Time History Analysis of an Elevated Water Tank Under Different Ground Motions

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***Abstract*—Elevated water tank is one of the most important structures in earthquake event. Elevated water tank is constructed for holding water at a certain height to pressurize the water distribution system. As known from very upsetting experiences, elevated water tanks were heavily damaged or collapsed during earthquake. Due to the high sensitivity of the elevated water tanks to the earthquake characteristics such as peak ground acceleration, frequency contents and the duration of earthquake records. The present work aims to understand the dynamic behavior of elevated water tank combined with UG sump under different earthquake recorded ground motions. Time History Analysis was carried out for an elevated RCC square water tank having different staging heights of 14 m, 17 m and 20 m under different five earthquake ground motions analyzed using StaadPro software. The tank responses such as Roof Displacement, Velocity, Acceleration, Base Shear, Drift and Natural frequency were observed and the results were compared for empty, half and full tank water fill conditions. The maximum seismic responses were observed in Bhuj earthquake and minimum in Kobe earthquake ground motion.**

***Index Terms*— Elevated water tank, Time history Analysis, Water filling conditions, Seismic Response.**

I. INTRODUCTION

Water is an imperative commodity as food and air for existence of life. The elevated water storage tank is constructed for holding water supply at a certain height to pressurize the water distribution system. Liquid storage tanks are widely used by municipalities and industries for storing water, inflammable liquids and other chemicals. Typical geometries of elevated tank include cylindrical, square, rectangular and toroidal. These elevated tanks have various types of support structures like RC shaft, RC braced frame, steel frame and masonry pedestal. The frame type is the usual type of staging in practice. Columns and braces are the main components of the frame type of staging. The water storage tanks which are most inevitable part of water supply system are expected to remain functional even after an earthquake. Earthquakes are the most destructive natural calamity, inter alia, in terms of loss of life and destruction of property. Due to large mass of tank and water concentrated at an elevation from base, water tanks are sensitive to earthquake loading and it experiences a high damage due to shaking of ground during earthquake. Large amount of energy released during this phenomenon reaches to water tank from origin of occurrence in the form of seismic waves, this seismic wave has different features like Peak ground acceleration, frequency contents, effective duration of the ground motion, which affects the performance of water tank.

During earthquakes, the elevated water tanks are critical and strategic structures, hence the damages of these structures may endanger drinking water supply, it may also lead to failure in preventing large fires and cause substantial economic loss. Seismic behavior of elevated tanks should be investigated in detail since these tanks are frequently used in seismic regions also and it is imperative to consider earthquake loading as a non-stationary process. Due to lack of awareness of supporting system some of the elevated tanks were heavily damages or collapsed.

II. LITERATURE REVIEW

Several researches were carried out on seismic behaviour of liquid storage tanks and a few published works on seismic response characteristics of RC water tanks are briefly discussed here.

Dipak Jivani, et.al. (2017) studied the dynamic behaviour of elevated water tank under different earthquake recorded ground motions. Time history analysis was carried out for elevated water having different staging height of 12m, 16m and 20m for the storage capacity of 250m³ and 500m³. From the observations, it was concluded that the roof displacement increases with increase in staging height and base overturning moment decreases with increase in staging height. Dona Rose KJ and Sreekumar M (2015) studied the response of the elevated circular type water tank subjected to dynamic forces. Tanks of various capacities of 800m³, 1000m³ and 1200m³ with different staging height of 12m, 15m and 18m were modelled using ANSYS software. Time history analysis of the water tank was carried out by using El Centro earthquake acceleration records for two cases namely, tank full and half level conditions considering the sloshing effect. The base shear and peak displacements were compared with IS code provision. The peak displacements value from the analysis were below the maximum permissible displacement for different water levels and the base shear values from the time history analysis found to increase with increase in staging height. Neha N Walde, et.al. (2015) studied the effect of different staging height of 12m, 15m, 18m, 21m, 24m and 27m for different soil conditions. The seismic analysis was carried out by considering two water tanks with different staging heights, having capacity of 50m³ and 250m³ respectively. The study was carried out to understand the behaviour under two different earthquake zones and. Medium soil sites and soft soil sites were considered for the analysis with constant zone V. While comparing both IS 1893-1984 and IS 1893 (part II), it was observed that the time period increased as the height increased and base shear for the case tank full condition was found to be increase in stiffness and overturning moment for tank full condition will be increased with increase in stiffness. Raji Ruth George and Asha Joseph (2016) have performed static structural, modal and transient analysis for a rectangular water tank with 400m³ capacity and the response behaviour of the tank with 100%, 75%, 50% and 25% water fill conditions were studied. It was observed that there was reduction in deformation as the water level is reduced. The frequencies of the tank decreased with increase in water level. It is inferred that the response behaviour of an RCC elevated rectangular tank is increased as the water level is increased.

III. OBJECTIVES

- To conduct a study of Time History Analysis of shaft type staging elevated water storage tank using StaadPro v8i software.
- To study the behaviour of the elevated tank under five earthquakes recorded ground motions (Bhuj, North Ridge, Kobe, Coalinga and Spitak) for 14m, 17m and 20m staging heights.
- To carry out the time history analysis for tanks with empty condition, fully filled condition and half-filled condition by using different earthquake ground motions.
- To compare the response histories such as displacement, velocity, acceleration, frequency, drift and maximum base shear.

IV. METHODOLOGY

A. Model Description

A RC elevated water tank having storage capacity of 500m³ is considered in this study. The container has a square of side 12m and the roof is an inverted square pyramid. There is a central access shaft that pierces through the container and provides access to the container roof. The inside of the container is accessed through the central support shaft through an opening. The support structure consists of 4 square shafts of side 1.8m on all four corners. The structure is combined with underground sump of capacity 350m³. The elevated tank is placed on shaft type structure with different staging height of 14m, 17m and 20m. For the study purpose, tank empty condition, tank full condition and tank half condition are considered. Total 45 combinations studied for tank empty, full and half condition by varying staging heights under five different earthquake ground motions.

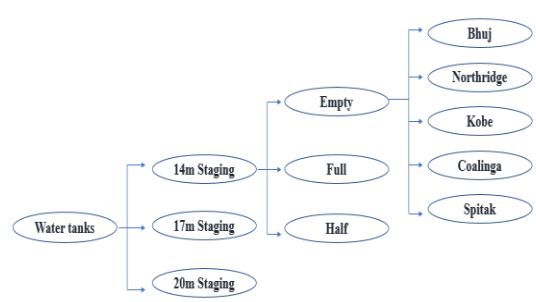


Fig. 1 Models for Time History Analysis

Table I. Structural data of the tank

Capacity	OHT: 500m³ UGS: 350m³
Tank dimension	12m x 12m
OHT height	4.4m
UGS tank height	3.6m
Circular shaft	175mm
Square shaft	150mm
Walls	225mm
OHT bottom slab thickness	200mm
Roof	150mm
Bottom slab sump	200mm
Raft below circular shaft	500mm
Clear distance between square shafts	10.2m
Staging height considered	14m, 17m and 20m

B. Selection of Ground motion

Ground motion is the basic and prime input for time history analysis of structure. The real ground motion records can be obtained from the records of previous earthquake events are preferred. Real ground motion are actual records of seismic shaking produced by earthquakes. For current study purpose total five numbers of real ground motions are considered for the dynamic analysis of the elevated water tank. Finite element model is modelled in StaadPro software.

Table II. Parameters of selected ground motion

Sl. No	Earthquake	PGA g	Magnitude (Richter scale)	Dura-tion (Sec)
1	Bhuj, Jan 26 2001	0.38	6.9	137
2	Northridge, Jan 17 1994	0.41	6.7	25
3	Kobe, Jan 17 1995	0.509	6.9	47
4	Coalinga, May 2 1983	0.48	6.2	25
5	Spitak, Dec 7 1988	0.43	6.8	20

C. Material properties

The concrete and steel bar properties are used in the modelling of the analysis of reinforced concrete elevated water tank structure in StaadPro.

Table III. Material Properties

Properties	Concrete	Steel bar
Unit weight	25 kN/m³	76 kN/m³
Compressive strength	M30	Fe500

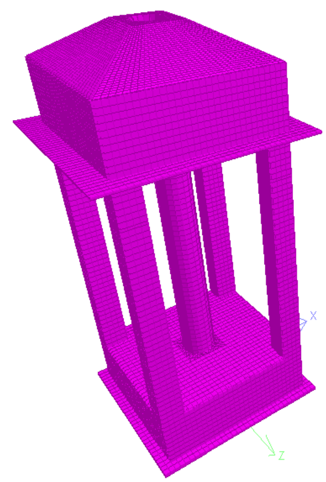


Fig 2. 3D model of the elevated water tank.

D. Time History Analysis

The study of time history analysis is to understand the actual behaviour of a structure at every addition of time, when it is subjected to a ground motion. The technique of time history analysis represents the most sophisticated method of dynamic analysis for the structure. The mathematical model of the structure is subjected to acceleration from earthquake at the base of the structure. Time history analysis consists of a step by step direct integration over a time interval, the equation of motion is solved with the acceleration, velocities and displacements of the previous step serving as initial function. The five earthquake ground motions selected are considered as an input motion for the time history analysis and applied at the base of the structure. The seismic performance of the elevated water tank under five different selected earthquake records will be examined for tank empty, full and half condition with different staging heights. For time history analysis StaadPro v8i software is used for the structure.

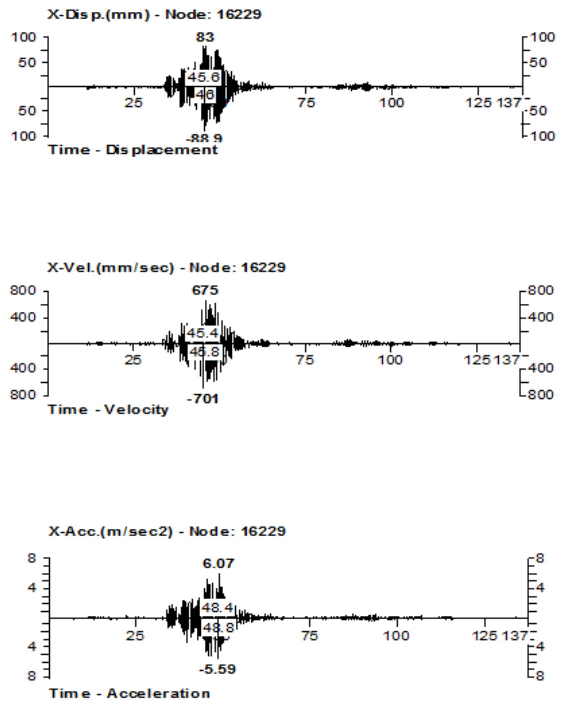


Fig 3. Time History graph of Bhuj earthquake 20m staging under full tank condition

V. RESULTS AND DISCUSSIONS

The Time history analysis is carried out for the tank with empty, half and full tank conditions using above mentioned parameters. For each filling condition, separate model is prepared according to staging height and all mentioned time histories.

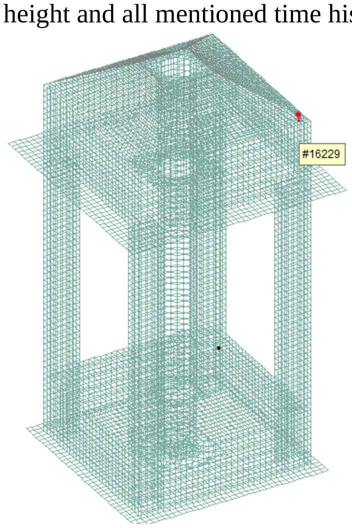


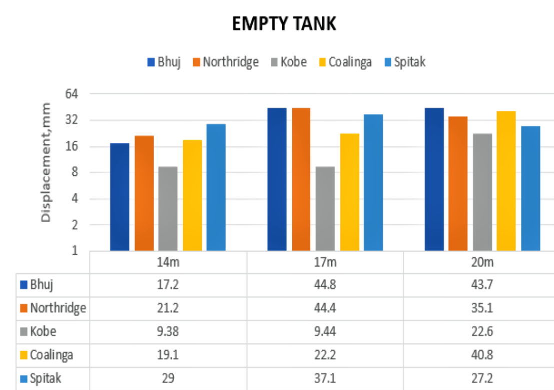
Fig 4. Node considered in the roof of the structure

The results are noted down in form of Roof displacement, velocity, acceleration, Base shear, frequency, storey drift and elemental bending moment.

The value of roof displacement, velocity and acceleration is taken by considering a node (node no. 16229) in the roof of the structure.

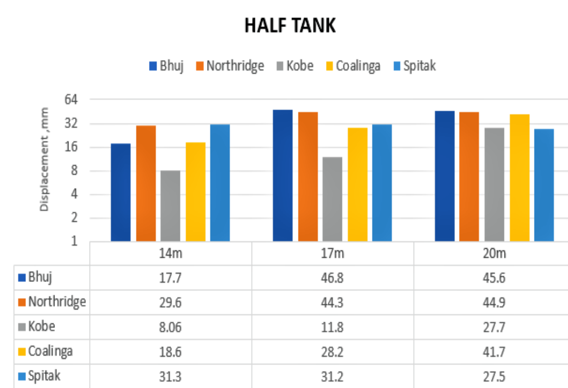
A. Roof Displacement

Roof displacement is an important serviceability criterion for any structure. Maximum roof displacement has been observed under Bhuj earthquake ground record in 20m staging height under full tank condition and minimum roof displacement observed under Kobe earthquake ground record in 14m staging height under empty tank condition. Bhuj earthquake having low PGA gives higher roof displacement for 17m and 20m staging height.



	14m	17m	20m
Bhuj	17.2	44.8	43.7
Northridge	21.2	44.4	35.1
Kobe	9.38	9.44	22.6
Coalinga	19.1	22.2	40.8
Spitak	29	37.1	27.2

Fig 4. Displacement comparison for Empty tank



	14m	17m	20m
Bhuj	17.7	46.8	45.6
Northridge	29.6	44.3	44.9
Kobe	8.06	11.8	27.7
Coalinga	18.6	28.2	41.7
Spitak	31.3	31.2	27.5

Fig 5. Displacement comparison for Half tank

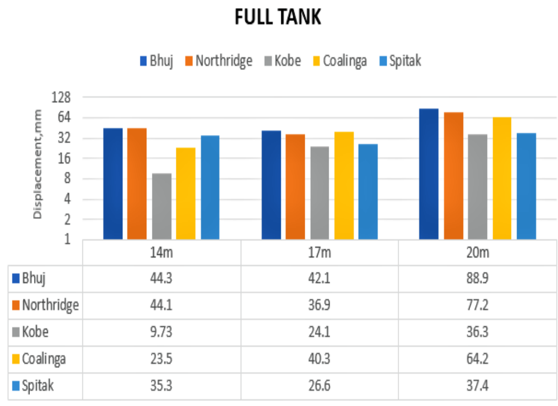


Fig 6. Displacement comparison for Full tank

It can be seen from the above graphs that the roof displacement is considerably decreases with increase in PGA value of earthquake.

B. Roof Velocity

Table IV. Roof velocity comparison of tank

Earthquake	Tank condition	Roof Velocity (mm/s) Staging height 14m	17m	20m
Bhuj	Empty	249	539	333
	Half	228	461	450
	Full	505	346	701
Northridge	Empty	229	455	284
	Half	328	415	299
	Full	440	269	501
Kobe	Empty	147	92.3	214
	Half	105	111	252
	Full	86.5	225	283
Coalinga	Empty	281	193	332
	Half	223	237	339
	Full	202	321	451
Spitak	Empty	440	476	254
	Half	408	381	243
	Full	445	240	338

Empty tank: The elevated water tank has maximum roof velocity of 539 mm/s at 48.8 s in Bhuj earthquake for 17m staging height and minimum velocity of 147 mm/s 14.3 s in Kobe earthquake for 14m staging height.

Half tank: The elevated water tank has the maximum velocity of 461 mm/s at 49.1 s in Bhuj earthquake for 17m staging height and minimum roof velocity of 105 mm/s at 13.3s in Kobe earthquake for 14m staging height.

Full tank: The elevated water tank has the maximum roof velocity of 701 mm/s at 45.8s in Bhuj earthquake for 20m staging height. The minimum velocity of 86.5 mm/s at 10.9s observed in Kobe earthquake for 14 m staging height.

The maximum roof velocity has been observed in Bhuj earthquake for 20 m staging height under full tank condition and minimum in Kobe earthquake for 14m staging height under full tank condition.

C. Roof Acceleration

Table V. Roof acceleration comparison of tank

Earthquake	Tank condition	Acceleration (m/sec^2) Staging height 14m	17m	20m
Bhuj	Empty	5	6.96	4.56
	Half	4.56	7.32	4.39
	Full	7.04	3.93	6.07
Northridge	Empty	3.45	5.22	3.17
	Half	3.9	4.52	2.99
	Full	4.97	3.01	3.69
Kobe	Empty	2.37	1.36	2.09
	Half	1.52	1.25	2.33
	Full	1.19	2.15	2.43
Coalinga	Empty	3.86	2.37	3.36
	Half	3.25	2.82	3.21
	Full	2.46	3.16	3.98
Spitak	Empty	7.4	6.67	3.39
	Half	6.53	5.06	3.18
	Full	5.89	3.22	3.01

Empty tank: The elevated water tank has the maximum roof acceleration of 7.4 m/s^2 13.4 s for 14m staging height due to Spitak earthquake ground motion while the minimum roof acceleration of 1.36 m/s^2 13.8 s for 17m staging height due to Kobe earthquake ground motion.

Half tank: the elevated water tank has the maximum roof acceleration of 7.32 m/s^2 at 44.7 s for 17m staging height due to Bhuj earthquake ground motion and the minimum roof acceleration of 1.25 m/s^2 at 10.8 s for 17m staging height due to Kobe earthquake ground motion for tank half condition.

Full tank: In this case the elevated water tank has the maximum roof acceleration of 7.04 m/s² at 44.6 s for 14m staging height due to Bhuj earthquake and minimum roof acceleration of 1.19 m/s² at 14 s for 14m staging height due to Kobe earthquake.

The maximum roof acceleration has been observed in Bhuj earthquake for 17m staging height with half tank condition whereas minimum observed in Kobe earthquake for 14m staging in tank full condition.

D. Base Shear

Base shear is an estimate of the maximum expected lateral force that occurs due to seismic ground motion at the base of the structure. The base shear depends in probability of significant ground motion and the level of ductility and over strength associated with various structural configurations and the total weight of the structure.

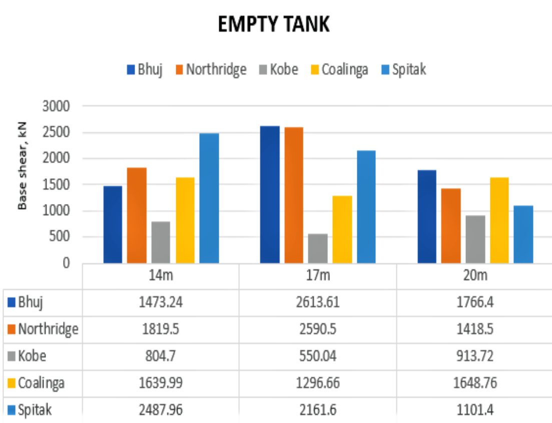


Fig 7. Base shear comparison for Empty tank

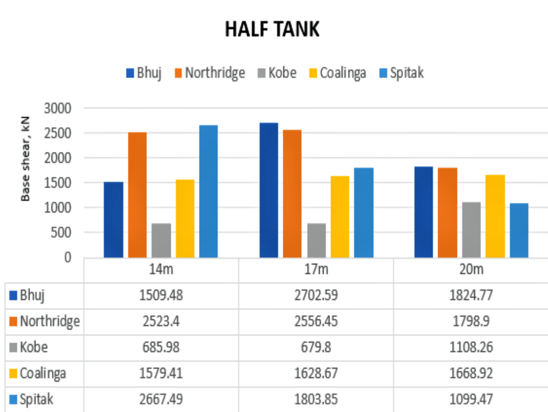


Fig 8. Base shear comparison for Half tank

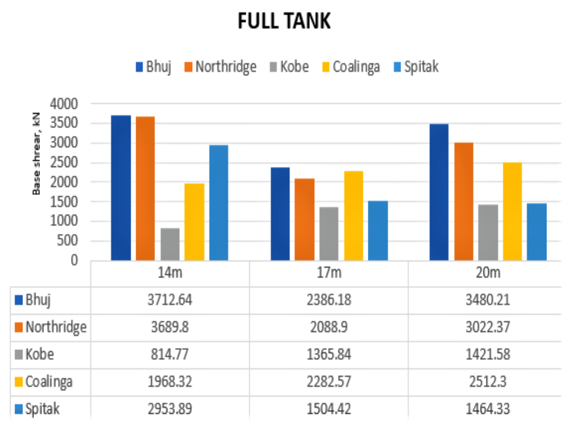


Fig 9. Base shear comparison for Full tank

The maximum response of base shear is observed in Bhuj earthquake for 14m staging height under full tank condition and minimum value observed in Kobe earthquake for 17m staging height under empty tank condition. It is observed that the base shear considerably decreases with increase in PGA value of earthquake.

E. Natural Frequency

Table VI. Natural frequency comparison

Staging ht.	Modes	Frequency (Hz)		
		Empty	Half	Full
14m	1	2.351	2.196	1.854
	2	2.351	2.196	1.855
	3	4.004	3.845	3.455
	4	11.514	8.111	6.306
	5	13.390	9.806	7.555
	6	13.390	9.807	7.556
	7	15.201	12.407	10.017
17m	1	1.572	1.476	1.255
	2	1.578	1.478	1.256
	3	3.243	3.119	2.815
	4	7.832	6.072	5.009
	5	10.04	8.169	6.706
	6	10.04	8.170	6.720
	7	12.627	10.194	10.012
20m	1	1.541	1.433	1.228
	2	1.541	1.444	1.229
	3	2.695	2.596	2.352
	4	10.670	7.708	6.603
	5	11.584	9.146	7.257
	6	11.584	9.147	7.258
	7	12.151	11.558	10.005

The modal analysis determines the vibration characteristics such as natural frequencies and corresponding mode shapes. For dynamic loading conditions, the mode shapes and natural frequencies are important parameters in the design of a structure.
From the above Table VI, it shows the natural frequencies of the elevated water tank decreases with increase in the water level of the tank and the natural frequencies decreases with increase in staging height of the elevated tank.

F. Drift

Storey drift is the displacement of one level relative to the other level above or below. Storey drift is calculated for elevated tank container. It is the displacement of wall at oht bottom slab level (i) minus the displacement of wall at sump roof slab level (i-1).

Table VII. Storey drift comparison

Earthquake	**Tank condition**	**Drift (mm)**		
		Staging height		
		14m	**17m**	**20m**
Bhuj	Empty	13.86	38.02	38.41
	Half	14.53	39.60	40.02
	Full	35.73	35.73	78.1
Northridge	Empty	17.03	37.64	30.75
	Half	37.46	37.46	39.46
	Full	35.55	31.26	67.78
Kobe	Empty	7.55	7.99	19.87
	Half	6.49	9.95	24.32
	Full	7.93	20.5	31.9
Coalinga	Empty	15.4	18.87	35.76
	Half	14.95	23.89	36.63
	Full	18.95	34.14	56.32
Spitak	Empty	23.37	31.42	23.94
	Half	25.28	26.5	24.13
	Full	24.48	22.51	32.85

Empty tank: the structure has the maximum storey drift of 38.41 mm for 20m staging height due to Bhuj earthquake and the minimum storey drift of 7.55 mm for 14m staging height due to Kobe earthquake.

Half tank: the structure has the maximum storey drift of 40.02 mm for 20m staging under Bhuj earthquake. Minimum storey drift of 6.49 mm have been observed in Kobe earthquake for 14m staging height.

Full tank: The structure has the maximum storey drift of 78.1 mm for 20m staging height due to Bhuj earthquake and the minimum value of 7.93 mm for 14m staging due to Kobe earthquake.

The maximum response of drift is observed in Bhuj earthquake for 20m staging height under tank full condition and minimum drift observed in Kobe earthquake for 14m staging height under half tank condition.

G. Bending Moment

The maximum bending moment from the time history analysis is generated at bottom slab of the overhead water tank. The elemental bending moment values are taken from plate stress contour as Mx and My in StaadPro in which the maximum values are considered.

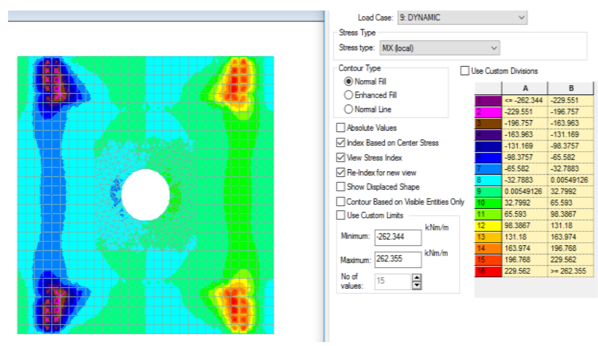


Fig 10. Maximum bending moment in slab of 20m staging for full condition, Bhuj earthquake

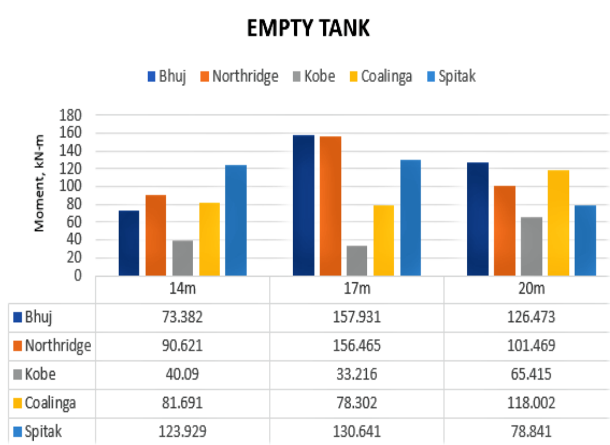


Fig 11. Bending moment comparison for empty tank

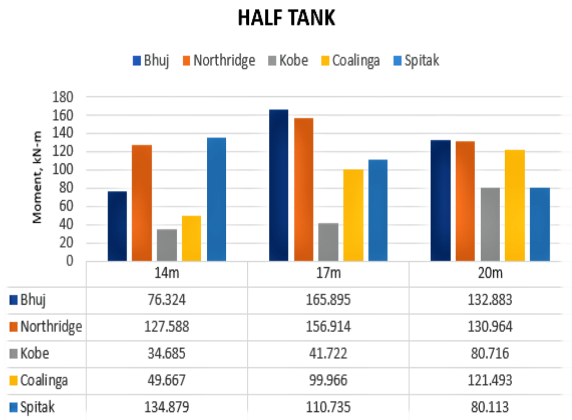


Fig 12. Bending moment comparison for Half tank

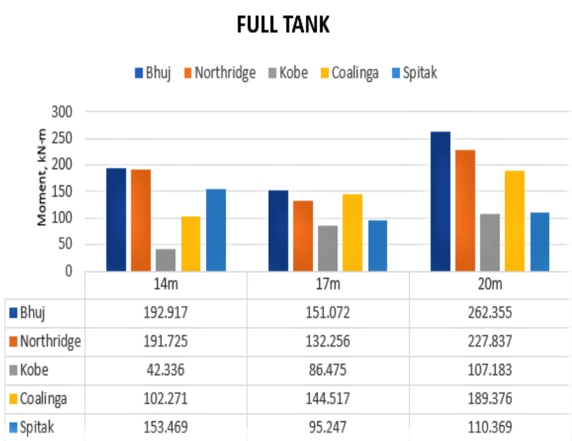


Fig 11. Bending moment comparison for Full tank

The maximum response of bending moment is observed in Bhuj earthquake for 20m staging height under tank full condition and minimum observed in Kobe earthquake for 17m staging height under empty tank condition.

VI. CONCLUSIONS

Based on the results obtained after the time history analysis of tank, following conclusions can be drawn.

- As the staging height increases the roof displacement increases. The roof displacement considerably decreases with increase in PGA value of earthquake.
- The response of base shear decreases with increase in PGA value of earthquake.
- The natural frequencies of the structure decreases with increase in water storage and decreases with increase in staging height of the tank.
- The tank responses such as roof displacement, velocity, acceleration, base shear, elemental moments are highly scattered, which shows that the structure is highly influenced by the characteristics of earthquake records.
- The critical response of the elevated water tanks does not always happen in full tank condition and it may occur even in empty case of the tank depending on the earthquake characteristics.

It can be summarized that low PGA value of earthquake has significant effect on elevated tank responses whereas high PGA value of earthquake has less effect on responses of the elevated water tank.

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