SEISMIC ANALYSIS AND DESIGN OF ELEVATED WATER TANK WITH COMPREHENSIVE SOIL-STRUCTURE INTERACTION ASSESSMENT

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Abstract -*Elevated water tanks have irregular mass distribution, making them susceptible to amplified seismic forces during earthquakes, potentially leading to structural failure or damage. Proper reinforcement and seismic design are essential to mitigate these risks and ensure reliable water distribution. The seismic performance of elevated water tanks is crucial for ensuring public safety and water supply resilience, especially in earthquake-prone regions. Elevated tanks face significant lateral loads due to their height and mass distribution. Neglecting Soil-Structure Interaction (SSI) in seismic analyses can lead to inaccurate assessments of structural behavior. This study investigates the seismic behavior of elevated water tanks on both level and sloping ground, considering fixed and flexible bases using the Response Spectrum Method (RSM) in accordance with IS 1893(Part 1): 2016, for seismic zones II and III, Finite Element Analysis (FEA) software SAP2000 v22 is employed to evaluate the effects of SSI. Three soil types soft, medium, and hard are considered, accounting for full and empty tank conditions. The numerical analysis reveals variations in structural response under seismic loading, with different slope angles exposing vulnerabilities associated with sloping ground. Results underscore the importance of incorporating SSI effects in seismic analysis to obtain realistic assessments of water tank performance. The inclusion of SSI captures the dynamic interaction between the tank and underlying soil, providing a more comprehensive understanding of structural behavior during seismic events. This study highlights the necessity of considering SSI in the design and assessment of elevated water tanks, particularly in earthquake-prone areas. By accounting for SSI, engineers can better mitigate risks and enhance the seismic resilience of water supply infrastructure.*

***Key Words*: Soil-Structure Interaction (SSI), Sloping Ground, Response Spectrum Method (RSM), Elevated water tank, Seismic zones**.

1.INTRODUCTION

Elevated water tanks are essential infrastructure components for various applications, including domestic, industrial, and agricultural purposes. The design and placement of these tanks are critical factors influencing their structural integrity, efficiency, and reliability. In many regions, the availability of flat land suitable for tank installation is limited, leading to the construction of water tanks on sloped ground. However, the unique challenges posed by sloped terrain necessitate careful consideration in the design and placement of water tanks to ensure optimal performance and longevity.

Water tanks positioned on sloped terrain introduce complexities that significantly impact their structural stability and seismic resilience. Unlike on level ground, the uneven foundation on a slope can lead to differential settlements, tilting, and rotation of the tank, posing risks to structural integrity. Additionally, gravitational forces acting on stored water increase lateral loads, heightening the potential for overturning moments and structural failure, especially during seismic events. Soil-Structure Interaction (SSI) effects become more pronounced, amplifying seismic forces, and exacerbating structural responses. The presence of a slope also raises the risk of sliding, particularly if foundations are inadequately anchored or soil conditions are unstable. Seismic events further intensify this hazard, potentially resulting in displacement or collapse. Understanding these complexities is crucial for engineering solutions that enhance the stability and resilience of water tanks on sloped ground, ensuring the safety and reliability of water supply infrastructure in challenging terrain conditions.

1.1 Soil-Structure Interaction (SSI)

Soil-Structure Interaction (SSI) is a fundamental aspect of structural engineering that considers the dynamic interplay between a structure and the underlying soil. In seismic regions, this interaction becomes paramount due to the potential for ground motion to significantly affect the behavior of structures. Traditionally, structural analysis has often neglected the influence of soil on structural response, treating structures as isolated entities.

However, in reality, the characteristics of the soil play a crucial role in determining how a structure will behave during seismic events. Factors such as soil stiffness, damping properties, and soil-structure resonance can all impact the structural response.

For elevated water tanks, which are subject to high lateral loads due to their height and mass, understanding SSI is particularly critical. The interaction between the water tank and the soil beneath it can lead to complex behaviors, including foundation rocking and soil amplification effects, which can significantly influence the tank's seismic performance.

To accurately account for SSI, engineers utilize advanced computational techniques such as Finite Element Analysis (FEA). These methods allow for the simulation of the coupled behavior of the structure and the soil, providing insights into how the two interact under seismic loading.

By incorporating SSI into structural analysis and design, engineers can obtain more realistic predictions of structural response during s eismic events. This enables them to assess the seismic vulnerability of elevated water tanks more accurately and develop appropriate mitigation measures to enhance their resilience.

Overall, understanding and accounting for Soil-Structure Interaction are crucial steps in ensuring the safety and reliability of structures, particularly in earthquake-prone areas. By considering the dynamic interaction between structures and their foundation soil, engineers can design more robust and resilient infrastructure capable of withstanding the forces imposed by seismic events.

2. METHODOLOGY

1. **Tank Geometry and Ground Conditions:** The study focused on an open elevated water tank with dimensions of 3m x 3m and a staging height of 6m. The seismic analysis considered both levelled and sloped ground, with ground slopes ranging from 0° to 30° at 5° intervals.
2. **Dynamic Model:** To evaluate dynamic behavior during seismic events, the tank was modelled as a two-mass structure, incorporating sloshing effects. The dynamic model accounted for impulsive and convective pressures to accurately represent liquid behavior. Parameters such as impulsive 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. Response Spectrum functions, guided by IS 1893(Part 1): 2016, were defined. The water tank, with dimensions 3m x 3m and a staging height of 6m, was modelled in the software. The analysis covered both full and empty tank conditions, considering seismic zones II and III, as well as varying soil types (soft, medium, and hard).
4. **Seismic Analysis Parameters:** The evaluations included fixed base analyses, examining parameters such as base shear, displacement, and modal characteristics for both full and empty tank conditions. Soil-Structure Interaction (SSI) analyses were conducted, comparing base shear, displacement, and modal characteristics between fixed and flexible bases.
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), seismic zones, and soil types on fixed base and flexible base responses (Soil-Structure Interactions)

3. PROBLEM FORMULATION AND ANALYSIS

This comprehensive evaluation encompasses analyzing the tank's behavior in full and empty conditions, assessing seismic response under varying soil conditions (soft, medium, and hard), and evaluating modal parameters, base shear, and displacements for fixed and flexible base conditions. Additionally, considerations extend to the tank's placement on both leveled and sloped ground, accounting for the effects of ground inclination on structural response. Compliance with relevant codes and standards ensures the integrity and safety of the water tank under seismic loading.

3.1 PRESENT STUDY

An open water tank measuring 3 x 3m with a freeboard of 0.3m and a depth of 3 meters. The tank is elevated 6m above the ground on a staging. The foundation is 1.5m below the level of the ground. The tank is situated in seismic zone II & III. M25 and Fe500 are the grades of concrete and steel, respectively. Concrete has a density of 25 kN/m^3.

Table 1: Dynamic characteristics of elevated water tank

Sl No.	Contents	Description
1	Structure	SMRF
2	Seismic Zones	II & III
3	Zone factor	0.10 & 0.16
4	Importance Factor	1.5
5	Response Reduction Factor	4
6	Soil type	Soft, Medium, Hard

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Table 2: Details of sizes of various components

COMPONENTS	SIZES (mm)
Wall thickness	180
Floor slab thickness	180
Floor beam	300 × 400
Braces	280 × 280
Columns	300 x 300

Table 3: Water pressure details

Water Pressure	ZONE II	ZONE III
Impulsive Pressure (kN/m²)	0.85	1.37
Convective Pressure (kN/m²)	0.24	0.39
Hydrostatic Pressure (kN/m²)	26.49	26.49

4. RESULTS AND DISCUSSION

4.1 FIXED BASE ANALYSIS This analysis focuses on the seismic response of the water tank resting on levelled and sloped ground, with ground slopes ranging from 0^0 to 30^0 with 5^0 intervals, under both full tank and empty tank conditions, with the water tank assumed to have a fixed base. Response Spectrum Function is defined for zone II and zone III considering 5% damping. The primary objectives include evaluating modal parameters, displacements at different heights, and base shear values for various sloping ground.

4.1.1 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 of an 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. Zone factor: 0.10 (Table 2, IS1893(Part 1):2016)
b. Importance Factor: 1.5 (Table 1, IS1893(Part 2):2014)
c. Response Reduction Factor: 4 (Table 2, IS1893(Part 2):2014)

Table 4: Modal parameters in zone II for empty tank condition

Ground sloping in degrees	Frequency (Hz)	Time Period (sec)
0	2.556	0.391
5	2.635	0.379
10	2.718	0.367
15	2.806	0.356
20	2.903	0.344
25	3.015	0.331
30	3.149	0.317

Table 5: Displacements in zone II for empty tank condition

Ground sloping in Degrees	Displacements(mm) at different height		
	3m	6m	9m
0	0.95	1.92	1.97
5	0.84	1.80	1.85
10	0.73	1.67	1.71
15	0.61	1.52	1.56
20	0.48	1.37	1.40
25	0.34	1.20	1.23
30	0.22	1.03	1.06

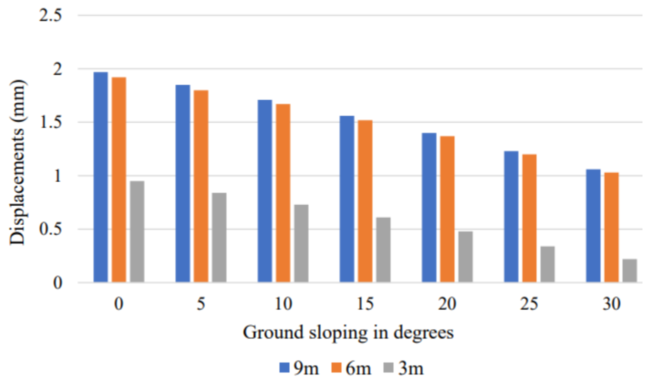

Figure 1: Displacement v/s Ground sloping in degrees in zone II for empty tank condition

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

Ground sloping in degrees	Base Shear (kN)
0	14.46
5	14.43
10	14.40
15	14.37
20	14.34
25	14.31
30	14.29

B. Full Tank Condition

This analysis focuses on evaluating the seismic response of the water tank resting on levelled and sloped ground, with ground slopes ranging from 0^0 to 30^0 with 5^0 intervals, under full tank condition, with the water tank assumed to have a fixed base. For the analysis of the full tank condition in Zone II, both impulsive and convective pressures are considered.

The modal parameters, displacements at different heights, and base shear for various ground sloping are presented below.

Table 7: Modal parameters in zone II for full tank condition

Ground sloping in degrees	Frequency (Hz)	Time Period (sec)
0	2.120	0.471
5	2.185	0.457
10	2.254	0.443
15	2.327	0.429
20	2.409	0.415
25	2.503	0.399
30	2.616	0.382

Table 8: Displacements in zone II for full tank condition

Ground sloping in Degrees	Displacements(mm) at different height		
	3m	6m	9m
0	1.13	2.32	2.37
5	1.04	2.25	2.30
10	0.94	2.17	2.22
15	0.82	2.07	2.12
20	0.67	1.94	1.99
25	0.49	1.71	1.75
30	0.31	1.47	1.51

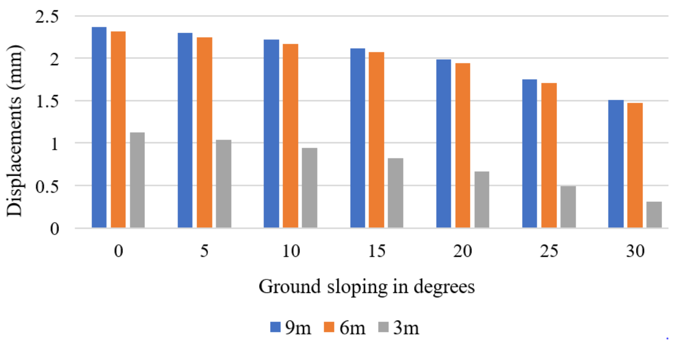

Figure 2: Displacement v/s Ground sloping in degrees in zone II for full tank condition

Table 9: Base Shear in zone II for full tank condition

Ground sloping in degrees	Base Shear (kN)
0	17.20
5	17.77
10	18.44
15	19.30
20	20.16
25	20.19
30	20.12

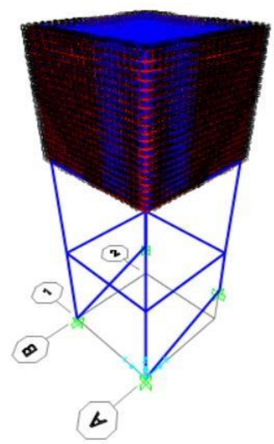

Figure 3: Typical Full tank model.

4.1.2 ANALYSIS OF WATER TANK IN ZONE III

A. Empty Tank Condition This analysis focuses on evaluating the seismic response of the water tank resting on levelled and sloped ground, with ground slopes ranging from 0^0 to 30^0 with 5^0 intervals, under empty tank condition, considering the dead load of the structure.

The Following factors are considered from relevant IS code, for seismic analysis in zone III.

a. Zone factor: 0.16 (Table 2, IS1893(Part 1):2016)
b. Importance Factor: 1.5 (Table 1, IS1893(Part 2):2014)
c. Response Reduction Factor: 4 (Table 2, IS1893(Part 2):2014)

Table 10: Displacements in zone III for empty tank condition

Ground sloping in Degrees	Displacements(mm) at different height		
	3m	6m	9m
0	1.52	3.08	3.15
5	1.35	2.89	2.96
10	1.17	2.68	2.74
15	0.97	2.44	2.51
20	0.76	2.19	2.25
25	0.55	1.92	1.98
30	0.35	1.65	1.71

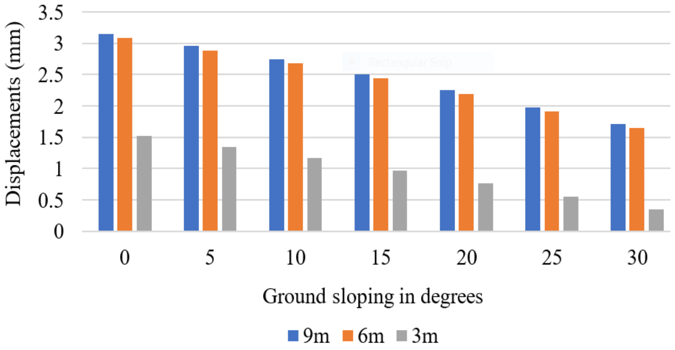

Figure 4: Displacement v/s Ground sloping in degrees in zone III for empty tank condition

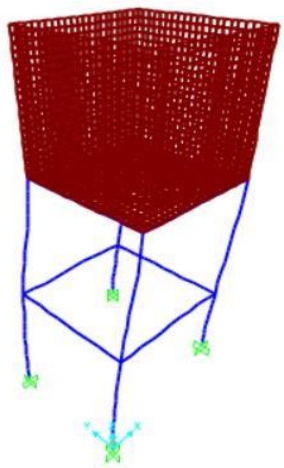

Figure 5: Deformed water tank model

Table 11: Base Shear in zone III for empty tank condition

Ground sloping in degrees	Base Shear (kN)
0	23.14
5	23.09
10	23.04
15	23.01
20	22.94
25	22.89
30	22.92

B. Full Tank Condition

This analysis focuses on evaluating the seismic response of the water tank resting on levelled and sloped ground, with ground slopes ranging from 0^0 to 30^0 with 5^0 intervals, under full tank condition. For the analysis of the full tank condition in Zone III, both impulsive and convective pressures are considered. The modal parameters, displacements at different staging heights, and base shear for various ground sloping are presented below.

Table 12: Displacements in zone III for full tank condition

Ground sloping in Degrees	Displacements(mm) at different height		
	3m	6m	9m
0	1.82	3.71	3.79
5	1.67	3.61	3.69
10	1.51	3.47	3.55
15	1.31	3.32	3.40
20	1.08	3.11	3.19
25	0.79	2.73	2.80
30	0.50	2.35	2.41

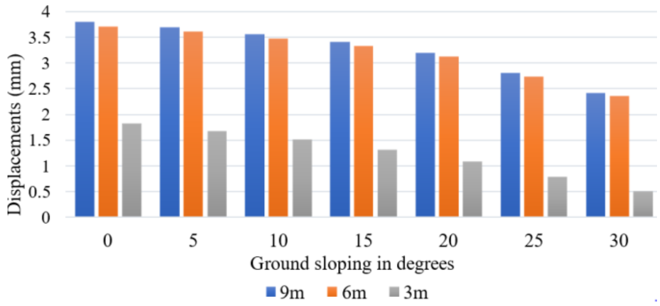

Figure 6: Displacement v/s Ground sloping in degrees in zone III for full tank condition

Table 13: Base Shear in zone III for full tank condition

Ground sloping in degrees	Base Shear (kN)
0	27.52
5	28.44
10	29.50
15	30.89
20	32.25
25	32.18
30	32.21

From Table 4 to 13, and Figure 1 to 6, the following observations are made:

1. Displacements and Base Shear are higher in full tank condition due to the presence of hydrostatic pressure. This indicates that the water mass exerts additional seismic forces on the structure.
2. The higher Base Shear values in Zone III indicate a more significant seismic force on the structure compared to Zone II.
3. The increase in ground sloping from 0^0 to 30^0 with 5^0 intervals generally increases structural stiffness, resulting in higher natural frequencies, and reduced lateral displacements in both Zone II and III.
4. The distribution of mass influences the displacement patterns during seismic events.

5. Displacements decrease as ground slope increases from 0^0 to 30^0 for both empty tank and full tank conditions. A steeper sloping ground may lead to increased structural stiffness, reducing the flexibility of the tank and resulting in smaller lateral displacements.
6. Increase in Base Shear is seen with an increase in ground slope from 0^0 to 30^0 for both empty tank and full tank conditions, indicating stability in lateral force distribution.

4.2 FLEXIBLE BASE ANALYSIS (SOIL-STRUCTURE INTERACTION)

The effects of Soil- Structure Interaction (SSI) on water tanks resting on levelled and sloped ground, considering factors such as soil characteristics, foundation design, and varying ground slopes from 0^0 to 30^0 with 5^0 intervals. The structural foundation consists of an isolated square footing of depth 500mm, located 1.5m below ground level. The soil is accurately modelled, extending 10m in width on both sides and reaching a depth of 15m.
The soil in the model is constrained with specific boundary conditions: restraints in the x-axis within the YZ plane, restraints in the y-axis within the XZ plane and fixity at the bottom of soil model. This involves dividing the modelled soil geometry into a grid or network of smaller elements to facilitate numerical analysis. Response Spectrum method of analysis is performed.

Table 14: Soil Properties (Swami saran, 2019)

Soil type	Unit weight (kN/m³)	Modulus of elasticity (kN/m²)	Poisson's ratio (μ)
Soft soil	16	25000	0.35
Medium soil	16	45000	0.35
Hard soil	18	95000	0.30

4.2.1 ANALYSIS OF WATER TANK IN ZONE II FOR EMPTY TANK CONDITION

The seismic analysis of a water tank resting on levelled and sloped ground in seismic zones II, considering soft, medium, and hard soil conditions, the analysis focuses on the seismic response of the water tank under the condition of an empty tank, considering the dead load of the structure.

i. Soft Soil Condition

Table 15: Modal Parameters in zone II (Soft soil) for empty tank condition

Ground sloping in degrees	Frequency (Hz)	Time Period (sec)
0	1.785	0.560
5	1.812	0.551
10	1.871	0.534
15	1.912	0.522
20	1.985	0.503
25	2.030	0.492
30	2.113	0.473

Table 16: Displacements in zone II (Soft soil) for empty tank condition

Ground sloping in Degrees	Displacements(mm) at different height			
	Base	3m	6m	9m
0	2.36	4.64	7.04	7.34
5	2.36	4.46	6.87	7.14
10	2.34	4.13	6.59	6.80
15	2.33	3.92	6.47	6.64
20	2.33	3.82	6.76	6.88
25	2.35	4.06	7.55	7.75
30	2.44	5.24	10.60	11.24

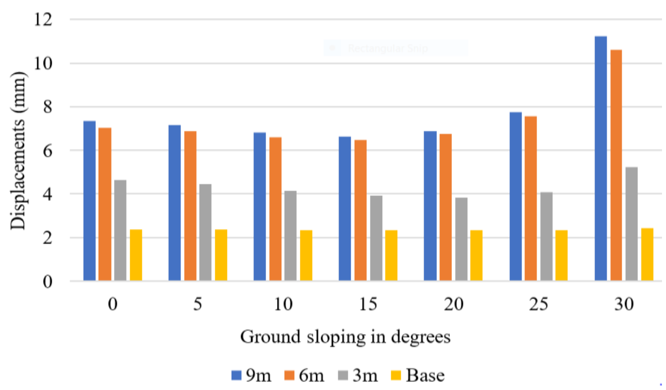

Figure 7: Displacements v/s Ground sloping in degrees in zone II (Soft soil) for empty tank condition

Table 17: Base Shear in zone II (Soft soil) for empty tank condition

Ground sloping in degrees	Base Shear (kN)
0	4914.76
5	4960.54
10	5000.22
15	5054.69
20	5105.69
25	5158.16
30	5216.99

Figure 8: Soil-Structure Interaction (SSI) model of water tank on sloped ground

ii. Medium Soil Condition

Table 18: Modal Parameters in zone II (Medium soil) for empty tank condition

Ground sloping in degrees	Frequency (Hz)	Time Period (sec)
0	1.950	0.512
5	1.991	0.502
10	2.051	0.487
15	2.106	0.474
20	2.183	0.458
25	2.244	0.445
30	2.338	0.427

Table 19: Displacements in zone II (Medium soil) for empty tank condition

Ground sloping in Degrees	Displacements(mm) at different height			
	Base	3m	6m	9m
0	1.43	3.57	5.64	5.91
5	1.43	3.36	5.40	5.67
10	1.41	3.05	5.08	5.33
15	1.41	2.76	4.75	4.99
20	1.40	2.37	4.33	4.54
25	1.40	2.08	4.03	4.21
30	1.40	1.73	3.74	3.86

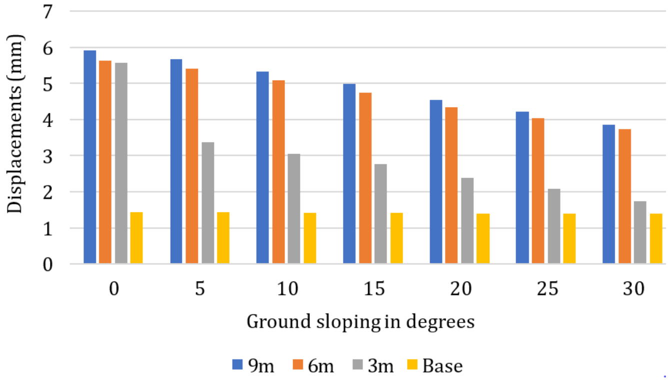

Figure 9: Displacements v/s Ground sloping in degrees in zone II (Medium soil) for empty tank condition

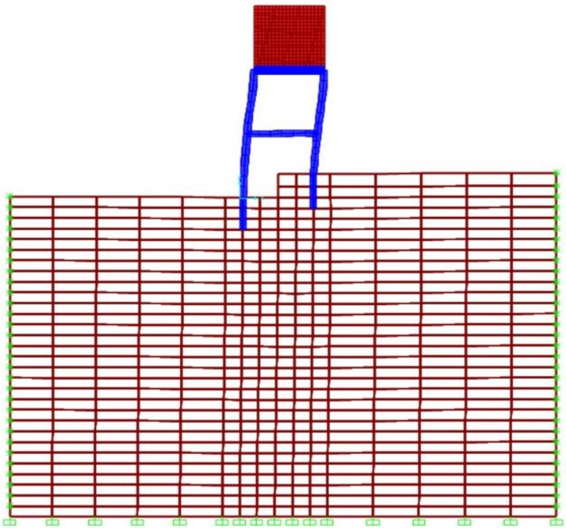

Figure 10: Deformed shape of water tank on sloped ground

Table 20: Base Shear in zone II (Medium soil) for empty tank condition

Ground sloping in degrees	Base Shear (kN)
0	4914.74
5	4960.40
10	5000.05
15	5054.58
20	5105.25
25	5158.17
30	5216.89

iii. Hard Soil Condition

Table 21: Modal parameters in zone II (Hard soil) for empty tank condition

Ground sloping in degrees	Frequency (Hz)	Time Period (sec)
0	2.094	0.477
5	2.150	0.465
10	2.208	0.452
15	2.276	0.439
20	2.353	0.424
25	2.428	0.411
30	2.526	0.395

Table 22: Displacements in zone II (Hard soil) for empty tank condition

Ground sloping in Degrees	Displacements(mm) at different height			
	Base	3m	6m	9m
0	0.75	2.23	3.66	3.82
5	0.75	2.12	3.58	3.73
10	0.75	1.99	3.47	3.63
15	0.75	1.83	3.34	3.50
20	0.75	1.62	3.16	3.33
25	0.75	1.41	2.94	3.09
30	0.75	1.16	2.65	2.80

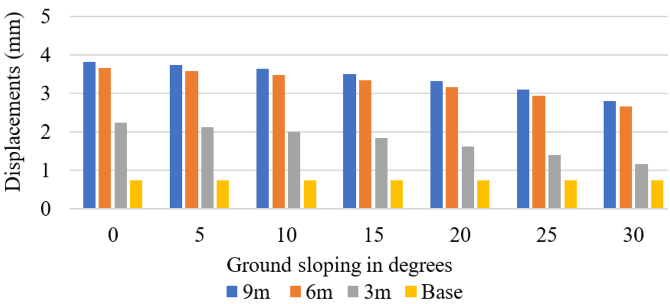

Figure 11: Displacements v/s Ground sloping in degrees in zone II (Hard soil) for empty tank condition

Table 23: Base Shear in zone II (Hard soil) for empty tank condition

Ground sloping in degrees	Base Shear (kN)
0	5526.85
5	5578.21
10	5622.82
15	5684.20
20	5741.12
25	5800.70
30	5866.90

4.2.2 ANALYSIS OF WATER TANK IN ZONE III FOR EMPTY TANK CONDITION

i. Soft Soil Condition

Table 24: Displacements in zone III (Soft soil) for empty tank condition

Ground sloping in Degrees	Displacements(mm) at different height			
	Base	3m	6m	9m
0	3.78	7.43	11.27	11.74
5	3.78	7.14	11.00	11.43
10	3.74	6.61	10.55	11.00
15	3.74	6.28	10.35	10.62
20	3.72	6.13	10.81	11.01
25	3.77	6.52	12.08	12.40
30	3.92	8.41	16.93	17.96

As the displacement values for $20^0$and 30^0 ground slopes are exceeding the limiting value (H/500) which is 12mm (IITK-GSDMA, 2007), Bracing systems are adopted to limit the displacement values as per relevant standards.

Table 25: Displacements for X-bracings (300mm x 300mm) in zone III (Soft soil) for empty tank condition

Ground sloping in Degrees	Displacements(mm) at different height			
	Base	3m	6m	9m
25	2.57	6.20	9.05	10.27
30	2.65	7.50	11.53	12.02

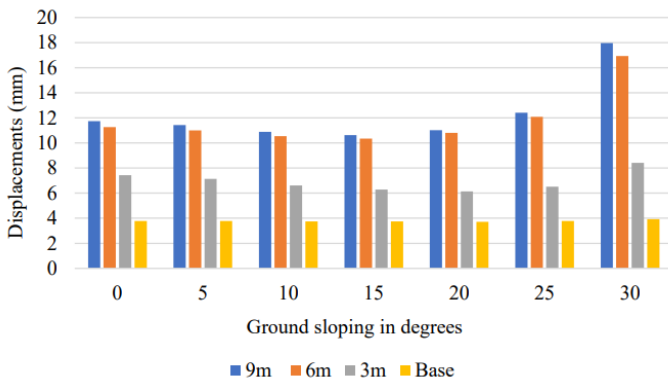

Figure 12: Displacements v/s Ground sloping in degrees in zone III (Soft soil) for empty tank condition.

Table 26: Base Shear in zone III (Soft soil) for empty tank condition

Ground sloping in degrees	Base Shear (kN)
0	7863.61
5	7936.60
10	8000.10
15	8087.36
20	8168.41
25	8253.06
30	8347.15

ii. Medium Soil Condition

Table 27: Displacements in zone III (Medium soil) for empty tank condition

Ground sloping in Degrees	Displacements(mm) at different height			
	Base	3m	6m	9m
0	2.29	5.72	9.02	9.46
5	2.28	5.38	8.65	9.08
10	2.26	4.89	8.12	8.52
15	2.25	4.41	7.61	7.98
20	2.24	3.79	6.96	7.26
25	2.24	3.33	6.46	6.74
30	2.24	2.79	6.00	6.19

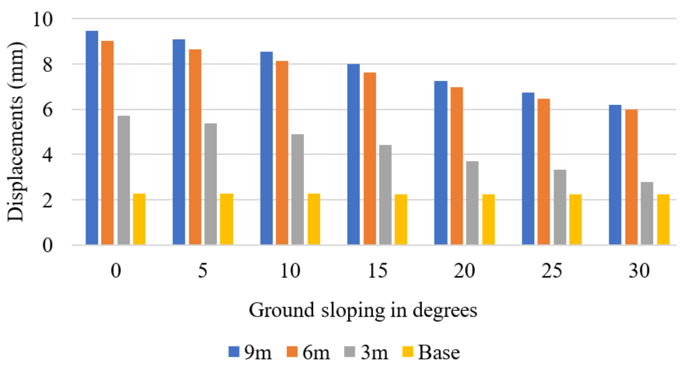

Figure 13: Displacements v/s Ground sloping in degrees in zone III (medium soil) for empty tank condition

Table 28: Base Shear in zone III (Medium soil) for empty tank condition

Ground sloping in degrees	Base Shear (kN)
0	7863.59
5	7936.63
10	8000.08
15	8087.33
20	8168.43
25	8258.36
30	8347.18

iii. Hard Soil Condition

Table 29: Displacements in zone III (Hard soil) for empty tank condition

Ground sloping in Degrees	Displacements(mm) at different height			
	Base	3m	6m	9m
0	1.20	3.57	5.86	6.11
5	1.20	3.40	5.73	5.97
10	1.20	3.19	5.56	5.81
15	1.20	2.93	5.34	5.60
20	1.20	2.61	5.08	5.34
25	1.20	2.26	4.70	4.96
30	1.20	1.86	4.24	4.48

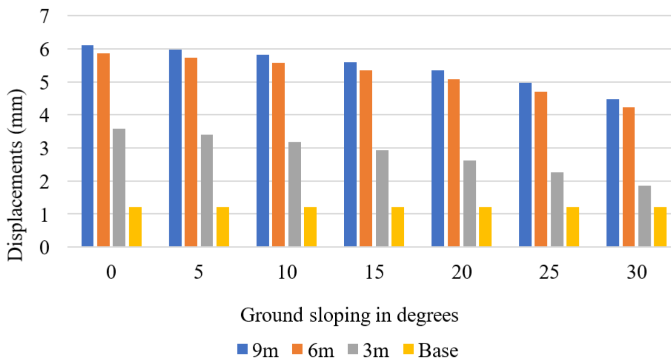

Figure 14: Displacements v/s Ground sloping in degrees in zone III (Hard soil) for empty tank condition

Table 30: Base Shear in zone III (Hard soil) for empty tank condition

Ground sloping in degrees	Base Shear (kN)
0	8842.96
5	8925.14
10	8996.51
15	9094.73
20	9185.92
25	9281.18
30	9387.04

4.2.3 ANALYSIS OF WATER TANK IN ZONE II FOR FULL TANK CONDITION

The seismic analysis of a water tank resting on levelled and sloped ground in seismic zones II, considering soft, medium, and hard soil conditions, the analysis focuses on the seismic response of the water tank under the condition of a full tank, considering both impulsive and convective pressures.

i. Soft Soil Condition

Table 31: Modal Parameters in zone II (Soft soil) for full tank condition

Ground sloping in degrees	Frequency (Hz)	Time Period (sec)
0	1.501	0.666
5	1.523	0.656
10	1.575	0.634
15	1.611	0.620
20	1.677	0.596
25	1.718	0.581
30	1.796	0.556

Table 32: Displacements in zone II (Soft soil) for full tank condition.

Ground sloping in Degrees	Displacements(mm) at different height			
	Base	3m	6m	9m
0	2.56	6.23	9.51	10.10
5	2.56	5.97	9.22	9.81
10	2.52	5.42	8.64	9.19
15	2.49	5.00	8.19	8.72
20	2.45	4.32	7.47	7.94
25	2.44	3.90	7.05	7.48
30	2.42	3.32	6.59	6.92

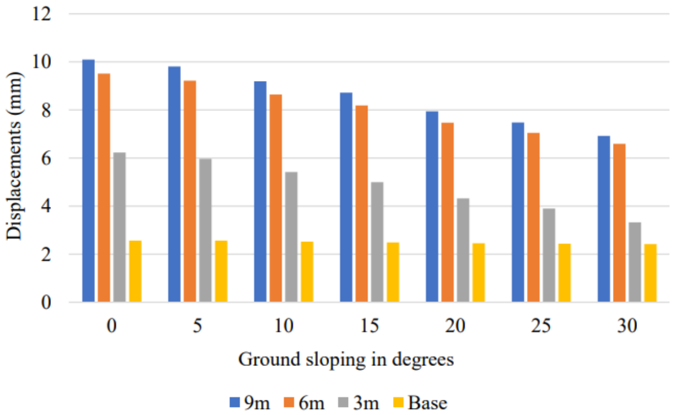

Figure 15: Displacements v/s Ground sloping in degrees in zone II (Soft soil) for full tank condition

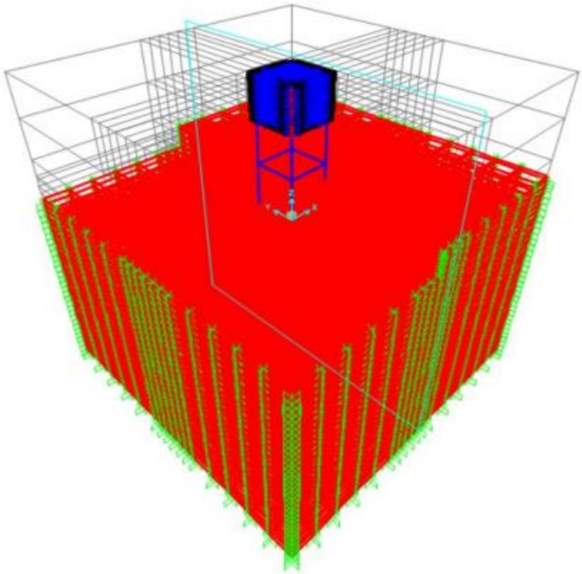

Figure 16: Full tank condition of elevated water tank on sloped ground

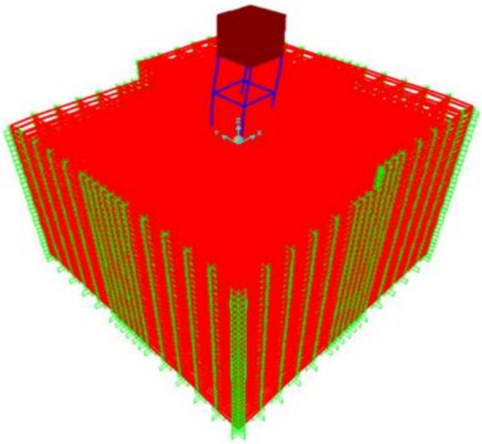

Figure 17: Deformed shape of elevated water tank on sloped ground

Table 33: Base Shear in zone II (Soft soil) for full tank condition

Ground sloping in degrees	Base Shear (kN)
0	4919.73
5	4965.31
10	5005.13
15	5059.42
20	5110.29
25	5163.08
30	5221.91

ii. Medium Soil Condition

Table 34: Modal Parameters in zone II (Medium soil) for full tank condition

Ground sloping in degrees	Frequency (Hz)	Time Period (sec)
0	1.632	0.612
5	1.666	0.600
10	1.717	0.582
15	1.764	0.566
20	1.831	0.546
25	1.884	0.530
30	1.965	0.508

Table 35: Displacements in zone II (Medium soil) for full tank condition

Ground sloping in Degrees	Displacements(mm) at different height			
	Base	3m	6m	9m
0	1.51	4.53	7.18	7.55
5	1.50	4.34	7.02	7.39
10	1.49	4.05	6.77	7.14
15	1.48	3.76	6.51	6.87
20	1.46	3.25	5.95	6.30
25	1.45	2.85	5.49	5.83
30	1.44	2.33	4.89	5.20

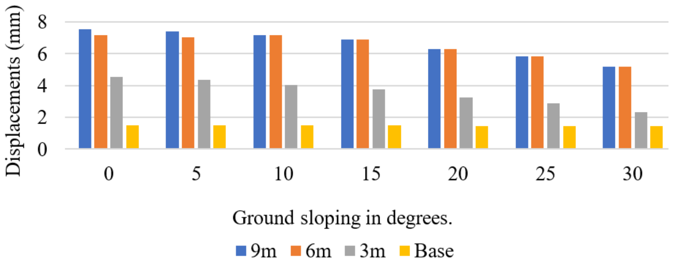

Figure 18: Displacements v/s Ground sloping in degrees in zone II (Medium soil) for full tank condition

Table 36: Base Shear in zone II (Medium soil) for full tank condition

Ground sloping in degrees	Base Shear (kN)
0	4919.71
5	4965.31
10	5005.00
15	5059.52
20	5110.23
25	5163.10
30	5221.93

iii. Hard Soil Condition

Table 37: Modal Parameters in zone II (Hard soil) for full tank

Ground sloping in degrees	Frequency (Hz)	Time Period (sec)
0	1.632	0.612
5	1.793	0.557
10	1.843	0.542
15	1.901	0.526
20	1.967	0.508
25	2.032	0.492
30	2.115	0.472

Table 38: Displacements in zone II (Hard soil) for full tank condition

Ground sloping in Degrees	Displacements(mm) at different height			
	Base	3m	6m	9m
0	0.76	2.50	4.13	4.29
5	0.76	2.40	4.07	4.24
10	0.76	2.28	4.00	4.17
15	0.76	2.11	3.88	4.05
20	0.76	1.89	3.73	3.91
25	0.76	1.70	3.57	3.75
30	0.76	1.44	3.55	3.55

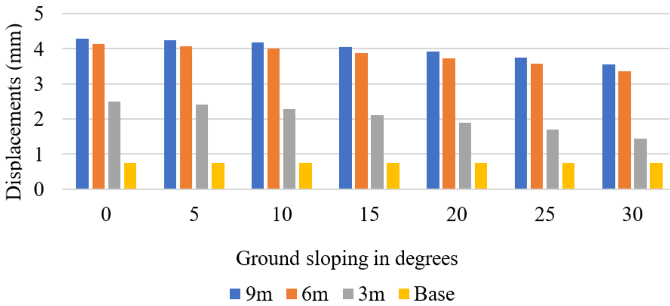

Figure 19: Displacements v/s Ground sloping in degrees in zone II (Hard soil) for full tank condition

Table 39: Base Shear in zone II (Hard soil) for full tank condition

Ground sloping in degrees	Base Shear (kN)
0	5531.82
5	5583.16
10	5627.75
15	5689.12
20	5746.15
25	5805.64
30	5871.85

4.2.4 ANALYSIS FOR WATER TANK IN ZONE III FOR FULL TANK CONDITION

i. Soft Soil Condition

Table 40: Displacements in zone III (Soft soil) for full tank condition

Ground sloping in Degrees	Displacements(mm) at different height			
	Base	3m	6m	9m
0	4.13	9.98	15.21	16.16
5	4.10	9.55	14.76	15.70
10	4.03	8.67	13.82	14.70
15	3.99	8.00	13.11	13.95
20	3.92	6.91	11.96	12.70
25	3.90	6.24	11.28	11.96
30	3.87	5.32	10.53	11.06

As the displacement values for 0^0, $5^0$and 15^0 ground slopes are exceeding the limiting values (H/500) which is 12mm (IIITK-GSDMA, 2007) Bracings systems are adopted to limit displacement values as per relevant standards.

Table 41: Displacements for X-bracings (300mm x 300mm) in zone III (Soft soil) for full tank condition

Ground sloping in Degrees	Displacements(mm) at different height			
	Base	3m	6m	9m
0	3.78	9.48	10.42	11.34
5	3.74	9.31	10.20	11.17
10	3.66	9.00	9.82	10.92

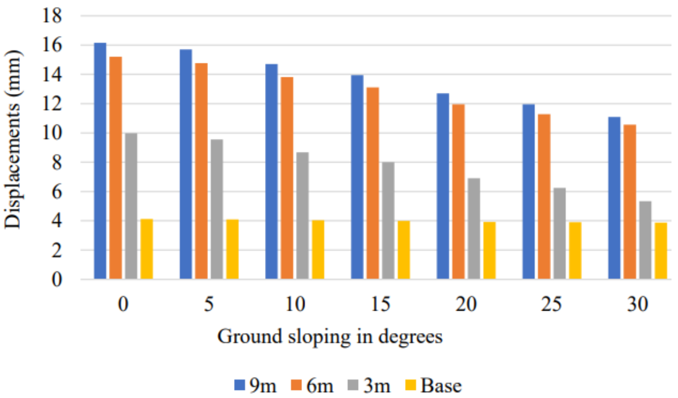

Figure 20: Displacements v/s Ground sloping in degrees in zone III (Soft soil) for full tank condition

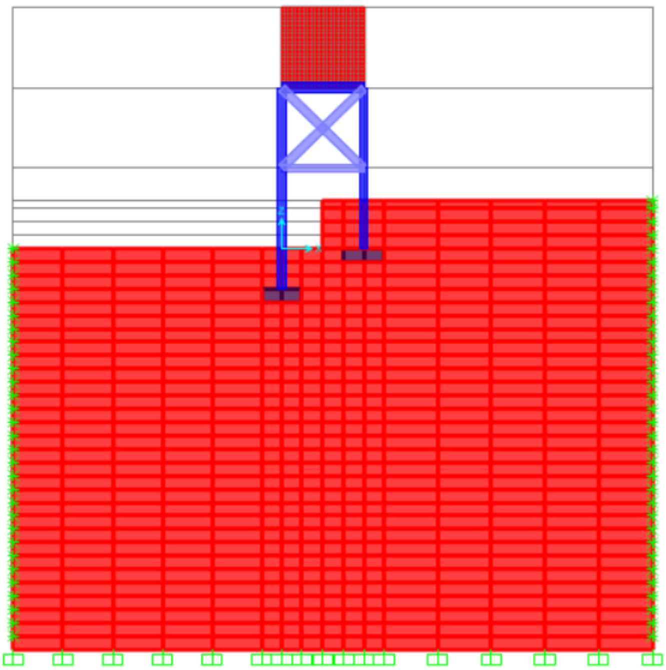

Figure 21: Water tank model with X-bracings (300mm x 300mm) in zone III (Soft soil) for full tank condition

Table 42: Base Shear in zone III (Soft soil) for full tank condition

Ground sloping in degrees	Base Shear (kN)
0	7871.62
5	7944.54
10	5627.75
15	8008.01
20	8176.35
25	8260.92
30	8353.77

ii. Medium Soil Condition

Table 43: Displacements in zone III (Medium soil) for full tank condition

Ground sloping in Degrees	Displacements(mm) at different height			
	Base	3m	6m	9m
0	2.42	3.24	11.49	12.08
5	2.41	6.94	11.23	11.82
10	2.39	6.49	10.83	11.42
15	2.37	6.01	10.41	11.00
20	2.33	5.20	9.53	10.09
25	2.32	4.56	8.79	9.33
30	2.30	3.74	7.83	8.32

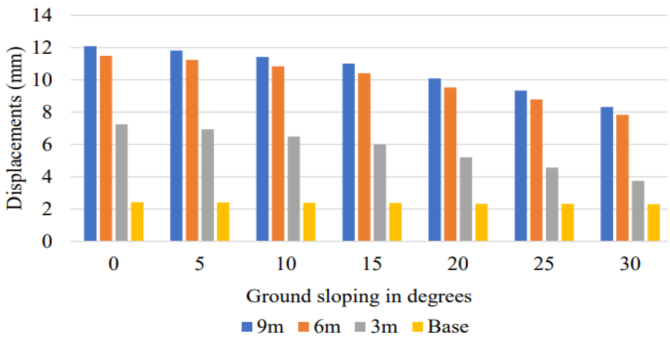

Figure 22: Displacements v/s Ground sloping in degrees in zone III (Medium soil) for full tank condition

Table 44: Base Shear in zone III (Medium soil) for full tank condition

Ground sloping in degrees	Base Shear (kN)
0	7871.39
5	7944.50
10	8008.01
15	8095.26
20	8176.35
25	8260.92
30	8355.08

iii. Hard Soil Condition

Table 45: Displacements in zone III (Hard soil) for full tank condition

Ground sloping in Degrees	Displacements(mm) at different height			
	Base	3m	6m	9m
0	1.22	4.00	6.61	6.87
5	1.22	3.85	6.52	6.79
10	1.22	3.65	6.39	6.67
15	1.22	3.38	6.21	6.49
20	1.21	3.04	5.97	6.25
25	1.21	2.72	5.71	6.00
30	1.21	2.33	5.39	5.69

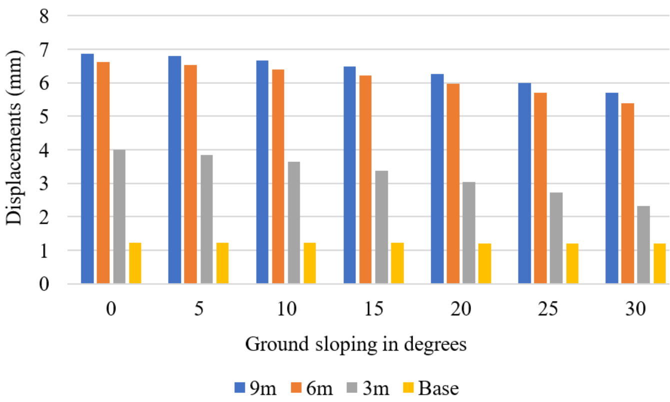

Figure 23: Displacements v/s Ground sloping in degrees in zone III (Hard soil) for full tank condition

Table 46: Base Shear in zone III (Hard soil) for full tank condition

Ground sloping in degrees	Base Shear (kN)
0	8850.87
5	8943.38
10	9004.41
15	9102.64
20	9193.87
25	9289.05
30	9394.96

5.CONCLUSION

1. Displacements and Base Shear are higher in full tank condition due to the 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 higher base shear values in Zone III indicate a more significant seismic force on the structure compared to Zone II.
4. The displacement values are higher in soft soil conditions due to higher flexibility, when compared to medium, and hard soil conditions.
5. The increase in ground sloping of elevated water tank from 0^0 to 30^0 with 5^0 intervals, increases structural stiffness, resulting in higher natural frequencies, and reduced lateral displacements in both Zone II and III.
6. In fixed based condition, displacements decrease as ground sloping increases from 0^0 to 30^0 for both empty tank and full tank conditions, suggests that a steeper sloping ground correlates with increased structural stiffness, resulting in reduced flexibility of the water tank and consequently causing smaller lateral displacements.
7. Base Shear values increase with sloping ground, suggesting increased resistance to seismic forces in fixed base condition.
8. Displacements and Base Shear are higher in flexible base (Soil-Structure interaction) condition due to effect of soil flexibility compared to fixed base.
9. Due to Soil-Structure Interaction, the seismic analysis reveals an increase in frequency of the water tank with higher ground sloping in Zone II and III for both empty and full tank condition. This signifies a corresponding improvement in structural stiffness.
10. The displacements of empty water tanks in seismic Zone II and III in soft soil, accounting for Soil-Structure Interaction, reveals that displacements decrease up to 15^0 ground slopes, indicating a stiffer response to seismic forces. However, beyond 15^0 ground slopes, displacements increase, suggesting a

shift towards greater soil flexibility and larger deformations.

11. Decrease in displacements of a full water tank on soft soil with increasing ground slope is attributed to enhanced structure stiffness, providing resistance against lateral movements.
12. In the case of medium and hard soils, for both empty tank and full tank conditions, as the ground slope increases, decreasing tank displacements, is due to inclination offering a stabilizing effect, minimizing lateral movements with supporting soils.
13. Observed displacements in zone III under both empty tank and full tank conditions, exceeding limiting values, indicating the need for strengthening measures to enhance structural stiffness. Hence, use of structural bracings is recommended.

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