Performance Study of Elevated Water Tanks under Seismic Forces

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Abstract – *Elevated water tanks are frequently used in seismic active regions and because of that the seismic behavior of them needs to be carefully analyzed and dealt with. Due to lack of understanding most of the elevated tanks were damaged in the past earthquakes and hence there is a need to properly understand the different factors governing the design. At present, IS 1893:1984 describes the seismic force criteria for elevated water tanks. The code does not take into account for the convective and impulsive pressure in the analysis of the tank and also assumes the tank to be a single degree of freedom system. The objective of this work is to assess the impact of earthquake forces on two types of tank systems based on their support mainly classified as Framed Staging and Shaft Staging. Response Spectrum Analysis is carried out and behavior of these staging systems is studied as per draft code Part II of IS 1893:2006 and IITk's GSDMA guidelines. Parameters such as Base Shear, Nodal Displacement, Overturning Moment, and Vibration Analysis are obtained from an FEM software STAAD-Pro.*

Key Words: Frame Type Staging, Shaft Type Staging, Single degree of freedom, Impulsive pressure, Convective pressure.

1. INTRODUCTION

The progress in the scientific research into the dynamic behavior of liquid storage tanks reflects the increasing significance of these structures. Early uses for liquid containers were found in the petroleum industry and in municipal water supply systems. As time progressed the use of these types of storage is not just limited to storage of flammable liquids or water but also extended to nuclear reactor installation and thus making the study of their vibration properties a matter of prime importance. Safety of elevated tanks is of significant importance as tanks carrying large volume of different types of liquids within them. Water tanks are circular, rectangular, square, conical or intze type. Based on their supporting system elevated tanks can be classified as framed staging and shaft staging tanks. Due to the importance of water in dire circumstances such as an earthquake this study is primarily focused on the seismic performance of an elevated water tank. The objective of this study is to analyze the two types of elevated water tanks namely Frame type and Shaft type using FEM software STAAD-Pro and compare their results and establish which one is better performing under seismic loads. The seismic design criteria in India is given by IS 1893-2002 (Part I) which illustrates minimum loading standards and IS 4326-1993 which gives the design and detailing requirements for constructions of building structures.

2. LITERATURE REVIEW

Significant research was carried out on seismic design of liquid storage tanks and a few published works on seismic response characteristics of reinforced concrete water tanks. G.W. Housner [1] investigated the response of the tanks which were supported on ground and elevated tanks during the Chilean earthquake of May 1960. He studied that when an elevated water tank is completely filled or completely empty it may be treated as a single degree of freedom system. Whereas when the tank is partially filled with water the same idealization does not hold good and hence stated the convective effect in the tank which was primarily due to the sloshing of water to the tank wall. Jain Sudhir k [2] investigated that the IS code provisions and observed there was absence of a proper value which should take into consideration the performance factor of the tank. Analysis of few tanks suggested that the idealization based on the code is not adequate enough to counter the lateral forces differences and the final result depends heavily on the dimensions of the tank and the stiffness of support system. Durgesh C Rai [3] investigated that the current design of the circular shaft type staging was very poor and the tanks designed using those parameters were extremely vulnerable under lateral loads. He also studied the tanks which were damaged in 2001 Bhuj earthquake and that was taken as a benchmark in his study. Pavan S Ekbote [4] studied the response of the elevated tank and considered certain parameters and theories which were recommended by G.W Housner [1] which are more acceptable and are being adopted in many of the international codes. Their aim was to study the performance of the elevated water tanks under different kinds of staging patterns. Rupachandra J Aware [5] investigated and studied the seismic performance of circular elevated water tank as per the draft code of IS 1893:2002 (part 2). It was mentioned that complex pattern of stresses are developed in the staging and circular walls of the tank. Their objective was to analyze the tank at different staging height corresponding to different seismic zones of India. Dona Rose K J [6] studied the response of an elevated circular type water tanks to dynamic forces. Tanks of various capacities with different staging height are modeled using ANSYS software. The analysis is carried out for two cases namely, tank full and half level condition considering the sloshing effect along with hydrostatic effect. Time history analysis using draft code of IS 1893-2002 (part2) and the acceleration data from El Centro earthquake was taken. The peak displacements and base shear obtained from the analysis were also compared along with displacements. Jay Lakahnakiya [7] analyzed the hydrodynamic pressure of intze tank and comparison of the cost of water tank for different staging conditions like shaft and frame type. Staging part was analyzed in Staad Pro. V8i and the design was done in excel worksheet. After the complete design the quantity of material has been found and then costing of water tank is done using supply and sewage board. Mor Vytankatesh K. et al [8] studied the impact of seismic forces on RC shaft and framed type with different capacities which were placed in different seismic zones. Comparison of elevated tanks with different system capacities and seismic zones states that these parameters may considerably change the seismic behavior of tanks.

3. OBJECTIVE

- To determine the hydrodynamic effects on elevated water tank, with different supporting systems i.e., framed staging and concrete shaft placed in different seismic zones, using the Housner's model.
- To determine maximum nodal displacement at the top.
- Free vibration analysis for both frame type and shaft type staging in Zone II and Zone IV.
- To determine overturning moment over the height for frame type and shaft type staging.
- To determine base shear for frame type and shaft type staging.

4. DESCRIPTION OF HOUSNER'S (1963) (1) MODEL

Elevated water tanks usually are never completely filled, due to which considering it as single degree of freedom system is not satisfactory. Therefore a partially filled tank cannot be idealized as a single degree of freedom system without taking into account the sloshing effect. The lateral stiffness for the frame type staging can be calculated by any FEM based software or manually, whereas the stiffness calculation for the shaft type staging is calculated by applying a horizontal force at the center of gravity of the tank and the unit nodal displacements are noted.

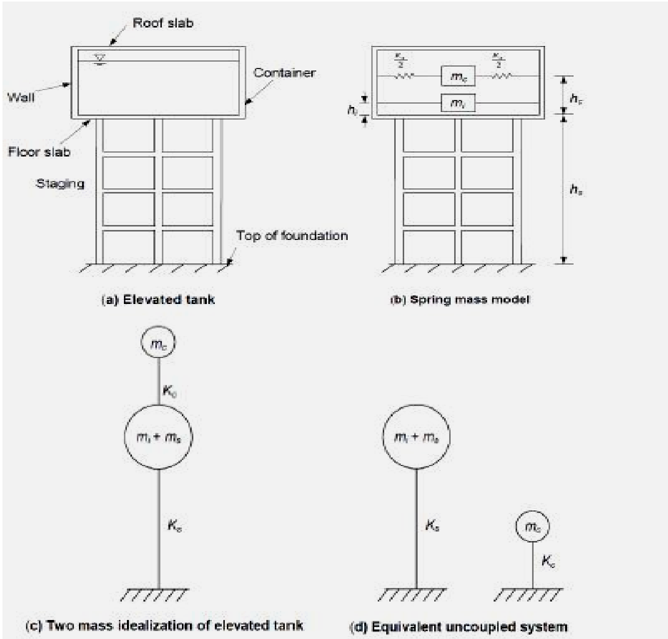

Fig 1 Two mass idealization as proposed by Housner

When the liquid mass in the tank is divided into two parts as shown in the above figure 1, the mass which vibrates along with the tank wall is called the impulsive mass. The mass which vibrates relative to the tank wall is called the convective mass. Housner (1963) [1] explained about the two mass model of elevated tank. In figure 1 we can see the masses "mc" and "mi" which represent the convective and impulsive masses respectively and "Kc" is corresponding stiffness. Figure 2 shows the pattern in which the impulsive and convective pressures are to be applied with "hi" and "hc" being the heights of the impulsive pressure (including base pressure) and convective pressure (including base pressure) respectively.

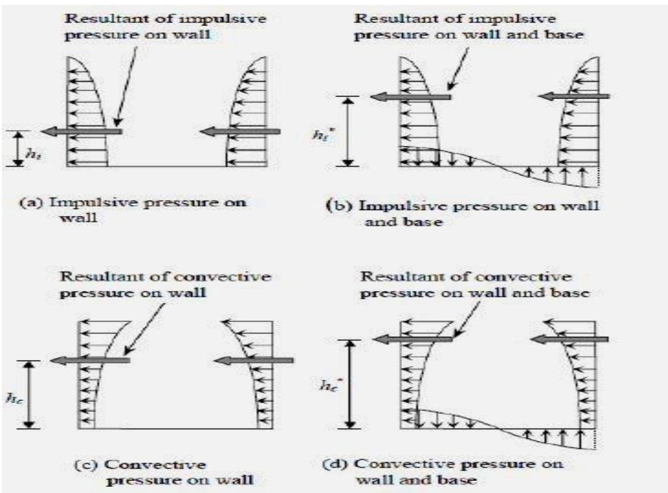

Fig 2 Hydrodynamic Pressure Distribution on Tank Walls

Parameters of elevated water tank

Sl. No	Parameters	Values
1	Diameter of the tank	10 m
2	Height of Cylindrical Wall	3 m
3	Thickness of Cylindrical Wall	200 mm
4	Height of Staging	20 m
5	Number of Columns	8
6	Size of Column	600 x 600 mm
7	Size of Top Ring Beam	200 x 600 mm
8	Size of Bottom Ring Beam	200 x 600 mm
9	Size of Bracing	200 x 400 mm
10	Thickness of Top Dome	120 mm
11	Thickness of Bottom Dome	200 mm
12	Density of Concrete	25 kN/m^3
13	Zone	II & IV
14	Response Reduction Factor	2.5
15	Importance Factor	1.5
16	Type of Soil	Hard (zone II), Soft (Zone IV)

Table 1 Parameters of the Elevated Tank

Values of Partial Safety Factor γf for Loads						
(Clauses 18.2.3.1, 36.4.1 and B- 4.3)						
Load Combination	Limit State of Collapse			Limit State of Serviceability		
	DL	IL	WL	DL	IL	WL
(1)	(2)	(3)	(4)	(5)	(6)	(7)
DL + IL	1.5		1.0	1.0	1.0	-
DL + WL	1.5	-	1.5	1.0	-	1.0
	or 0.9(1)					
DL + IL + WL	1.2			1.0	0.8	0.8

Table 2 Applied Load Combinations

NOTES

1. While considering earthquake effects substitute EL for WL.
2. For the limit state of serviceability, the values of γf given in this table for short term effects. While assessing the long term effects due to creep the dead load and hat part of the live load likely to be permanent may only be considered.
3. (1) This value is to be considered when stability against overturning or stress reversal is critical.

5. ELEVATED TANK WITH FRAME TYPE STAGING

Frame type stagings are used widely as compared to shaft type staging primarily because they are much better in performance. Earthquakes in the recent past have proved that the frame type staging performs much better than the shaft type staging. It primarily performs better because of the higher redundancy and due to the fact that it more ductile. The frame type staging consists of combination of beams and columns which makes it much more ductile and performs better in the event of an earthquake. The geometric properties of the tank primarily depend on the capacity and the height of the staging may vary from 10 to 20m. Generally for circular type of tank the diameter usually depends on the capacity.

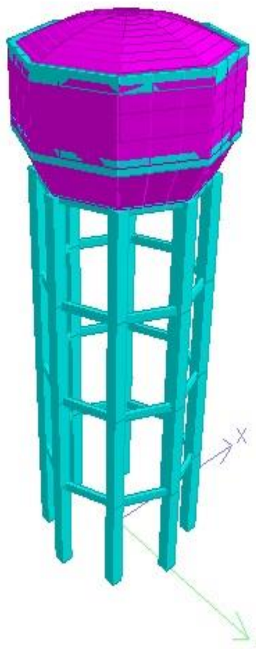

Fig 3 Framed Type model prepared in Staad-Pro

6. ELEVATED TANK WITH SHAFT TYPE STAGING

Due to their ease of construction and more solid form the shaft type staging is adopted for larger capacities. Earthquakes in the recent past have proved that the shaft type staging is much more vulnerable as compared to the frame type staging. The lack of ductility and also lower redundancy of the shaft adds to the vulnerability of it.

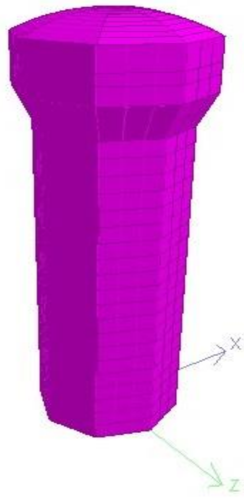

Fig 4 Shaft Type model prepared in Staad-Pro

However for STAAD Pro analysis the pressures applied on the base of the wall of the tank and on the base slab are taken to be

i. ρ g hi*(impulsive mode) = 1x9.81x4.44 = 43.55 kN/m2

ii. ρ g hc*(convective mode) = 1x9.81x3.67 = 36.00 kN/m2

Where

ρ = Density of Water (kN/m^3).
g = Acceleration due to gravity (m/sec^2).
hi* = Height of Impulsive mass above the bottom of the tank (including base pressure).
hc*= Height of Convective mass above the bottom of the tank (including base pressure).
The shaft type staging can also be imagined as an inverted pendulum and hence it can be assumed that maximum resistance is going to be offered by the hollow shaft section. The load carrying capacity can be seriously hampered if there is any damage to the staging at the critical section. The dimensions of the tank primarily depend on the capacity and the height of the staging may vary from 10 to 20m. Generally for circular type of tank the diameter usually depends on the capacity it is supposed to carry but the thickness of the shaft usually varies between 120 mm to 200mm.

7. RESULTS AND DISCUSSION

1. <u>Results for Convective Pressure</u>

i. Time Period

Convective Mode		
Mode	Frame Type	Shaft Type
1.00	2.09340	0.31858
2.00	2.09340	0.31858
3.00	1.43227	0.12214
4.00	0.21799	0.07298
5.00	0.21788	0.07298
6.00	0.19351	0.06481

Table 3 Time Period for Frame & Shaft type Staging

- Time periods in various modes for the frame type staging are much higher compared to those of shaft type staging.

ii. Comparison of Base Shear

Base Shear (kN)		
Type of Staging	Zone II	Zone IV
Shaft	567.81	1848.52
Frame	369.77	981.46

Table 4 Base Shear Results for frame & Shaft type Staging

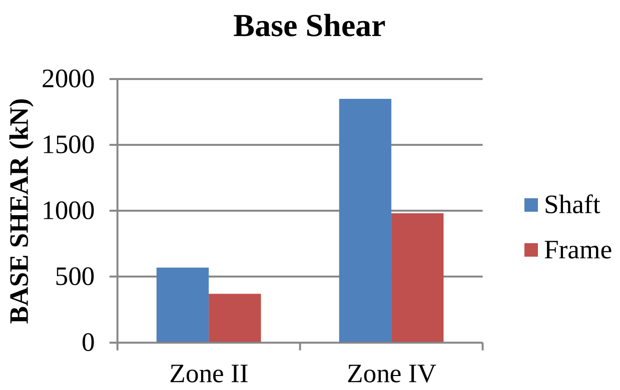

Chart-1 Base Shears in Convective Mode

- Figure 5 shows that the base shears for the frame type staging in Zone II and Zone IV are comparatively lower compared to those of shaft type staging.

iii. Nodal Displacements in Convective Mode

Nodal Displacements (mm)		
Type of Staging	Zone II	Zone IV
Shaft	3.509	11.331
Frame	70.069	231.98

Table 5 Nodal Displacements for frame & Shaft type Staging

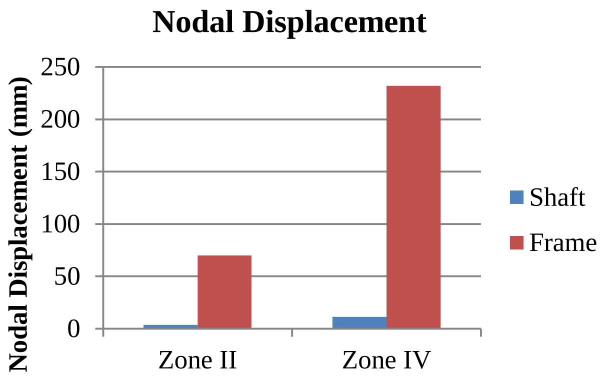

Chart-2 Nodal Displacements in Convective Mode

- From the above figure it is clear that the nodal displacements are higher for the frame type staging as compared to those of shaft type staging.
- It also proves that the frame type staging is more flexible as compared to shaft type staging.
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iv. Overturning Moments in Convective Mode

Overturning Moments (kN-m)		
Type of Staging	Zone II	Zone IV
Shaft	323.61	1424.66
Frame	232.631	732.113

Table 6 Overturning Moment for Frame & Shaft type Staging

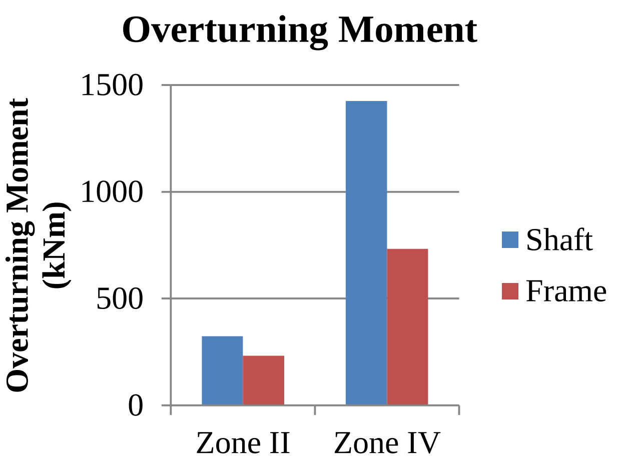

Chart-3 Overturning Moment

- Since overturning moment is a governing factor in the design of an elevated water tank, it is observed that the overturning moment is higher for the shaft type staging as compared to frame type staging.

2. Result for Impulsive Pressure

i. Time Period

Impulsive Mode		
Mode	Frame Type	Shaft Type
1.00	2.214770	0.341130
2.00	2.214770	0.341130
3.00	1.521870	0.129660
4.00	0.218130	0.073630
5.00	0.218140	0.073630
6.00	0.193500	0.067270

Table 7 Time Period Results for Frame & Shaft type Staging

- Time periods for the frame type staging are much higher as compared to those of shaft type staging.
- Also as seen in the above table the time periods in impulsive mode values are much higher as compared to those in convective mode.

ii. Base Shear

Base Shear (kN)		
Type of Staging	Zone II	Zone IV
Shaft	710.46	2855.44
Frame	629.03	2507.02

Table 8 Base Shears for frame & Shaft type Staging

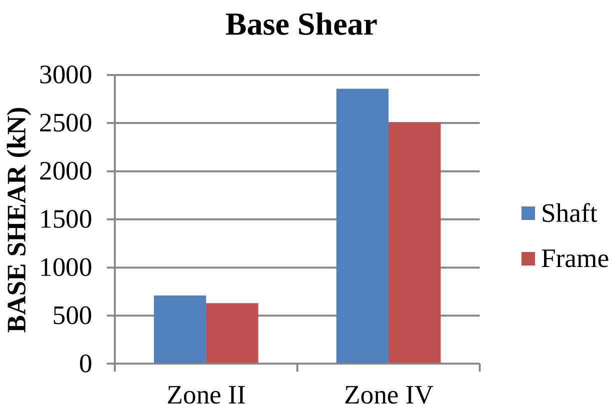

Chart-4 Base Shears in Impulsive Mode

- Figure 8 shows that the Base shears for the frame type staging in Zone II and Zone IV are comparatively lower compared to those in shaft type staging.
- It can also be seen that the base shear values of the impulsive mode are higher as compared convective mode.

iii. Nodal Displacements

Nodal Displacements (mm)		
Type of Staging	Zone II	Zone IV
Shaft	38.66	154.22
Frame	148.53	600.707

Table 9 Nodal Displacements in Impulsive Mode

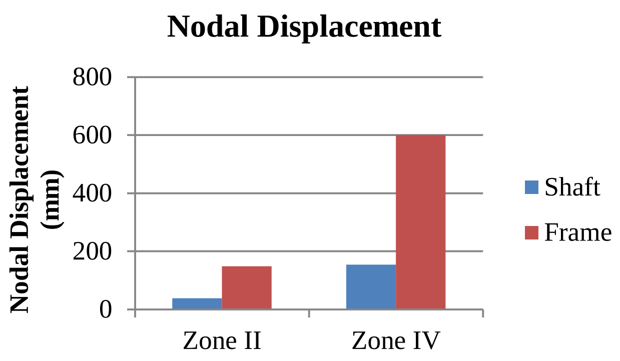

Chart-5 Nodal Displacements in Impulsive Mode

- From the above figure it is clear that the nodal displacements are higher for the frame type staging compared to those in shaft type staging.
- It may also be seen in the impulsive mode that the displacement values are much higher compared to those in convective mode.

iv. Overturning Moments

Table 10 Overturning Moments for Frame & Shaft type Staging

Overturning Moments (kN-m)		
Type of Staging	Zone II	Zone IV
Shaft	829.52	2420.14
Frame	466.026	1871.95

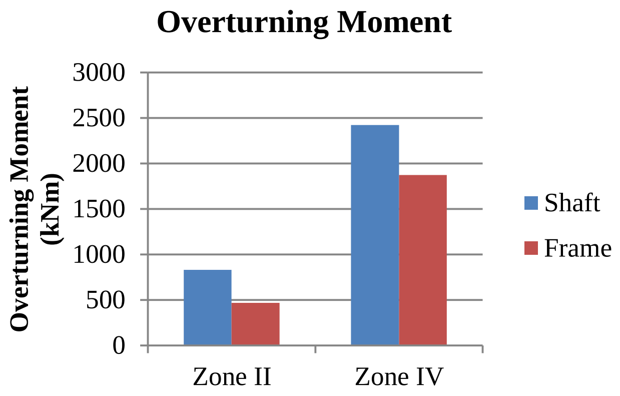

Chart-6 Overturning Moment

- Since overturning moment is a governing factor in the design of an elevated water tank, it is observed that the overturning moment is higher for the shaft type staging as compared to that in frame type staging.
- Also the overturning moment values in impulsive mode are much higher as compared to the convective mode.

8. CONCLUSIONS

- Base shear is higher in the shaft type staging as compared to the frame type staging for convective and impulsive mode.
- The increment in base shear is much higher as compared to hard soil to soft soil.
- The nodal displacement values in shaft type are very low as compared to the frame type staging which suggests that the frame type staging is much more flexible and can return to its original position after a large deflection from its mean position.
- The nodal displacement values are much higher in impulsive mode as compared to convective mode.
- The shaft type staging has higher base shear values but lower nodal displacements values suggesting that the shaft type staging is brittle compared to frame type staging.
- During designing an elevated water tank primary importance is given to the overturning moment, since large mass accumulates at the top of slender supporting system it is observed that the overturning moment for frame staging is less than that of tanks supported on shaft type staging.
- Time period in convective and impulsive are similar for both frame type and shaft type staging.
- Sloshing wave height is approximately same for the tanks, as it majorly depends on the capacity of the tank.

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