Seismic Performance of Circular Elevated Water Tank

Rupachandra J. Aware[1], Dr. Vageesha S. Mathada[2]

[2]Guide, Shri Vitthal Education & Research Institute College of Engineering, Pandharpur

Abstract: ***Liquid storage tanks are used in industries for storing chemicals, petroleum products, and for storing water in public water distribution systems. Behaviour of Cylindrical liquid storage tanks under earthquake loads has been studied as per Draft code Part II of IS 1893:2002. A FEM based computer software (STAAD -PRO) used for seismic analysis of tanks which gives the earthquake induced forces on tank systems. Draft code Part II of IS 1893:2002 which will contain provisions for all types of liquid storage tanks. Under earthquake loads, a complicated pattern of stresses is generated in the tanks. Poorly designed tanks have leaked, buckled or even collapsed during earthquakes. Common modes of failure are wall buckling, sloshing damage to roof, inlet/outlet pipe breaks and implosion due to rapid loss of contents. Elevated water tanks should be competent of keeping the expected performance during and after earthquake. It has large mass concentrated at the top of slender supporting structure hence extremely vulnerable against horizontal forces due to earthquake. Staging is formed by a group of columns and horizontal braces provided at intermediate levels to reduce the effective length of the column. In this research, a circular cylindrical elevated water tank is analysed by using finite modelling techniques. This paper presents the study of seismic performance of the elevated water tanks for various heights and various seismic zones of India. The effect of height of water tank, earthquake zones on Nodal displacement have been presented in this paper with the help of analysis of 20 models for same parameters. Analysis is carried out by using finite element software STAAD-PRO.***

Keywords: Elevated Circular Cylindrical Tank, Damages, Frame type staging, Nodal Displacement, Finite Element Software (STAAD-PRO).

1. Introduction

Elevated tank structures are normally used to store water for domestic activities and also fire fighting purposes. Their safety performance is a critical concern during strong earthquakes. The failure of these structures may cause serious hazards for citizens due to the shortage of water or difficulty in putting out fires during earthquakes. Some elevated tanks have shown insufficient seismic resistance in past earthquakes which had prevented the fire fighting process and other emergency response efforts (Barton and Parker, 1987). There have been several studies in which the dynamic behaviour of liquid storage tanks have been analyzed, however most of them have focused on ground level cylindrical tanks, and very few of them have concentrated upon behaviour of elevated tanks. They are heavy structures which a greater portion of their weight is concentrated at an elevation much about the base. Critical parts of the system are columns and braces through which the loads are transmitted to the foundation. Due to the high sensitivity of elevated water tanks to earthquake characteristics such as frequency contents, peak ground acceleration and effective duration of the earthquake records, it seems necessary to ponder the earthquake loading as a non-stationary random pattern.

2. Literature Review

Significant research was carried out on a seismic design of liquid storage tanks and a few published works on seismic response characteristics of reinforced concrete (RC) water tanks are reviewed in this section. Jain and Sajjad [11] reviewed the I.S. code provisions for seismic design of elevated water tanks, based on seismic codes of other countries and reports of several investigations and made a valid observation that the seismic design force in IS 1893-1984 is rather low owing to the absence of suitable performance factor that must be in the range of 3.0-4.5. Jaiswal and Jain [9,10] proposed major modifications in respect of seismic design of liquid storage tanks, recognizing the limitations in the provisions of IS: 1893-1984 and provided commentary & examples on the modified provisions. Vamsidhar [13] analyzed sixteen different types of tanks using IS: 1893-1984 and the proposed specification IS: 1893-2002 (part-2) draft code. It has been observed that there is an increase of 15% to 25% in hydrodynamic forces over hydrostatic forces and 50% increase of base shear in zone- IV as compared to the current specifications. Hirde et. al [3] studied the seismic performance of elevated water tanks of various heights & capacities under varying zones & soil types of India. It was concluded that earthquake forces decrease with increase in staging height for the reason that with increasing staging height the structure becomes more flexible. Gaikwad [1] reviewed the behaviour of elevated water tank by performing static and dynamic analysis, to compare the analysis results of elevated water tank, in order to study the effect of hydrodynamic forces on elevated water tank. Gaikwad[2] studied the behaviour of elevated water tank with framed staging when subjected to lateral earthquake load using IITK-GSDMA Guidelines. Ekbote [12] conducted a study to know the behaviour of supporting system. Different supporting systems such as radial bracing and cross bracing have been used and compared. The reasons for failure of elevated tanks were reviewed and realized that improper behavior of supporting system and improper geometrical selection of staging patterns are the main causes.

3. Modes of Failures

The damage modes of the tanks are as follows
1) Buckling in the side walls
2) Failure of the tank roofs and their junctions
3) Sliding and lifting

4) Local fracture on the bases of the tanks and uneven settlement
5) Failure of anchor bolts
6) Cracking of annular parts of the base plate

1) Buckling in the side walls

The buckling modes of the side walls of tanks include shear buckling and bending buckling. The bending buckling includes diamond buckling and elephant foot bulges. These buckling modes are associated with geometry parameters of the tanks such as height to radius ratio and radius to thickness ratio. Shear buckling occurs for small ratios of height to radius and bending buckling predominantly occurs for large ratios. Shear buckling is caused by shear force and brings about many large diagonal wrinkles in the centre of a tank side wall. Diamond buckling is one of the bending buckling modes caused by the bending moment and it is generated on the base of a tank. When the buckling occurs, the cross section at the buckling region bends inward and has many wrinkles. Because the deformation is drastic, the structural strength (proof force) of the tanks decreases suddenly. Diamond buckling became widely know after it occurred in many wine storage tanks in the 1980Greenville-Mt. Diablo earthquake. The elephant foot bulge is another bending buckling mode. This buckling mode was widely seen in the 1964 Alaska mega earthquake, the 1971 San Fernando earthquake and the 1994 Northridge earthquake and can cause spill incidents of liquid in the tanks through crack penetration. In the elephant foot bulge, the buckling cross section expands outward in a ring and the structural strength (proof force) decreases relatively gently through a gradual increase of the expansion. The occurrence condition of diamond buckling and the elephant foot bulge depends on the circumferential stress due to the internal pressure in the tanks, that is, hoop stress. The former occurs when the hoop stress is smaller and the latter occurs when the hoop stress is larger. In the 1995 Hyogoken - Nanbu earthquake, many observations of diamond buckling and elephant foot bulges were made in cylindrical liquid storage tanks.

(a) (b)

Figure 3.1: (a) Elephant Foot Buckling (b) Diamond Shape Buckling

2) Failure of the tank roofs and their junctions

The failure of tank roofs and their junctions is mainly caused by sloshing. This occurred in the 1964 earthquakes in Niigata and Alaska. More recently, the roofs and junctions of some petroleum tanks failed in the Kocaeli earthquake in Turkey and in the Chi-Chi earthquake in Taiwan, both in 1999. In Japan, a few petroleum tanks also failed in the 2003 Tokachi-Oki earthquake. In all three of these earthquakes, the floating roofs were damaged and fires broke out.

(a) (b)

Figure 3.2: (a) Damage to the roof or the Upper shell of the tank (b) Sliding and lifting of base plates

3) Sliding and lifting

The sliding of tanks and lifting of base plates were observed in the 1964 Alaska earthquake. Sliding and lifting of base plate is shown in fig. 3.2 (b)

4) Local fracture on the bases of tanks, uneven settlement and failure of anchor bolts

Local fracture on the bases of tanks, uneven settlement and failure of anchor bolts occurred in the 1995 Hyogoken - Nanbu earthquake. Failure of anchor bolt shown in fig. 3.3 (a).

5) Cracking of annular parts of base plates

In the 1978 Miyagiken-Oki earthquake, cracking of annular parts of base plates occurred in petroleum tanks and stored petroleum leaked out. Cracking of annular parts of base plates of tank is shown in fig. 3.3(b).

(a) (b)

Figure 3.3: (a) failure of anchor bolts (b) cracking of annular parts of base plates

4. Spring Mass Model for Elevated Tank:-

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 liquid mass which accelerates along with the wall and induces impulsive hydrodynamic pressure on tank wall and similarly on base. Liquid mass in the upper region of tank undergoes sloshing motion. This mass is termed as convective liquid mass and it exerts convective hydrodynamic pressure on tank wall and base.

Thus, 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.

A qualitative description of impulsive and convective hydrodynamic pressure distribution on tank wall and base is given in Figure 3.1

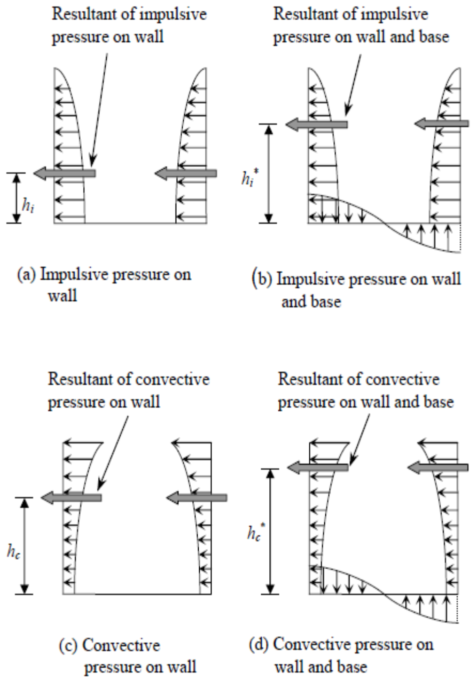

Figure 4.1: A qualitative description of impulsive and convective hydrodynamic pressure distribution on tank wall and base

4.1 Description of Model

Most elevated tanks are never completely filled with liquid. Hence a two-mass idealization of the tank is more appropriate as compared to a one mass idealization, which was used in IS 1893: 1984. Two mass model for elevated tank was proposed by Housner (1963b) and is being commonly used in most of the international codes.
Structural mass *ms*, includes mass of container and one-third mass of staging. Mass of container comprises of mass of roof slab, container wall, gallery, floor slab, and floor beams.

Staging acts like a lateral spring and one-third mass of staging is considered based on classical result on effect of spring mass on natural frequency of single degree of freedom system.

The response of the two-degree of freedom system can be obtained by elementary structural dynamics. However, for most elevated tanks it is observed that the two periods are well separated. Hence, the system may be considered as two uncoupled single degree of freedom systems. This method will be satisfactory for design purpose, if the ratio of the period of the two uncoupled systems exceeds 2.514. If impulsive and convective time periods are not well separated, then coupled 2-DOF system will have to be solved using elementary structural dynamics. In this context it shall be noted that due to different damping of impulsive and convective components, this 2-DOF system will have non-proportional damping.

For elevated tanks [5], the two degree of freedom system of Figure c can be treated as two uncoupled single degree of freedom systems (Figure d), one representing the impulsive plus structural mass behaving as an inverted pendulum with lateral stiffness equal to that of the staging, Ks and the other representing the convective mass with a spring of stiffness, Kc. For tank shapes other than circular and rectangular (like intze, truncated conical shape), the value of h / D shall correspond to that of an equivalent circular tank of same volume and diameter equal to diameter of tank at top level of liquid; and mi , mc , hi, hi*, hc , hc* and Kc of equivalent circular tank shall be used.

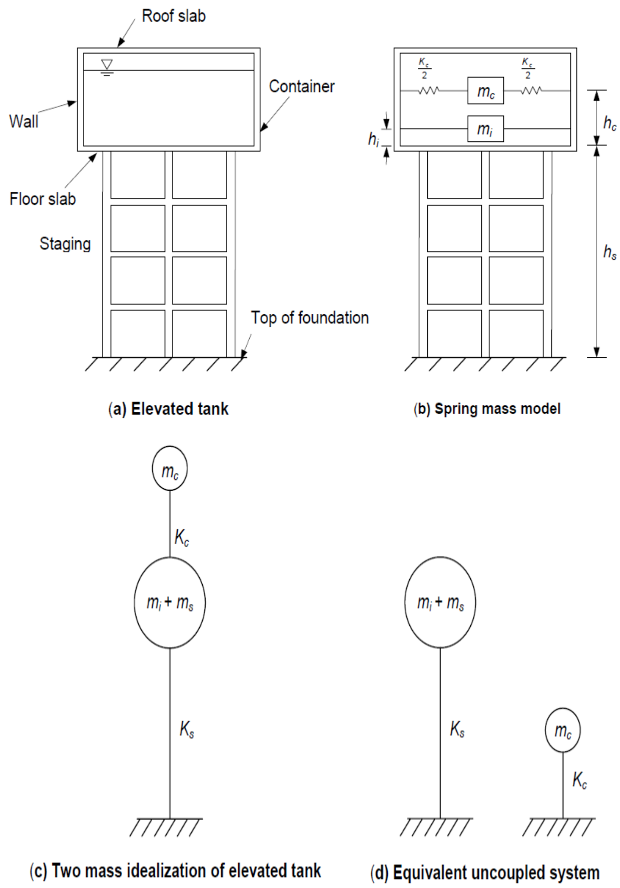

Figure 4.2: Two Mass Idealization of Elevated Tank

For elevated tanks with moment resisting type frame staging, the lateral stiffness can be evaluated by computer analysis or by simple procedures or by established structural analysis method.

For elevated tanks with shaft type staging, in addition to the effect of flexural deformation, the effect of shear deformation may be included while calculating the lateral stiffness of staging.

Lateral stiffness of the staging is the horizontal force required to be applied at the centre of gravity of the tank to cause a corresponding unit horizontal displacement. The flexibility of bracing beam shall be considered in calculating the lateral stiffness, *Ks* of elevated moment resisting frame type tank staging.

4.2 The important factors that affect the magnitude of earthquake forces are-

(a) Seismic zone factor, Z

India has been divided into four seismic zones as per IS 1893 (Part 1): 2002 for the Maximum Considered Earthquake (MCE) and service life of the structure in a zone. Different zone have different zone factor. Figure 3.3 shows seismic zone map of India. India is divided into four seismic zones. There are three types of soil considered by IS 1893 (Part 1): 2002 i.e. soft medium and hard soil.

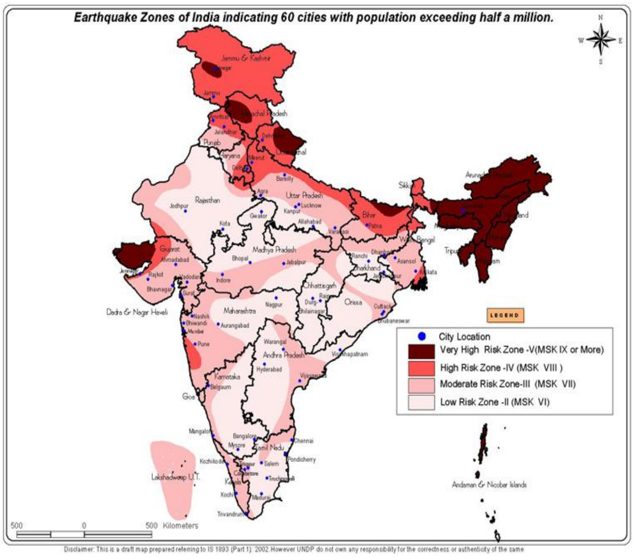

Figure 4.3: Earthquake Zones of India

(b) Importance factor, I

Importance factor depends upon the functional use of the structures, characterized by hazardous consequences of its failure, post-earthquake functional needs, historical value, or economic importance. Elevated water tanks are used for storing potable water and intended for emergency services such as fire fighting services and are of post earthquake importance. So importance factor is 1.5 for elevated water tank.

(c) Response reduction factor, R

Response reduction factor depends on the perceived seismic damage performance of the structure, characterized by ductile or brittle deformations. R values of tanks are less than building since tanks are generally less ductile and have low redundancy as compared to building. For frame confirming to ductile detailing i.e. special moment resisting frame (SMRF), R value is 5.

(d) Structural response factor, (Sa/g)

It is a factor denoting acceleration response spectrum of the structure subjected to earthquake ground vibrations, and depends on natural period of vibration and damping of the structure.

5. Objective of the Study

The main objective of this study is to examine the nodal displacement of Elevated circular cylindrical water tank supported on frame staging considering different height and zone and plotting the graphs as max. nodal displacement Vs height and max. nodal displacement Vs zone.

5.1 Capability of Staad- Pro software

STAAD.Pro.v8i is the most popular structural engineering software product for 3D model generation, analysis and multi-material design. It has an intuitive, user-friendly GUI, visualization tools, powerful analysis and design facilities and seamless integration to several other modelling and design software products. For static or dynamic analysis of bridges, containment structures, embedded structures (tunnels and culverts), pipe racks, steel, concrete, aluminium or timber buildings, transmission towers, stadiums or any other simple or complex structure, STAAD.Pro has been the choice of design professionals around the world for their specific analysis needs.

5.2 Modelling of Water tank

For this study, water tanks with five different heights such as 5m, 10m, 15m, 20m and 25m are considered, and each water tank is placed in Zone 2, 3, 4, and 5. The effect of heights of tank and earthquake zones on nodal displacement is observed with the help of analysis of 20 models having same parameters.

Here the seismic coefficient method is performed for the water tank by using the software package STAAD.Pro. Special care needs to be taken while modelling water tank in STAAD.Pro in defining properties and orientation of various elements. It is also necessary to choose the proper element type and specify ply orientation. Here line elements are used for modelling the ring beam, bracing, column and area elements (Plate) are used for top dome, bottom slab, and cylindrical wall.

Steps followed for modelling the staging and tank container STAAD-PRO:

1) **Modelling geometry:** Here water tank geometry is model by using grid system.
2) **Define element type:** Here frame type element is used for top ring beam, bottom ring beam, bracing, column and area element (plate) is used for top dome, bottom slab, and cylindrical wall.
3) **Define Material properties:** Here we provide the properties of the beam and plate such as elastic modulus, Poisson's ratio, mass density, compressive strength etc
4) **Define Section properties:** Prismatic rectangle sections define the width and depth for top ring beam, bottom ring beam, bracing, and prismatic circle define the diameter for column. Area sections define thickness for plate element.
5) **Seismic Definition:** In seismic definition select type of code, define zone, response reduction factor, importance factor, type of soil, type of structure, damping ratio, and foundation depth etc.
6) **Apply loads and boundary condition:** Define menu provides option for specifying the boundary conditions and loads.
7) **Base Shear results:** The solution is obtained using the display option in main menu.

5.3 Problem Description

Model 1

An elevated, circular cylindrical shape water container is supported on RC staging of 8 columns with horizontal bracings of 225 x 300 mm at four levels i.e. height of panel is equal to 3m. Staging conforms to ductile detailing as per IS 13920. Grade of concrete and steel are M25 and Fe415, respectively. Tank is located on hard soil in seismic zone II. Density of concrete is 25kN/m². The FEM structural software STAAD - PRO is used to model the elevated circular cylindrical water tank as shown in Fig. Columns and beams in the frame type support system are modelled as frame elements. Top domes, container walls and bottom slab of container are modelled with thin plate elements. Other dimensions of the elevated tanks are illustrated in Table 5.1.

5.1: Parameters of Elevated Water Tank

S.N	Parameters	Values
(1)	(2)	(3)
1	Diameter of tank	10 m
2	Height of Cylindrical Wall	5 m
3	Thickness of Cylindrical Wall	150 mm
4	Height of staging	12 m
5	Height of Panel	3 m
6	Number of columns	8
7	size of column	450 mm dia.
8	size of top ring beam	150x300 mm
9	size of bottom ring beam	450x800 mm
10	size of bracing	225x300 mm
11	thickness of bottom slab	225 mm
12	thickness of dome	75 mm
13	density of concrete	25 kN/sq.m
14	Zone	IV(0.24)
15	Response reduction factor	5 (SMRF)
16	Importance factor	1.5 for water tank
	Type of soil	hard soil

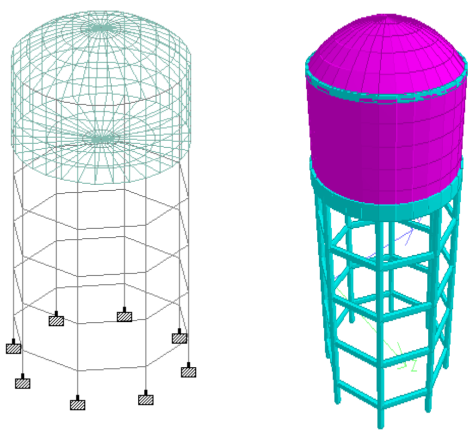

Figure 5.1: a) Typical cylindrical b) 3D View of cylindrical water tank water tank

6. Results obtained from STAAD PRO analysis

In this paper an attempt is made to study the seismic performance of the elevated water tanks. For all the above mentioned 20 water tanks, analysis has been carried out by using STAAD-PRO software. Earthquake analysis is carried out for different heights and different earthquake zones. The main objective of this paper was to study the effect on nodal displacement on reinforced concrete elevated water tank in seismic zones II, III, IV and V for different heights of the elevated water tank.

6.1. Max. Nodal Displacement obtained from Staad-Pro Analysis

Max nodal displacement of 20 models shown in table 6.1. Nodal displacement is maximum at roof of any tank. The position of node where maximum displacement in5m height of tank is shown in fig 6.1 (a) and the position of node where maximum displacement in 10m height of tank is shown in fig. 6.1 (b)

Table 6.1: Maximum Nodal Displacement

Sr. No.	*Tank Height*	*Zone*	*Nodal Displacement (mm)*
1	5m	II	39.916
		III	63.866
		IV	95.800
		V	143.699
2	10m	II	60.286
		III	96.457
		IV	144.686
		V	217.029
3	15m	II	76.793
		III	122.869
		IV	184.304
		V	276.456
4	20m	II	89.657
		III	143.452
		IV	215.178
		V	322.767
5	25m	II	100.598
		III	160.956
		IV	241.435
		V	362.152

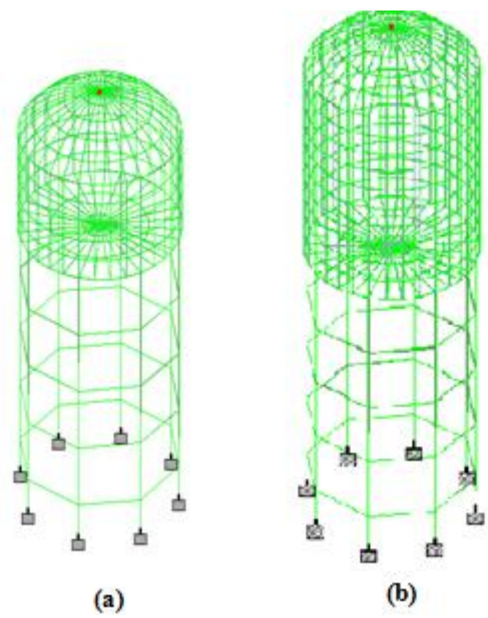

Figure 6.1: Position of node (a) Max. nodal displacement occurred at node no. 14 in 5m tank (b) Max. nodal displacement occurred at node no. 20 in 10m tank

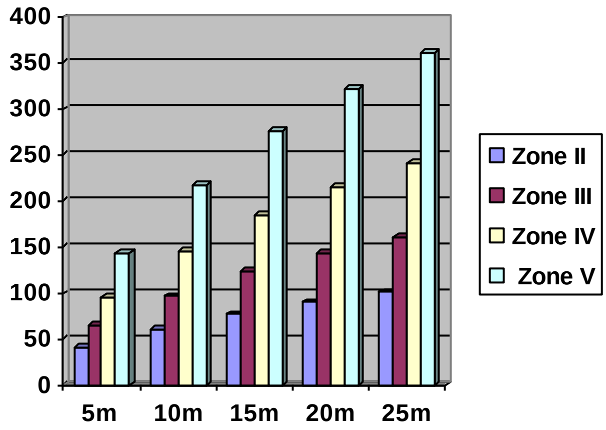

Figure 6.2: Maximum Nodal Displacement Vs Height of tank

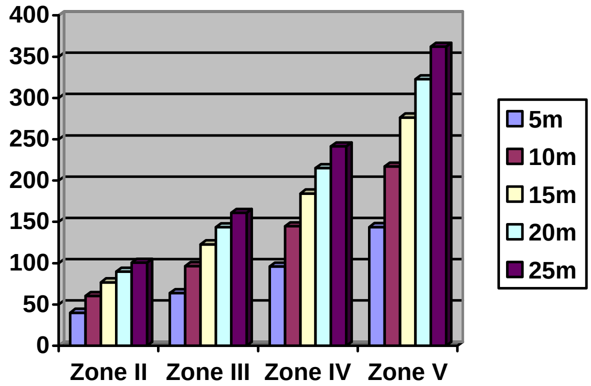

Figure 6.3: Maximum Nodal Displacement Vs Earthquake Zones

7. Discussions on Results

1. Effect of Nodal Displacement on Base Shear

The results obtained from analysis are analyzed and shown in graphical form. The table 6.1 reveals maximum nodal displacement from STAAD PRO analysis, though it is evident that 5m height of water tank with zone II gives the minimum value of displacement which is 39.916mm, and 25m height of water tank with zone V gives the maximum value of displacement which is 362.152mm. Fig 6.2 and Fig 6.3 shows the graph of maximum nodal displacement Vs height and maximum nodal displacement Vs Zone respectively. From fig 6.2, it is observed that the nodal displacement successively increases with respect to height of water tank and from fig. 6.3, it is observed that the nodal displacement is increases with respect to earthquake zones.

8. Conclusion

1) Design of water tank is a very tedious method. Particularly design of elevated cylindrical water tank involves lots of mathematical formulae and calculation. It is also time consuming. Hence Staad – pro gives all results such as base shear, nodal displacement etc. from the analysis immediately.
2) As height of water tank increases max. nodal displacement increases.
3) Water tank height 5m zone II gives minimum nodal displacement.
4) Above all the models of analysis, maximum nodal displacement is minimum for WT5MZ2 and maximum for WT25MZ5
5) Present study will be useful to Civil Engineers to understand the behaviour of elevated water tank for various heights and also to get the feel of effect of earthquake zones of India on earthquake forces and nodal displacement.

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