EFFECT OF STRATIFIED SOIL DEPOSIT ON SEISMIC BEHAVIOUR OF ELEVATED WATER TANK

Nayana N[1], L.Govindaraju[2]

[1]*P.GStudent, Department of Civil Engineering ,U.V.C.E, Bangalore University,Bengaluru*
[2]*Professor,Department of Civil Engineering,U.V.C.E,Bangalore University,Bengaluru*

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Abstract *-.As a vital infrastructure, elevated water tanksneed to be built to withstand all the forces expected to act during their life time. An elevated water tank attracts high lateral loads due to the huge mass concentrated at high elevation. The dynamic interaction between an elevated water tank and the underlying soil, especially in earthquake- prone regions, is a major factor that significantly influences the seismic performance of the water tank. In earthquake- resistant building designs, the inclusion of Soil-Structure Interaction (SSI) effects in the analysis is crucial for obtaining realistic performance of water tank during seismic events.*

Water tanks situated on sloping ground face heightened vulnerability to earthquakes, primarily due to irregularities in both plan and elevation. But many water tanks are routinely analyzed under earthquake loadings without accounting for Soil-Structure Interaction (SSI). From a practical standpoint, this approach is strongly discouraged, emphasizing the necessity of considering Soil-Structure Interaction (SSI) for a comprehensive and accurate seismic assessment of water tanks

In the present study, the seismic behavior of an elevated water tank positioned at leveled and sloping ground has been studied, considering flexible base (Soil-Structure Interaction) using Time History Method (THM)for seismic zone II . The numerical analysis is carried out using the Finite Element Analysis (FEA) softwareSAP2000 v22, and it evaluates the effects of Stratified Soil-Structure Interaction (SSI) using combination of soil profile –Soft clay and loose sand, considering one with a full tank and one with an empty tank condition. The study reveals the structural response of the elevated water tank under seismic loading, and the variation in ground sloping exposes the structural vulnerabilities associated with different sloping ground, and consequently highlights the significance of incorporating the effects of stratification in seismic analysis.

Key Words**: Soil-Structure Interaction (SSI), Underlying soil, Time History Method (THM), Elevated water tank, Seismic Analysis, Finite Element Analysis (FEA)**.

1. INTRODUCTION

The allocation of water in a particular area relies heavily on the configuration of its water reservoir. Typically, overhead water tanks are favored as they capitalize on gravitational force to generate the necessary pressure for water distribution, eliminating the necessity for extensive pumping infrastructure. The Indian subcontinent frequently faces natural disasters like earthquakes, droughts, floods, and cyclones. With over 60% of India susceptible to earthquakes, as per the seismic code IS: 1893(Part- 1):2016, the stability of elevated water tanks becomes paramount. The substantial water mass atop slender supports poses a significant risk for tank failure in seismic events. Given their frequent use in seismic regions, the seismic performance of elevated tanks warrants meticulous examination. Instances of tank collapses or severe damage often stem from inadequate understanding of support systems and erroneous selection of staging designs. Liquid storage encompasses various forms such as underground, ground-supported, and elevated tanks. Municipalities and industries rely on these tanks to store water, flammable substances, and more. Consequently, uninterrupted water supply is vital for firefighting amid earthquakes, mitigating property damage and potential casualties. Therefore, ensuring the continued functionality of water tanks in the aftermath of seismic events is imperative.

Dynamic analysis of these tanks must encompass both the water's movement relative to the tank and the tank's motion relative to the ground. A closed tank behaves as a one-mass structure, regardless of its water content, while a tank with a free water surface transforms into a two-mass structure due to water sloshing during earthquakes. Hence, thorough seismic analysis is imperative, as poorly designed structures, not earthquakes, pose the primary threat to lives.Designing elevated water tanks on sloped ground demands a deep understanding of geotechnical and structural engineering principles. Evaluation of soil conditions, slope stability, and seismic factors is crucial for determining an appropriate foundation design. Moreover, considerations like tank capacity, material strength, and environmental factors significantly influence structural integrity. Sloping terrain impacts load distribution, necessitating adjustments in foundation and support systems.

2. SOIL-STRUCTURE INTERACTION (SSI)

Soil-Structure Interaction (SSI) stands as a corner stone in structural engineering, accounting for the dynamic interconnection between a structure and the underlying soil. Especially in seismic zones, this interaction gains paramount importance as ground motion can profoundly influence structural behavior. Historically, structural analysis has often overlooked the soil's influence, treating structures in isolation. Yet, in practice, soil characteristics wield significant sway over a structure's seismic response. Variables like soil stiffness, damping properties, and soil-structure resonance all exert notable impacts on structural behavior during seismic events.

Indeed, for elevated water tanks, SSI assumes heightened significance owing to the substantial lateral loads they endure due to their height and mass. The interplay between the tank and the underlying soil can engender intricate phenomena, such as foundation rocking and soil amplification effects, profoundly shaping the tank's seismic response. Understanding these dynamics is pivotal for enhancing the tank's resilience and seismic performance.To accurately account for SSI, engineers utilize advanced computational techniques such as Finite Element Analysis (FEA).

These methodologies facilitate the modeling of the coupled behavior between structures and soil, offering insights into their interaction under seismic loads. Integrating SSI into structural analysis and design empowers engineers to derive more accurate forecasts of structural response during seismic events. This enables them to better evaluate the seismic susceptibility of elevated water tanks and devise appropriate measures to bolster their resilience.

In essence, comprehending and incorporating Soil-Structure Interaction represent pivotal strides in ensuring the safety and dependability of structures, particularly in seismically active regions. By accounting for the dynamic interplay between structures and their foundation soil, engineers can craft sturdier and more resilient infrastructure capable of withstanding the rigors of seismic events.

2.1 TIME HISTORY ANALYSIS

Time history analysis is a step-by step analysis of the dynamic response of a structure to a specified loading that may vary with time. Analysis is used to determine the seismic response of a structure under dynamic loading of representative earthquake. In this method, the structure is subjected to real ground motion records. The effect of soil structure interaction on the water tank for the entire study is carried out using Bhuj earthquake (2001) data with peak acceleration 1.0382 m/s^2

3. METHODOLOGY

1. **Tank Geometry and Ground Conditions:** The study focused on an open elevated water tank with dimensions of 4m x 4m and a staging height of 8m. The seismic analysis considered sloped ground, with ground slopes ranging from 0° to 20° at 5° intervals.

2. **Dynamic Model:** To evaluate dynamic behavior during seismic events, the tank was modeled as a two-mass structure, incorporating sloshing effects. The dynamic model accounted for impulsive and convective pressures to accurately represent liquid behavior. Parameters such asimpulsive and convective masses, time period, design horizontal seismic coefficient, total base shear, and base moment were determined according to IS 1893(Part 2): 2014 and IITK-GSDMA Guidelines.
3. **Numerical Analysis:** Finite Element Method (FEM) software SAP2000 v22 was employed for numerical analysis. Time history analyses were performed. The water tank, with dimensions 4m x 4m and a staging height of 8m, was modeled in the software. The analysis covered both full and empty tank conditions, considering combination of soil profiles.
4. **Seismic Analysis Parameters:** The evaluations included flexible base analyses, examining parameters such as displacement, and modal characteristics for both full and empty tank conditions for four combination of soil profile.
    1. Combination 1 – 9m soft clay + 9m loose sand
    2. Combination 2 – 4m soft clay + 14m loose sand
    3. Combination 3 – 6m soft clay + 6m loose sand + 6m soft clay
    4. Combination 4 –6m loose sand + 6m soft clay + 6m loose sand.
5. **Analysis Sequencing:** The analyses were systematically arranged to cover seismic considerations for water tanks. Sequentially, the study investigated the impact of water tank capacity(full or empty), and stratified soil layers.

4. PROBLEM FORMULATION AND ANALYSIS

The structural analysis considers flexible bases (Soil-Structure Interaction). Dynamic analysis, using the Time history in Zone II and Base shear, Displacement, and Modal parameters. The seismic analysis considered both leveled and sloped ground, with ground slopes ranging from 0° to 20° at 5° intervals for both empty and full tank conditions are examined, incorporating the structure's dead load and hydrostatic pressure. Hydrodynamic pressures including impulsive and Convective forces vertically along the wall height. This approach ensures a comprehensive understanding of the structural response for effective design and safety.

5. PRESENT STUDY

An open water tank measuring 4 x 4m with a free board of 0.3m and a depth of 3 meters. The tank is elevated 8m above the ground on a staging. The foundation is 2.0m below the level of the ground. The tank is situated in seismic zone II. M30 and Fe500 are the grades of concrete and steel, respectively. Concrete has a density of25 kN/m^3.

Table 1: Dynamic characteristics of elevated water tank

Sl No.	Contents	Description
1	Structure	SMRF
2	Seismic Zones	II
3	Zone factor	0.10
4	Importance Factor	1.5
5	Response Reduction Factor	4
6	Soil type	Combinaton of soft clay and loose sand

Table 2: Details of sizes of various components

COMPONENTS	SIZES(mm)
Wall thickness	250
Floor slab thickness	250
Floor beam	400×500
Braces	400×400
Columns	500x500

Table 3: Soil properties(Swami saran 2019)

Soil type	Unit weight (kn/m^3)	Modulus of elasticity (kn/m^2)	Poisson's ratio (μ)
Soft clay	18	15000	0.4
Loose sand	18.5	24000	0.3

6. RESULTS AND DISCUSSION

FIXED BASE ANALYSIS: Analysis has been performed forsoft soil for both empty and full tank condition on varying ground slope from 0 to 20 degree with 5 degree intervals.

ANALYSIS OF WATER TANK IN ZONE II

A. Empty Tank Condition: This analysis focuses on the seismic response of the water tank under the condition ofan empty tank, considering the dead load of the structure.The following factors are considered from relevant IS codes, for seismic analysis in zone II.

a. Zonefactor:0.10(Table2,IS1893(Part1):2016)
b. ImportanceFactor:1.5(Table1,IS1893(Part2):2014)
c. ResponseReductionFactor:4(Table2,IS1893(Part 2):2014)

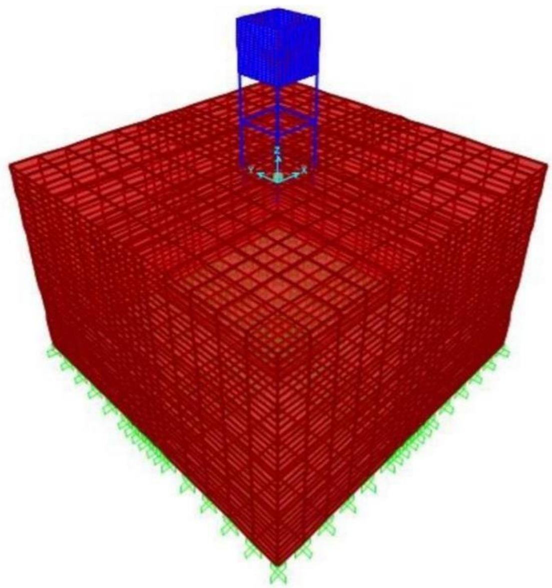


Figure 1: Soil-Structure Interaction (SSI) model

1. Combination 1 – 9m Soft clay + 9m loose sand

Table4: Modal parameters in for empty tank condition

Ground slope in degrees	Frequency(Hz)	Time Period (sec)
0	0.705	1.410
5	0.722	1.385
10	0.723	1.383
15	0.732	1.362
20	0.746	1.339

Table 5 : Displacements for empty tank condition

Ground slope in Degrees	Displacements(mm) at different heights			
	Base	4m	8m	11m
0	189.5	207.7	226.6	236.1
5	188.9	204.6	223.1	232.6
10	189.3	202.4	220.8	230.2
15	188.8	200.6	218.8	228.2
20	188.6	197.6	215.8	225.2

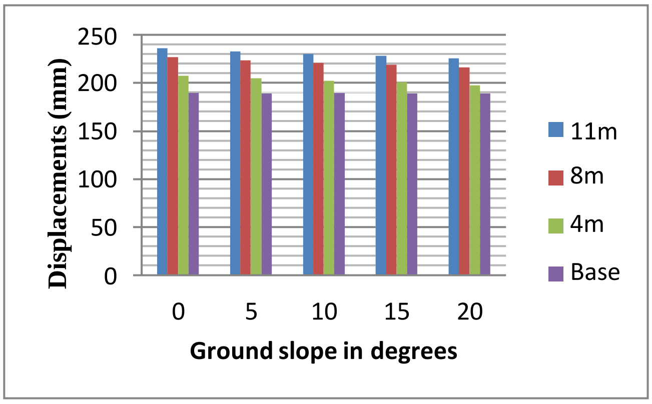


Figure 2: Displacements v/s Ground slope in degrees forcombination 1 Soil profile in empty tank condition

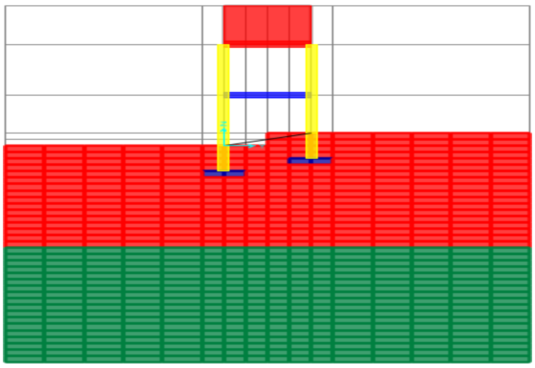


Figure 3: Soil-Structure Interaction model of water tank onsloped ground for combination 1 soil profile.

Table 6: Base Shear in zone II for empty tank condition

Ground slope in degrees	Base Shear(kN)
0	9070.301
5	9462.75
10	9637.94
15	9800.86
20	11318.8

1. Increasing ground Sloping leads to higher frequencies and shorter time periods. This signifies a corresponding improvement in structural stiffness.
2. The analysis of empty water tank for combination 1, considering stratified Soil-Structure Interaction (SSI) exhibits a decrease in displacements at different heights 4m, 8m, 11m as the ground sloping increases, indicating potential stability with steeper ground slopes.
3. Base shear values increases with increase in ground sloping suggests stability and effective resistance to seismic forces.

2. Combination 2 – 4m Soft clay + 14m loose sand

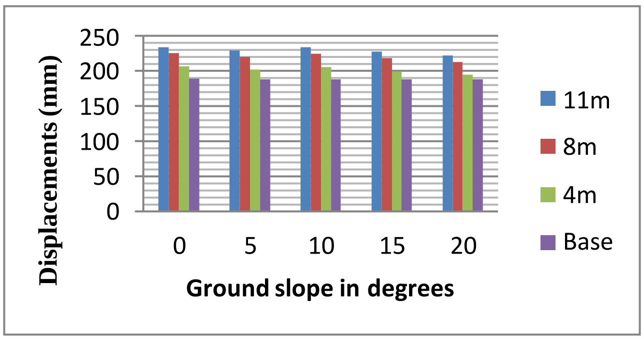
Table 7: Modal Parameters for empty tank condition

Ground slope in degrees	Frequency(Hz)	Time Period (sec)
0	0.738	1.354
5	0.756	1.321
10	0.745	1.340
15	0.764	1.307
20	0.778	1.284

Table 8: Displacements for empty tank condition

Ground slope in Degrees	Displacements (mm) at different heights			
	Base	4m	8m	11m
0	188.7	206.4	225.1	234.1
5	188.6	201.7	219.8	228.7
10	188.5	205.5	225.0	234.1
15	187.7	199.1	217.9	227.5
20	188.5	194.5	212.6	221.5

Figure 4: Displacements v/s Ground slope in degrees for combination 2 Soil profile in empty tank condition



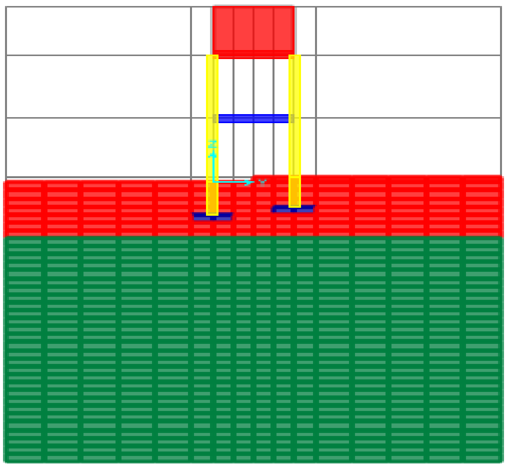


Figure 5: Soil-Structure Interaction model of water tank on sloped ground for combination 2 soil profile

Table 9: Base Shear for combination 2 soil profile inempty tank condition

Ground slope in degrees	Base Shear (kN)
0	11240.07
5	13935.73
10	12226.65
15	14808.51
20	11318.85

1. The displacements of the water tank in combination 2, considering 4m clay +14m sand reveals a different pattern. Displacements decreases up to a 10^0 ground slope, indicating a stiffer response to seismic forces. However at 10^0, displacement increases as frequency decreases due to stiffness variation suggesting a shift towards greater flexibility.. However, beyond 10^0 displacements decreases indicating a stiffer response to seismic forces. Thus indicating the effect of stratification.
2. The variation of Base Shear with deformations with increase in sloping ground ranging from 0^0 to 20^0 with 5^0 intervals, underscore the structure's ability to manage seismic forces effectively.
3. The seismic analysis reveals an increase in frequency and a decrease in time period of the water tank with higher ground sloping beyond 10^0. This signifies a corresponding improvement in structural stiffness.

3. Combination 3 – 6m Soft clay + 6m Loose sand + 6m Soft clay

Table 10: Modal Parameters for empty tankcondition

Ground slope indegrees	Frequency(Hz)	Time Period (sec)
0	0.630	1.586
5	0.640	1.550
10	0.659	1.510
15	0.620	1.612
20	0.635	1.574

Table 11: Displacements for empty tank condition

Ground slope in Degrees	Displacements (mm) at different heights			
	Base	4m	8m	11m
0	187.9	196.1	214.4	223.5
5	186.9	195.4	213.6	221.9
10	185.4	192.5	212.6	220.8
15	188.1	194.3	213.2	221.4
20	188.1	189	204.2	212.8

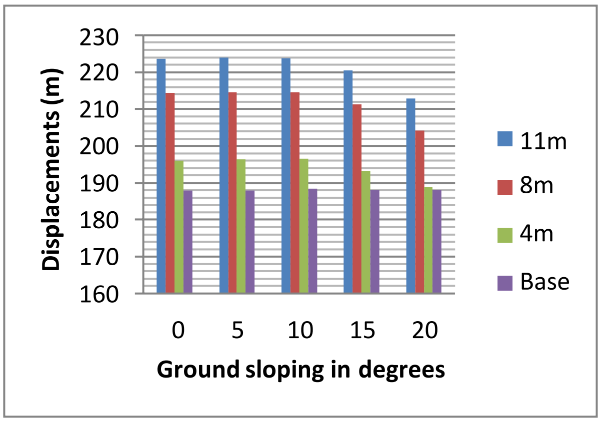


Figure 6: Displacements v/s Ground slope in degrees forcombination 3 Soil profile in empty tank condition

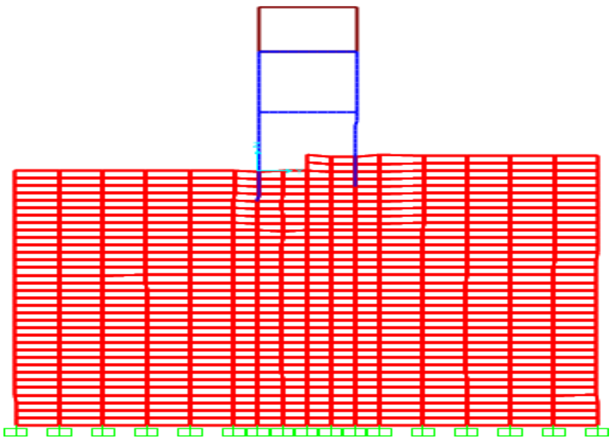


Figure 7: Deformed shape of water tank on slopedground

Table 12: Base Shear for combination 3 soil profile inempty tank condition

Ground slope in degrees	Base Shear (kN)
0	10736.11
5	10896.68
10	10956.30
15	9990.45
20	10835.21

1. The variation in displacement and frequency with increase in sloping ground ranging from 0^0 to 20^0 with 5^0 intervals is lighter , indicating stiffer soil profile.
2. The variation of Base Shear with deformations with increase in sloping ground ranging from 0^0 to 20^0 with 5^0 intervals, underscore the structure's ability to manage seismic forces effectively

.

4. Combination 4 – 6m loose sand + 6m Soft clay + 6m loose sand

Table 13: Modal Parameters for empty tank condition

Ground slope in degrees	Frequency(Hz)	Time Period (sec)
0	0.647	1.544
5	0.632	1.582
10	0.709	1.410
15	0.722	1.385
20	0.724	1.380

Table 14: Displacements for empty tank condition.

Ground slope in Degrees	Displacements (mm) at differentheights			
	Base	4m	8m	11m
0	187.9	193.0	210.1	218.8
5	189.4	199.2	216.5	225.2
10	189.4	198.0	215.3	224.1
15	189.0	194.3	210.2	218.6
20	188.5	190.2	205.1	213.4

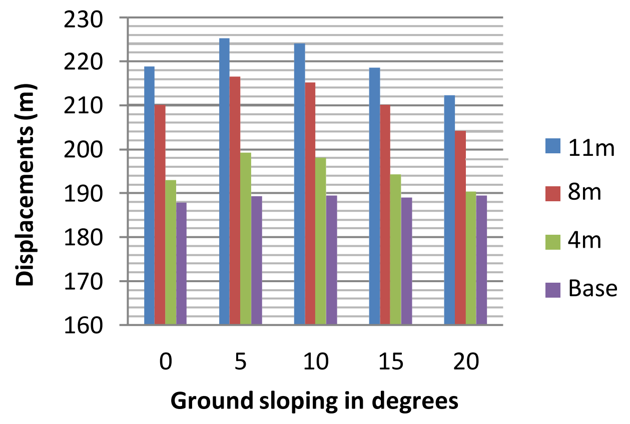


Figure 8: Displacements v/s Ground slope in degrees for combination 4 Soil profile in empty tank condition

Figure 9: Soil-Structure Interaction model of water tank onsloped ground for combination 4 soil profile

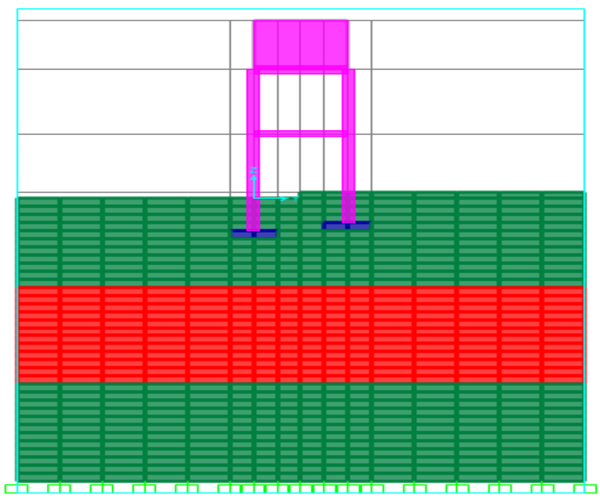


Table 15: Base Shear for combination 4 soil profile in empty tank condition

Ground slope in degrees	Base Shear (kN)
0	9472.59
5	7823.30
10	8218.80
15	8500.00
20	8829.09

1. The displacements of the empty water tank conditions reveals a different pattern. Displacements increases for 5^0 ground slope suggesting greater soft soil flexibility and larger deformation ns. However, beyond 5^0 displacements decreases indicating a stiffer response to seismic forces.
2. Base shear values increase with increasing ground slope beyond 5^0. Increase in Base Shear suggests stability and effective resistance to seismic forces.
3. The seismic analysis reveals an increase in frequency and a decrease in time period of the water tank with higher ground sloping beyond 5^0. This signifies a corresponding improvement in structural stiffness.

B. FULL TANK CONDITION

The seismic analysis of a water tank resting on leveled and sloped ground considering different soil combination, the analysis focuses on the seismic response of the water tankunder the condition of a full tank, considering both impulsive and convective pressures.

Following factors are considered from relevant IS code, forseismic analysis in zone II.

Zone factor: 0.10 (Table 2, IS1893 (Part 1):2016)

Importance Factor: 1.5 (Table 1, IS1893 (Part 2):2014)

Response Reduction Factor: 4 (Table 2, IS1893 (Part 2):2014)

Table 16: Water pressure details for zone II

Water pressure	Zone II
Impulsive (kN/m²)	2.126
Convective (kN/m²)	0.202
Hydrostatic pressure (kN/m²)	26.487

5. Combination 1 – 9m Soft clay + 9m loose sand

Table17: Modal Parameters for full tank condition

Ground slope in degrees	Frequency(Hz)	Time Period (sec)
0	0.699	1.428
5	0.718	1.391
10	0.720	1.388
15	0.726	1.375
20	0.739	1.35

Table 18 :Displacement for full tank condition

Ground slope in Degrees	Displacements (mm) at different heights			
	Base	4m	8m	11m
0	190.1	231.3	262.0	274.9
5	189.7	212.6	234.5	245.0
10	189.4	205.7	226.0	235.9
15	188.9	204.3	225.2	234.0
20	188.2	200.5	220.4	229.8

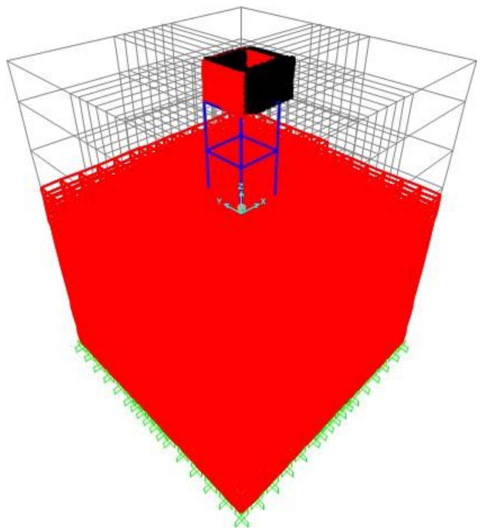


Figure 10: Full tank condition of elevated water tank on slopedground

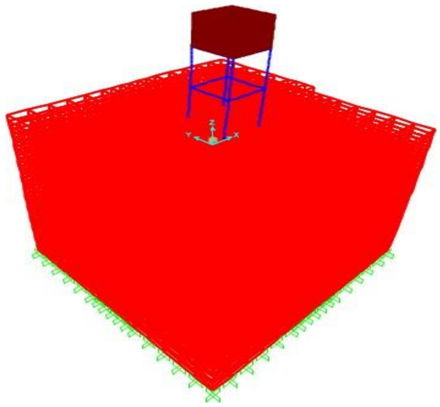


Figure 11: Deformed shape of elevated water tank onsloped ground

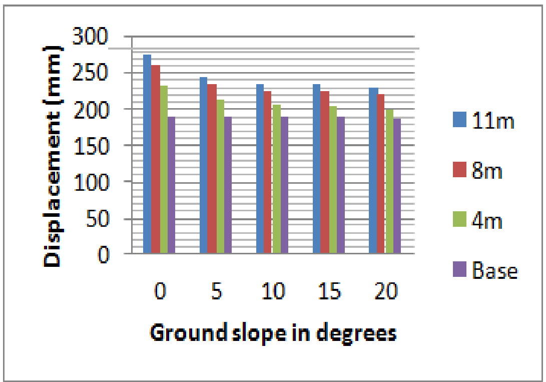


Figure 12: Displacements v/s Ground slope in degrees for combination 1 Soil profile in full tank condition

Table 19: Base Shear for combination 1 soil profile in full tankcondition

Ground slope in degrees	Base Shear (kN)
0	9086.38
5	9582.75
10	9730.94
15	9885.86
20	12532.85

1. Displacement is more in full tank condition due to application of water pressure.
2. Increasing ground Sloping leads to higher frequencies and shorter time periods.This signifies a correspondingimprovement in structural stiffness.
3. The analysis of full water tank for combination 1, considering stratified Soil-Structure Interaction (SSI) exhibits a decrease in displacements at different heights4m, 8m, 11m as the ground sloping increases, indicating potentialstability with steeper ground slopes.
4. Base shear values increases with increase in ground sloping suggests stability and effective resistance to seismic forces.

6. Combination 2 – 4m Soft clay + 14m loose sand

Table 20: Modal Parameters for full tank condition

Ground slope indegrees	Frequency (Hz)	e Period(sec)
0	0.731	1.366
5	0.749	1.333
10	0.759	1.351
15	0.758	1.318
20	0.772	1.294

Table 21 Displacement for full tank condition

Ground slope in Degrees	Displacements (mm) at different heights			
	Base	4m	8m	11m
0	189.3	228.3	257.3	269.0
5	189.4	218.6	245.1	256.1
10	188.7	211.7	235.5	245.7
15	188.4	200.1	226.4	237.6
20	188.6	191.3	223.8	235.8

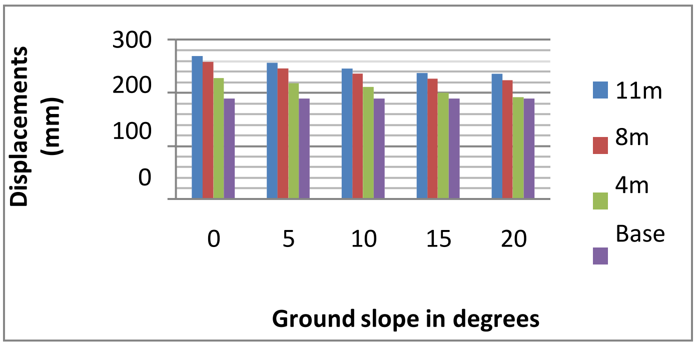


Figure 13: Displacements v/s Ground slope in degees for combination 2 Soil profile in full tank condition.

1. The analysis of full water tank for combination 2, considering the effect of stratification exhibits a

decrease in displacements at different heights 4m, 8m,11m as the ground sloping increases, indicating potentialstability with steeper ground.

2. Increasing ground Sloping leads to higher frequencies and shorter time periods.This signifies a correspondingimprovement in structural stiffness.

7. Combination 3 – 6m Soft clay + 6m loose sand+6m soft clay

Table 22: Modal Parameters for full tank condition

Ground slope in degrees	Frequency(Hz)	Time Period (sec)
0	0.626	1.594
5	0.640	1.561
10	0.654	1.527
15	0.667	1.499
20	0.648	1.539

Table 23: Displacements for full tank condition

Ground slope in Degrees	Displacements (mm) at different heights			
	Base	4m	8m	11m
0	189.5	208.8	234.2	245.0
5	188.1	203.4	226.7	236.8
10	187.9	198.2	219.3	228.1
15	188.2	188.5	200.4	208.0
20	188.0	188.6	207.0	212.8

Table 24: Base Shear for combination 3 soil profile in fulltank condition

Ground slope in degrees	Base Shear (kN)
0	10835.12
5	10298.69
10	9863.32
15	10008.32
20	12632.02

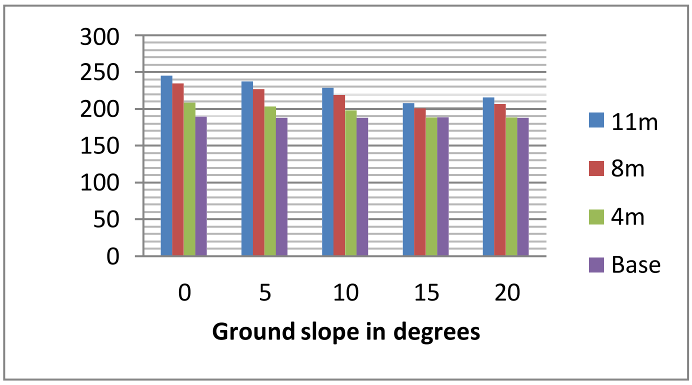


Figure 14: Displacements v/s Ground slope in degrees forcombination 3 Soil profile in full tank condition

1. The displacements of the water tank in combination 3 in full tank reveal a different pattern. Displacements decreases up to a 15^0 ground slope, indicating a stiffer response to seismic forces. However at 20^0, displacement increases as frequency decreases due to stiffness variation suggesting a shift towards greater flexibility. Thus indicating the effect of stratification.
2. The variation of frequency 20^0 due to stiffness variationenhances the effect of stratification.
3. The variation of Base Shear with deformations with increase in sloping ground ranging from 0^0 to 20^0 with 5^0 intervals, underscore thestructure's ability to manage seismic forces effectively.

8. Combination 4 – 6m Loose sand + 6m Soft clay + 6mLoose sand

Table 25: Modal Parameters for full tank condition

Ground slope in degrees	Frequency(Hz)	Time Period (sec)
0	0.64	1.558
5	0.629	1.453
10	0.701	1.418
15	0.710	1.408
20	0.720	1.388

Table 26: Displacements for full tank condition

Ground slope in Degrees	Displacements (mm) at different heights			
	Base	4m	8m	11m
0	187.8	203.2	227.5	237.6
5	189.7	207.8	231.9	242.2
10	189.5	204.6	227.3	237.2
15	189.8	198.8	221.0	230.2
20	189.8	196.7	218.6	228.1

Table 27: Base Shear for combination 4 soil profile in full tank condition

Ground slope in degrees	Base Shear (kN)
0	9500.60
5	7924.34
10	8315.50
15	8556.3
20	8925.15

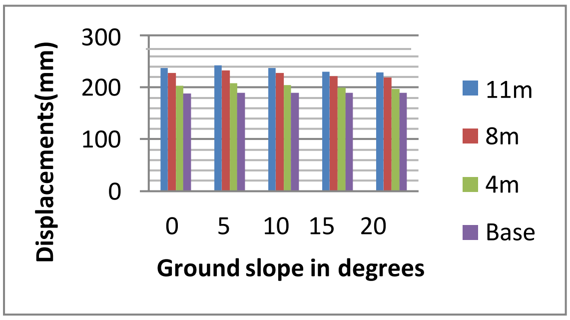


Figure 15: Displacements v/s Ground slope indegrees for combination 4 Soil profile in full tank condition.

1. The displacements of the empty water tank conditions reveal a different pattern. Displacements increases for 5^0 ground slope suggesting greater soft soil flexibility and larger deformations. However, beyond 5^0 displacements decreases indicating a stiffer response to seismic forces.
2. Base shear values increase with increasing ground slope beyond 5^0. Increase in Base Shear suggests stability and effective resistance to seismic forces.
3. The seismic analysis reveals an increase in frequency and a decrease in time period of the water tank with higher ground sloping beyond 5^0. This signifies a corresponding improvement in structural stiffness

4.CONCLUSION

Based on the results of detailed analysis of an elevated water tank resting on leveled and sloping ground, the following conclusions can be made,

1. Displacements and base shear are higher in full tank condition due to presence of hydrostatic pressure. This indicates that the water mass exerts additional seismic forces on the structure.
2. In a full tank condition, the effect of sloping ground on displacement is influenced by the additional mass of water.
3. The effect of stratified soil layers alters the frequency ofsoil mass due to which the displacement variation of thestructure can be observed in stratified soil layers.
4. Whenever structure is resting on stratified soil deposits,frequency of soil mass must be determined so that if soil mass has lower frequency it will lead to larger displacements in structures resting on them.
5. The effect of stratification is illustrated when alteration of frequency is observed as the slope angle of ground increases from 0� t0 20� due to stiffness variation in soilmass.
6. In case of Combination 1(9m soft clay +9m loose sand) and Combination 2 (4m soft clay+14m loose sand) soil profile it can be observed that the displacement for Combination 1 soil profile at the top of the tank is high because of low frequency when compared to Combination 2 soil profile.
7. In case of Combination 3(6m soft clay+6m loose sand+6m soft clay) and Combination 4 (6m loose sand+6m soft clay + 6m loose sand) soil profile it can be observed that the displacement for Combination 3 soil profile at the top of the tank is high because of low frequency when compared to Combination 4 soil profile.
8. The seismic responses of water tank resting on stratifiedsoil deposits depends on natural frequency of soil mass and displacement is inversely proportional to frequency.
9. Base Shear values increases with sloping ground, suggest increased resistance to seismic forces in flexible base condition.

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