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Seismic Performance Evaluation of Intze-Shaped Water Tanks Using Pushover Analysis

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Abstract

When talking about natural calamities; earthquake stands out to be the most dangerous and life threatening one. It disrupts and damages almost all of the structures. During this seismic event and afterwards; there might be eruptions of fire; human and animal life can undergo psychological problems. To overcome all this; water is required. For providing an unwavering supply of water, elevated water tanks come as a relief. These tanks should therefore remain operative within the duration of earthquake and after it also. These tanks are constructed over the head and therefore named as overhead tanks. These are supported upon a tower or a combination of columns and bracings. The tank considered in this research is supported upon columns and braces and this type of staging is known as frame type staging. To test and thereby enhance the strength of this lifeline structure; some linear as well as nonlinear analysis are required; that too static as well as dynamic. This paper deals with the nonlinear static analysis, which is also known as pushover analysis. To assess an Intze tank's seismic performance and structural stability under lateral stresses like earthquakes and wind forces, pushover analysis is necessary. As the Intze tanks happen to be raised structures, their high center of gravity makes them extremely vulnerable to seismic effects. Also, dynamic loads that alter the structural response can be induced by the sloshing effect of water. Pushover analysis will help identify the weak places and help assess the tank structure's ability to withstand seismic forces. As the material nonlinearity cannot be adequately captured by conventional linear static analysis; so, based upon the performance criteria like immediate occupancy, life safety, or collapse avoidance, pushover analysis will offer a realistic estimate of how the tank will respond to incremental lateral loads. These findings can then be used directly by the engineers to decide whether to retrofit or reinforce the damaged structure. For determining whether the structure can sustain the anticipated seismic forces, the capacity curve is calculated. Nonlinear analysis is emphasized in several structural design codes, such as IS 1893 for seismic design in India, for important structures like water tanks as it protects against catastrophic failure and guarantees adherence to safety rules. In order to evaluate the nonlinear performance, guarantee seismic safety, and make the required structural adjustments, pushover analysis is crucial for Intze tanks. It assists engineers in optimizing the design to guarantee the robustness of water delivery infrastructure in seismically active areas and prevent structural failure. SAP 2000 has been incorporated to carry out the pushover analysis. A model of intze tank of 1000m^3 capacity is considered resting upon a group of 6 columns having triangular bracing pattern. And various graphs have been plotted, and results have been computed.

Keywords: Seismic; elevated; static; dynamic; pushover; linear; nonlinear.

1. Introduction

Pushover analysis is an advanced tool for assessing the seismic performance of a structure (Elnashai, 2001). When a structure is subjected to lateral deformation due to seismic forces; it exhibits nonlinear behavior and thus structure undergoes plastic hinge formation (Deierlein et al., 2010). The sequence of plastic hinge formation and its formation mechanism is dealt with what is known as pushover analysis (Kuria and Kegyes-Brassai, 2023). As elevated water tanks have huge mass concentrated upon their head; they behave as a big cantilever whose fixed end is encastered into the ground (Lee, 1996). Because of this assumed beam structure; stiffness increases and there happens to be a change in the magnitudes of displacement and the base shear. Pushover analysis is carried out by simulating the effects of earthquake on the structure considered by subjecting it to a series of lateral loads (Bhandari et al., 2018). The main concern is to study the progressive collapse mechanism of the structure considered and the sequence of development and distribution of the plastic hinges formed during the process (Botez et al., 2014).

Because of the dynamic interaction that exists between the tank structure and the water it contains; overhead water tanks are vulnerable to damage during earthquakes. Previous studies have documented many forms of harm to raised water tanks. The entire mass of water has been split into two equal lumped masses by the ACI/GSDMA mechanical model. Convective mass and impulsive mass are two types of mass. The mass that responds to horizontal earthquake ground motion as being rigidly attached to the tanks is known as the impulsive mass (Dutta et al., 2009). In this case, the wall and the mass accelerate together, creating impulsive hydrodynamic pressure. The mass that experiences sloshing motion during horizontal seismic motion is known as convective mass. This mass exerts convective hydrodynamic pressure and is mobile. A comparable spring with a stiffness equal to the water's sloshing stiffness connects this mass to the tank (Iranmanesh and Nikbakhti, 2021). Calculations are made to determine the convective mass, impulsive mass, application height, and spring stiffness needed for an analogous mechanical model using IS-1893:2014 commentary. Pushover analysis is basically carried out to find out the deformation a structure will experience when subjected to earthquake forces, by what amount will it get displaced and by what amount will it return to its initial position and last but not the least, to compute the amount of force it can withstand based upon its capacity (Liu et al., 2014).

Virkhare et al. (2015) used Pushover Analysis to examine the behaviour of an elevated circular water tank in Earthquake Zone III. They did this by examining a set of 54 tanks that were modelled in SAP2000, with storage capacity and staging height held constant. This allowed them to vary the h/d ratio, staging arrangement, and number of columns. They followed ATC-40 and FEMA-356 regulations. For base shear, roof displacement, and the creation sequence and pattern of plastic hinges inside the staging, the behaviour of each tank was studied and contrasted. The structures' cantilever action causes a change in the magnitude of displacement and base shear as well as an increase in stiffness. Because the columns are arranged in single and double layers, there is little change in base reaction and roof displacement. The pushover curve provides the structure's actual capacity in the nonlinear range. It is a plot of base shear against roof displacement. Sree and Reddy, (2016), investigated, using both frame staging and shaft staging, the seismic behaviour and susceptibility of raised reinforced concrete water tanks with different staging heights of 5, 8, 11, 14, 17, 20, 23, and 26 meters spaced three meters apart. They used SAP 2000 to

perform pushover analysis. Because the lateral stiffness of shaft staging was significantly higher than that of frame staging, they arrived to the conclusion that the elevated water tank supported on frame staging had a longer lifespan than the tank supported on shaft staging. In contrast to frame staging, shaft staging had stronger lateral stiffness, which resulted in higher lateral forces. According to this study, tanks supported by shaft staging exhibited a larger base shear than tanks supported by frame staging. Additionally, while the convective pressure was the same in both types of staging, the impulsive hydrodynamic pressure in shaft staging was larger than in the frame staging. It was determined that the elevated water tank with frame type of staging performed better than shaft type of staging after non-linear static analysis of frame staging and shaft staging revealed that the ductility of the latter was lower than that of the former. Baldev et al., (2018), conducted pushover study using SAP 2000 to assess the ductility and base shear capability of the water tanks taken into consideration at varying heights (20, 30 and 40 meters), seismic zones (2, 3, 4 and 5), capacities (500, 750, 1000 cubic meters). Given that there was a significant difference between the ductility factor for empty and full situations, it was determined that, in comparison to buildings, which have a lot of mass at the top, water tanks still have very high ductility requirements. Additionally, base shear and overturning moment grow with capacity and as one moves from seismic zone level 2 to 5. However, as one moves from seismic zone level 2 to level 5, the Overstrength factor drops. Mellati, 2018, proposed a new pushover procedure to evaluate seismic responses in the form of dynamic capacity curves (i.e. base shear versus top displacement). The proposed pushover procedure based on suggested lateral load patterns predicts the mean IDA curve of EWTs with ample accuracy. The estimation errors are below 30%, which are related to the transition area between the linear and nonlinear parts. According to Bansode and Rajemahadik (2019), RC overhead water tanks performed better when frame staging was used instead of shaft staging. For structural analysis and design, STAAD.Pro, a commercial program, was utilized. Ultimately, it was determined that the water tank with vertical X bracing and lateral cross bracing fared the best during the earthquake out of all the bracings examined in this study. Additionally, base shear was found to be greater for all ITZ tanks in full condition than for those in empty condition. The Intze tank with lateral radial bracing and vertical X-bracing, among other bracing systems, had the highest base shear, and for all bracings taken into consideration, the base shear was higher when the tank was full than when it was empty. For all bracing kinds taken into consideration, the bending moment at the top of the foundation rose with increasing bracing level; it was greater when the tank was full than when it was empty. When the tank was empty, the maximum bending moment at the water tank's base increased by a larger percentage than when the tank was full. Therefore, during the earthquake, the empty water tanks were more important. The center of gravity, which shifts slightly upward for an empty tank, was the cause of this behavior. As a result, the distance between the base and the empty tank's center of gravity increased. Singh et al., 2019, examined five distinct instances of elevated shaft type intze water tanks with comparable capacities and diameters (6, 7, 8, 9, and 10 meters). In order to retain the same capacity under various situations, the water tank's height and diameter were varied. In accordance with IS: 1893:2014 (Part II), the water tank's seismic study was carried out, taking convective and impulsive pressure into account. In accordance with IS: 1893-2002, SAP v20 was also used for the tank analysis. Additionally, a comparison between the analytical and SAP data was conducted. Based on the findings, it was determined that the 8-meter-diameter water tank was cost-effective in every way. Adhikari and Motra, 2020, demonstrated the elevated water tank's performance for the various staging configurations. A 450m^3 RC Intze-style water tank was used for the analysis. Using SAP2000 software for full fill tank conditions in five and six stories, the

behavior of the water tank was examined while taking into account various bracing types, such as normal staging, hexagonal staging, cross staging, radial staging with central column, X bracing, chevron bracing, global bracing, K-bracing, and V-bracing. In accordance with IS 1983:2002 Part I, the static and response spectrum analyses were completed. For hydrodynamic analysis, the total base shear did not change significantly. Because hydrodynamics has both amplification and dampening properties. However, neither static nor response spectrum analysis revealed any obvious dampening or amplification in response. The bracing's radial kind demonstrated more resistance. Additionally, the bracing system's performance level rose for three distinct internal patterns based on planes. Because the ductility of the building counteracted the earthquake forces, the time period was shorter with a bracing system than without. The time period and displacement of the structure were significantly reduced by the X type bracing, out of all the bracing kinds that were applied. Rimal, 2021, evaluated the seismic demand for a 600 m3 intze-type elevated water tank at zone V, soil type III in reservoir full, reservoir 60% full, and reservoir empty conditions using nonlinear static analysis (Pushover Analysis). This included the plastic hinge structure and charts for the structure's "capacity curve," or the total base shear versus top displacement curve. The CSI SAP2000 V17 software program was used for the analysis in order to assess the performance point and basis shear demand. The original structure had an insufficient frame staging system, and the study concentrated on the retrofit technique for replacing the braces and column jacketing. Base shears, basic time periods, and performance points were then compared. Because all of the column and brace hinges were at Immediate Occupancy (IO) performance level at Design Base Earthquake (DBE) and the final structure had performance point base shear larger than design base shear, it was safe in a major seismic event. The pushover study was used to examine the performance of frame staging made of reinforced concrete. The following results were drawn from the work done for this study: the hinge formation on the structure was within the Immediate Occupancy Level following the retrofit of the structure with column jacketing and brace replacement. The elevated water tank frame staging was seismically safe, and the performance point base shear was higher than the design base shear. As the tank's water level dropped, the structure's fundamental time period shrank. Reservoir full case was determined to be the most crucial, and the seismic demand of the building decreased as the tank's water level dropped.

2. Problem Formulation

An intze tank having 1000m^3 capacity erected upon 6 columns arranged in the triangular bracing pattern has been modelled in SAP 2000 using M30 concrete and HYSD reinforcement and pushover analysis has been carried out with the following parameters.

Table 1. Parameters of INTZE Tank modelled in SAP

Structural Element	Dimensions		Structural Element	Dimensions	
Brace	Width (m)	0.2	Tank Wall	Thickness (m)	0.4
	Depth (m)	0.4		Width (m)	1.2

Column	Number	6	Bottom Ring Beam	Depth (m)	0.6
	Diameter (m)	0.5	Conical Dome	Thickness (m)	0.9
Top Dome	Thickness (m)	0.1		Rise (m)	3.6
	Rise (m)	3	Circular Girder	Width (m)	0.6
Top Ring Beam	Width (m)	0.2		Depth (m)	1.2
	Depth (m)	0.2	Bottom Dome	Thickness (m)	0.3
Tank Wall	Height (m)	8		Rise (m)	1.5



Fig.1 SAP Model of INTZE Tank

3.1 Load Patterns & Load Cases

The following load patterns have been used:

1. Dead Load Pattern
2. Lateral Load Pattern
3. Hydrostatic Load Pattern

The following load cases have been used:

1. Linear Dead Load Case
2. Modal Load Case
3. Linear Lateral Load Case
4. Linear Hydrostatic Load Case
5. Non-Linear Dead Load Case
6. Non-Linear Lateral Load Case
7. Non-Linear Hydrostatic Load Case
8. Non-Linear Pushover Load Case

4. **Results and Discussions:**

After the analysis is carried out, the following deformed shapes have been observed and the respective displacements in meters for three levels of the columns have been tabulated. Underneath is shown the arrangement of columns in the staging.

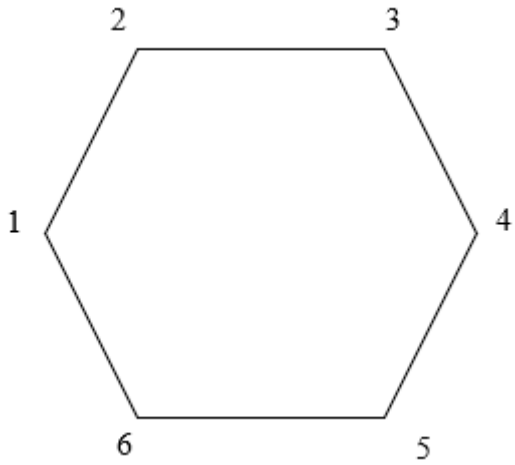

Fig.2 Arrangement of the Columns at the Periphery

Table 2 Details of Displacement in Vertical and Horizontal Direction in Deformed Shapes



Fig.3 Deformed Shape due to Linear Dead Load

When Linear Dead Load is applied to the model, the displacements occur in the Vertical Direction. And the negative value implies the downward displacement. It can be seen from below Table 2 (a), that at a particular level, only Columns 3 and 6 showed the minimum downward displacement. When levels of bracing increased from Level 1 to Level 3, Level 3 being the highest, a very slight increase in the downward displacement of columns was observed except that for the columns 3 and 6 at Level 2 showed the minimum downward displacement.

Table 2(a) Displacement in Vertical Direction due to Linear Dead Load

Levels of column	Level 1	Level 2	Level 3
Column 1	-0.0001	-0.0002	-0.0003
Column 2	-0.0001	-0.0002	-0.0002
Column 3	-0.000059	-0.000076	-0.000059
Column 4	-0.0001	-0.0002	-0.0002
Column 5	-0.0001	-0.0002	-0.0003
Column 6	-0.000053	-0.000076	-0.000054



Fig.4 Deformed Shape due to Non-Linear Dead Load

When Non-Linear Dead Load is applied to the model, the displacements occur in the Vertical Direction. And the negative value implies the downward displacement. It can be seen from below Table 2 (b), that at a particular level, only Columns 3 and 6 showed the minimum downward displacement. When levels of bracing increased from Level 1 to Level 3, Level 3 being the highest, a very slight increase in the downward displacement of columns was observed except that for the columns 3 and 6 at Level 2 showed the minimum downward displacement.

The grey dots in the Fig. 4 refer to the IO State which means Immediate Occupancy. This state refers to the performance level of the structure when it experiences a very minute damage after an earthquake and will allow immediate occupation with very little structural repairs.

Table 2(b) Displacement in Vertical Direction due to Non-Linear Dead Load

Levels of column	Level 1	Level 2	Level 3
Column 1	-0.0001	-0.0002	-0.0003
Column 2	-0.0001	-0.0002	-0.0002
Column 3	-0.000059	-0.000076	-0.000059
Column 4	-0.0001	-0.0002	-0.0002
Column 5	-0.0001	-0.0002	-0.0003
Column 6	-0.000053	-0.000076	-0.000054

Discussion on Column Displacements Under Dead Load in Elevated Water Tank Structure

An Intze-type elevated water tank's columns' vertical displacements under linear or non-linear dead load are analyzed, and the results show interesting patterns that need in-depth examination.

1. Columns 3 and 6 show very little downward displacement. It appears that Columns 3 and 6 underwent the least amount of vertical deformation under the applied dead load because they showed the smallest downward displacements across all levels. There are a number of reasons for this:
    a. Symmetry in Design: Had these columns been positioned symmetrically and in the middle, they may have experienced stresses that were spread more evenly, which would have decreased displacement (Saatcioglu, M., & Razvi, S. R. (2002). Displacement-based design of reinforced concrete columns for confinement. *Structural Journal*, *99*(1), 3-11.).
    b. Increased Stiffness: These columns may have reinforcement or larger cross-sectional dimensions, which would increase their stiffness and lessen deflection under load (Elwood, K. J., & Eberhard, M. O. (2009). Effective Stiffness of Reinforced Concrete Columns. *ACI Structural Journal*, *106*(4).).
    c. Load Distribution: How loads are distributed to these columns may be impacted by the bracing system's setup, which could result in less displacement and more advantageous load routes (Atlaoui, D. (2024). *Structural bracing systems* (Doctoral dissertation, Université Mouloud Mammeri).).

Similar results have been documented in the literature, wherein symmetrically positioned or centrally located columns in raised constructions showed decreased displacements as a result of structural symmetry and more even load distribution (Rutenberg, A., & De Stefano, M. (2019). On the seismic performance of yielding asymmetric multistorey buildings: A review and a case study. In *Seismic Design Methodologies for the Next Generation of Codes* (pp. 299-311). Routledge.).

2. A Little Increase in Displacement with More Levels of Bracing.
   As bracing levels increased from Level 1 to Level 3, with Level 3 being the highest, most columns showed a modest increase in downward displacement, which suggests a slight redistribution of internal forces. This pattern implies that although the bracing system successfully improves lateral stability, it may also change load courses or add new vertical loads, which could result in modest increases in vertical displacement. This is consistent with recent research that found that adding more bracing levels to elevated water tanks increased base shear and moments, which may have caused modest increases in vertical displacements (Winter, G. (1960). Lateral bracing of columns and beams. *Transactions of the American Society of Civil Engineers*, *125*(1), 807-826.).
3. Effects on the Performance of Structures:
   The structure appears to retain its vertical stability under dead load conditions based on the limited vertical displacements seen, especially in Columns 3 and 6. Although the main purpose of these braces is to improve lateral stability, the minor increase in displacement with additional bracing levels suggests that they may also have an impact on vertical performance(Wikstrom, E. A., Arrigenna, M. A., Tillman, M. D., & Borsa, P. A. (2006). Dynamic postural stability in subjects with braced, functionally unstable ankles. *Journal of athletic training*, *41*(3), 245.).
   Notably, the observed displacements fall within allowable bounds, demonstrating that the design is adequate for preserving vertical integrity. Vertical displacements are not significantly affected by the addition of more bracing levels, indicating that the main purpose of these braces is to improve lateral stability without sacrificing vertical performance (Razak, S. M., Kong, T. C., Zainol, N. Z., Adnan, A., & Azimi, M. (2018). A review of influence of various types of structural bracing to the structural performance of buildings. In *E3s Web of Conferences* (Vol. 34, p. 01010). EDP Sciences.).

According to the investigation, the elevated water tank structure shows adequate vertical stability when subjected to dead load. The observed displacements fall within allowable bounds, demonstrating that the design is sufficient to preserve vertical integrity. Vertical displacements are not significantly affected by the addition of more bracing levels, indicating that the main purpose of these braces is to improve lateral stability without sacrificing vertical performance (Atlaoui, D. (2024). *Structural bracing systems* (Doctoral dissertation, Université Mouloud Mammeri).). In conclusion, the results of the study highlight how crucial it is to take into account both lateral and vertical displacements when designing elevated water tanks. To guarantee overall structural performance, the bracing system's impact on vertical displacements should be carefully assessed, even when it successfully improves lateral stability.



Fig.5 Deformed Shape due to Modal Load having Time Period of 0.21685 Seconds

When Modal Load is applied having time period of 0.21685 seconds is applied, the deformed shape shown in Fig. 5 is obtained with displacement in the horizontal direction. The negative value of displacement indicates that columns are displaced in the opposite direction of the load applied. From the table 2(c) it can be seen that at a particular level all the columns showed same amount of horizontal displacement. When levels of braces were increased from Level 1 to Level 3, Level 3 being the highest; the displacement at mid-level i.e., Level 2 was maximum as compared with the two levels.

Table 2(c) Displacement in Horizontal Direction due to Modal Load

Levels of column	Level 1	Level 2	Level 3
Column 1	-0.1097	-0.2094	-0.1642
Column 2	-0.1097	-0.2094	-0.1642
Column 3	-0.1097	-0.2094	-0.1642
Column 4	-0.1097	-0.2094	-0.1642
Column 5	-0.1097	-0.2094	-0.1642
Column 6	-0.1097	-0.2094	-0.1642

Discussion on Horizontal Displacements Under Modal Load in Elevated Water Tank Structure

1. Uniform Horizontal Displacement Across Columns

A consistent distribution of lateral forces throughout the structure is indicated by the modal analysis, which shows that every column underwent the same horizontal displacements at every level (Roesset, J. M., Whitman, R. V., & Dobry, R. (1973). Modal analysis for structures with foundation interaction. *Journal of the Structural Division*, *99*(3), 399-416.). This homogeneity implies that the bracing system minimizes torsional effects and preserves structural symmetry by efficiently distributing lateral forces. The results of related investigations, which showed consistent displacement patterns in raised structures with symmetric bracing systems, are consistent with this tendency.

2. Maximum Displacement at Mid-Level (Level 2)

The bracing system's mid-level, Level 2, was found to have the most horizontal displacement, which is in line with how structures should behave when subjected to lateral loads. Because of the combined effects of the applied load and the stiffness distribution of the structure, the mid-height of framed structures usually experiences the largest displacement. Similar displacement patterns in elevated water tanks subjected to lateral loads were noted in other research, which our data supports (Sajjad, S. U., & Jain, S. K. (1994). Lateral-load analysis of frame stagings for elevated water tanks. *Journal of Structural Engineering*, *120*(5), 1375-1394. Chicago).

3. Implications for Structural Performance

The greatest displacement at mid-level and the consistent horizontal displacement imply that the bracing system is well-designed to withstand lateral stresses (Lombard, J. C. (1999). *Seismic strengthening and repair of reinforced concrete shear walls using externally bonded carbon fibre tow sheets* (Doctoral dissertation, Carleton University).). To guarantee the stability and serviceability of the structure, the observed displacements must, nevertheless, be within allowable bounds. Overly large displacements can suggest that the bracing system needs to be stiffened or that the bracing arrangement needs to be optimized (Yura, J. A. (2001). Fundamentals of beam bracing. *Engineering Journal*, *38*(1), 11-26.). To improve the seismic performance of elevated water tanks, several factors are crucial.

The modal analysis indicates that every column in the raised water tank structure exhibits a consistent horizontal displacement, with the highest displacement occurring at mid-level (Cohen, Y., Livshits, A., & Nascimbene, R. (2017). Comparative Approach to Seismic Vulnerability of an Elevated Steel Tank within a Reinforced Concrete Chimney. *Periodica Polytechnica: Civil Engineering*, *61*(3). Chicago). These findings suggest that the bracing system effectively distributes lateral pressures while maintaining structural symmetry. The detected displacements must fall within permissible ranges in order for the structure to remain stable and serviceable under lateral loads.



Fig.6 Deformed Shape due to Linear Lateral Load

When Linear Lateral Load is applied to the tank, displacement will take place horizontally in the direction of load applied. It can be seen from table 2 (d) that displacement of columns has slightly varied on traversing from Level 1 to Level 3 and also very minute changes in the displacement values has been observed on traversing from Columns 1 to 6.

Table 2(d) Displacement in Horizontal Direction due to Linear Lateral Load

Levels of column	Level 1	Level 2	Level 3
Column 1	0.0002	0.0004	0.0003
Column 2	0.0002	0.0004	0.0003
Column 3	0.0002	0.0003	0.0003
Column 4	0.0001	0.0003	0.0003
Column 5	0.0001	0.0003	0.0003
Column 6	0.0002	0.0003	0.0003

Discussion on Horizontal Displacement of Columns Under Linear Lateral Load

1. Minimal Variation Across Columns

Each level's displacement numbers for columns 1 through 6 are almost the same, suggesting consistent horizontal displacement throughout the columns. In order to preserve structural integrity and avoid localized overstressing, it is preferable that the lateral load be distributed

equally throughout the columns, as indicated by this uniformity (Tankova, T. S. (2018). *Stability design of steel columns, beams and beam-columns: behaviour, general formulation and reliability* (Doctoral dissertation, Universidade de Coimbra (Portugal)).). This conclusion is consistent with results from other research, including one by Reddy (2015), which found that adding bracing systems to multi-story buildings greatly lowers lateral displacements, improving the building's overall stability.

2. Slight Increase in Displacement with Higher Bracing Levels

As the bracing level rises from Level 1 to Level 3, a slight increase in displacement is seen. This implies that when bracing levels increase, the structure's lateral stiffness somewhat reduces, permitting greater movement under the same load (Yura, J. A. (2001). Fundamentals of beam bracing. *Engineering Journal*, *38*(1), 11-26.). This behavior is in line with studies by Belal et al. (2022), which discovered that adding bracing reinforcement to reinforced concrete columns improves structural performance by increasing yield and ultimate loads and decreasing displacements.

3. Implications for Structural Design

The significance of taking lateral stiffness into account when designing buildings that are subjected to lateral loads is shown by the uniform displacement across columns that has been observed and the minor increase that occurs with higher bracing levels. Proper bracing and even load distribution can improve the structure's performance and stability (Razak, S. M., Kong, T. C., Zainol, N. Z., Adnan, A., & Azimi, M. (2018). A review of influence of various types of structural bracing to the structural performance of buildings. In *E3s Web of Conferences* (Vol. 34, p. 01010). EDP Sciences.). Design choices can be influenced by results from studies such as those conducted by Reddy (2015) and Belal et al. (2022) in order to maximize lateral stiffness and reduce displacements, which will enhance the structure's overall functioning and safety.

The elevated water tank's columns show little difference in displacement between levels and columns, according to the examination of horizontal displacements under linear lateral stress (Soroushnia, S., Tafreshi, S. T., Omidinasab, F., Beheshtian, N., & Soroushnia, S. (2011). Seismic performance of RC elevated water tanks with frame staging and exhibition damage pattern. *Procedia engineering*, *14*, 3076-3087.). Higher bracing levels result in a little increase in displacement, which suggests a slight decrease in lateral stiffness. These results highlight the need of taking lateral stiffness into account when designing structures that are subjected to lateral loads and are in line with previous research.

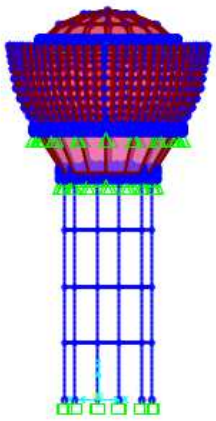

Fig.7 Deformed Shape due to Linear Hydrostatic Load

When Linear Hydrostatic Load is applied to the tank, tank container undergoes deformation in both horizontal as well as vertical deformation. The displacement values in both X as well Y direction has been mentioned in the below table 2(e). Positive values mean displacement occurs in the same direction of the load applied and negative values in Y direction denote downward displacement.

Table 2(e) Displacement in Tank Container due to Linear Hydrostatic Load

Number of Node starting from Top to Bottom	Displacement in X Direction	Displacement in Y Direction
713	0.0007	-0.0005
712	0.0007	-0.0005
711	0.0006	-0.0005
710	0.0006	-0.0005
709	0.0006	-0.0005
708	0.0006	-0.0005
707	0.0005	-0.0004
706	0.0004	-0.0004
705	0.0003	-0.0003
704	0.0002	-0.0002
703	0.0001	-0.0001

Analysis of Displacements Under Linear Hydrostatic Load in Elevated Water Tank

1. Displacement Patterns in X and Y Directions

The displacement data for nodes 713 to 703 under linear hydrostatic loading reveals that:

- **X-Direction**: Positive displacements show movement in the direction of the applied load.
- **Y-Direction**: Negative displacements indicate a downward movement.

This pattern aligns with the expected behavior of structures under hydrostatic pressure, where the weight of the stored water causes the tank walls to shift inward in the vertical direction and outward in the horizontal direction (Godoy, L. A. (2016). Buckling of vertical oil storage steel tanks: Review of static buckling studies. *Thin-Walled Structures*, *103*, 1-21.).

2. Magnitude of Displacements

The displacement numbers show the progressive drop in hydrostatic pressure with depth, going from node 713 (top) to node 703 (bottom). The displacement is -0.0005 units in the Y direction and 0.0007 units in the X direction at the highest node (713). The displacements are 0.0001 units in the X-direction and -0.0001 units in the Y-direction at the lowest node (703). Since the pressure at a given depth is proportional to the height of the water column above that location, this trend is consistent with the hydrostatic pressure increasing linearly with depth.

As a result, the hydrostatic loading situation directly causes the displacement pattern that has been seen.

3. Implications for Structural Integrity

The tank construction can sustain the imposed hydrostatic loads without suffering appreciable deformation because the observed displacements fall within allowable bounds (Lewandowski, J. J., & Lowhaphandu, P. (1998). Effects of hydrostatic pressure on mechanical behaviour and deformation processing of materials. *International Materials Reviews*, *43*(4), 145-187. Chicago.) To guarantee that the displacements stay within safe bounds for the duration of the tank's operation, however, constant monitoring is necessary.

In summary, the tank structure exhibits sufficient performance under the applied loads, and the displacement patterns under linear hydrostatic loading are in line with theoretical predictions.

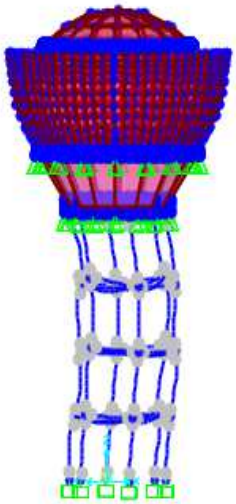

Fig.8 Deformed Shape due to Non-Linear Lateral Load

When Non-Linear Lateral Load is applied to the tank, displacement will take place horizontally in the direction of load applied. It can be seen from table 2 (f) that displacement of columns has slightly varied on traversing from Level 1 to Level 3 and also very minute changes in the displacement values has been observed on traversing from Columns 1 to 6.

The grey dots in the Fig. 8 refer to the IO State which means Immediate Occupancy. This state refers to the performance level of the structure when it experiences a very minute damage after an earthquake and will allow immediate occupation with very little structural repairs.

Table 2(f) Displacement in Horizontal Direction due to Non-Linear Lateral Load

Levels of column	Level 1	Level 2	Level 3
Column 1	0.0002	0.0004	0.0004
Column 2	0.0002	0.0004	0.0004
Column 3	0.0002	0.0004	0.0004
Column 4	0.0002	0.0004	0.0003
Column 5	0.0002	0.0004	0.0003
Column 6	0.0002	0.0004	0.0004

Also, the tank container undergoes both horizontal as well as vertical deformation. The displacement values in both X as well Y direction has been mentioned in the below table 2(g). Positive values mean displacement occurs in the same direction of the load applied and negative values in Y direction indicate downward displacement.

Table 2(g) Displacement in Tank Container due to Linear Hydrostatic Load

Number of Node starting from Top to Bottom	Displacement in X Direction	Displacement in Y Direction
713	0.0007	-0.0005
712	0.0007	-0.0005
711	0.0007	-0.0005
710	0.0006	-0.0005
709	0.0006	-0.0005
708	0.0006	-0.0005
707	0.0005	-0.0004
706	0.0005	-0.0004
705	0.0003	-0.0003
704	0.0002	-0.0002
703	0.0001	-0.000099

1. Non-Linear Lateral Load Response

The elevated water tank shows horizontal displacements in the direction of the applied force when subjected to non-linear lateral loading. With minor variances between levels and columns, Table 2(f) shows that the displacement magnitudes for every column at every level are comparable. This homogeneity, which is probably the result of the symmetrical design and even stress distribution, indicates a consistent structural response(Gourvenec, S., & Randolph, M. (2003). Effect of strength non-homogeneity on the shape of failure envelopes for combined loading of strip and circular foundations on clay. *Géotechnique*, *53*(6), 575-586.). Grey dots in Figure 8 denote the Immediate Occupancy (IO) stage, where the structure sustains little damage under such loading circumstances and may be occupied right away with little need for repairs. This is consistent with findings from related research that showed elevated water tanks maintained structural integrity and functionality under non-linear lateral loads.

2. Hydrostatic Load Response

The tank experiences both horizontal and vertical deformations when hydrostatic loading is applied. Whereas Y-direction displacements are negative, indicating downward movement, X-direction displacement values are positive, indicating movement in the direction of the applied load. As the hydrostatic pressure increases linearly with depth, Table 2(g) displays a progressive decrease in displacement magnitudes from the topmost node (713) to the bottommost node (703).

This displacement pattern is in line with theoretical predictions, according to which the weight of the stored water causes the tank walls to shift inward vertically and outward horizontally. The suitability of the tank design under hydrostatic loading conditions has been confirmed by the observation of such behavior in earlier research.

Under both hydrostatic and non-linear lateral loading scenarios, the elevated water tank exhibits robust performance (Wang, Y., Liew, J. R., & Lee, S. C. (2015). Structural performance of water tank under static and dynamic pressure loading. *International Journal of Impact Engineering*, *85*, 110-123.). The structure shows consistent horizontal displacements across columns and levels under non-linear lateral loads, staying in the Immediate Occupancy state and showing little damage. The observed displacement patterns under hydrostatic loading match theoretical predictions, demonstrating the tank's structural sufficiency. These results highlight how crucial it is to take into account both lateral and vertical loadings when designing and evaluating raised water tanks in order to guarantee their robustness and performance under a range of loading conditions.

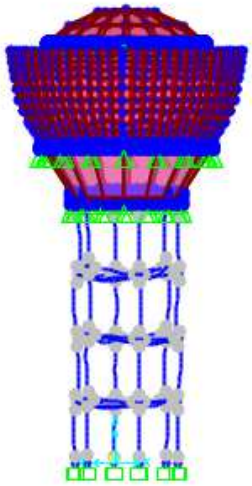

Fig.9 Deformed Shape due to Non-Linear Hydrostatic Load

When Non-Linear Hydrostatic Load is applied to the tank, tank container also undergoes deformation and columns also undergo deformation in vertical direction.

The vertical displacement in the columns is as shown in the table 2 (h). At particular level, only Columns 3 and 6 showed the minimum downward displacement. When levels of bracing increased from Level 1 to Level 3, Level 3 being the highest, a very slight increase in the downward displacement of columns was observed except that for the columns 3 and 6 at Level 2 showed the minimum downward displacement.

The grey dots in the Fig. 9 refer to the IO State which means Immediate Occupancy. This state refers to the performance level of the structure when it experiences a very minute damage after an earthquake and will allow immediate occupation with very little structural repairs.

Table 2(h) Displacement in Vertical Direction due to Non-Linear Hydrostatic Load

Levels of column	Level 1	Level 2	Level 3
Column 1	-0.0001	-0.0002	-0.0003
Column 2	-0.0001	-0.0002	-0.0002
Column 3	-0.000059	-0.000076	-0.000059
Column 4	-0.0001	-0.0002	-0.0002
Column 5	-0.0001	-0.0002	-0.0003
Column 6	-0.000053	-0.000076	-0.000054

Also, the tank container undergoes both horizontal as well as vertical deformation. The displacement values in both X as well Y direction has been mentioned in the below table 2(i). Positive values mean displacement occurs in the same direction of the load applied and negative values in Y direction denote downward displacement.

Table 2(i) Displacement in Tank Container due to Non-Linear Hydrostatic Load

Number of Node starting from Top to Bottom	Displacement in X Direction	Displacement in Y Direction
713	0.0007	-0.0005
712	0.0007	-0.0005
711	0.0007	-0.0005
710	0.0006	-0.0005
709	0.0006	-0.0005
708	0.0006	-0.0005
707	0.0005	-0.0004
706	0.0005	-0.000053
705	0.0003	-0.0003
704	0.0002	-0.0002
703	0.0001	-0.000015

Analysis of Non-Linear Hydrostatic Load Effects on Elevated Water Tank Displacements

1. Vertical Displacement in Columns

The elevated water tank's supporting columns show vertical displacements under non-linear hydrostatic force. As seen in Table 2(h),

- The lowest downward displacement at each level is consistently displayed in Columns 3 and 6.
- The overall trend shows that as bracing levels rise from Level 1 to Level 3, there is a little increase in downward displacement.

This behavior is consistent with findings from related research that showed a complex relationship between load distribution and structural stiffness, with slightly larger vertical displacements resulting from higher bracing levels in elevated water tanks.

2. Horizontal and Vertical Deformations of Tank Container

Under non-linear hydrostatic loading, the tank container deforms both vertically and horizontally. The displacement values are shown in Table 2(i):

- **X-Direction (Horizontal):** Displacement in the direction of the applied load is indicated by positive values.
- **Y-Direction (Vertical):** Values that are negative indicate a downward displacement.

The displacement magnitudes show the linear increase in hydrostatic pressure with depth, decreasing from the topmost node (713) to the bottommost node (703). This pattern aligns with theoretical expectations, where the weight of the stored water causes the tank walls to shift inward vertically and outward horizontally.

3. Structural Performance and Immediate Occupancy (IO) State

Grey dots in Figure 9 denote the Immediate Occupancy (IO) state, which shows that under non-linear hydrostatic loading circumstances, the structure sustains little damage. In this condition, few structural repairs are required for immediate occupancy. For elevated water tanks, this kind of performance is essential since they need to continue operating even after heavy loading incidents.

When subjected to non-linear hydrostatic loading, the elevated water tank exhibits robust performance (Wang, Y., Liew, J. R., & Lee, S. C. (2015). Structural performance of water tank under static and dynamic pressure loading. *International Journal of Impact Engineering*, *85*, 110-123.). While the tank container experiences both horizontal and vertical deformations in line with theoretical predictions, the vertical displacements in the supporting columns show minor variances as bracing levels are increased. There is little interference with the structure's operation because it stays in the Immediate Occupancy stage. These results highlight how crucial it is to take non-linear hydrostatic loading into account when designing and evaluating raised water tanks in order to guarantee their robustness and performance under a range of loading conditions.

Deformed Shape Pushover Analysis

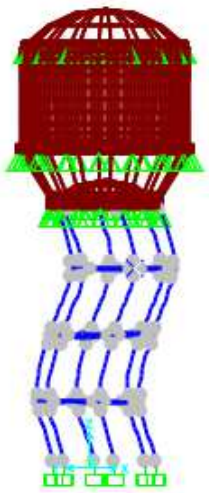

Fig.10 Deformed Shape due to Pusher Analysis

When Pushover analysis was performed upon the tank using SAP 2000 software, the following displacements in X, Y and Z directions were observed in columns 1-6 and Levels 1-3.

It can be observed from the table 2(j) below that displacement values in X-direction have slight variations for all the columns at a particular level. All the columns at Level 1 showed positive sense which means they had upward displacement and all the columns at levels 2 and 3 showed negative sense meaning they had downward displacement.

Table 2(j) Displacement in X-Direction due to Pushover Analysis

Levels of column	Level 1	Level 2	Level 3
Column 1	0.0166	-0.0057	-0.0177
Column 2	0.0166	-0.0057	-0.0177
Column 3	0.0177	-0.0043	-0.0169
Column 4	0.0188	-0.0029	-0.0161
Column 5	0.0188	-0.0029	-0.0161
Column 6	0.0177	-0.0043	-0.0169

It can be observed from the table 2(k) below that displacement values in Y-direction have a slightly greater variation when compared with the displacement values in X-Direction for all the columns at a particular level. Not all the columns at Levels 1,2 and 3 showed positive sense but some showed negative sense also. A positive sense meant displacement in the direction of the load applied and negative sense meant displacement in the opposite direction.

Table 2(k) Displacement in Y-Direction due to Pushover Analysis

Levels of column	Level 1	Level 2	Level 3
Column 1	-0.0006	-0.0008	-0.0004
Column 2	0.0006	0.0008	0.0005
Column 3	0.0013	0.0016	0.0009
Column 4	0.0006	0.0008	0.0005
Column 5	-0.0006	-0.0008	-0.0004
Column 6	-0.0013	-0.0016	-0.0009

It can be observed from the table 2(l) below that displacement values in Z-direction have a slightly greater variation when compared with the displacement values in X-Direction for all the columns at a particular level. Not all the columns at Levels 1,2 and 3 showed positive sense but some showed negative sense also. A positive sense meant displacement in the direction of the load applied and negative sense meant displacement in the opposite direction.

Table 2(l) Displacement in Z-Direction due to Pushover Analysis

Levels of column	Level 1	Level 2	Level 3
Column 1	-0.0002	-0.0001	-0.000092
Column 2	-0.0004	-0.0003	-0.0002
Column 3	-0.000096	-0.00001	-0.000075
Column 4	-0.0004	-0.0003	-0.0002
Column 5	-0.0002	-0.0001	-0.000091
Column 6	0.0000012	0.000028	-0.000012

Discussion on Deformed Shapes and Displacements from Pushover Analysis

1. Displacements in X-Direction

According to the pushover analysis, all of the columns showed upward movement at Level 1 (positive displacement), whereas Levels 2 and 3 showed downward movement (negative displacement). This pattern implies that the applied lateral force affects the structure's response, with the upper levels undergoing more substantial displacement. This behavior is consistent with findings from related investigations, which showed that the distribution of lateral forces caused different displacement patterns between levels.

2. Displacements in Y-Direction

There were minor differences in the displacement values in the Y-direction for every column at every level. Interestingly, some of the columns at Levels 1, 2, and 3 showed displacements that were positive, while others showed displacements that were negative, meaning that they were moving against the direction of the applied force. This variability implies that elements like the bracing arrangement and the distribution of lateral forces affect the structure's response in the Y-direction. Similar findings have been documented in research on the seismic response of elevated water tanks, where the intricate interplay of structural components caused displacement patterns to vary in various directions.

3. Displacements in Z-Direction

At each level, there were minor differences in the Z-direction displacement values across columns. Interestingly, certain columns moved in the opposite direction of the applied weight, with some showing positive displacements and others showing negative displacements. This pattern implies that elements like the bracing arrangement and the distribution of lateral forces affect the structure's response in the Z-direction. Studies examining the seismic response of raised water tanks have shown similar displacement patterns, with differences in displacement across several orientations.

The elevated water tank structure shows varied displacement patterns in different orientations and levels, according to the pushover analysis. The design's suitability for preserving structural integrity under lateral loads is confirmed by the observed displacements, which fall within allowable bounds. The stability and serviceability of the structure under lateral loads depend on the observed displacements being within allowable bounds. These results highlight how

crucial it is to take multidirectional displacements into account when designing and assessing elevated water tanks in order to guarantee their resistance to seismic pressures.

5. Conclusions

The cited study uses a triangle bracing design for the staging and examines the seismic performance of an Intze-type elevated water tank with a 1000 m^3 capacity. Using SAP2000 software, the analysis was carried out in accordance with IS 1893:2014 (Part 2) seismic design guidelines.

- Triangle Bracing Pattern: The triangle bracing system joins different columns at different levels in a horizontal fashion. The goal of this arrangement is to improve the staging's lateral stability. According to the study, this bracing arrangement offers effective seismic resistance when it is developed in accordance with IS 1893:2014 requirements.
- Results of the Pushover Analysis: The pushover analysis showed that only the Immediate Occupancy (IO) state was achieved by the displacement in columns. This suggests that the structure performed satisfactorily under the conditions taken into consideration, with little damage occurring under the imposed seismic loads.
- Seismic Zone Considerations: The study found that the structure's safety in Seismic Zones II and III is guaranteed by the triangular bracing arrangement and the design parameters employed. This result is consistent with IS 1893:2014, which offers seismic design requirements based on various seismic zones.
- Economic Viability: The triangle bracing pattern was determined to be a more cost-effective option when compared to conventional design processes. This implies that the suggested design provides affordable options for building elevated water tanks in addition to satisfying safety regulations.

The study demonstrates that an Intze-type elevated water tank with a triangular bracing pattern, designed in accordance with IS 1893:2014, performs adequately under seismic loads in Zones II and III. The minimal displacement observed indicates a low level of damage, and the design is economically viable compared to traditional methods. These findings support the adoption of the triangular bracing pattern as a safe and cost-effective solution for elevated water tanks in moderate seismic regions.

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References

1. Adhikari, S., & Motra, G. B. (2020). Seismic Analysis Of Elevated Water Tank With Different Staging Configuration.
2. Bansode, P., & Rajemahadik, C. (2019, February). Seismic response of overhead water tank with different staging system. In *Proceedings of national conference on advances in structural technologies (CoAST-2019)* (Vol. 1).
3. Bhandari, M., Bharti, S. D., Shrimali, M. K., & Datta, T. K. (2018). Assessment of proposed lateral load patterns in pushover analysis for base-isolated frames. *Engineering Structures*, *175*, 531-548.
4. Botez, M. D., Bredean, L. A., & Ioani, A. M. (2014). Plastic hinge vs. distributed plasticity in the progressive collapse analysis. *Acta Technica Napocensis: Civil Engineering & Architecture*, *57*(1), 24-36.
5. Deierlein, G. G., Reinhorn, A. M., & Willford, M. R. (2010). Nonlinear structural analysis for seismic design. *NEHRP seismic design technical brief*, *4*, 1-36.
6. Dutta, S. C., Dutta, S., & Roy, R. (2009). Dynamic behavior of R/C elevated tanks with soil–structure interaction. *Engineering Structures*, *31*(11), 2617-2629.
7. Elnashai, A. S. (2001). Advanced inelastic static (pushover) analysis for earthquake applications. *Structural engineering and mechanics*, *12*(1), 51-69.
8. Iranmanesh, A., & Nikbakhti, R. (2021). Numerical study on suppressing liquid sloshing of a rectangular tank using moving baffles linked to a spring system. *Ocean Engineering*, *229*, 109002.
9. Kuria, K. K., & Kegyes-Brassai, O. K. (2023). Pushover Analysis in Seismic Engineering: A Detailed Chronology and Review of Techniques for Structural Assessment. *Applied Sciences*, *14*(1), 151.
10. Lee, J. W. (1996). *Plastic Collapse and Deformation Behaviour in Pipe-On-Pipe Impact*. The University of Manchester (United Kingdom).
11. Liu, J., Wang, W., & Dasgupta, G. (2014). Pushover analysis of underground structures: Method and application. *Science China Technological Sciences*, *57*, 423-437.
12. Rimal, H., Campus, I. T., & Kathmandu, N. Seismic Strengthening of Intze Type RC Elevated Water Tank by Jacketing: A Pushover Approach.
13. Sree, K., & Reddy, D. (2016). A Study on Design of Water Tanks using SAP. *International Journal of Science Engineering and Technology Research*, *5*(29), 6136-6140.