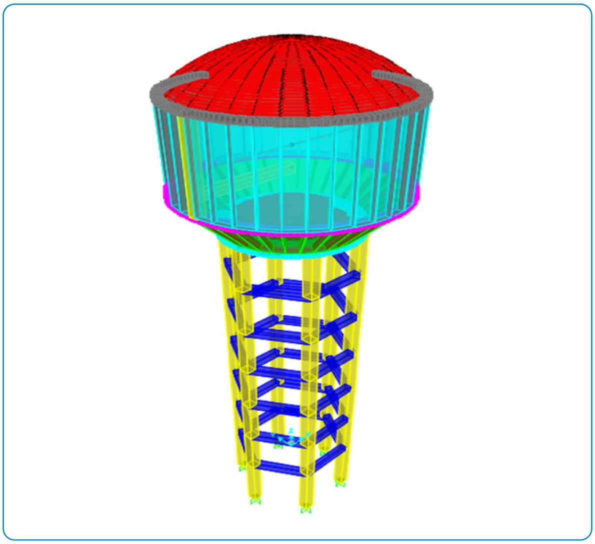
Tank Modelling And Analysis

The Intze tank was modeled and analyzed using SAP 2000 software. The characteristic compressive strength of concrete was considered to be 25 N/mm2, corresponding to M25 grade concrete. For reinforcement, High Yield Strength Deformed Bars (HYSD) were applied with a minimum yield strength of 500 N/mm2.

The foundation of the elevated water tank was assumed to behave as a rigid base, and the effects of soil–structure interaction were not included. The numerical model included only the main structural components responsible for carrying loads. These components consisted of the supporting columns, bottom, middle, and top ring beams, bottom dome, conical shell, cylindrical wall, and the top dome. Secondary and non-structural elements such as staircases, access ladders, walkways, galleries, and railings were excluded from the analysis. The supporting columns and bracing members were represented using two-node frame elements capable of resisting axial forces, shear forces, and bending moments. Similarly, the bottom, middle, and top ring beams were also modeled as frame elements to simulate their load-carrying behavior. The tank container components, including the bottom dome, conical shell, cylindrical wall, and top dome, were modeled using thin shell elements to realistically represent both membrane and bending actions.

Figure 1

SAP 2000 Model for 600 cum Full Filled RC Elevated Intze Tank



The water was modeled according to (Bureau of Indian Standards, 2014) – Criteria for Earthquake Resistant Design of Structures: Liquid Retaining Tanks, in which the liquid mas is divided into impulsive and convective components. The impulsive mass was treated as being rigidly attached to the tank structure and modeled as a lumped mass connected to the tank wall with a very rigid massless frame. The convective mass, which affects the sloshing effect, was modeled as a lumped mass connected to the tank through a horizontal linear spring with stiffness as calculated.

Material non linearity was introduced through non linear concrete constitutive models accounting for cracking in tension and crushing in compression, plastic hinge formation in column and braces, yielding of reinforcement under cyclic loading. To account the material non linearity, plastic hinges were assigned at critical locations such as column bases, column-brace junctions, ring beam-column connections. For a tank with slender staging columns with high center of mass, geometric non linearity arising from P- delta effects was considered in the analysis.

Non linear time history analysis required real earthquake acceleration records. The ground motions referred for this study were selected from the available ground motion records for El Centro Earthquake (1940) with PGA 0.31882g, Kobe earthquake(1995) with PGA 0.509 and LACC_NOR-1 with PGA 0.2215g, which is available in SAP2000. The ground motion records were scaled before being applied at the base of the structure in the horizontal direction.

The same ground motion records scaled for 0.1g to 1g and the incremental records were applied for all Intze tanks i.e. 300 cum capacity, 600 cum capacity and 1000 cum capacity, and for all tank fill conditions. The non linear time history analysis was performed in SAP 2000 using the direct integration method. Appropriate time step size was selected to ensure numerical stability and accuracy of results. Damping was incorporated using Rayleigh damping to represent energy dissipation in both the structure and the contained water. Different damping rations were considered for impulsive and convective modes to realistically model the dynamic response. An incremental non linear time history analysis was carried out with incremental steps of 0.1g from 0.1g to 1g for each earthquake. The analysis was carried out by applying the processed ground motion records over the entire duration of the earthquake, allowing the structure to respond in the non linear range. The results obtained from the non linear time history analysis included time histories of displacement of highest point of the top dome. The peak displacement of highest point of the top dome was determined for each incremental peak ground acceleration and used for the development of fragility curves.

Results and Discussion

Results From Displacement of Top of the Tank

The values of peak displacement of top of the tank were extracted from incremental non linear time history analysis. The peak displacements were extracted for each tanks with all tank fill conditions under three selected earthquakes, increasing the PGA from 0.1g to 1g. The peak displacement of top of the tank for Kobe Earthquake are tabulated here.

Table 2

Peak Displacement of top of the tank for Kobe Earthquake

PGA (g)	Peak Displacement of the top of the tank (mm)								
	Empty			Half filled			Full filled		
	300	600	1000	300	600	1000	300	600	1000
0.1	41.418	41.587	46.395	42.063	47.625	57.312	54.762	61.466	74.672
0.2	78.156	86.853	96.228	79.95	97.533	115.078	85.706	119.009	119.899
0.3	105.255	106.359	128.977	107.884	136.118	151.172	114.462	164.245	171.08
0.4	139.438	135.769	166.766	140.351	187.13	211.614	163.603	199.872	233.293
0.5	170.884	178.518	222.778	171.892	234.476	254.777	210.668	253.799	278.649
0.6	204.871	210.782	285.266	205.891	245.278	299.822	260.619	289.566	337.033
0.7	245.083	256.96	325.381	249.616	299.992	350.001	308.409	339.329	382.506
0.8	292.32	336.234	372.389	298.09	355.235	390.666	342.534	397.033	412.026
0.9	344.03	384.037	392.716	347.887	412.279	446.336	362.391	453.582	476.766
1	396.971	435.224	448.051	401.598	469.349	502.813	417.255	510	547.557

From the above data, a graph of Peak displacement of top of the tank vs PGA was plotted.

Figure 2

Peak Displacement of Top of the Tank vs PGA for 300 Cum Tank Under Kobe Earthquake

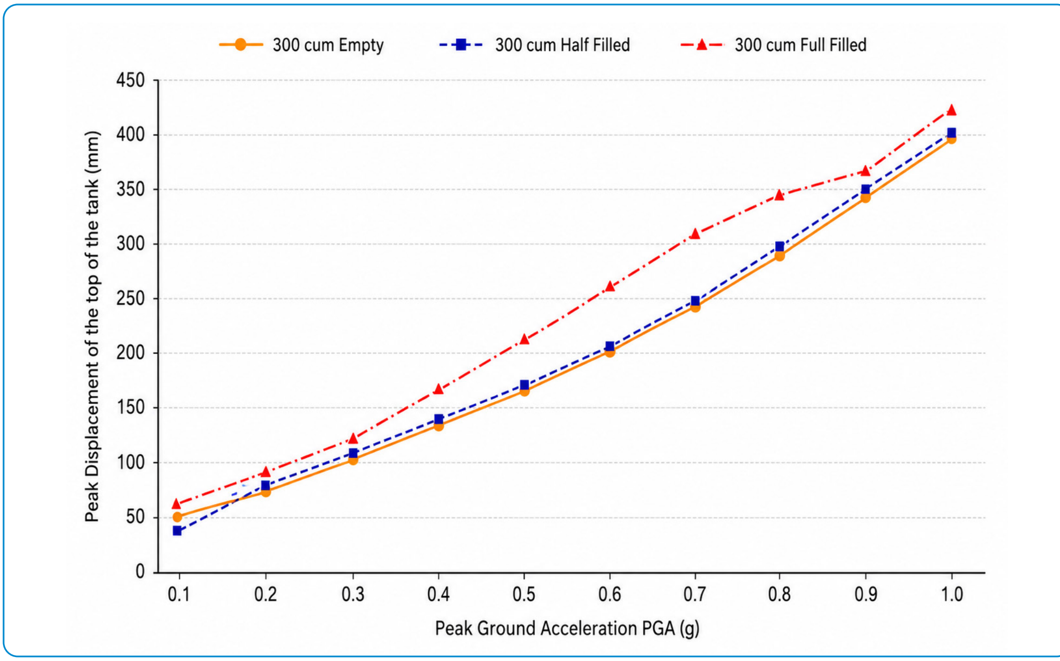


Figure 3

Peak Displacement of Top of the Tank vs PGA for 600 cum tank under Kobe Earthquake

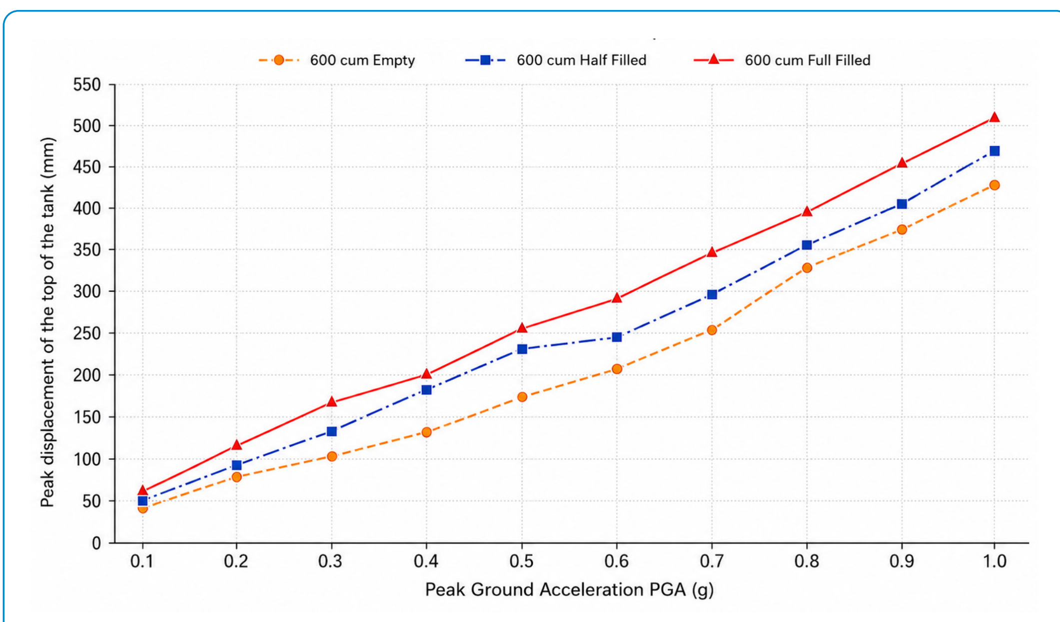
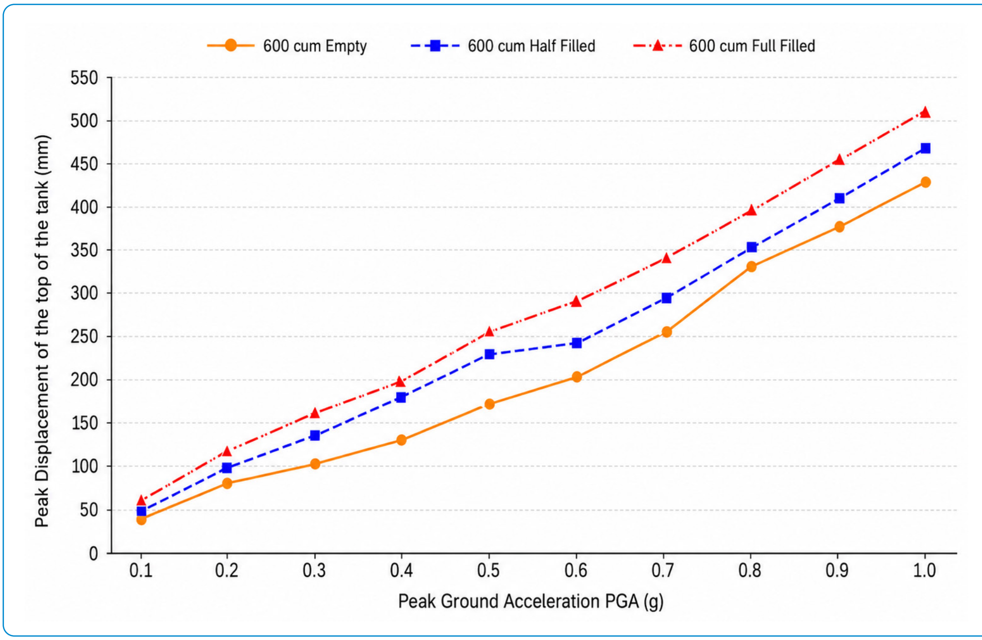


Figure 4

Peak Displacement of Top of the Tank vs PGA for 1000 Cum Tank Under Kobe Earthquake



These graphs for all capacity tanks clearly indicated a non linear increase in peak top displacement with increasing PGA. At lower PGA levels, the displacement response increased almost linearly, suggesting that the tanks remained largely within elastic range. As PGA increased, a sharp increase in displacement was observed, indicating the stiffness degradation cracking of reinforced concrete components and amplification of dynamic response. Among the three tank capacities, the 1000 cum tank was found to exhibit the highest vulnerability, followed by the 600 cum tank, while 300 cum tank showed comparatively lower vulnerability across all conditions. Larger tanks possessed higher total mass and longer natural time periods, which resulted in greater lateral flexibility and amplified displacement demand under strong ground motion. The 300 cum tank, being relatively lighter and stiffer, attracted lower seismic inertial forces and showed smaller peak top displacement. The 600 cum tank exhibited moderate vulnerability, acting as a transitional case between the smaller and larger tanks. The 1000 cum tank, due to its greater height, larger container mass, higher mass of water stored and slender staging system, was found to be highly displacement-sensitive and therefore more prone to damage.

Analyzing the tank fill conditions, all tanks showed comparatively lower displacement demand in case of empty condition, due to the absence of hydrodynamic water mass. As the tanks were filled with water, the hydrodynamic mass increased the total seismic inertial mass, resulting into higher values of displacement of top of the tank. So, from the results of peak displacement of top of the tanks, the full filled condition was found the most vulnerable, followed by half filled condition and the empty condition exhibited minimum vulnerability.

Based on the displacement demand curves, the overall vulnerability ranking could be expressed as:

- o Based on tank capacity conditions: 1000 cum tank > 600 cum tank > 300 cum tank
- o Based on tank fill conditions: Full filled tank > Half filled tank > Empty tank

Results From Fragility Curves

Fragility curves were developed for the incremental non linear time history analysis of all capacity tanks (300, 600 and 1000 cum) with three tank fill conditions (empty, half filled and full filled). The peak drift of the top of the tank was extracted from each analysis and tabulated. The tabulated peak drift of top of the 1000 cum tank for Kobe Earthquake is presented below.

Table 3

Peak Drift of Top of the 1000 Cum Tank for Kobe Earthquake

S.No.	PGA	Drift (%)		
			Half Filled	Full Filled
1	0.1g	0.13255714	0.16374857	0.21334857
2	0.2g	0.27493714	0.32879429	0.34256857
3	0.3g	0.36850571	0.43192	0.4888
4	0.4g	0.47647429	0.60461143	0.66655143
5	0.5g	0.63650857	0.72793429	0.79614
6	0.6g	0.81504571	0.85663429	0.96295143
7	0.7g	0.92966	1.00000286	1.09287429
8	0.8g	1.06396857	1.11618857	1.17721714
9	0.9g	1.12204571	1.27524571	1.36218857
10	1g	1.28014571	1.43660857	1.56444857
7	0.7g	0.92966	1.00000286	1.09287429
8	0.8g	1.06396857	1.11618857	1.17721714
9	0.9g	1.12204571	1.27524571	1.36218857
10	1g	1.28014571	1.43660857	1.56444857

From the above table, the median PGA at which the structure reaches various limit states (μ) and logarithmic standard deviation (β) were calculated

Table 4

Values of μ and β for 1000 Cum Tank for Kobe Earthquake

S.N.	Tank Fill Condition	Limit State of Performance	Critical Drift Value (%)	μ	β
1	Empty	Immediate Occupancy (IO)	1%	0.7781	0.0462
		Life Safety (LS)	2%	1.5672	0.0462
		Collapse Prevention (CP)	4%	3.1569	0.0462

S.N.	Tank Fill Condition	Limit State of Performance	Critical Drift Value (%)	μ	β
2	Half Filled	Immediate Occupancy (IO)	1%	0.6983	0.0301
		Life Safety (LS)	2%	1.4726	0.0301
		Collapse Prevention (CP)	4%	3.1058	0.0301
3	Full filled	Immediate Occupancy (IO)	1%	0.6383	0.0496
		Life Safety (LS)	2%	1.4128	0.0496
		Collapse Prevention (CP)	4%	3.1269	0.0496

From the above values of μ and β, cumulative probability distribution function was generated for each tank fill conditions and fragility curves were obtained.for each tank fill conditions and fragility curves were obtained.

Figure 5

Fragility Curve for 1000 Cum RC Elevated Empty Intze tank Under Kobe Earthquake

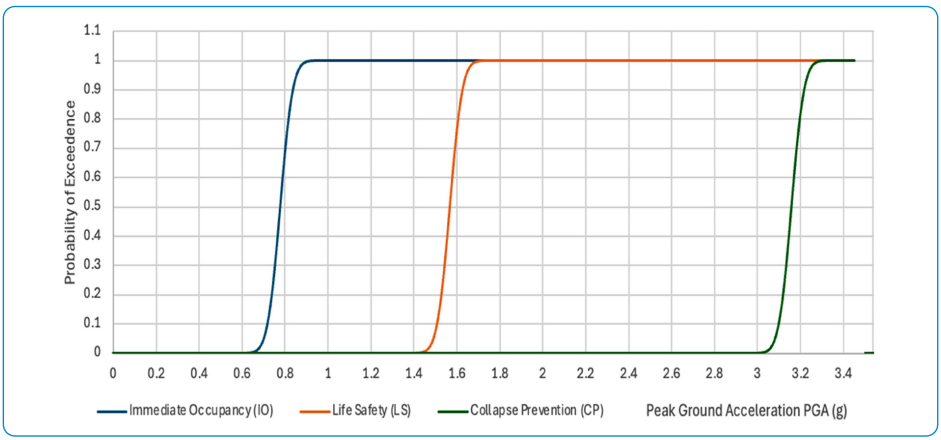


Figure 6

Fragility Curve for 1000 Cum RC Elevated Half Filled Intze Tank Under Kobe Earthquake

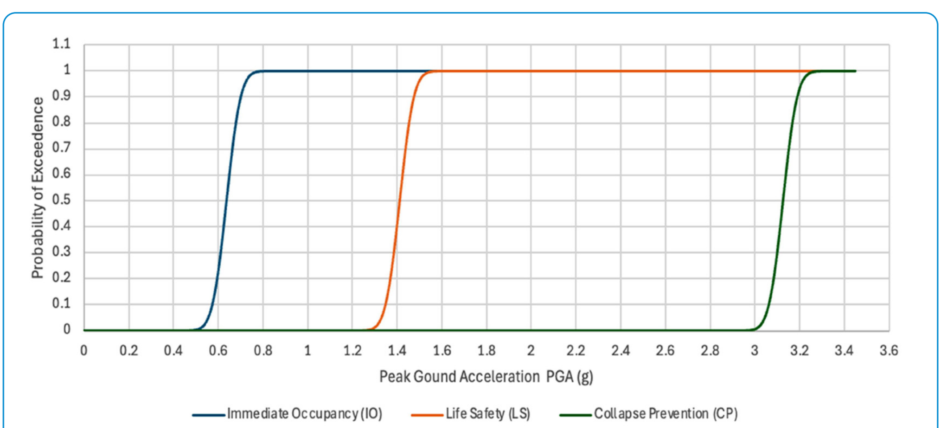
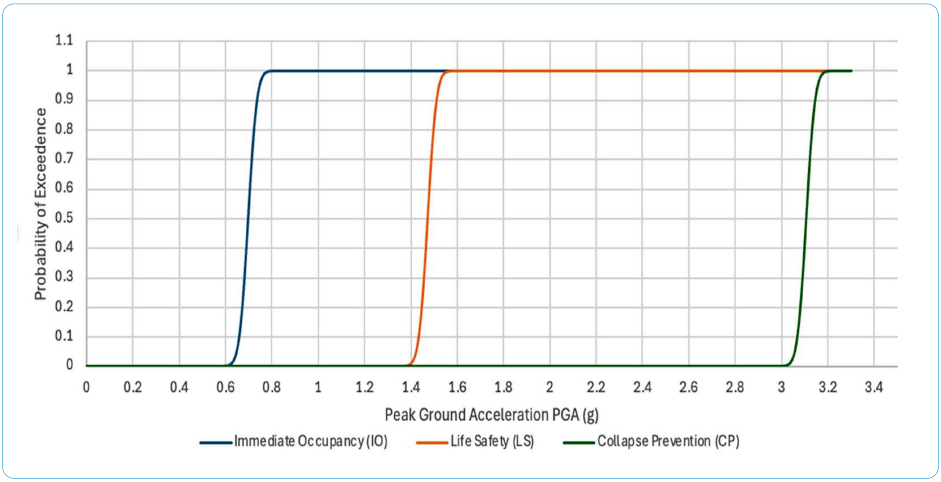


Figure 7

Fragility Curve for 1000 Cum RC Elevated Full Filled Intze Tank under Kobe Earthquake



Analyzing the developed fragility curves for 1000 cum empty tank under Kobe Earthquake, the probability of exceeding Immediate Occupancy level was found to be negligible at PGA values below approximately 0.60g. The 50% probability of exceeding IO was observed at 0.7-0.8g, and the probability of exceeding IO was observed at around 1g. Similarly, the probability of exceeding LS level was found negligible below PGA values 1.4g, 50% probability of exceeding LS being around 1.57g and that of exceeding LS was found to be 1.84g. Also, the probability of exceeding CP level was found negligible below PGA values 3g, 50% probability of exceeding CP being around 3.16g and that of exceeding CP was found to be 3.43g.

Analyzing the developed fragility curves for 1000 cum half filled tank under Kobe Earthquake, the probability of exceeding Immediate Occupancy level was found to be negligible at PGA values below approximately 0.56g. The 50% probability of exceeding IO was observed at around 0.7g, and the probability of exceeding IO was observed at around 0.87g. Similarly, the probability of exceeding LS level was found negligible below PGA values 1.34g, 50% probability of exceeding LS being around 1.47g and that of exceeding LS was found to be 1.64g. Also, the probability of exceeding CP level was found negligible below PGA values 2.8g, 50% probability of exceeding CP being around 3.11g and that of exceeding CP was found to be 3.28g.

Analyzing the developed fragility curves for 1000 cum full filled tank under Kobe Earthquake, the probability of exceeding Immediate Occupancy level was found to be negligible at PGA values below approximately 0.45g. The 50% probability of exceeding IO was observed at around 0.64g, and the probability of exceeding IO was observed at around 0.84g. Similarly, the probability of exceeding LS level was found negligible below PGA values 1.22g, 50% probability of exceeding LS being around 1.40g and that of exceeding LS was found to be 1.62g. Also, the probability of exceeding CP level was found negligible below PGA values 2.7g, 50% probability of exceeding CP being around 3.10g and that of exceeding CP was found to be 3.26g.

A comparative assessment of the three filling conditions revealed that the empty tank condition exhibited the highest seismic resistance, while the full filled condition was the most vulnerable. The half filled condition showed intermediate behavior. It could be observed that the vulnerability of water storage tanks became directly influenced by the level of water stored at the time of an earthquake. The increased vulnerability arose from a complex interaction of hydrodynamic forces, structural flexibility and mass participation. The empty tank condition involved only the self weight of the structural components, resulting in much lower inertial forces. When the tank was full, the entire volume of stored water contributed to the seismic inertia forces generated during ground shaking. Although the half filled condition also included water mass, the total participating mass was lower than that of full filled case. Consequently, the full filled tank experienced the highest base shear demand, making it more susceptible to cracking, yielding and potential instability.

The increased vulnerability could also be described in terms of reduction in structural ductility demand capacity. While RC staging systems were designed to exhibit ductile behavior, the increased axial load due to full water mass significantly reduced the available ductility capacity of columns. High axial compression accelerated the stiffness degradation under cyclic loading. Under full filled conditions, columns experienced combined high axial load and bending, yielding occurred earlier and post-yield deformation capacity was reduced. In contrast, the empty tank condition imposed lower axial load, allowing the columns to sustain largest inelastic deformations without collapse. This reduction in ductility capacity under full filled conditions contributed significantly to higher seismic vulnerability.

Conclusion

The present study focused on the seismic performance evaluation and vulnerability assessment of an elevated RC Intze tank using an incremental non linear time history analysis, incorporating realistic modeling of both structural elements and fluid-structure interaction. Primary structural components, including columns, bracing beams, ring beams and tank container elements were modeled using a combination of frame and shell elements, while the stored water was represented through impulsive and convective mass components. The impulsive mass was treated as rigidly attached to the tank walls, and the convective mass was modeled as a lumped mass connected through horizontal springs.

The analysis revealed that the impulsive mass of the water governs the base shear, overturning moments and hydrodynamic pressures, particularly for tanks with short periods or stiff staging systems. On the other hand, the convective mass contributed primarily to free surface sloshing and longer period oscillations, which significantly affected the lateral displacements and pressure variations on tank walls in taller tank. The P-Delta effect in staging system amplified lateral displacements in braces, The non linear time history analysis results indicated that ignoring material and P - delta effects could underestimate demands on the columns and overall tank stability.

The peak displacement of top of the tank demonstrated that tank full filled condition was found to be the most vulnerable for tanks with same storage capacity due to large inertia mass responding to the defined earthquake record. For the same fill conditions, the tanks with more storage capacity were found to be more vulnerable while excited under same ground motion record.

The study of fragility curves demonstrated that the probability of exceeding defined damage state was found to be more for the tank with higher storage capacity for same tank filling condition, whereas the probability of exceeding a damage state was found to be more for tank filled condition, followed by the half filled condition and minimum for the empty tank condition.

This study, after vulnerability assessment, concludes that tanks with higher storage capacity with tank fully filled conditions are the most vulnerable than the tanks with low storage capacity having half filled and empty conditions.

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