A STUDY ON THE SEISMIC RESPONSE OF ELEVATED WATER TANK

Jayadeep K. S[1], Thejaswini R.M[2], L Govindaraju[3]

[1]P.G Student, Department of Civil Engineering, U.V.C.E, Bangalore University, Bengaluru
[2]Assistant Professor, Department of Civil Engineering, G.S.K.S.J.T. Institute, Bengaluru
[3]Professor, Department of Civil Engineering, U.V.C.E, Bangalore University, Bengaluru

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Abstract - *Water tanks have been the most vital lifeline structures. They serve as an essential component for most water supply schemes in urban and rural areas. Water storage is generally based on overhead water tanks since the required pressure in the water delivery process is achieved by gravity in elevated tanks rather than the need for large pumping systems. These elevated tanks consist of a large water mass at the top supported by a tall staging which is extremely weak against horizontal forces caused due to earthquakes. The selection of a suitable staging system plays a major role in the behaviour of elevated water tanks during earthquakes since these tanks are often utilized in seismically active regions. The ductility and energy absorbing capacity of such elevated tanks are less compared to conventional building and hence seismic safety of such structures are very important. Soil-structure interaction (SSI) is one of the most essential components of structural analysis. This interaction can change the Dynamic characteristics of a structure, which can be advantageous or detrimental to its performance. Conventional fixed base analysis disregards the effect of soil flexibility, resulting in an unsafe design. The present work is focused on the study of seismic response of elevated water tank considering the sloshing effect and to evaluate the behaviour considering Soil-Structure Interaction (SSI) effect in seismic Zone (II and III). Different soil conditions are also adopted as per IS1893(Part 2):2014. Modelling and analysis has been carried out using FEM based software SAP2000.*

Key Words: Dynamic analysis, Soil-Structure Interaction (SSI), Sloshing.

1.INTRODUCTION

The design of a water tank in a specific location determines how much water is distributed. water storage is generally based on overhead water tanks since the required pressure in the water delivery process is achieved by gravity in elevated tanks rather than the need for large pumping systems. Natural calamities such as earthquakes, droughts, floods, and cyclones are all common on the Indian subcontinent. More than 60% of India is prone to earthquakes, according to the seismic code IS:1893(Part-1):2016. Elevated water tanks have a large water mass at the top of a slender staging that is the most important concern for the tank's failure during earthquakes. Because elevated tanks are often utilized in seismically active areas, their seismic behaviour must be thoroughly examined. Some of the water tanks collapsed or were severely damaged due to a lack of understanding of the supporting system and an incorrect geometrical selection of staging patterns. Liquid storage can take several forms, including underground, ground-supported, elevated, and so on. Municipalities and industries utilise liquid storage tanks to store water, flammable liquids, and other materials. As a result, water supply is critical for putting out the fire that may break out during earthquakes, resulting in property damage and loss of life. As a result, water tanks should continue to work in the aftereffects of the earthquake. The collapse of a water tanks owing to serious damage in staging, in which not meeting the ductility criterion was one of cause observed in the previous earthquake. Water tanks also collapsed during the Bhuj (2001) earthquake because of flexural cracks in the shaft type tank staging. Hence seismic safety is utmost concern especially in earthquake prone regions. The seismic analysis of elevated tank can be carried out by idealising the structure into two different mass models firstly as per IS: 1893-1984 (i.e., lumped mass model) and secondly as per IS: 1893- (Part 2)2014 (i.e., two mass model). The motion of the water relative to the tank, as well as the motion of the tank relative to the ground, must be included in the dynamic analysis of these tanks. A closed tank is essentially a one-mass structure whether it is full of water or fully empty. If the tank has a free water surface, water will slosh around during the earthquake, thereby making the tank a two-mass structure. It is stated that earthquakes do not kill individuals; it is buildings that are poorly designed that do. As a result, adequate seismic analysis of the structure is vital.

Soil structure interaction (SSI) is a collection of phenomena in the response of structure caused by the flexibility of the foundation soils as well as in the response of soils caused by the presence of structures. In general, it lengthens, the apparent system period and increases the relative contribution of the rocking component of ground motion to the total response. In many cases, SSI is simply ignored in design without establishing whether it will increase or decrease the response of the structure. Further, soil conditions at a given site may amplify the response of a structure. By neglecting the amplification effect of the soil where the water tank is located may lead to a lead to an under-designed structure resulting in a premature collapse during an Earthquake.

1.1 Sloshing:

Liquid sloshing is a type of wave motion that occurs when a tank is partially full. In terms of the safety of oil and liquefied natural gas transit by sea, the sloshing phenomena are of enormous theoretical and practical importance in coastal and offshore engineering. The liquid inside a partially filled tank is prone to severe oscillations and considerable impact pressure on the tank when external excitations are of large amplitude or near the natural frequency of sloshing.

1.2 Scope of the study:

The scope of the study is to observe the response of the elevated water tank when subjected to seismic effect considering the effects of SSI. Further, the behaviour of water tank when resting on different soil conditions such as soft, medium, and hard during seismic actions need to be observed. Since sloshing phenomena increases severe oscillations, sloshing effect is also considered.

1.3 Objectives of the Present study:

a) To perform dynamic analysis using the Response spectrum method.
b) To evaluate response parameters such as base shear, base moment, Displacements and Modal Period and Frequencies.
c) To evaluate displacements and modal parameters due to soil-structure interaction (SSI) in seismic zone II and III in different soil conditions.
d) To restrict staging displacement under the allowed limit of (H/500).

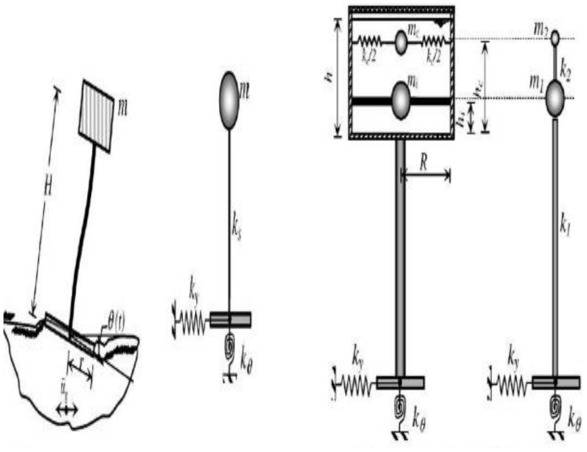
1.4 Methodology:

Elevated water tanks can be analysed by idealising the structure into two different mass models

a) Lumped mass model (IS1893:1984)
b) Two-Mass model (IS1893(part 2):2014)

Lumped mass model: It is also called the single-mass model. Considering this analysis method, the tanks can be idealised as a single degree of freedom system where the mass is assumed to be concentrated at the centre of gravity of the tank. The idealisation of water tanks as a system with a single degree of freedom (i.e., Lumped mass model) can be considered when the tanks are completely filled with water or when it is empty. Elevated tanks are never filled completely and hence this model fails to account for the sloshing of water. Hence the tanks can be analysed considering it as lumped mass only when it is fully filled or empty.

Two mass model: Most elevated tanks are never completely filled with water, there is always a free surface for the movement of water inside the tank. During earthquakes, due to seismic excitation, the liquid in the lower region of the tank behaves like a mass that is rigidly connected to the tank wall which is termed as impulsive mass. The liquid in the upper region of the tank excites with the horizontal acceleration during earthquakes and undergoes sloshing effect (Convective mass). Hence a two-mass idealization of the tank is more ideal to account sloshing effect as compared to one mass idealization which is used in IS 1893:1984. Two mass Models for elevated tanks was proposed by Housner (1963) which is used in most of international codes



(a)Lumped mass model (b) Two mass model

Fig: 1 Tank Model Idealisation

1.5 Problem statement: An RC open square water container of 3m x 3m x 3m (including freeboard of 0.3 m) is considered. The tank is supported on a staging of height 6m above ground level. The depth of the foundation is 1.5m below ground level. Grade of concrete and steel are M25 and Fe500, respectively. Density of concrete is 25 KN/m^3.

Table -1: Details of Structural Elements of Elevated Tank

Sl.no	Contents	Dimension
1	Staging height	6m
2	Depth of water tank	3m
3	Freeboard	0.3m
4	Column	300mm x 300mm
5	Beam	300mm x 400mm
6	Floor slab	180mm
7	Walls	180mm
8	Bracing	300mm x 300mm

Table -2: Dynamic characteristics of elevated water tank

Sl.no	Contents	Description
1	Structure	SMRF
2	Seismic zone	II & III
3	Zone factor	0.10 &0.16
4	Importance factor	1.5
5	Response Reduction factor	4
6	Soil type	I, II &III

Table -3: Water pressure details

Water Pressure	Zone II	Zone III
Impulsive pressure (kN/m^2)	0.8536	1.367
Convective Pressure (kN/m^2)	0.2407	0.3853
Hydrostatic pressure (kN/m^2)	26.487	

2. Modelling and Analysis & Results

Modelling and analysis has been carried out using FEM based software SAP2000. Two parameters were considered in the present study namely fixed base and flexible base (SSI).

2.1 Fixed Base Analysis

In fixed base analysis the fixity is considered at the ground level and response spectrum method is carried out considering the different zones (Zone II and Zone III) and response spectrum curve is generated for different soil conditions. Figure 2 displays the fixed base condition.

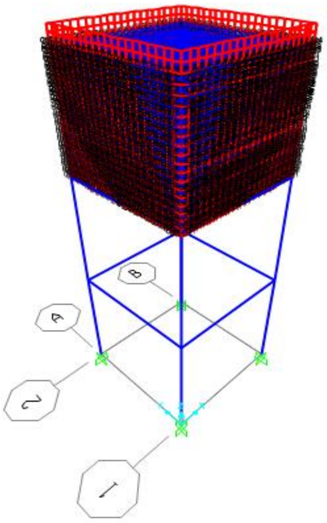


Fig: 2 Fixed Base Model with water Pressures

a) The Empty tank analysis is carried out considering the dead load of the structure.
b) The Full tank analysis is carried out considering the dead load of the structure and Hydrostatic (water) load.
c) The parameters such as Base shear, Base moment, Displacement and Modal Parameters are considered.

Table -4: Base Shear and Base Moment

Zone	Soil Type	Empty Tank condition		Full Tank condition	
		Base Shear (KN)	Base Moment (KN-M)	Base Shear (KN)	Base Moment (KN-M)
II	Hard soil	14.63	96.63	18.07	116.11
	Medium soil	14.63	96.63	20.43	131.30
	Soft soil	14.63	96.63	20.43	131.30
III	Hard soil	23.40	154.61	28.91	185.77
	Medium soil	23.40	154.61	32.69	210.08
	Soft soil	23.40	154.61	32.69	210.08

Table -5: Modal period & Frequencies for Empty tank condition

Output Case	Mode No	Time Period (Secs)	Frequencies (Cyc/Sec)
Modal	1	0.375	2.66

Modal	2	0.375	2.66
Modal	3	0.262	3.80

Table -6: Modal period & Frequencies for Full tank Condition

Output Case	Mode No	Time Period (Secs)	Frequencies (Cyc/Sec)
Modal	1	0.452	2.210
Modal	2	0.452	2.210
Modal	3	0.292	3.422

Table -7: Displacement for Full tank condition

Height (m)	Displacement(mm) Zone II			Displacement(mm) Zone III		
	Soft soil	Medium soil	Hard soil	Soft soil	Medium soil	Hard soil
9	2.6	2.6	2.3	4.1	4.1	3.7
6	2.5	2.5	2.1	4	4	3.6
3	1.2	1.2	1.1	2	2	1.8
Base	0	0	0	0	0	0

Table -8: Displacement for Empty tank condition

Height (m)	Displacement(mm) Zone II	Displacement(mm) Zone III
9	1.9	2.9
6	1.7	2.8
3	0.9	2.4
Base	0	0

(a) The Base shear, Displacement, Modal period, and frequencies obtained from the analysis for two seismic zones for empty tank and Full tank conditions are tabulated.

(b) The time period for the empty tank is 0.375s.

(c) The time period for the Full tank is 0.452s.

(d) The base shear, base moment and displacement are same for different types of soils (Hard, Medium, and soft soil) in respective seismic zones for empty tank condition, this is due to the same average acceleration coefficient (Sa/g)

(Sa/g) = 2.5 for $0.10s < T < 0.40s$ (Hard soil)

$0.10s < T < 0.55s$ (Medium soil)

$0.10s < T < 0.55s$ (soft soil)

(e) In full tank condition the Base shear, Base moment and displacement in respective zones are higher in soft and medium soil conditions but less in hard soil conditions.

- **Soil-Structure Interaction:**

The Response of the structure evaluated considering fixed base model neglecting the effect of soil-structure interaction (SSI) may alter the behaviour of the structure in real-time and consequently may be beneficial or detrimental to the performance of structures. So, in the present study, a comparison between fixed base analysis and flexible base (SSI) analysis is done. In this present work, actual soil condition is modelled and analyzed for earthquake conditions as shown in Fig.3. Parameters such as displacement and modal period and frequencies are compared.

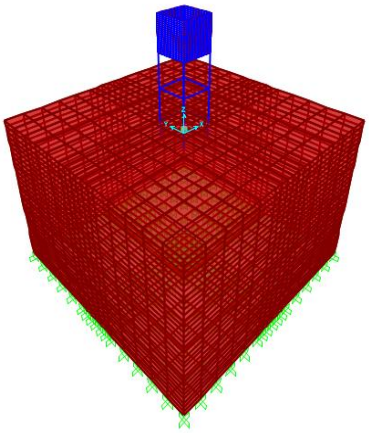


Fig: 3 Soil- Structure interaction Model

Table -9: Soil properties (Analysis and design of substructures - Swami saran)

Soil Type	Unit Weight (kN/m³)	Modulus of Elasticity (kN/m²)	Poisson's Ratio (µ)
Hard soil	18	95000	0.3
Medium soil	16	35000	0.4
Soft soil	16	15000	0.4

(a) Isolated square footing of depth 500mm is provided at 1.5m below ground level.

(b) The soil is modelled using finite Element software SAP2000.

(c) The width of soil is 10m on either side and the depth of 15m is considered.

(d) Graphs are plotted to show displacement comparison between fixed and flexible bases.

(e) The displacement of the staging has to be restricted to a ratio of (H/500) i.e,12mm.

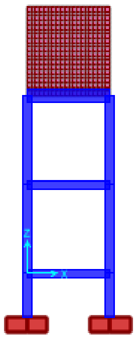


Fig: 4 Elevated tank with isolated square footing

Empty Tank condition:

(a) Soft soil:

Table -10: Displacement for Empty tank condition

Height(m)	Displacement(mm)	
	Zone II	Zone III
9	11.8	18.9
6	10.7	17.2
3	8.9	14.2
Base	7.1	11.4

Table -11: Modal period & Frequencies for Empty Tank Condition

Output Case	Mode No	Time Period (Secs)	Frequencies (Cyc/Sec)
Modal	1	1.276	0.783
Modal	2	1.276	0.783
Modal	3	1.118	0.894

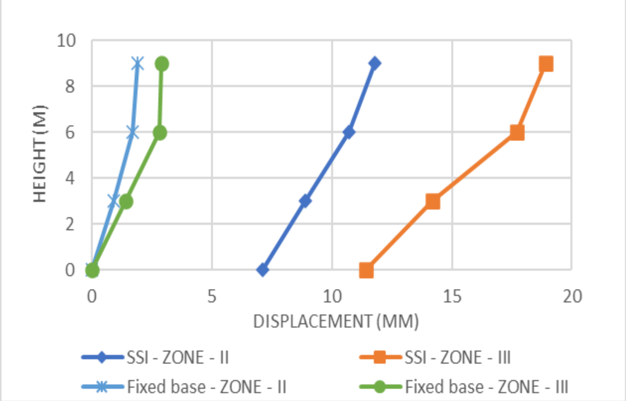


Chart -1: Displacement v/s Height of tank resting on soft soil.

(b) Medium soil:

Table -12: Displacement for Empty tank condition

Height(m)	Displacement(mm)	
	Zone II	Zone III
9	7.5	11.9
6	6.9	11.1
3	5.3	8.6
Base	3.8	6.1

Table -13: Modal period & Frequencies for Empty tank condition

Output Case	Mode No	Time Period (Secs)	Frequencies (Cyc/Sec)
Modal	1	0.836	1.195
Modal	2	0.836	1.195
Modal	3	0.732	1.365

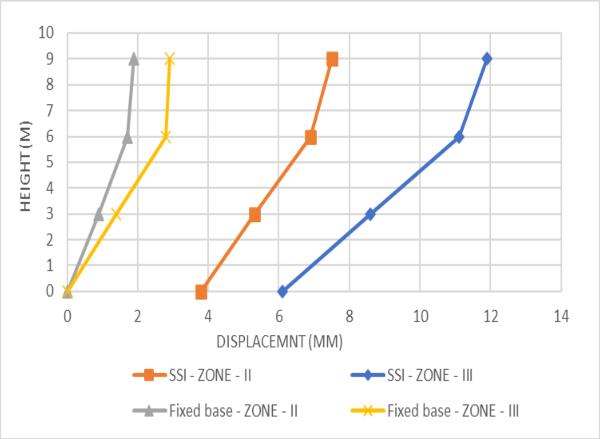


Chart - 2: Displacement v/s Height of tank resting on medium soil.

(a) Hard soil:

Table -14: Displacement for Empty tank condition

Height(m)	Displacement	
	Zone II	Zone III
9	6.5	10.3
6	6.1	9.7
3	4	6.4
Base	1.8	2.9

Table -15: Modal period & Frequencies for Empty tank condition

Output Case	Mode No	Time Period (Secs)	Frequencies (Cyc/Sec)
Modal	1	0.535	1.866
Modal	2	0.535	1.866
Modal	3	0.455	2.197

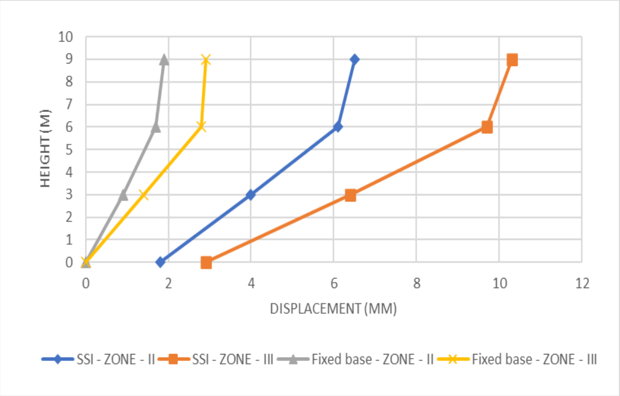


Chart - 2: Displacement v/s Height of tank resting on Hard soil

Full Tank condition:

(a) Soft soil:

Table -16: Displacement for Full tank condition

Height (m)	Displacement(mm)			
	Zone II without Braces	Zone II Diagonal Bracing (300mm X 300mm)	Zone II without Braces	Zone II Cross Bracing (300mm X 450 mm)
9	13.9	10.3	22.2	12.6
6	12.6	9.2	20.1	11.3
3	9.8	8.2	15.7	10
Base	7.3	7.2	11.6	8.7

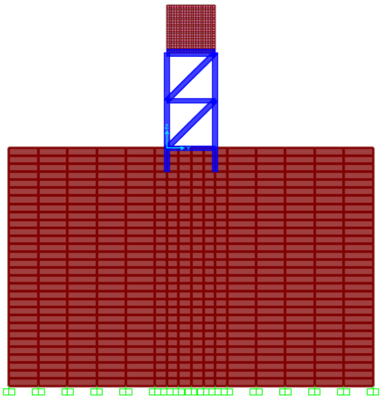


Fig: 5 Elevtaed tank with Diagonal bracing

Table -17: Modal period & Frequencies for Full tank condition

Output Case	Mode No	Time Period (Secs)	Frequencies (Cyc/Sec)
Modal	1	1.279	0.781
Modal	2	1.279	0.781
Modal	3	1.118	0.894

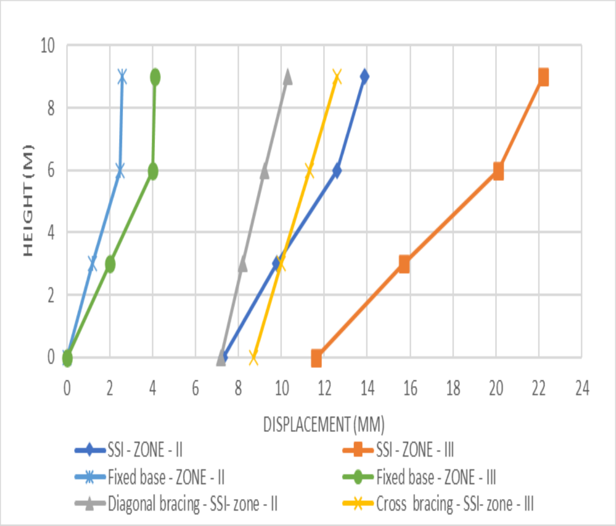


Chart - 4: Displacement v/s Height of tank resting on soft soil

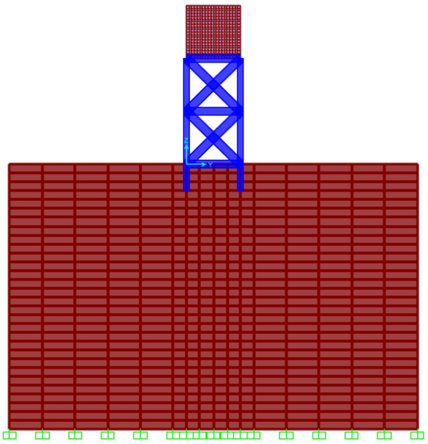


Fig: 6 Elevtaed tank with Cross bracing

(b) Medium soil:

Table -18: Displacement for Full tank condition

Height (m)	Displacement(mm)		
	Zone II	Zone III	Zone II Cross Bracing (300mm X 450 mm)
9	8.9	14.2	9
6	8.2	13.2	8
3	6.1	9.7	7
Base	3.9	6.2	6.1

Table -19: Modal period & Frequencies for Full tank condition

Output Case	Mode No	Time Period (Secs)	Frequencies (Cyc/Sec)
Modal	1	0.839	1.190
Modal	2	0.839	1.190
Modal	3	0.732	1.365

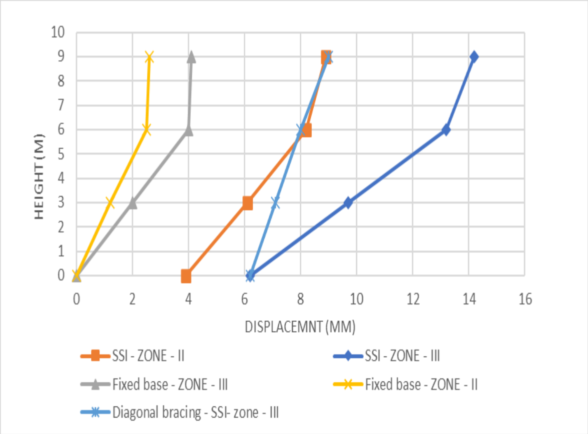


Chart - 5: Displacement v/s Height of tank resting on medium soil.

(c) Hard soil:

Table -20: Displacement for Full tank condition

Height (m)	Displacement(mm)	
	Zone II	Zone III
9	7.9	12.1
6	7.2	11
3	4.6	7.2
Base	2.1	2.8

Table -21: Modal period & Frequencies for Full tank condition

Output Case	Mode No	Time Period (Secs)	Frequencies (Cyc/Sec)
Modal	1	0.548	1.823
Modal	2	0.548	1.823
Modal	3	0.491	2.035

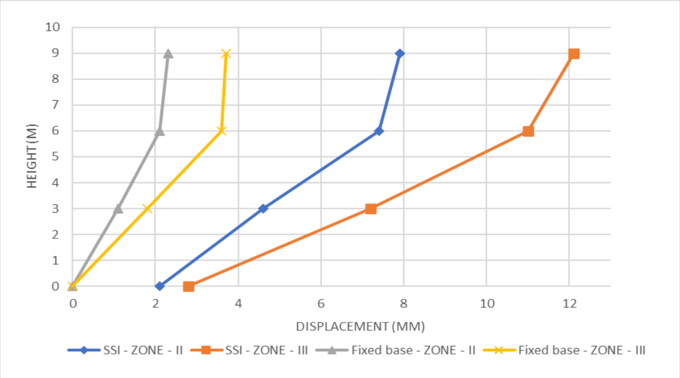


Chart - 6: Displacement v/s Height of tank resting on Hard soil.

Table 22: Sloshing wave height in different seismic zones

Zone	Soil Type	Sloshing wave height (m)	Freeboard (m)
II	Soft soil	0.1689	0.3
	Medium soil	0.138	0.3
	Hard soil	0.1017	0.3
III	Soft soil	0.2718	0.3
	Medium soil	0.2214	0.3
	Hard soil	0.162	0.3
IV	Soft soil	0.407	0.3
	Medium soil	0.332	0.3
	Hard soil	0.244	0.3
V	Soft soil	0.612	0.3
	Medium soil	0.498	0.3
	Hard soil	0.366	0.3

a) The sloshing wave heights for different zones in different soil conditions are calculated.

b) A freeboard of height 0.3m is provided.

c) The sloshing wave height increases as the seismic zone changes from II to V.

d) The freeboard of 0.3m is sufficient in seismic Zone II and zone III for all the soil conditions and for hard soil for seismic zone IV.

e) The provided freeboard of 0.3m is not sufficient in zone IV and V and the tank has to be redesigned with a higher freeboard.

CONCLUSIONS:

1. Base shear in full tank condition is higher than empty tank condition due to absence of water.
2. Freeboard height of 0.3m is sufficient for sloshing wave height in Zone II and Zone III and the tank must be redesigned for Zone IV & Zone V.
3. Time period and displacement are higher in full tank condition due to the presence of water.
4. The total base shear and base moment in full tank condition are more than that total base shear and base moment in empty tank condition, the design will be governed by full tank conditions.
5. The soil structure interaction (SSI) show increase in values of displacement and Time period when compared with fixed base analysis due to soil flexibility, hence SSI needs to be considered.
6. The maximum displacement increases with seismic zones and maximum displacement is observed in soft soils.
7. The maximum displacement shall not exceed (H/500), but in soft soils the displacements have exceeded permissible limits and different Bracing systems are adopted to limit the displacement values.
8. In soft soils the displacement values are higher compared to medium and hard soils and use of bracings are recommended in soft soils only.
9. The SSI effect has increased the time period of the structure by 3 times in soft soil conditions when compared to fixed base time period

REFERENCES:

1. Housner G W (1963) “The Dynamic Behaviour of Water Tanks”. Bulletin of the Seismological society of America, 53(2),381-387.
2. Chandrasekaran, A.R., Krishna, J., “Water towers in seismic zones”. In: Proceedings of the Third World Conference on Earthquake Engineering, New Zealand, vol. IV, pp. 161–171, 195.
3. IITK-GSDMA (2007). “Guidelines for seismic design of liquid storage tanks”, National Information Centre for Earthquake Engineering, IIT Kanpur.
4. IS:3370 (Part-I) – 1965 code of practice for concrete structures for the storage of liquids. (General requirements).
5. IS 1839 (Part 2): 2014 – Criteria for earthquake resistant design of structures. (Liquid retaining tanks).
6. IS 1893 (Part 1): 2016 – Criteria for earthquake Resistant Design of structures. (General provisions and buildings).

BIOGRAPHIES:

JAYADEEP K.S
P.G Student, Department of Civil Engineering, U.V.C.E, Bangalore University, Jnana Bharathi Campus, Bengaluru 560056.

Thejaswini R. M.
Assistant professor in Govt. S.K.S.J.T.I Research scholar, Department of Civil Engineering, U.V.C.E, Bangalore University, Bengaluru

L. Govindaraju
Professor, Department of Civil Engineering, U.V.C.E, Bangalore University, Jnana Bharathi Campus, Bengaluru 560056.