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Analysis of Elevated Liquid Storage Tank on Sloping Ground with Variable Heights

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Abstract

Past earthquake events have shown that even well-designed elevated water tanks can suffer severe damage or collapse. Much of this damage occurs due to a limited understanding of the behavior and appropriate selection of supporting systems during the design process. With a large mass concentrated at the top of slender supports, these tanks are especially vulnerable to horizontal seismic forces. Therefore, it is crucial to evaluate the strength and performance of these structures against such forces, particularly based on the seismic conditions of the region. The seismic performance of elevated water tanks for India's critical seismic zone is presented in this report for a range of staging heights and sloping terrain, including zero, twenty, and thirty degrees. The Response Spectrum Method (RSM) in ETABS software is used to analyse a total of nine combinations while taking into account two mass idealization systems. The tank responses including base shear, storey displacement, shear forces, and bending moments in the columns have been analyzed to recommend the most suitable staging configuration for various earthquake zones across India. To suggest column diameter for particular zone considering cost parameter, optimization is also done for the best staging configuration. As per IIT Kanpur and Gujrat state disaster management authority guidelines, critical direction of seismic forces is considered and quantity of steel and concrete required is obtained. Results show that on zero slope ground all parameters will perform better during seismic events for all seismic zones.

Keywords: Seismic analysis, elevated storage tank, liquid storage, response spectrum method, different slopes, comparative analysis

INTRODUCTION

Liquid storage tanks are essential components in various sectors, such as municipal water supply, industrial processes, and agricultural irrigation, and they play a crucial role in ensuring the availability of water and other fluids. Ensuring the structural integrity and stability of liquid storage tanks is crucial in their design, because these tanks are designed to withstand a variety of operational and environmental conditions, including changing internal fluid pressure, wind, and even the effects of seismic activity. The response of a liquid storage tank when subjected to ground motion resulting from seismic activities is challenging because the tanks contain fluids known to vibrate, which in turn increases the forces exerted on the tank wall. One of them is related to liquid sloshing that occurs when the liquid contained in the tank moves, exerting additional forces on the structure of the base and walls. In this case, if the fluid–structure interaction is increased owing to seismic movement, there may be a danger of damage or complete failure of the tank.

If the tank is not designed to support such behavior, there will be excessive forces on the wall and possible structural failure due to the splashing of the liquid. Sloshing also affects the pressure

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distribution of the tank; the pressure is distributed unevenly, leading to effects such as buckling or deformation of the walls. Thus, certain modifications are implemented in the construction of new liquid storage tanks to reduce the impact of sideways forces, known as sloshing, and ensure tank stability. In addition to these structural changes, the behavior of the soil beneath the tank foundation is one of the determinants of the dynamic response of the tank during an earthquake. Therefore, the stiffness and damping properties of the soil affect the behavior of the tank under dynamic loads and vary with different types of soils.

AIM AND OBJECTIVES

The objectives of the research are:

- To examine the dynamic behavior of elevated storage reservoir.
- To model and analyse the impact of different sloping ground conditions on tank performance.
- To model and analyse the impact of different tank height and their performance.

LITERATURES REVIEW

Seismic analysis of liquid storage tanks by replacing the previous simple lumped mass model with more accurate two- or three-mass models for impulsive, convective, and rigid liquid components. It also has a load factor for bracing girders in elevated tanks, which concerns the lateral stiffness and vibration period. This leads to better prediction of seismic forces and virtually estimates the dynamic response of different structures, which reduces the risk and designs buildings that are stronger in areas that have a higher rate of earthquakes [1].

Water tanks have shown vulnerability to torsional failures in past earthquakes such as the 1952 Kern County and 1993 Killari events. Torsional amplification was significant when the torsional-to-lateral natural period ratio was between 0.7 and 1.25. In the 1993 Killari earthquake, the tank collapsed vertically because of such vibrations. Although these tanks are generally symmetric, factors such as the asymmetrical placement of ladders, pipes, water sloshing, and construction irregularities can create accidental eccentricities, leading to severe torsional responses. This study focused on assessing torsional vulnerability by evaluating whether the critical period ratio falls within a specified range [2].

Alternate staging configurations for elevated water tanks reduce torsional response during earthquakes. Tanks are vulnerable when their torsional to lateral time period ratio (J) is within the range of 0.7 1.25. Various configurations, such as adding radial beams, central columns, concentric rows of columns with circumferential or radial beams, and angular bracing, were analyzed to shift J outside this range. Closed-form expressions for torsional and lateral stiffness were derived and validated using SAP 80 finite element analysis, showing errors under 10% for most cases. The results indicate that the first three configurations are significantly more effective in increasing J for tanks with fewer columns, whereas diagonal bracing significantly improves the performance of tanks with many panels. These configurations are useful for both new designs and the seismic retrofitting of existing tanks to minimize torsional vulnerability [3].

Buckling failure of unreinforced steel conical water tanks is highlighted by collapse in Fredericton, Canada. To improve safety, a numerical analysis was conducted to assess the effects of adding rectangular longitudinal stiffeners. Two configurations were studied: a retrofit case with stiffeners welded to the shell but free at the base and a new design case with stiffeners anchored to the bottom slab. A parametric study was conducted using an advanced shell element model that incorporated material and geometrical nonlinearity and imperfections. According to the best solution for increasing the structural safety and efficiency of steel conical tanks is to employ longitudinal stiffeners. The test results also showed that the augmentation of stiffeners greatly improved the buckling capacity without adding much material, and the use of a stiffener reducer favored a new and retrofitting tank design [4].

The behavior of the bases was isolated and ground supported in cylindrical liquid storage tanks using three methods of analysis. First, using the modal superposition technique, it was ascertained that based on the studied structures, the nonclassical damping approximation was negligible. Second, the methodologies of the response spectrum technique enable the computation of peak responses with remarkable accuracy; hence, it is important to select the correct modal combination factors. Finally, modal parameters were described and quantified in terms of closed-form solutions, and some considerations were provided for practical design. In conclusion, the estimated results, aspects of classical damping, response spectrum analysis, and simplified approaches confirm the applicability of the data ore to seismic analysis of base-isolated tanks [5].

Impact of various supporting systems on the seismic behavior of elevated water tanks with FSI. In the analysis, shell elements were applied to model the truncated cone and walls of the container, whereas frame elements were applied to analyze the frame-type supports. Similarly, shell elements were applied to represent the shaft-type support system of the structure. An analysis of the fluid-elevated tank interaction was performed using the finite element method (FEM). Transient dynamic analysis was also carried out using an FEM software program to assess the seismic performance of the beams and columns of the tank. Rayleigh damping was used in the time history analysis. The results also indicate that the tanks with frame supports have the most aggressive response within the time period of 9-10 seconds while the tanks with shaft supports exhibited the most aggressive response for the time period of 5-10 seconds. Moreover, the study conveys the findings of the effect of the support system on the quantity of sloshing displacement and roof displacement, which shows that although the support system makes a significant contribution to sloshing displacement, it influences the roof displacement to a considerable extent. The displacements in the shaft-supported tanks are approximately 83% and 12%, respectively, lower than those of frame-supported tanks [6].

Structure interaction under dynamic loads: This study examines the dynamic response of elastic liquid storage tanks with internal baffles. Using the ADINA software, the tank walls and baffles were modeled as elastic, isotropic materials, while the contained water was treated as an inviscid, compressible fluid. The simulation captures the fluid motion and pressure using 3D fluid elements and models the tank structure with shell elements. The analysis examined the hydrodynamic pressure and tank wall displacement during the dynamic events. A parametric study showed that well-designed baffles effectively reduced sloshing and dynamic loads, improved tank stability, and guided optimal seismic design [7].

The seismic performance of elevated water tanks supported on concrete shafts was evaluated using a validated finite element model that accounts for fluid–structure interactions, including impulsive and sloshing effects. A time-history analysis under horizontal seismic excitation was conducted using the modal superposition method to compute the shear and overturning moments at the shaft base. The model incorporated tank wall flexibility and different damping for impulsive and convective components and showed strong agreement with Housner's method and current design practices. The results confirm the accuracy of the existing codes for a specific tank and ground motion, and future work is suggested for broader parametric studies [8].

Damage patterns in reinforced concrete elevated water tanks under seismic loading, focusing on frame-staging systems. An analysis of past earthquake failures revealed that plastic hinges, deep column cracks, and beam shear failures are common in such tanks. Using dynamic time history analysis on a 900 m^3 tank model, this study identifies dominant failure modes, including shear in beams and axial forces in columns. The results show that as the earthquake acceleration increases, bending-related tensile damage begins at the beam ends, with visible damage beginning around 0.3 g acceleration. Field observations also confirmed typical failure modes, such as joint cracking and torsion in frame-staged tanks [9].

The seismic failure mechanisms of elevated concrete tanks with shaft and frame staging were evaluated using linear and nonlinear analyses of their response modification factors (R) under multiple earthquake records. The models include the effects of fluid–structure interaction, multicomponent ground motions, and P–Delta effects. The results reveal that current code-based methods may underestimate inelastic demands, especially in shaft staging, and suggest improved modeling to better distribute the ductility. Frame staging systems are different from conventional moment-resisting building frames because of the concentrated top mass and, as a result, undergo a full plastic hinged mechanism under seismic loading, and thus reinforcement is absolutely necessary [10].

METHODOLOGY

The object of detailed consideration in this article is an elevated water tank with a storage volume of five lakh litters. The specifics of the structure, such as its dimensions and height, their stability, and the type of ground they are constructed on and at what slope, all need to be determined about the tank in the target area in order to analyze its performance during an earthquake. One of the challenges that this analysis focuses on affects water tanks standing at higher grounds; thus, the additional challenge of slopes that are dragging down with water tanks needs to be considered, especially in seismically prone regions. To ensure the stability and safety of the tank, it is necessary to understand how such fluctuations affect it. The research methodology of this study is a systematic way of analyzing the response of an elevated water tank in different scenarios. The first is to generate a precise digital replica of the real-world geometry, material makeup, and loading conditions of the water tank. With three different slopes, which are cube faces that are assumed to slope at 20° and 30°, this model is expected to mimic how a real tank would tank if built on leveled and inclined terrain. In addition, the proposed model considers three varying fundamental heights of the tanks, 9 m, 12 m, and 15 m, to capture the effects of height changes on the seismic behavior of the tank. Figures 1, 2, and 3 show tanks with a twenty-degree slope that are nine, 12, and 15 m high, respectively. A thirty-degree slope tank with height of nine, 12, and 15 m is shown in Figures 4-6, respectively. Finally, Zero-slope tanks with heights of nine, 12, and 15 m are shown in Figures 7-9, respectively. The medium soil type used in this study is an important factor that affects the response of structures to earthquakes. Table 1 lists the tank description, and Table 2 lists the load combinations applied to the tank. The behavior of elevated water tanks is significantly influenced by soil-structure interactions, especially when the tanks are built on uneven ground. Because they reflect the typical conditions in many areas where elevated water tanks are installed, medium soil conditions were selected. Additionally, the tank must be able to withstand strong earthquake forces because it is presumed to be situated in Seismic Zone 5, the highest seismic zone [11–13].

Table 1. Tank description.

S.N.	Tank data	Parameters
1	Capacity of Tank	500 m^3
2	Wall thickness	150 mm
3	Staging Height	12 m
4	Panel Height	3 m
5	Number of Columns	12
6	Size of Columns	350 mm x 750 mm
7	Size of Top Ring Beam	300 mm x 600 mm
8	Size of Bottom Ring Beam	300 mm x 600 mm
9	Grade of Concrete	M25
10	Thickness of Bottom Slab	200 mm
11	Concrete density	25 kN/sq. m
12	Response Reduction Factor	5
13	Importance Factor	1.5 for water tank
14	Soil Type	Medium
15	Seismic zone	Zone V
16	Density of concrete	25 kN /sq. m

This methodology comprises several important steps. To simplify the intricate relationships between the structure and the ground, the necessary assumptions are first made regarding the material properties of the foundation and tank, as well as the boundary conditions. These assumptions were necessary to create a feasible model that could be applied to the analysis. Subsequently, a dynamic analysis of the structure of the tank under the force of the seismic load was performed using FEA. The present work includes an analysis of the displacement, stress, and overall stability of the tank owing to the simulation of the earthquake forces according to Zone 5 seismic requirements. This research will focus on gaining relevant information concerning the behavior of elevated water tanks on sloping ground, with special reference to seismic considerations. The study also determined the factors that influence the stability and safety of such buildings based on varying angles of slopes, flat terrains, heights of tanks, and ground type. The research outcomes should help in designing and furthering the guidelines of raised water tanks in seismic regions in order to remain safe and functional even under conditions of extreme seism. Thus, the method used in this study presents a systematic procedure for analyzing the seismic behavior of raised water tanks on sloping grounds. It takes into account various parameters, including the type of soil, slope of ground, height of the tank, and the seismic zone, to ensure that due consideration has been taken and meets actual user or planner demand Figures 1-9.

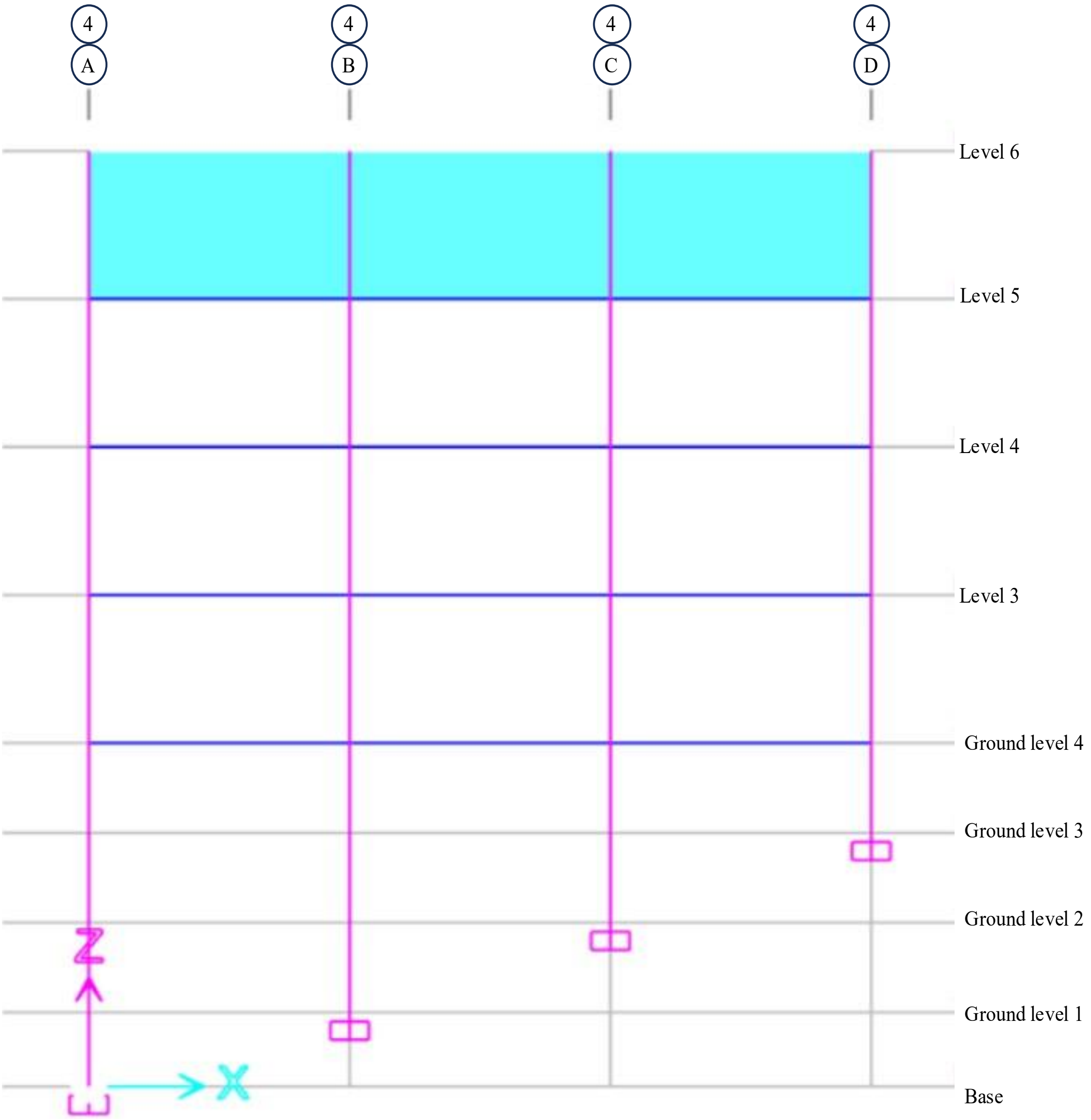

Figure 1. 20-degree slope and 9-meter height.

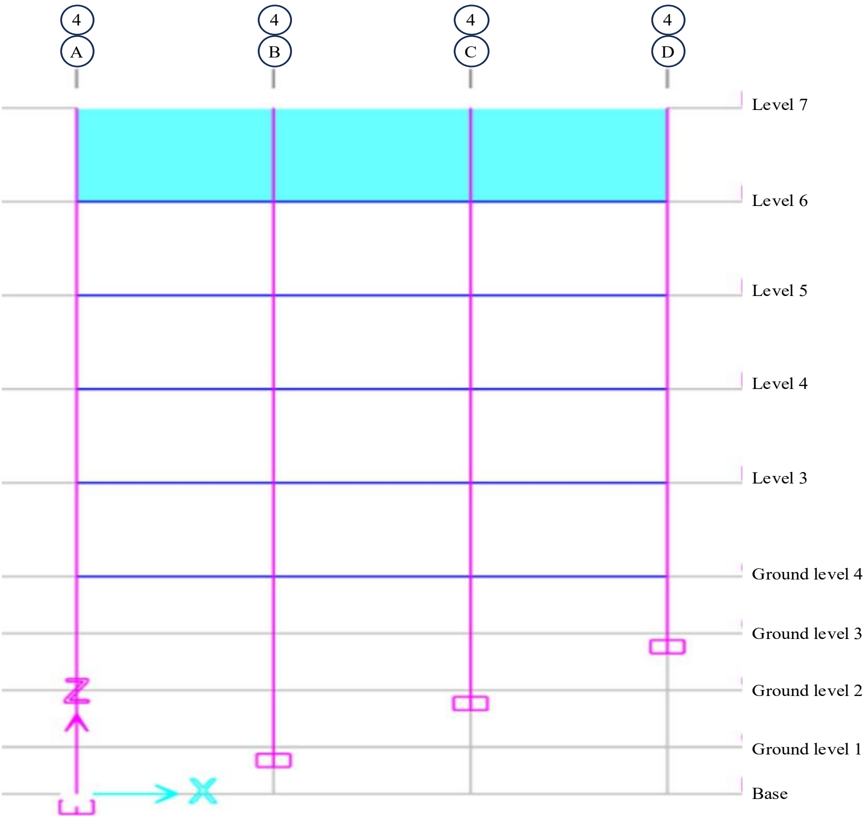

Figure 2. 20-degree slope and 12-meter height.

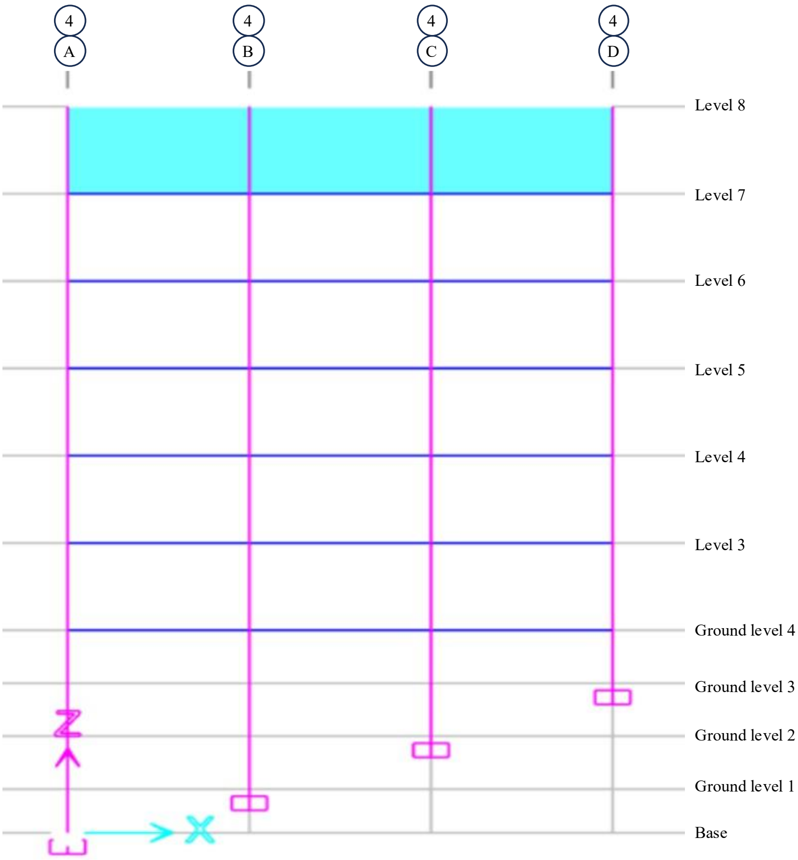

Figure 3. 20-degree slope and 15-meter height.

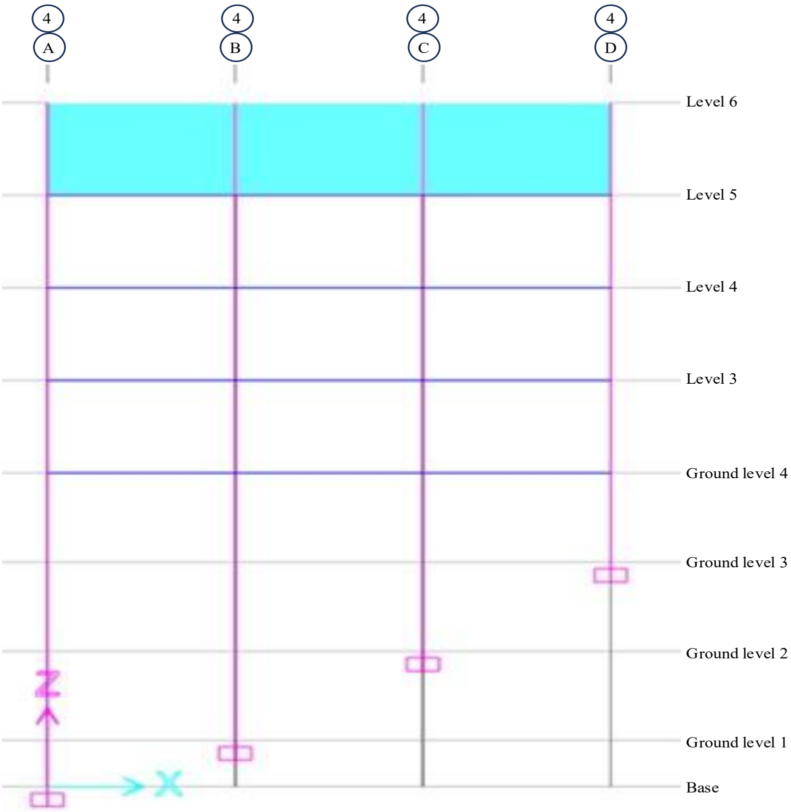

Figure 4. 30-degree slope and 9-meter height.

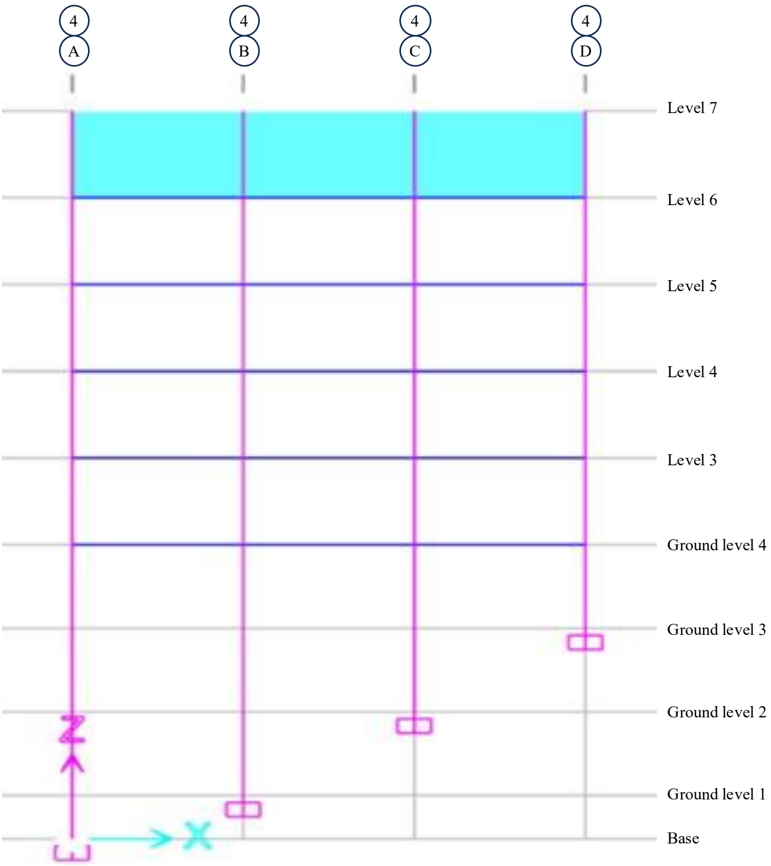

Figure 5. 30-degree slope and 12-meter height.

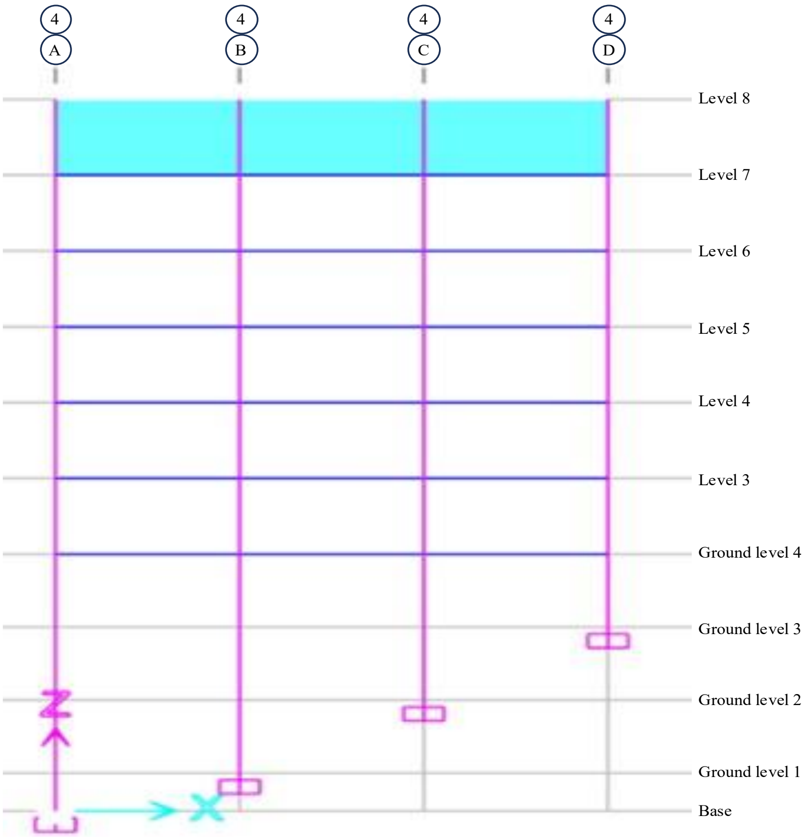

Figure 6. 30-degree slope and 15-meter height.

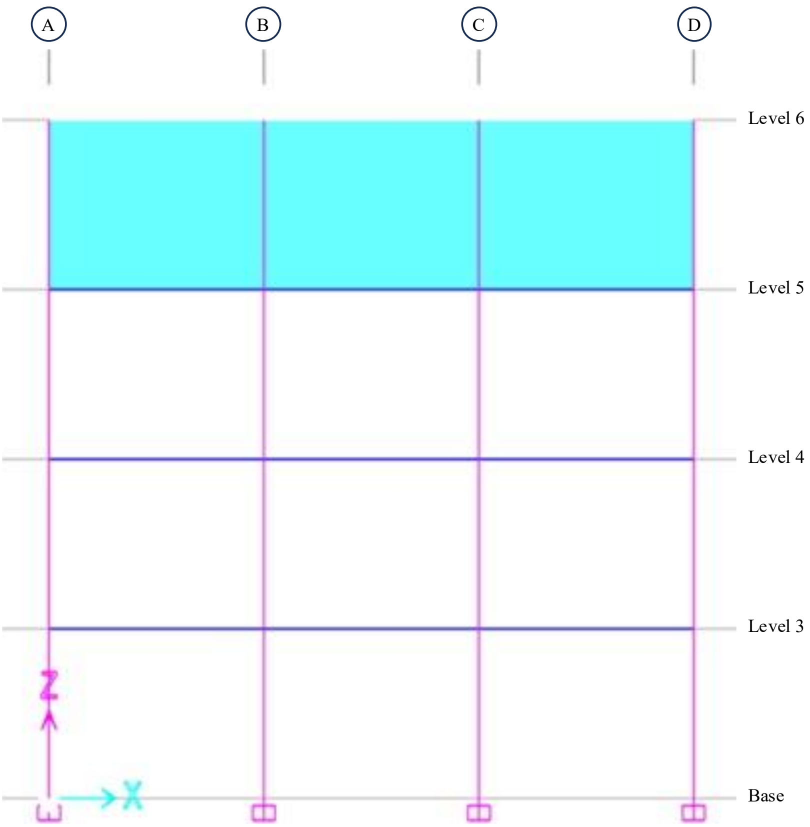

Figure 7. Flat ground and 9-meter height.

Journal of Geotechnical Engineering
Volume 12, Issue 3
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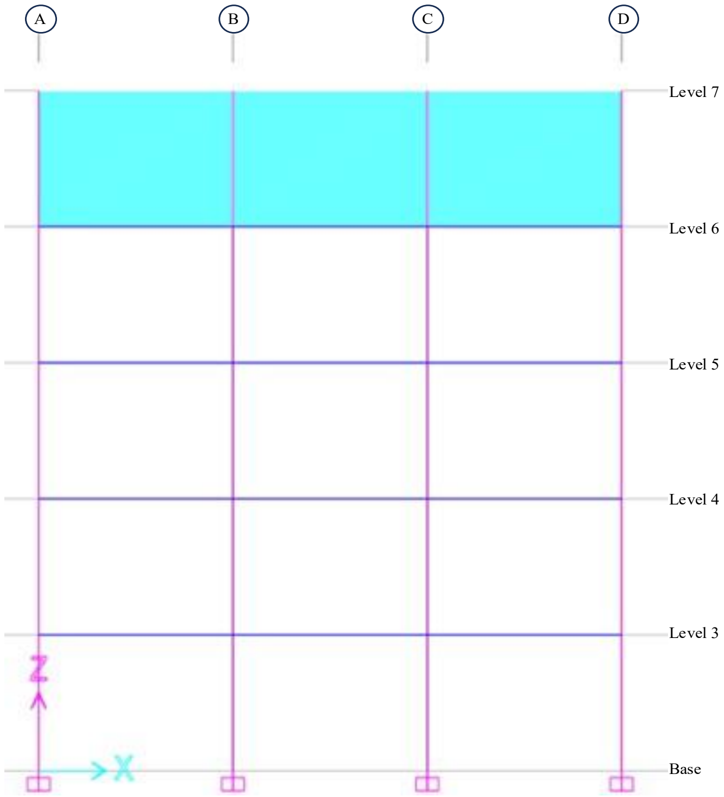

Figure 8. Flat ground and 12-meter height.

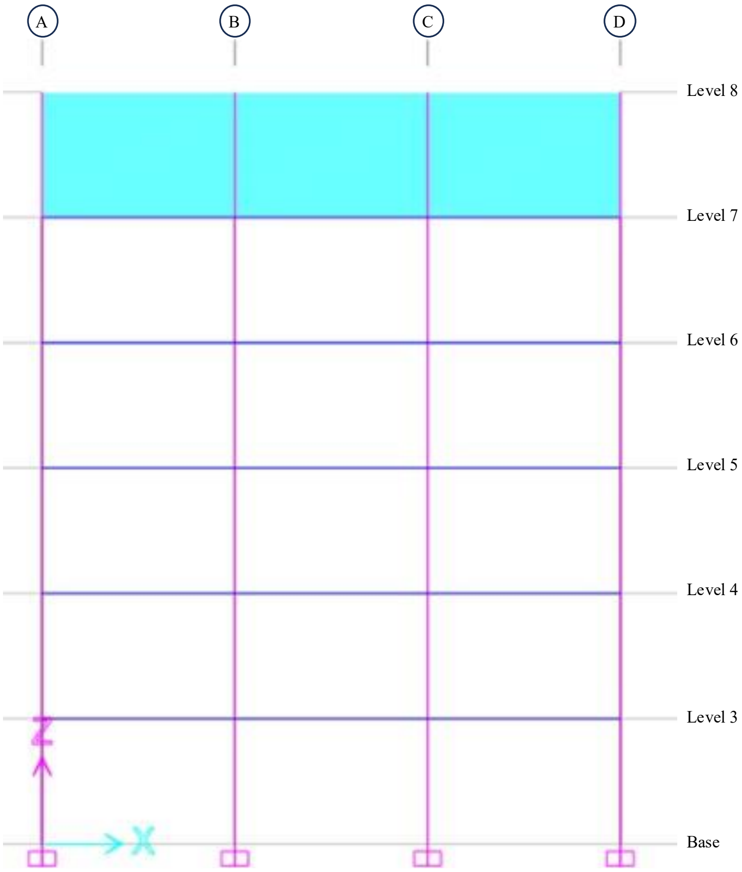

Figure 9. Flat ground and 15-meter height.

Table 2. Load combinations considered for seismic analysis.

S.N.	Design load combination for zone 4 and zone 5
1	1.5 DL + 1.5 LL
2	DL + LL
3	1.2 [DL + LL ± (EQX ± 0.3 EQZ)] 1.2 [DL + LL ± (EQY ± 0.3 EQZ)]
4	1.5 [DL ± (EQX ± 0.3 EQZ)] 1.5 [DL ± (EQY ± 0.3 EQZ)]
5	0.9 DL ± 1.5 (EQX ± 0.3 EQZ) 0.9 DL ± 1.5 (EQY ± 0.3 EQZ)

RESULTS AND DISCUSSION

Seismic analysis of a 5 lakh liter elevated water tank placed on flat and sloping ground (10°, 20°, and 30°) at heights of 9 m, 12 m, and 15 m using the Response Spectrum Method for zone V with medium soil. Parameters such as base shear, story displacement, and drift are evaluated through detailed finite element modelling, accounting for sloping ground effects and soil-structure interaction. This research aims to identify how varying slopes and tank heights influence seismic performance, providing design insights for improved resilience of elevated tanks in earthquake-prone uneven terrains.

Base Shear Comparison Between 20 and 30 Degrees with Varying Heights 9 m, 12 m and 15 m, Respectively

Base shear comparisons for 20° and 30° sloping ground with heights of 9 m, 12 m, and 15 m are shown in tabular form in Tables 3, 4, and 5, respectively, and graphically represented in Figures 10, 11, and 12. The tables and figures show that as the ground slope and height of the tank increased, the base shear also increased.

Table 3. Base shear at 20-degree-sloping ground under zone V.

20 Degree Base Shear			
Story	***9m***	***12m***	***15m***
GF	4452.3296	6230.4547	6433.7698
1	4451.7687	6229.6529	6432.9488
2	4442.4082	6216.4924	6419.3172
3	4418.4851	6183.2049	6384.7610
4	4373.2154	6119.5663	6319.3872
5	4301.386	5941.512	6214.8356

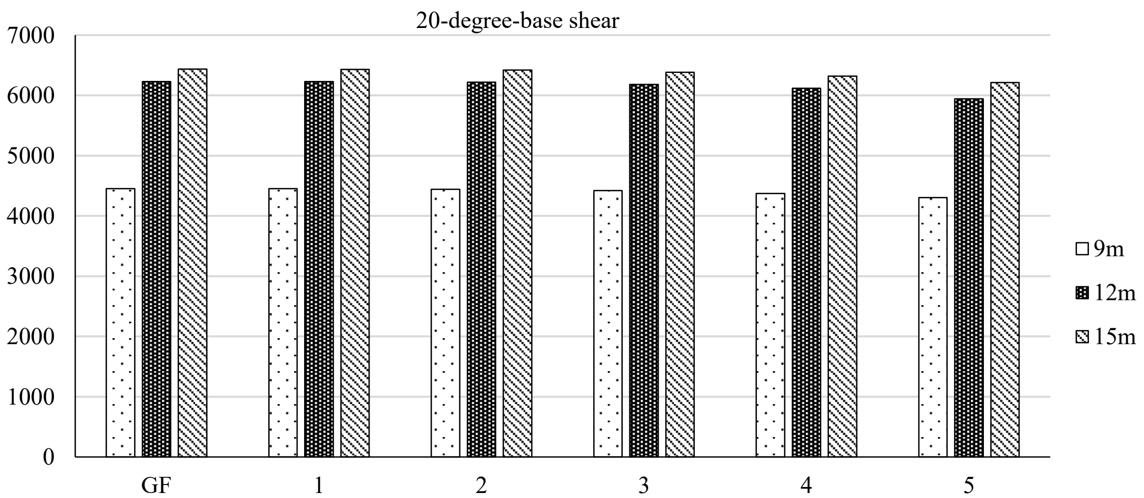

Figure 10. Base shear of 20-degree-sloping ground under zone V.

Table 4. Base shear of 30-degree-sloping ground under zone V.

30 Degree Base Shear			
Story	***9m***	***12m***	***15m***
GF	6049.6846	6114.908	6247.5626
1	6049.3582	6114.574	6247.2186
2	6043.9104	6109.032	6241.5721
3	6029.9873	6094.983	6227.2904
4	6003.6406	6068.404	6199.9867
5	5961.8363	6025.897	6094.7712

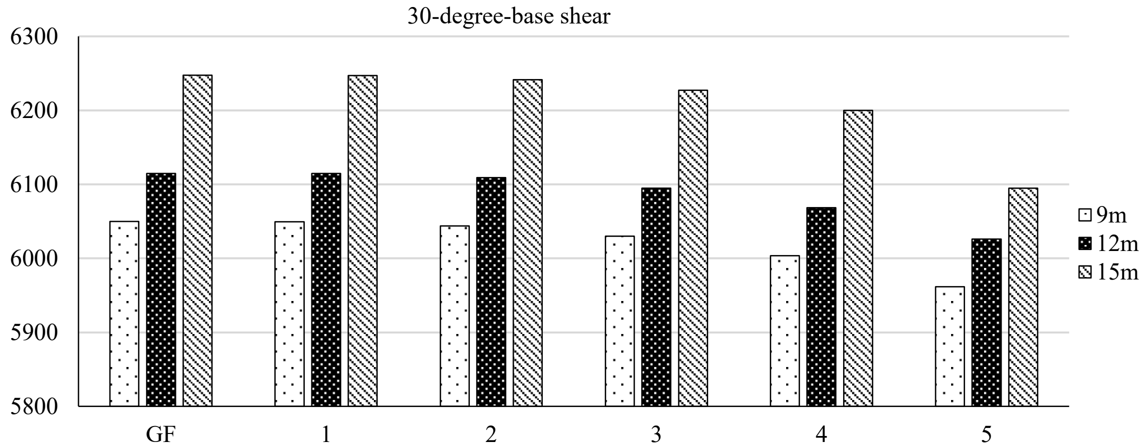

Figure 11. Base shear of 30-degree-sloping ground under zone V.

Table 5. Base shear of flat ground under zone V.

Flat ground base shear			
Story	***9m***	***12m***	***15m***
GF	3546.3246	5050.3193	6086.3938
1	3544.84	5048.3654	6084.0312
2	3522.0649	5015.9214	6045.2544
3	3463.8904	4933.6749	5947.1745
4	3353.8189	4778.0805	5759.6662
5	3179.089	4529.2401	5317.6704

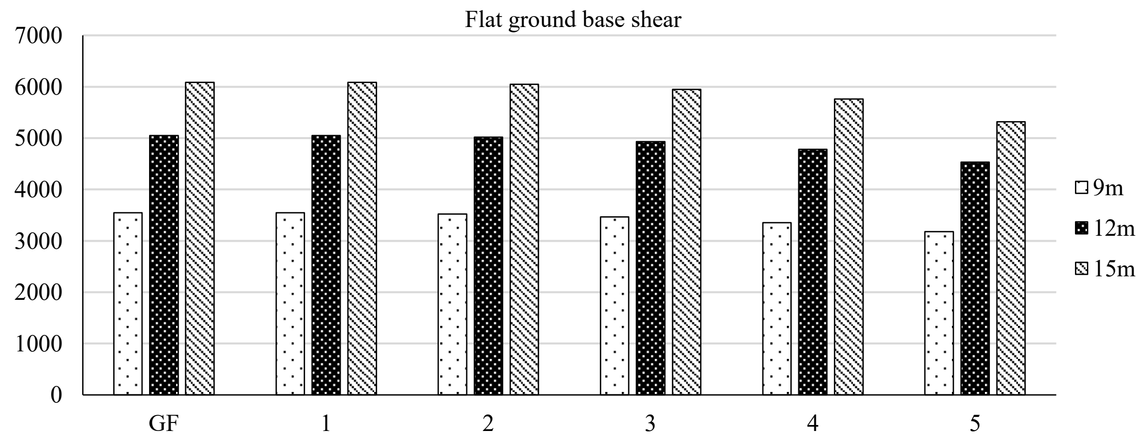

Figure 12. Base shear of flat ground under zone V.

Story Displacement Comparison Between 20 and 30 degrees with Varying Heights 9 m, 12 m and 15 m, Respectively

The comparison of the story displacement of 20 and 30 degree sloping ground having 9m, 12m, and 15m are presented in tabulated format in Tables 6-8, respectively, and Figures 13-15 show the graphical representation. The tables and figures that as the ground slope and height of the tank increased, the story displacement also increased.

Table 6. Story displacement of 20-degree-sloping ground under zone V.

20-degree-story displacement			
Story	***9m***	***12m***	***15m***
GF	2.439	1.4408963	1.807
1	3.496	5.2571454	8.429
2	9.754	9.5845584	17.228
3	15.608	15.260272	26.813
4	17.263	19.587685	35.714
5	22.109	23.929271	44.49

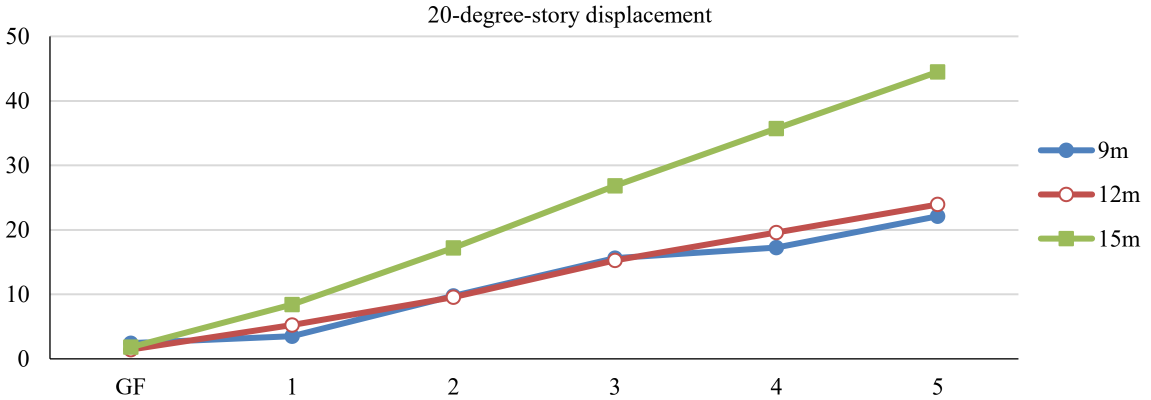

Figure 13. Story displacement of 20-degrees-sloping ground under zone V

Table 7. Story displacement of 30-degree-sloping ground under Zone V.

30-degree-story displacement			
Story	***9m***	***12m***	***15m***
GF	2.542	1.916	2.461
1	3.664	6.923	11.495
2	10.221	12.664	23.535
3	16.372	20.222	36.714
4	18.161	26.046	49.051
5	23.386	31.945	61.36

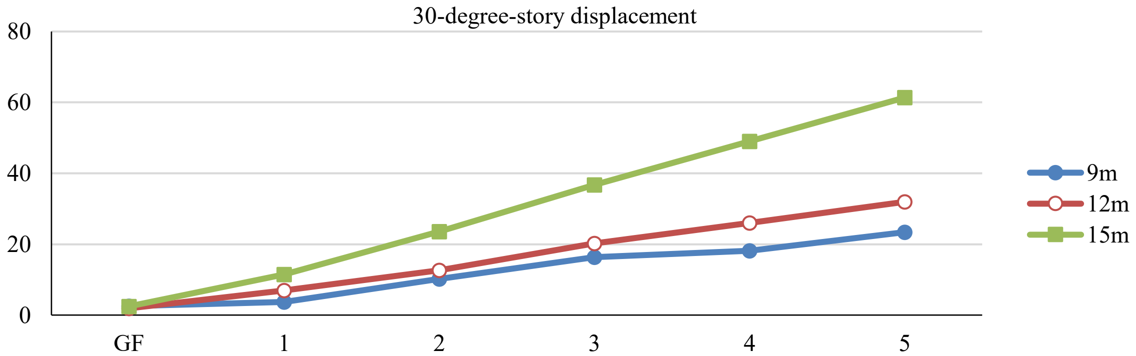

Figure 14. Story displacement at 30-degree-sloping ground under zone V.

Journal of Geotechnical Engineering
Volume 12, Issue 3
ISSN: 2394-1987

Table 8. Story displacement of 30-degree-sloping ground under Zone V.

Flat ground story displacement			
Story	***9m***	***12m***	***15m***
GF	2.308	1.419	1.28
1	3.334	5.454	6.32
2	9.465	10.08	13.07
3	15.161	15.811	20.91
4	16.683	20.117	26.541
5	21.05	24.339	32.651

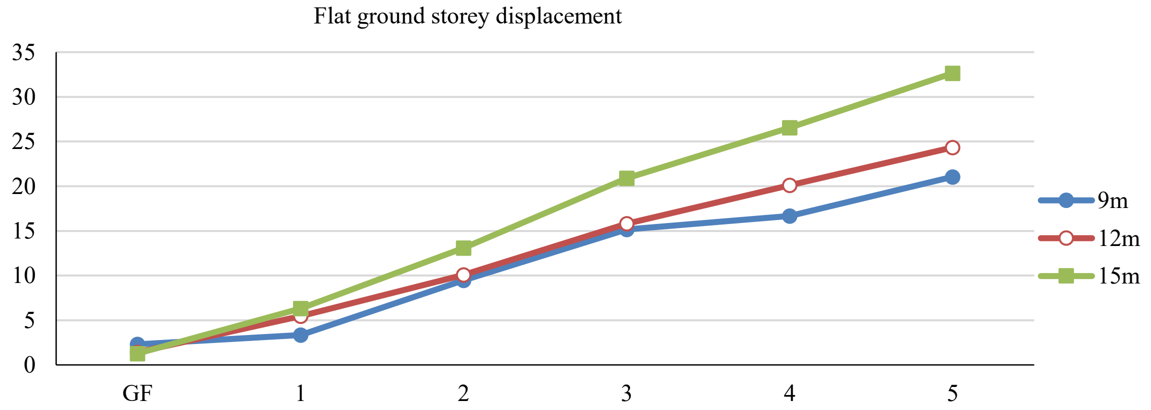

Table 15. Story displacement of 30-degree-sloping ground.

Story Drift Comparison Between 20 and 30 Degrees with Varying Heights 9 m, 12 m and 15 m, respectively

The comparison of the story displacement of 20 and 30 degree sloping ground having 9 m, 12 m, and 15 m are presented in tabulated format in Tables 9, 10, and 11, respectively, and Figures 16-18 show the graphical representation. The tables and figures that as the ground slope and height of the tank increased, the story drift changed.

Table 9. Story drift of 20-degree-sloping ground under zone V.

20-degree-story drift			
Story	***9m***	***12m***	***15m***
GF	0.000868	0.000686	0.00086
1	0.000935	0.0012727	0.002089
2	0.001956	0.0013521	0.00275
3	0.001829	0.0017735	0.002995
4	0.000557	0.0014437	0.002967
5	0.001615	0.0014475	0.002926

Table 10. Story drift of 30-degree-sloping ground under zone V.

30 Degree Story Drift			
Story	***9m***	***12m***	***15m***
GF	0.000905	0.000913	0.001172
1	0.00098	0.001678	0.002851
2	0.002049	0.001794	0.003762
3	0.001922	0.002362	0.004118
4	0.000602	0.001943	0.004113
5	0.001742	0.001966	0.004103

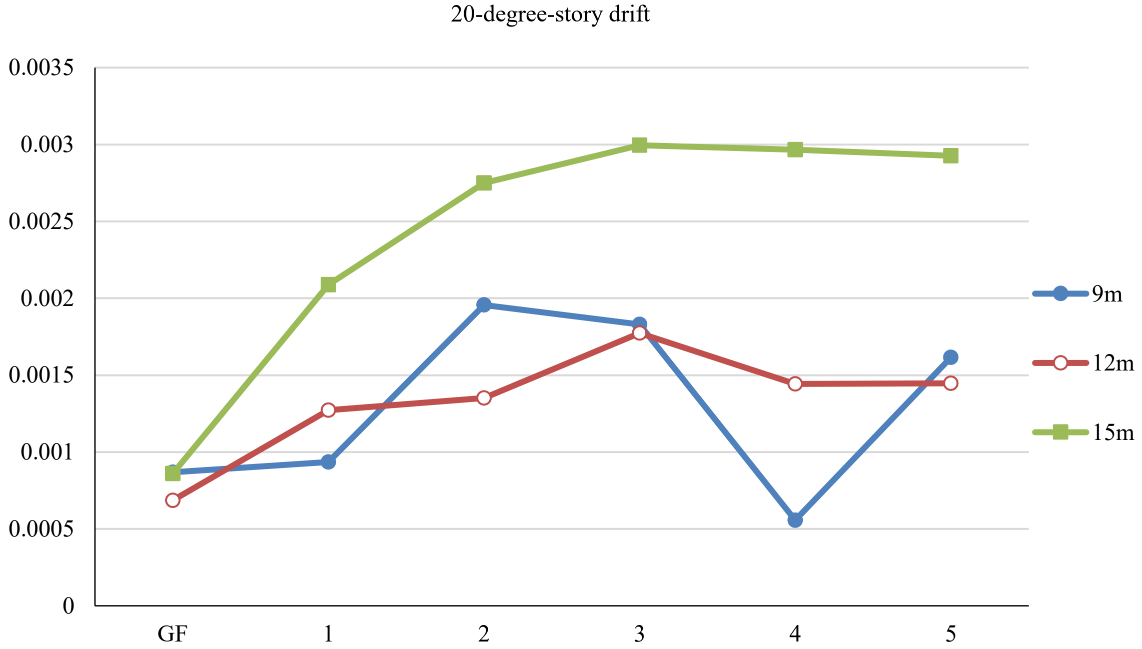

Figure 16. Story drift of 20-degree-sloping ground under zone V.

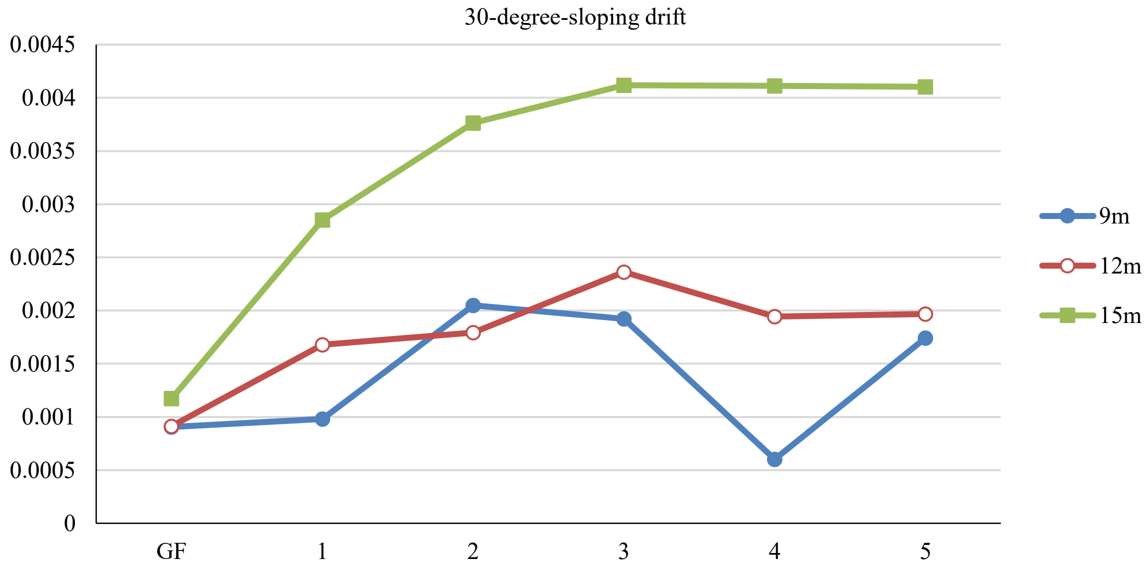

Figure 17. Story drift of 30-degree-sloping ground under zone V.

Table 11. Story drift of flat sloping ground under zone V.

Flat ground story drift			
Story	***9m***	***12m***	***15m***
GF	0.000857	0.000724	0.000657
1	0.000918	0.001344	0.00159
2	0.001916	0.001413	0.002076
3	0.00178	0.001824	0.002227
4	0.001514	0.001437	0.002151
5	0.001426	0.001407	0.002037

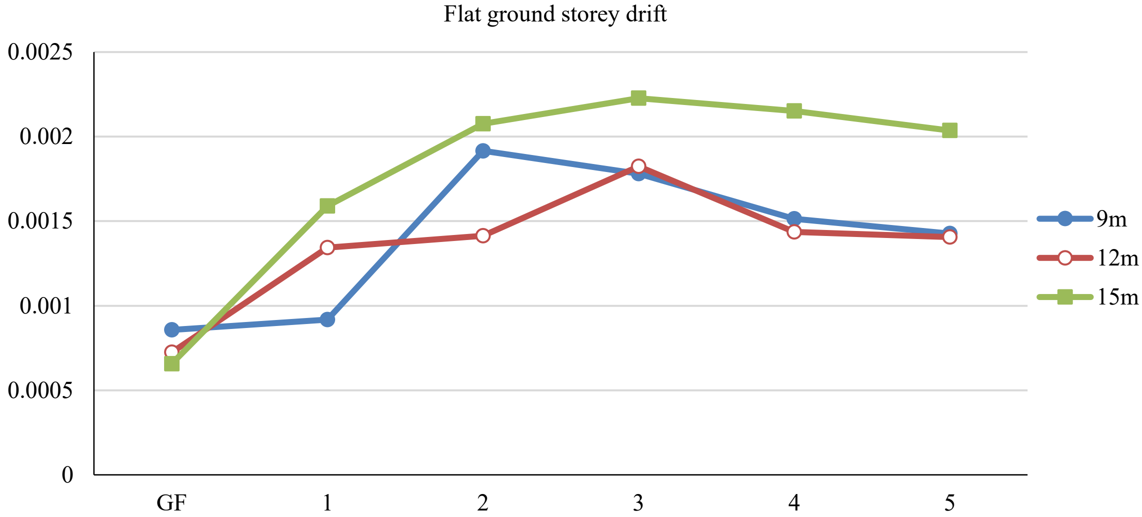

Figure 18. Story drift of flat sloping ground under zone V.

CONCLUSIONS

Elevated water tanks are essential infrastructure components, particularly in regions that have experienced frequent seismic activity. Ensuring their structural integrity is vital for maintaining water supply during and after an earthquake. This project aimed to analyze the seismic performance of an elevated water tank on sloping ground under various configurations of height, slope angle, and seismic zone. The analysis was carried out using dynamic modeling, with particular attention paid to the base shear, overturning moment, story drift, and displacement under varying conditions. The results help to clarify the seismic vulnerability of water tanks, especially in high-risk areas such as Seismic Zone 5.

1. The height of the tank and the applied base shear have a major impact on the seismic response of elevated water tanks; taller tanks experience higher seismic forces and displacements.
2. Taller tanks are more susceptible to seismic activity because they show greater story displacements and drift, particularly at the upper storys, when exposed to higher base shear (20° and 30°).
3. Base shear increases in direct proportion to tank height and ground slope; the 15meter tank records the highest seismic forces, while the 9-meter tank consistently experiences the lowest.
4. The tank's drift and story displacement increased as the base shear increased; tanks exposed to 30 °base shear in both sloping and flat ground conditions experienced the greatest effects.
5. The sloped terrain intensifies the seismic effects on the tank structure, as evidenced by the higher seismic forces experienced by elevated water tanks on sloping ground, as opposed to those situated on flat ground.
6. The need for improved design considerations for taller tanks is highlighted by the fact that taller tanks exhibit higher seismic forces, base shear, and displacement values. Across all seismic loading conditions, the 15m tank shows the most significant impact.
7. Because there is an increase in force as a structure decreases, the lower stories of the tanks are the most vulnerable to failure and any cracks; hence, there is a need to reinforce these stories for structural stability during an earthquake.
8. Therefore, the containers on sloping and in the seismically prone areas are considered to have a slightly lower safety coefficient as compared to similar tanks on flat ground, which means that the tanks on slopes should be constructed with caution.

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