Seismic Analysis of Cylindrical Liquid Storage Tanks

Akshaykumar B. Patil[1], Prof.V.M.Sapate[2]

[1]1M.Tech Student, Structural Engineering, G.H. Raisoni University, Amravati
[2]2Professor, Structural Engineering, G.H. Raisoni University, Amravati

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Abstract - Liquid storage tanks are widely utilized in industries for storing chemicals, petroleum products, and water in public distribution systems. The behaviour of cylindrical liquid storage tanks under earthquake loads has been studied in accordance with Draft Code Part II of IS 1893:2002. Seismic analysis of these tanks is conducted using FEM-based software, such as STAAD-PRO, which calculates the earthquake-induced forces on tank systems. The Draft Code Part II of IS 1893:2002 includes provisions for various types of liquid storage tanks. Under earthquake loads, tanks experience a complex pattern of stresses. Poorly designed tanks may leak, buckle, or even collapse during earthquakes. Common failure modes include wall buckling, roof sloshing damage, inlet/outlet pipe breaks, and implosion due to rapid content loss. In this study, a circular cylindrical elevated water tank with a capacity of 500 cubic meters is analysed using finite element modelling techniques. This paper examines the seismic performance of elevated water tanks of different heights and located in various seismic zones of India. The impact of tank height and seismic zone on earthquake forces is presented through the analysis of 20 models with consistent parameters, using the finite element software STAAD-PRO.

Key Words: Elevated circular cylindrical tank, structural damage, frame-type staging, base shear, finite element software (STAAD-PRO)

1.INTRODUCTION

Elevated tank structures are commonly used to store water for domestic use and firefighting. Ensuring their safety during strong earthquakes is crucial, as their failure can lead to serious hazards, including water shortages and difficulties in extinguishing fires. Historical events have shown that some elevated tanks lack sufficient seismic resistance, which has hindered firefighting and emergency response efforts (Barton and Parker, 1987). Although many studies have analyzed the dynamic behavior of liquid storage tanks, most have focused on ground-level cylindrical tanks, with few addressing the behavior of elevated tanks. These structures are heavy, with a significant portion of their weight concentrated well above the base. The columns and braces, which transmit the loads to the foundation, are critical components. Given the high sensitivity of elevated water tanks to earthquake characteristics such as frequency content, peak ground acceleration, and effective duration, it is essential to consider earthquake loading as a non-stationary random pattern.

There are numerous reports in the literature about the damage to liquid storage tanks caused by previous earthquakes. Significant damage occurred to both concrete and steel storage tanks during major seismic events such as the 1933 Long Beach, 1952 Kern County, 1964 Alaska, 1964 Niigata, 1966 Parkfield, 1971 San Fernando, 1978 Miyagi Prefecture, 1979 Imperial County, 1983 Coalinga, 1994 Northridge, and 1999 Kocaeli earthquakes (Rinne, 1967; Shibata, 1974; Kono, 1980; Manos and Clough, 1985; Sezen and Whittaker, 2006).

Severe damage was also observed in elevated water tanks during the 1960 Chilean, 1997 Jabalpur, and 2001 Bhuj earthquakes in India. During the Bhuj earthquake, many elevated tanks suffered significant damage, including flexural cracks in the circumferential direction near the base of their supporting shafts. Three elevated water tanks in the highest intensity shaking zones collapsed. Heavy damage to cylindrical buried concrete tanks was noted in the 1995 Kobe earthquake, and an underground concrete tank experienced severe wall collapse during the 1971 San Fernando earthquake (Jennings, 1971).

The failure mechanisms of liquid storage tanks depend on various factors such as construction material, tank configuration, tank type, and supporting mechanism. Reported damage to liquid-containing structures (LCS) during past earthquakes includes one or more of the following categories:
1. Buckling of the shell caused by excessive axial compression due to exerted overturning moment (elephant-foot buckling).
2. Deformation, cracks, and leakage in the side shell.
3. Damage to the roof or upper shell of the tank due to sloshing of the contained liquid in tanks with insufficient freeboard between the liquid surface and the roof.
4. Spillover of the stored liquid.
5. Failure of piping and other accessories connected to the tank due to the relative movement of the flexible shell.
6. Damage to the supporting structure in elevated water tanks.
7. Damage to the anchor bolts and foundation system.
8. Failure of supporting soil due to over-stressing.

2. Seismic Impact on Liquid Storage Tanks

During the 1964 Niigata earthquake, various damage modes, including modes 3 and 4 from excessive sloshing, mode 8 from soil liquefaction, and modes 7 and 5, were prominently observed. In the 1964 Alaska and 1971 San Fernando earthquakes, the lower part of the side shell bulged around the perimeter due to mode 1 (elephant-foot buckling), caused by the excessive overturning moment generated during the seismic event.
When tanks contain hazardous materials, liquid spillover (mode 4) and subsequent fires following a major earthquake can result

in more severe damage than the earthquake itself. For example, the extensive uncontrolled fire during the Niigata earthquake at Showa Petroleum blazed for about 15 days, causing significant destruction to the plant and nearby residential apartments (Niigata Nippo Co., 1964). The 1964 Niigata and Alaska earthquakes resulted in considerable losses in petroleum storage tanks, prompting many engineers and researchers to investigate the seismic behaviour of liquid storage tanks, especially those containing hazardous materials like petroleum.
An example of damage mode 4 is the oil spill into the harbour at the Sendai Refinery of Tohoku Petroleum Company during the 1978 Miyagi earthquake (Hazardous Material Technology Standards Committee: Fire Defence Agency, 1979). During the Northridge earthquake, major lifeline facilities in the Los Angeles area experienced se vere damage, including five steel tanks in the San Fernando Valley area. Buckling was the prominent form of damage in all the affected tanks, and several other tanks suffered roof collapses due to the excessive sloshing of the stored liquid (Lund, 1996). It is important to note that the damage modes in concrete tanks differ from those in steel tanks. In steel tanks, the most common types of damage include elephant-foot buckling, failure of the anchorage system, and sloshing damage to the roof and upper shell (see Figure).

In practice, fully anchoring the base of a tank is not always feasible or economical. Consequently, many tanks are either unanchored or only partially anchored at their base. If a tank is not rigidly anchored to the ground, the overturning moment generated by an earthquake can be significant enough to cause the tank base to lift off the ground. When the tank base falls back down after lift-off, high compressive stresses are generated in the wall near the base, leading to elephant-foot wall buckling. This type of damage is more common in steel tanks due to their greater flexibility compared to concrete tanks.Some studies indicate that base lift-off in tanks with flexible soil foundations does not generate high axial compressive stresses in the tank wall. As a result, unanchored tanks with flexible base support are less susceptible to elephant-foot buckling but are more prone to uneven settlement of the foundation (Malhotra, 1995; Malhotra, 1997A).Conversely, damage mode 2 is the most common type of damage in concrete tanks. Stresses from large hydrodynamic pressures, combined with additional stresses from the substantial inertial mass of concrete, can cause cracking, leakage, and ultimately, tank failure. Therefore, the design criteria for concrete tanks focus on crack control.

Elevated water tanks are particularly vulnerable to seismic excitations due to the large mass concentrated at the top of the shaft structure. Strong lateral seismic motions can induce large tensile stresses on one side of the concrete shaft, potentially leading to severe cracking or even collapse of the concrete pedestal.

As previously mentioned, many elevated tanks collapsed during the 1960 Chilean, 1997 Jabalpur, and 2001 Bhuj earthquakes due to insufficient reinforcement in the shaft section.

Fig -1: Elephant Foot Buckling

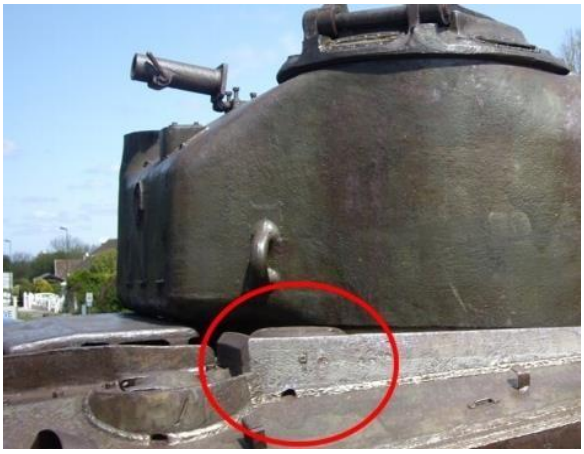

Fig -2: Elephant Foot Buckling

3. Spring Mass Model For Elevated Tank

When a tank containing liquid with a free surface is subjected to horizontal earthquake ground motion, both the tank wall and the liquid experience horizontal acceleration. The liquid in the lower region of the tank acts like a mass rigidly connected to the tank wall. This mass is known as the impulsive liquid mass, which accelerates with the wall and exerts impulsive hydrodynamic pressure on both the tank wall and the base. Meanwhile, the liquid in the upper region of the tank undergoes a sloshing motion previously mentioned, many elevated tanks collapsed during the 1960 Chilean, 1997 Jabalpur, and 2001 Bhuj earthquakes due to insufficient reinforcement in the shaft section. The upper liquid mass, known as the convective liquid mass, exerts convective hydrodynamic pressure on the tank wall and base. Thus, the total liquid mass is divided into two parts: impulsive mass and convective mass. In the spring-mass model of the tank-liquid system, these two liquid masses must be appropriately represented. Figure below provides a qualitative description of the distribution of impulsive and convective hydrodynamic pressures on the tank wall and base.

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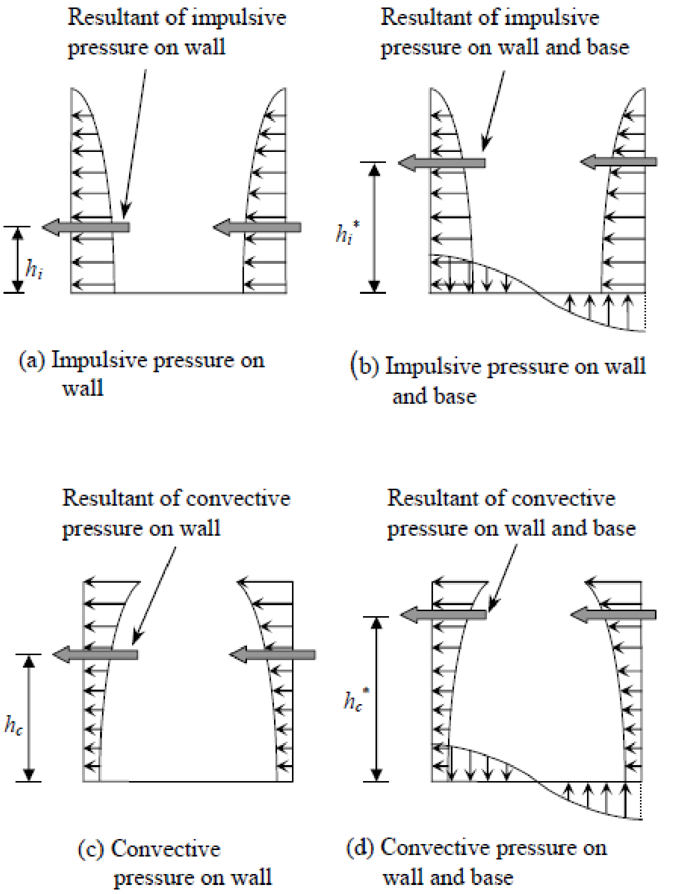

Fig -3: qualitative description of impulsive and convective hydrodynamic pressure distribution on tank wall and base

4. Description of Model

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 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.

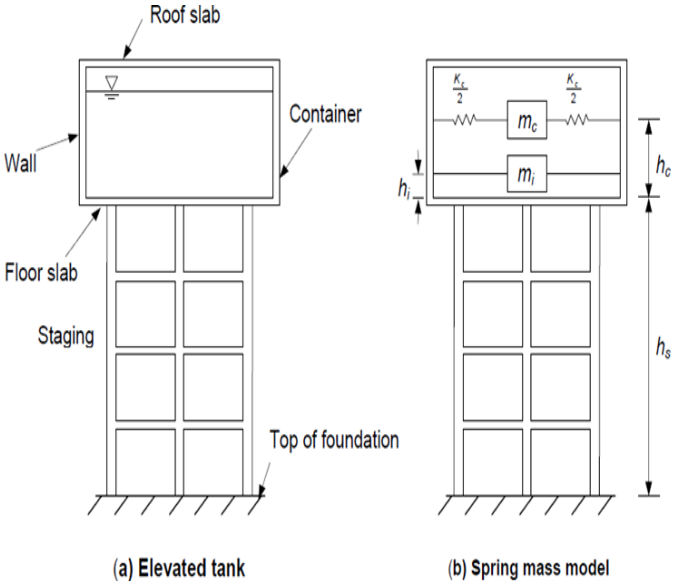

Fig -4: Model of Tank

a) 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 (Sameer and Jain, 1992), 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. The important factors that affect the magnitude of earthquake forces are

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b) Seismic zone factor- 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 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.

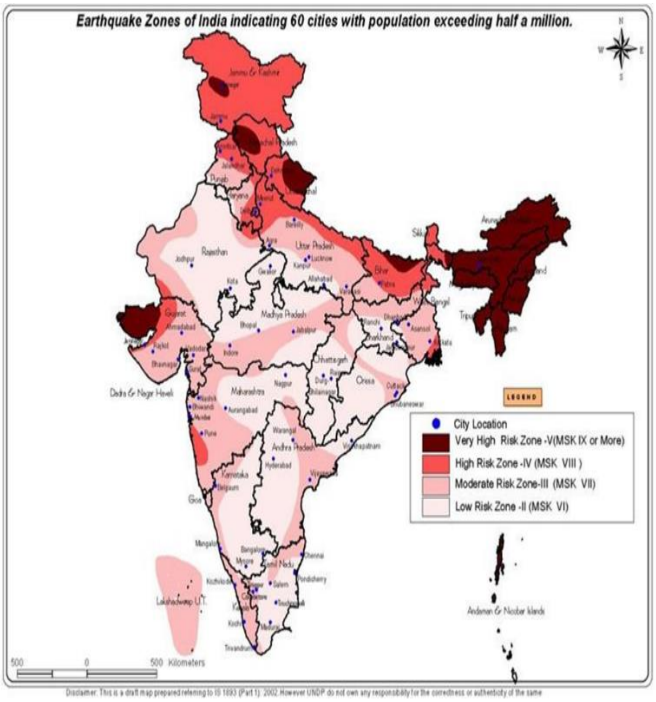


Fig -5: Sesmic Zone of India

c) Importance factor- 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.

d) Response reduction factor- 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.

e) 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. OBJECTIVES

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

6. METHODS OF BASE SHEAR

STAAD.Pro v8i is a leading software product for structural engineering, known for its capabilities in 3D model generation, analysis, and multi-material design. It features an intuitive, user-friendly interface, robust visualization tools, advanced analysis and design functionalities, and seamless integration with various other modeling and design software. Whether for static or dynamic analysis of bridges, containment structures, tunnels, culverts, pipe racks, steel, concrete, aluminum, or timber buildings, transmission towers, stadiums, or any other simple or complex structures, STAAD.Pro is the preferred choice of design professionals worldwide for their specific analysis needs.

7. MODELING OF WATER TANK

In this study, water tanks with varying heights of 5m, 10m, 15m, 20m, and 25m are analyzed. Each tank is evaluated in seismic Zones 2, 3, 4, and 5. The impact of tank height and earthquake zones on base shear is examined through the analysis of 20 models with consistent parameters.

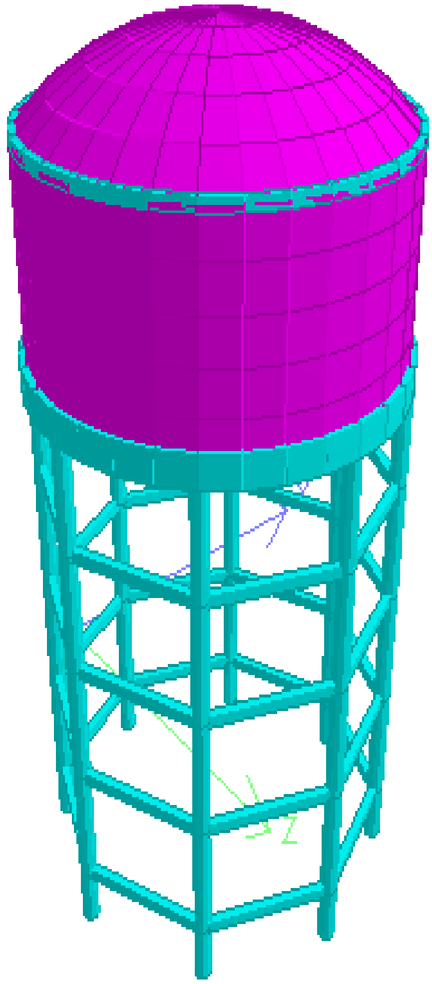


Fig -6: 3D model of Tank

8. PROBLEM STATEMENT

Problem Description Model 1 An elevated, circular cylindrical shape water container of 500 m^3 capacity 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/m^2. 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. Charts

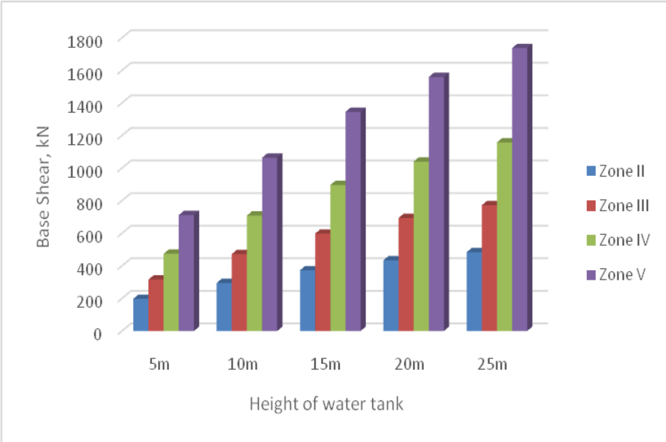
Table -1: Parameter of structure

S.N	Parameters	Values
1	Grade of Concrete	M25
2	Grade of Steel	Fe415
3	Diameter of tank	10 m
4	Height of Cylindrical Wall	5 m
5	Thickness of Cylindrical Wall	150 mm
6	Height of staging	12 m
7	Height of Panel	3 m
8	Number of columns	8
9	Size of column	450 mm dia.
10	Size of top ring beam	150x300 mm
11	Size of bottom ring beam	450x800 mm
12	Size of bracing	225x300 mm
13	thickness of bottom slab	225 mm
14	thickness of dome	75 mm
15	Density of concrete	25 kN/cu.m.
16	Zone	II
17	Response reduction factor	5 (SMRF)
18	Importance factor	1.5 for water tank
19	Type of soil	hard soil

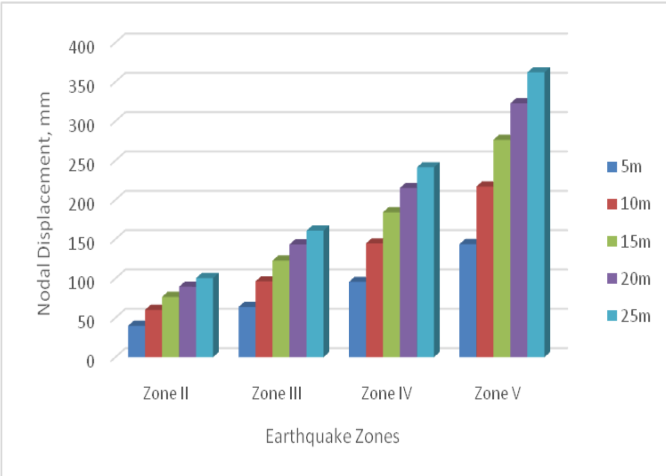
Table -2: Base Shear obtained from Staad-Pro Analysis

Sr. No.	Tank Height	Zone	Base Shear (kN)
1	5m	II	197.528
		III	315.927
		IV	474.184
		V	711.569
2	10m	II	295.078
		III	472.538
		IV	708.807
		V	1063.726
3	15m	II	372.76
		III	597.907
		IV	896.114
		V	1344.917

Graph 1- Comparative Graph of Base Shear v/s Height of tank



Graph 2- Nodal Displacement v/s Earthquake Zones



9. RESULT AND DISCUSSION

In this paper, an attempt is made to study the seismic performance of elevated water tanks. The analysis was conducted on 20 water tanks using STAAD-Pro software, considering various heights and earthquake zones. The main objective was to examine the impact of seismic forces on reinforced cement concrete elevated water tanks in seismic zones II, III, IV, and V across different heights.

Effect of Height of Water Tank on Base Shear

The analysis results are presented graphically. Graph 1 illustrates the impact of varying tank heights on base shear across zones II, III, IV, and V. It shows that base shear peaks at a height of 10m and decreases from 10m to 25m for each earthquake zone. Additionally, for a fixed height of 5m, base shear increases progressively from Zone II to Zone V.

Effect of Earthquake Zone on Base Shear

Graph 2 depicts the effect of earthquake zones on base shear for water tank heights of 5m, 10m, 15m, 20m, and 25m within a specific zone. The graph indicates that base shear increases progressively from Zone II to Zone V. For Zone II specifically, base shear increases up to a height of 10m and then decreases from 10m to 25m.

10. CONCLUSION

Designing a water tank, especially an elevated cylindrical water tank, is a complex and time-consuming process due to the numerous mathematical formulas and calculations involved. STAAD-Pro, however, provides immediate base shear values from its analysis.

1. Base shear increases from Zone II to Zone V when all parameters, including the height of the water tank, are kept constant.

2. Base shear reaches its peak at a height of 10m and then decreases from 10m to 25m, with all other parameters, including the seismic zone, remaining constant.

3. This study will be valuable for civil engineers to understand the behavior of elevated water tanks at various heights and to comprehend the impact of different earthquake zones in India on seismic forces

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