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Structural and dynamic properties of elevated water tanks for better performance during earthquakes

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ABSTRACT

This research deals with the study of the various factors affecting the performance of circular shaped elevated water tanks made of reinforced concrete material with framed staging with filled as well as empty conditions due to past Indian earthquakes. Six ground accelerations have been picked out based on the strong motion parameters. Eight numbers of existing tanks have been selected with different storage capacity and structural configurations. Seismic performances such as base shear, base moment and hydrodynamic pressure are calculated using Response Spectrum method for the ground accelerations selected. The results due to all the ground accelerations are compared with that obtained by the elastic design response spectrum available in IS1893: part1 (2016). Eventually, it has been found out that the performances of each tank for every acceleration is highly influenced by the structural configuration, mainly for empty tanks. Hence, this research is intended to achieve desirable performances of water tanks during the occurrences of earthquakes by providing appropriate number of columns and horizontal bracing configuration. To ensure this, an experimental investigation has also been done on two models, tank 1 of capacity 105.86 m^3 and tank 2 of 223.278 m^3, to determine the dynamic properties of tanks.

Keywords: Lateral stiffness; Natural time period; Base shear; Hydrodynamic pressure; Ground accelerations.

1. INTRODUCTION

Elevated water tanks (EWT) are very essential for storing drinking water in public distribution system and storing chemical in case of industries. Giving importance to the dynamic analysis of EWTs started after the occurrence of Chilean earthquakes in the year 1960. Since the requirement of water after the occurrence of an earthquake is an urgent need, the main job of the earthquake engineer is to ensure that water tanks are functional even after the occurrence of the earthquakes. Failing which, it leads to big problems. Based on the location, water tanks are classified into underground water tank, ground supported water tank and elevated water tank. Similarly, they are classified based on the shape of the containers. They are circular tank, rectangular tank, intze tank, circular tank with conical bottom, and spherical tank. Staging used for EWTs are classified into two. They are shell tubular and framed structures. This research mainly deals with study of seismic performance of circular shaped EWTs made of reinforced concrete material with framed staging. The characteristic compressive strength of concrete is taken as 30 N/mm^2. Configuration of EWT resembles the performance of the cantilever beam. As the mammoth amount of mass is lumped at the top of the slender staging system, mainly filled water tanks, EWTs are highly susceptible to horizontal loads mainly due to earthquakes. The motion of the water stored in the container causes the dynamic forces on EWTs. In addition to the lateral load due to earthquakes, hydrodynamic pressure will be induced by both impulsive and convective masses. Poor construction, heavy gravity load compared to conventional buildings and improper design detailing cost the water tanks which are ranging from minor cracks to Catastrophe of tanks.

'Indian Institute of Technology, Kanpur – Gujarat State Disaster Management Act (IITK-GSDMA) guideline for seismic design of liquid storage tanks' is the only available guidelines in India for elevated water

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tanks. Seismic performances of EWTs are very extensively investigated by many researchers experimentally as well as analytically. However, only a few investigations are there for Indian earthquakes and this research focuses on how the dynamic properties such as lateral stiffness, seismic masses, and natural time period and seismic responses such as base shear, base moment, roof displacement, hydro dynamic pressure got influenced by the EWT configuration tank storage capacity, number of columns in the supporting system, number of horizontal bracing configurations, and container height to diameter ratio, in addition to the Indian ground accelerations. These factors are of unique values for the eight numbers of tanks selected in this research and it has been decided to determine how these variations are going to affect the performance of EWTs.

CHETAN *et al*. [1] found out that structures designed for strong ground shaking require structural components to remain linearly elastic, allowing for damage. The response reduction factor (R) is used to lower base shear, with different values suggested by countries. Viscous dampers' influence on R is limited. The finite element (FE) approach should be used in conjunction with material properties, nonlinear hinge properties, and seismic response of water tanks. NAYAK and THAKARE [2] investigate seismic vulnerability in India after the 2001 Bhuj earthquake, focusing on seismic diagnosis and retrofitting of existing structures. A case study of an elevated water tank was conducted, using non-destructive tests and DER rating techniques. A simple seismic retrofit method was found effective in maintaining the tank's functionality.

VINOD KUMAR *et al*. [3] examines the seismic responses of liquid storage elevated tanks with and without soil structure interaction (SSI) effects. It analyzes the effects of SSI on peak seismic responses, displacement, and overturning moments. Factors like slenderness ratio and staging time period are investigated. Soft soil is more susceptible to overturning moments, and as slenderness increases, overturning moments decrease. KASTURE and SANGITA MISHRA [4] found out that Sloshing is a violent fluid motion in water tanks, causing deformations and ruptures. It can lead to critical failure in overhead tanks. Tuned liquid dampers can help manage sloshing. Tank design should consider dynamic response during sloshing, comparing it to impact loads, temperature stresses, and critical loads. Experimental analysis, such as shake table analysis, should validate simulation results with theoretical calculations.

GURUSAMY and KUMAR [5] explore nonlinear shallow water sloshing in partially filled tanks under high excitation amplitude, affecting devices like Tuned Liquid Dampers. Results show resonant frequency is sensitive to excitation amplitude and dispersion parameter, increasing by 45% for large aspect-ratio tanks. KI *et al*. [6] examines sloshing load dynamics in a cylindrical tank targeting nuclear reactors in the ocean, analyzing pressure distribution and revealing harmonic pressure exceeding peak pressure near the water surface. SANGIORGIO *et al*. [7] presents a multicriteria analysis of elevated storage tank performance and degradation levels, identifying frequent damage, causes, and worst-case structures. Results help identify maintenance and intervention strategies for extended tank life.

NAYAK and THAKARE [8] investigates seismic vulnerability in India post-2001 Bhuj earthquake using a systematic investigation metrology and retrofitting strategies. It assesses an existing elevated water tank using non-destructive tests and IS codes. Various retrofitting methods are adopted to improve the tank's drift and flexural capacity. Results show a simple seismic retrofit method is effective. RIMAL *et al*. [9] suggested that elevated water tanks are crucial for uninterrupted water supply after earthquakes. Limited studies exist for smooth bars, but they make up a significant fraction. Analytical fragility functions show soil flexibility and water content significantly affect seismic fragility, especially at higher damage states. Tanks are most vulnerable when fully filled with water, with the difference increasing with ground motion intensity.

KONAR [10] proposes a slender Tuned Sloshing Damper (STSD) that can serve as an overhead water tank (OWT) with a consistent damping ratio, despite liquid depth fluctuation. The STSD allows liquid depth to fluctuate within a feasible range, improving damping. The design of the STSD for a real-life apartment building shows significant seismic vibration control, with consistent performance despite 66.7% liquid depth fluctuation, comparable to conventional TSD.

For calculating the dynamic responses of EWTs, The damping ratio of all the tanks was assumed as 5% and the time interval of NTP in the response spectrum graph was maintained as 0.02 sec. Response spectrum of all ground accelerations were compared with Elastic Response Spectrum (ERS) of IS1893 (part 1): 2016 [11]. Once construction of ERS was over, response spectrum analysis of all the tanks was done for the six ground accelerations and the response quantities such as base shear, base moment, hydrodynamic pressure and sloshing wave height were obtained as per IITK-GSDMA guidelines. The results were interpreted based on the storage capacity, numbers of columns supporting the container, horizontal bracing configurations, and peak ground parameters of ground accelerations. A simplified dynamic analysis procedure was also suggested for the seismic performance of elevated water tanks subject to ground accelerations due to earthquakes [12]. GHATEH *et al*. [13] did an approach to establish seismic response factors for tanks ranging from small to very big in size. Out of the various factors considered, it was found out that tank storage capacity is the main factor affecting the seismic response factors of tanks. It was concluded that the same response factors should not be used for all types of tanks, instead, it has to be used according to the tank size.

HIRDE *et al*. [14] emphasized the importance of EWTs in the seismic prone region especially after the occurrence of an earthquake. Seismic performances of 240 models of EWTs were studied by varying different parameters such as the height of tanks, soil conditions, and seismic zones. BELOSTOTSKIY *et al*. [15] did a numerical simulation of partially filled thin cylindrical tanks considering the sloshing effects for both linear and non-linear conditions. Numerical simulation technique was developed to study the oil tank performance when subjected to earthquake excitation and the results showed good efficiency and practical importance. Further investigation was also suggested. It is mentioned in the introduction section. In addition to the fluid-structure interaction, partitioned and simultaneous solution procedures were investigated.

CHADUVULA *et al*. [16] considered the fluid- soil-structure interaction effects on the seismic performance of EWTs. It was found out that base shear, base moment and hydrostatic pressures were increasing with the increase in acceleration and the results obtained experimentally were compared with the results obtained using various codes.

SOROUSHNIA *et al*. [17] were aimed at exhibiting the damage pattern of EWTs during the occurrence of earthquakes. It was also verified that performances of elevated tanks with framed staging were better than that with shaft staging. MORI *et al*. [18] proposed an originally conceived 3-D schematization of Housner's fluid–wall interaction model for the seismic assessment of heritage-listed two EWTs; one was taller and another one was shorter. At the maximum level earthquake, collapse conditions were identified on both the tanks. Eventually, while a viscous dissipative bracing was designed for the tall tank, it was a double concave sliding surface base isolation for the short tank. CHEN and KIANOUSH [19] suggested the assumption of consistent mass approach and the flexibility effects on the wall instead of lumped mass and rigid wall respectively and shape functions were assumed for the five mode shapes of the tank wall. The results showed that the method suggested was accurate and it is necessary to consider two mode shapes to get the desirable results.

Having gone through the related literature, it is found that there is less research on 'how the natural time period (NTP) varies from tank to tank with respect to the structural configuration. Therefore, in this research eight water tanks of varying capacity with different number of columns along with horizontal bracing configurations have been selected. Also, it has been planned to check if the calculated values of NTP for each tank are lying away from the acceleration-sensitive region (ASR) of the response spectra of six ground accelerations selected.

2. STRUCTURAL CONFIGURATIONS OF EWTS AND GROUND ACCELERATIONS

Eight water tanks in Tuticorin district, India, were collected and analyzed for structural detailing, storage capacity, weight, and staging height. All the tanks are designed as per the Indian standards IS 456: 2000 and IS 3370 Part IV [20, 21]. The container portion of the tanks has been designed adopting the moment and shear coefficient given in IS 3370 - Part IV by 'Working Stress Method' using M30 mix and Fe 415 steel for uncracked condition. The structure has been analysed for wind zone for wind pressure of 1500 N/sq. m and for Seismic Zone II. The forces due to seismic effect are governing and the design has been done to take care of the seismic forces. The design of columns have been done by 'Limit State Method' satisfying IS 456-2000 [20]. The braces have been designed by steel beam theory to take care of the reversal of stresses. The structural frame and horizontal bracing detailing are shown in Figs. 1 & 2 respectively. Table 1 shows the structural properties of EWTs. They were constructed recently in Tuticorin district, India. The structural frame detailing and the types of horizontal bracing configurations assigned are shown in Figs. 1 and 2 respectively. Storage capacity, overall weight, the height of staging and all other important structural parameters have been studied and they are depicted in Table 1. The lateral stiffness of each tank has been calculated following the procedure available in the guidelines [22–24] using StaadPro software [25].

The six significant ground accelerations, namely Bhuj, Gopeshwar, Bhatwari, Ghansiali, Ummulong, and Mawphlang were selected based on the strong ground motion characteristics, i.e., peak ground acceleration (PGA), peak ground velocity (PGV) and peak ground displacement (PGD) after interpreting all the ground accelerations occurred in India due to 10 various earthquakes. The details of GAs are shown in Fig. 3. All the six ground accelerations are unique [26]. i.e, Gopeshwar and Bhatwari are having maximum peak ground acceleration (PGA), Ummulong and Mawphlang are having maximum peak ground displacement, and Bhuj is having peak value in all three formats. Ghansiali is identified as medium ground acceleration. Next, the locations of the NTPs of the eight tanks on the response spectra of these ground acceleration of different peak ground parameters were calculated. Table 2 shows the peak values detailing of the ground accelerations selected.

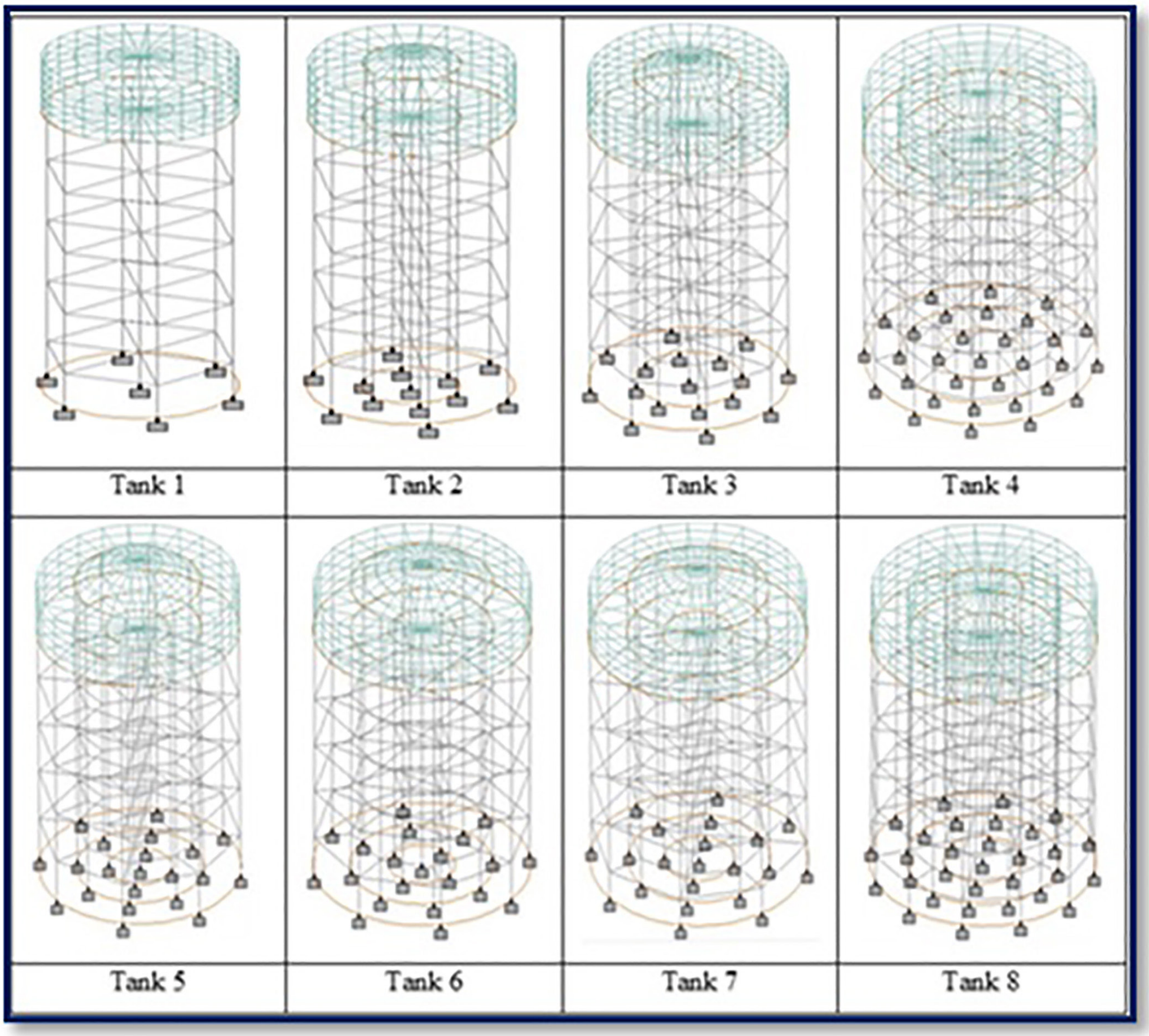


Figure 1: Structural frame details of different water tanks.

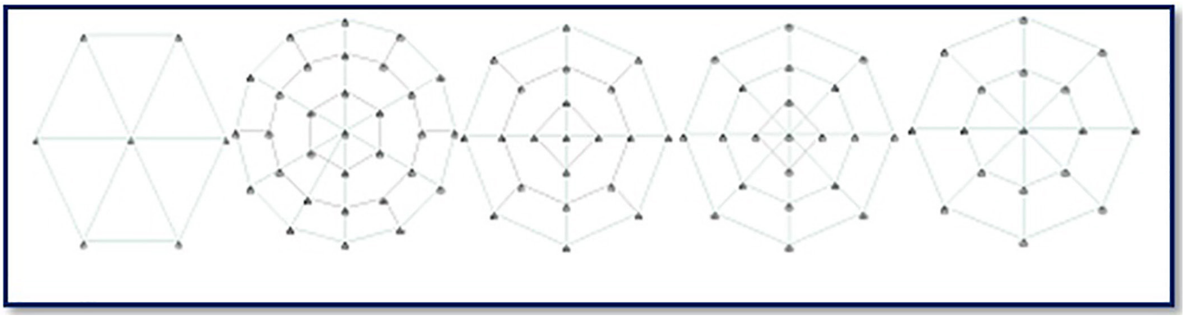


Figure 2: Horizontal bracing configurations of elevated water tanks.

Then-after, the ERS for each Ground acceleration was constructed using the software called prism [27]. Prism software is used mainly for earthquake analysis of Single Degree of Freedom System (SDOF) system. Its features include time history analysis of various hysteresis models, construction of elastic and inelastic response spectrum, and modification of earthquake records.

Table 1: Structural properties of elevated water tanks.

SL. NO	STRUCTURAL PROPERTIES	TANK 1	TANK 2	TANK 3	TANK 4	TANK 5	TANK 6	TANK 7	TANK 8
1.	Capacity (m^3)	105.86	223.278	429.439	522.456	693.663	764.496	846.727	989.632
2.	Diameter (m)	7.14	9.5	12.825	18.58	15.96	17.24	18.46	19.74
3.	Height of the container (m)	3.0	3.55	3.55	3.95	3.45	3.45	3.575	3.95
4.	Height to diameter ratio	0.42	0.374	0.277	0.213	0.216	0.2	0.194	0.2
5.	No of columns	7	13	17	31	21	21	21	31
6.	W_w(KN)	1038.5	2190.36	4212.79	5125.30	6804.84	7500.0	8306.40	9708.29
7.	W_c(KN)	677.38	1536.56	2845.88	7847.77	4494.86	5230.92	6093.59	7223.57
8.	W_s(KN)	748.04	1333.02	2022.03	4321.10	3098.82	3390.18	3648.01	4122.91
9.	$W_c + W_s/3$ (KN)	926.73	1930.90	3519.8	9288.1	5527.8	6360.9	7309.5	8597.8
10.	h_{cg}^*(m)	0.778	0.865	0.8024	0.891	0.461	0.6349	0.56	0.923
11.	m_i (tonne)	45.528	94.893	133.12	121.88	166.47	178.35	194.74	227.61
12.	m_c(tonne)	55.057	120.570	279.13	378.78	492.50	554.26	619.80	712.5
13.	h_i(m)	1.125	1.33125	1.3312	1.528	1.3406	1.3406	1.3406	1.528
14.	h_i^*(m)	2.7	3.7718	5.325	8.4046	6.703	7.3734	7.3734	7.7425
15.	h_c(m)	1.8	1.9968	1.9525	2.2412	2.002	1.966	1.8947	2.2005
16.	h_c^*(m)	2.625	3.3725	5.325	9.1687	7.5968	8.0437	8.2225	8.659
17.	h_s(m)	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7
18.	h_{cg}(m)	16.478	16.566	16.502	16.591	16.161	16.335	16.26	16.623

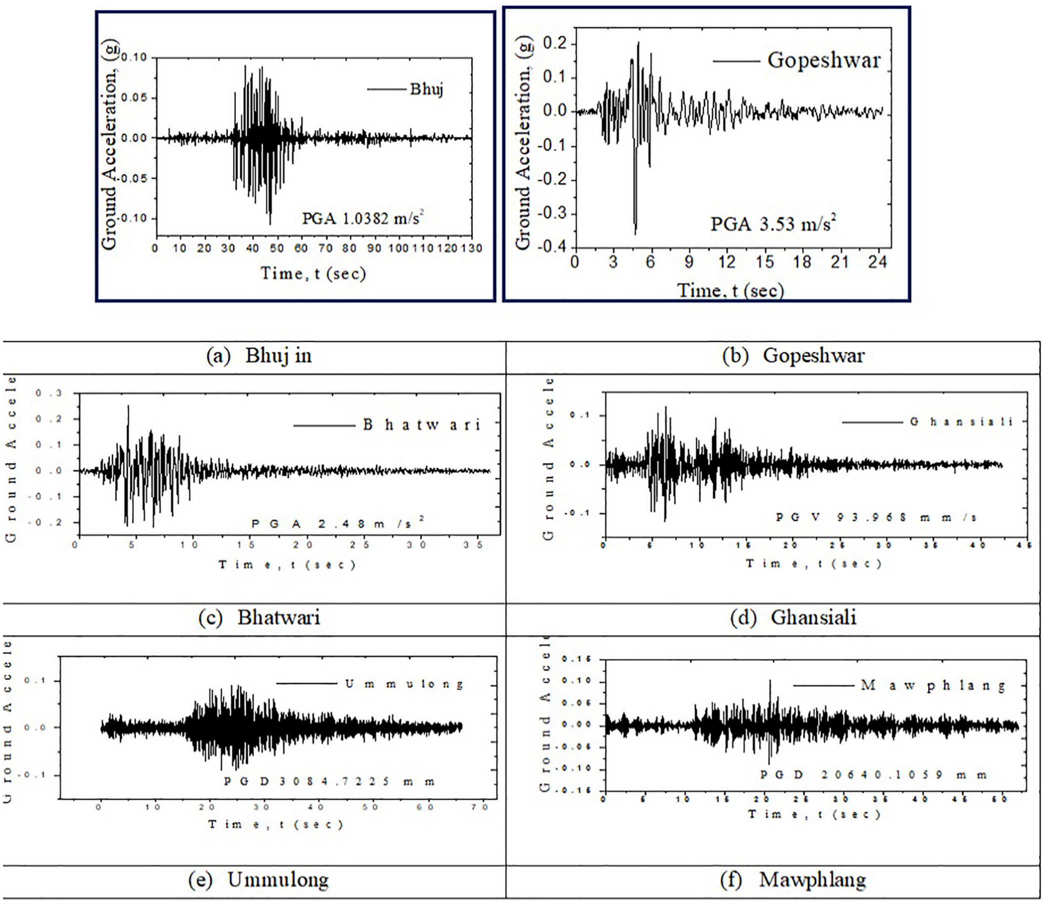


Figure 3: Ground accelerations recorded during some of the Indian earthquakes.

Table 2: Details of ground accelerations.

SL. NO	STATIONS	MAGNITUDE, DATE AND HYPO CENTRAL DISTANCE (Km)	PEAK GROUND ACCELERATION, *Üg* (g)	PEAK GROUND VELOCITY, *Üg* (mm/s)	PEAK GROUND DISPLACEMENT, *Ug* (mm)
1	Bhuj	7.7, 26/01/2001, 9	0.106	450.900	2982.303
2	Gopeshwar	6.6, 29/3/1999, 17.3	0.360	455.953	162.158
3	Bhatwari	7, 20/10/1991, 21.7	0.253	168.832	603.000
4	Ghansiali	7, 20/10/1991, 39.3	0.118	93.968	879.688
5	Ummulong	6.1, 10/1/1990/314.5	0.090	102.022	3084.722
6	Mawphlang	6.1, 10/1/1990, 351.2	0.104	89.617	2103.986

3. SPRING-MASS IDEALISATION OF ELEVATED WATER TANK

As per the GSDMA-IITK guidelines, EWT with water is idealized as the two degrees of freedom system. They are impulsive mode and convective mode. During the earthquake excitation, the water available in the lower portion of the tank container will act as a mass that is rigidly connected to the tank wall. This mass is called impulsive mass. The water available in the upper portion of the tank is affected by the sloshing effects and this mass is called convective mass. The hydrodynamic pressures due to impulsive mass and convective mass are called impulsive hydrodynamic pressure and convective hydrodynamic pressure, respectively. Lateral stiffness of staging (K_s) was calculated by applying a lateral load on a rigid bar extending from the base slab of the tank to its center of gravity. Dividing the lateral load applied by the deflection induced gave the lateral stiffness. Seismic response quantities such as base shear, base moment and hydrodynamic pressure of EWT, filled with water, are calculated using response spectrum method. In the modal analysis of filled tanks, two DOF system is divided into two numbers of single DOF systems and the response of two systems are calculated separately. Finally, they are combined together in order to get the total response using SRSS (Square root of summation of squares) method. After the calculation of NTPs for both filled and empty tanks, their dynamic responses are obtained from normalised acceleration response spectrum curves of all ground accelerations [28, 29].

In addition to the hydrostatic pressure, the other major force to be considered during an earthquake is the hydrodynamic pressure. It is of two types. They are Impulsive as well as convective hydrodynamic pressure. They correspondingly act on the impulsive and convective mass respectively. The spring-mass idealization of the elevated water tank filled with water as two degrees of freedom system is shown in Fig. 4.

4. RESPONSE SPECTRUM ANALYSIS OF ELEVATED WATER TANKS

The response spectrum of single DOF is constructed using prism software. It is based on the Newmark 'β' method [28]. Once NTPs are calculated, the values of the spectral acceleration coefficient (Sa/g) are noted from the response spectrum of individual ground acceleration. The damping ratio of all the tanks was assumed as 5% and the time gap of NTP in the response spectrum graph is maintained as 0.02 sec. Response spectrum curves of all ground accelerations were compared with ERS of Indian code IS 1893: part 1(2016).

As the tanks are located in zone III, the corresponding zone factor is 0.16. The important factor and response reduction factor are taken as 1.5 and 2.5 respectively [22]. Formulae used for the calculation of NTPs, are shown in Eqs (1) and (2). Once construction of ERS was over, response spectrum analysis of all tanks were done for all the ground accelerations and the response spectrum quantities such as base shear, base moment, hydrodynamic pressure and sloshing wave height were obtained. Base shear and base moment were directly proportional to the weight of the tank and horizontal spectral acceleration (Sa/g) of each response spectrum. These results were compared with the results obtained for the ERS available IS1893: part1 (2016). The results were interpreted based on the storage capacity, numbers of columns supporting the container, horizontal bracing configurations and peak ground parameters of ground accelerations.

Values of design horizontal acceleration spectrum for impulsive mode $(A_h)i$ are calculated using the Eq (3) and values of convective mode $(A_h)c$ and of the empty tank (A_h) are also calculated similarly. Table 3 shows the values of the design horizontal acceleration spectrum of all the tanks due to Bhuj ground acceleration for both filled and empty conditions.

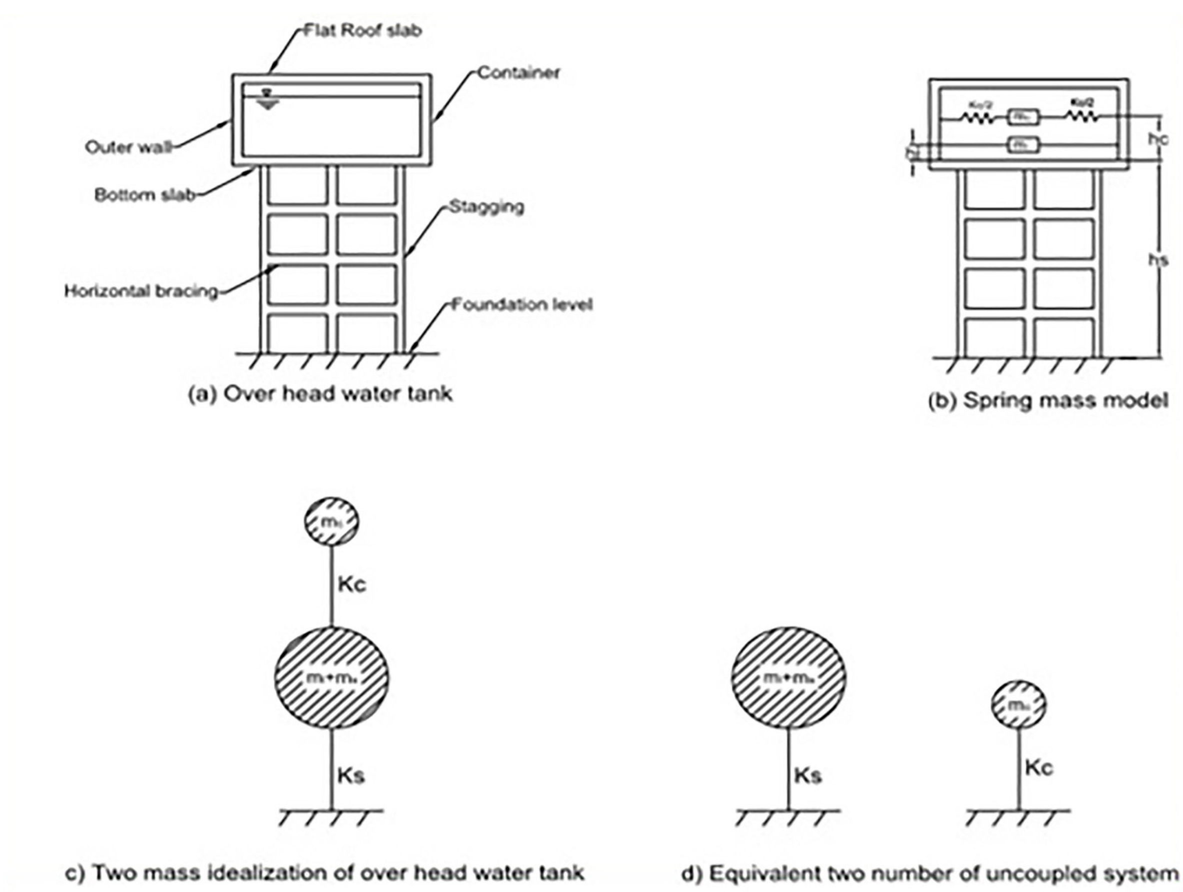


Figure 4: Spring-mass idealisation of elevated water tank.

Table 3: Calculation of design horizontal acceleration spectrum values of tanks.

TANK NO.	Z	I	R	$(Sa/g)_i$	$(Sa/g)_c$	(Sa/g)	$(A_h)_i$	$(A_h)_c$	A_h
1				1.79	0.391	1.789	0.086	0.018	0.085
2				0.816	0.237	1.793	0.039	0.011	0.086
3				1.3	0.203	1.859	0.062	0.009	0.089
4	0.16	1.5	2.5	1.794	0.199	1.86	0.086	0.009	0.089
5				1.556	0.169	1.799	0.074	0.008	0.086
6				0.976	0.197	1.753	0.046	0.009	0.084
7				0.74	0.199	1.168	0.035	0.009	0.056
8				1.799	0.197	1.799	0.086	0.009	0.086

$$T_i = 2\pi\sqrt{\frac{m_i + m_s}{K_s}} \quad (1)$$

$$T_c = C_c\sqrt{\frac{D}{g}} \quad (2)$$

$$(A_h)_i = \frac{Z}{2}\frac{I}{R}\left(\frac{S_a}{g}\right) \quad (3)$$

$$V_i = (A_h)_i (m_i + m_s)\, g \tag{4}$$

$$V_c = (A_h)_c m_c g \tag{5}$$

$$V = \sqrt{V_i^2 + V_c^2} \tag{6}$$

$$M_i^* = (A_h)_i \left[m_i (h_i^* + h_s) + m_s h_{cg} \right] g \tag{7}$$

$$M_c^* = (A_h)_c m_c (h_c^* + h_s) g \tag{8}$$

$$M^* = \sqrt{M_i^{*2} + M_c^{*2}} \tag{9}$$

$$p_{iw} = Q_{iw}(y)(A_h)_i \rho g h . \cos\varphi \tag{10}$$

$$Q_{iw}(y) = 0.866 \left[1 - \left(\frac{y}{h} \right)^2 \right] \tanh\left(0.866 \left(\frac{D}{h} \right) \right) \tag{11}$$

$$p_{cw} = Q_{cw}(y)(A_h)_c \rho g D \left[1 - \frac{1}{3} \cos^2 \varphi \right] \cos\varphi \tag{12}$$

$$Q_{cw}(y) = 0.5625 \frac{\cosh\left(3.674 \dfrac{y}{D} \right)}{\cosh\left(3.674 \dfrac{h}{D} \right)} \tag{13}$$

$$p_{ww} = (A_h)_i t \rho_m g \tag{14}$$

$$p_v = (Av)\rho g h\ (1 - y / h)$$

Where (15)

$$Av = \frac{2}{3} \left(\frac{Z}{2} \times \frac{I}{R} \times \frac{S_a}{g} \right)$$

$$p = \sqrt{(p_{iw} + p_{ww})^2 + p_{cw}^2 + p_v^2} \tag{16}$$

$$d_{\max} = \left(A_h \right)_c R \frac{D}{2} \tag{17}$$

Eqs (4) and (5) shows the formulae used for calculating the base shear of impulsive and convective mode and the total base shear of filled tanks is calculated using Eq (6). Similarly, Eqs (7)–(9) are used for calculating the base moment of filled tanks. For example, the calculated base shear and base moment for tanks due to the Bhuj earthquake are tabulated in Table 4.

Eqs (10) and (11) & Eqs (12) and (13) are used for calculating the hydrodynamic pressure of impulsive and convective mode respectively. Eqs (14) and (15) are used for calculating the hydrodynamic pressure due to inertia on the tank wall and pressure on the tank wall due to vertical ground acceleration respectively. Combining above all pressure, the resultant pressure is calculated using the Eq (16). The maximum height of the sloshing wave is calculated using the Eq (17). Hydrodynamic pressure distribution due to the various forms mentioned above and also the maximum height of the sloshing wave of all the tanks due to Bhuj Ground acceleration are shown in Table 5.

Table 4: Calculation of base shear and base moment due to Bhuj earthquake.

TANK NO.	BASE SHEAR			BASE MOMENT			V(N) M(N.m)	
	IMPULSIVE MODE, V_i (N)	CONVECTIVE MODE, V_c (N)	TOTAL BASE SHEAR, V (N)	IMPULSIVE MODE, M_i (N.m)	CONVECTIVE MODE, M_c (N.m)	TOTAL BASE MOMENT, M (N.m)	BASE SHEAR, V (N)	BASE MOMENT, M (N.m)
1	117999.3	10150.11	118435	2018147	186000.7	2026701	79624.81	1312058
2	114093.5	13506.98	114890.3	1996026	257611.9	2012581	77617.85	1285779
3	301134.1	26771.24	302321.8	5337906	562865.2	5367500	219641.8	3624528
4	903244.2	35587.99	903945.1	15759769	885028.9	15784600	800225.2	13276536
5	535085.7	39362.2	536531.5	9409255	917013.2	9453835	413051.8	6675330
6	380244.5	51533.54	383720.7	6764036	1223599	6873819	298215.8	4871355
7	327496.9	58205.62	332629.1	5787456	1392424	5952604	259636.9	4221696
8	935387.7	66281.18	937733.1	16864039	1614543	16941150	742545.2	12343329

Table 5: Calculation of hydro dynamic pressure and sloshing wave height.

TANK NO.	P_{iw} (y = 0)	P_{iw} (y = h)	P_{cw} (y = 0)	P_{cw} (y = h)	P_{ww}	p_v	$P_{iw} + p_{ww}$	p_{cw}	p_v	p	SLOSHING HEIGHT (m)
1	1.866	0	0.246	0.497	0.257	2.040	2.124	0.246	2.040	2.955	0.169
2	1.037	0	0.217	0.399	0.147	2.472	1.184	0.217	2.472	2.749	0.135
3	1.667	0	0.335	0.473	0.273	2.472	1.940	0.335	2.472	3.160	0.161
4	2.662	0	0.309	0.475	0.430	2.864	3.093	0.309	2.864	4.227	0.161
5	2.188	0	0.360	0.479	0.336	2.707	2.524	0.360	2.707	3.719	0.162
6	1.304	0	0.479	0.601	0.199	2.570	1.503	0.479	2.570	3.016	0.204
7	0.950	0	0.541	0.651	0.160	2.472	1.110	0.541	2.472	2.763	0.221
8	2.677	0	0.509	0.648	0.518	2.864	3.195	0.509	2.864	4.321	0.220

5. RESULTS AND DISCUSSION

5.1. Acceleration response spectrum

Six ground accelerations are filtered out from the history of past Indian earthquakes based on their strong motion characteristics such as duration, magnitude, PGA, PGV, and PGD [29, 30]. Table 2 shows the details of ground accelerations selected. The response spectrum of displacement, velocity, and acceleration are readily constructed for the six ground accelerations selected using prism software and it is accompanied by EDRS of IS 1893: part 1(2016). Acceleration response spectrum is normalized by dividing it by peak ground acceleration and it is along with the Displacement response spectrum is shown in Figs. 5(a) & (b). Acceleration response spectrum is used for determining dynamic response (Sa/g) of EWTs and the displacement response spectrum is used for knowing how much deformation a tank is subject to during an earthquake [31, 32]. As far as ERS of IS1893 is concerned, the value of the spectral acceleration coefficient (Sa/g) is 1 at zero NTP and it is gradually going on increasing upto 0.1 sec and reaches the maximum value of 2.5. The maximum value is stabilized upto to the NTP of 0.4 sec and then after it starts decreasing gradually. In this similar way, the response spectrum for all other ground accelerations looks like. Even though amplitudes of Normalised Acceleration Response spectrum of all ground accelerations are more than 2.5, they exist just for a few seconds. Generally, amplitudes of response spectra are over by NTP of 0.5 sec and if the NTP of the tank is lying in between 0 to 0.5 sec, the corresponding spectral acceleration coefficient will be very high. Afterward, the longer is the NTP, lesser is the spectral acceleration coefficient. The NTPs of the impulsive mode of all tanks are slightly more than 1sec and that of convective mode is very long, i.e., from 3 sec to 5.9 sec leading to very less value of spectral acceleration coefficient and thus base shear and base moment. This is why convective mode contributes very little in seismic response quantities compared to impulsive mode. Therefore, when designing EWTs, it is to be ensured that NTPs of tanks are not lying in between 0.1 sec to 0.6 sec.

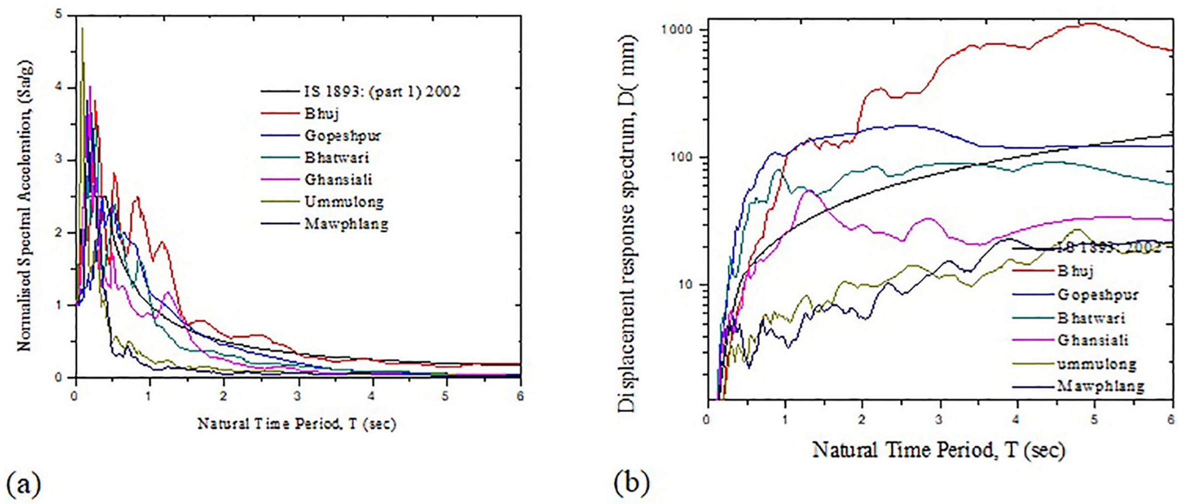


Figure 5: Acceleration and displacement response spectrum of the different ground acceleration.

Table 1 shows all the structural properties of all tanks. At first, the height to diameter ratio (h/D) and total mass (m) of the tank are calculated and using these two values, other parameters are calculated referring charts available in IITK-GSDMA guidelines. As EWTs are numbered in ascending order with respect to the storage capacity, the parameters such as weight of water, the weight of the container and convective mass are increasing from tank 1 to tank 8. The weight of staging is maximum for tank 4 as it is provided with 31 numbers of columns and also horizontal bracing of three sets of ring beams. The horizontal bracings provided for different tanks are shown in Fig. 2. The height of all tanks is almost equal and is equal to 15.7 m.

5.2. Lateral stiffnesses and natural time periods

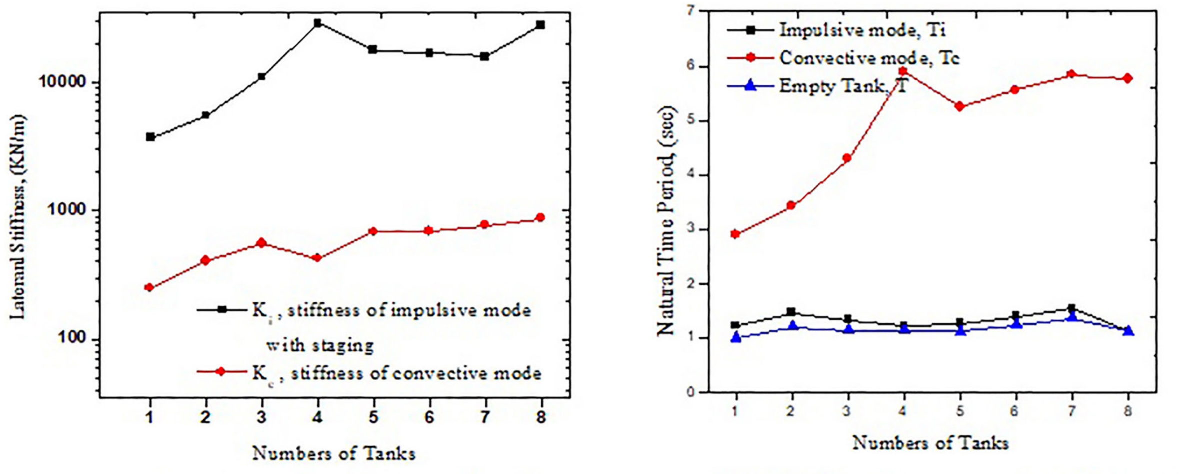
Generally, amplitudes of acceleration response spectra reach maximum at NTP of 0.5 sec and if the NTP of the tank is lying in between 0 to 0.5 sec, the corresponding spectral acceleration coefficient will be very high. Afterward, the longer is the NTP, the lesser is the spectral acceleration coefficient. The NTPs of the impulsive mode of all tanks are slightly more than 1sec and that of convective mode is very long, i.e., from 3 sec to 5.9 sec leading to very less value of spectral acceleration coefficient and thus base shear and base moment. This is why convective mode contributes very little in seismic response quantities compared to impulsive mode. Therefore, when designing EWTs, it is to be ensured that the NTPs of tanks are not lying in between 0.1 sec to 0.6 sec.

At first, the height to diameter ratio (h/D) and total mass (m) of the tank are calculated and using these two values, other parameters are calculated referring to charts available in guidelines (IITK 2007) [22]. Generally, NTPs are mainly influenced by two factors namely mass of the tanks and lateral stiffness. Weight of water (Ww), weight of container (Wc), and weight of staging (Ws) required for the calculation of NTPs are calculated and depicted in Table 1. The values of Ww , Wc , and Ws from tank 1 to tank 8 are ranging from 1038.5 kN to 9708.3 kN, 677.38 kN to 7223.6 kN, and 748.04 kN to 4122.9 kN respectively. As EWTs are numbered in ascending order with respect to the storage capacity, the parameters such as weight of water, the weight of the container and weight of staging are increasing from tank 1 to tank 8.

The weight of staging is maximum for tank 4, the value is 4321.1 kN, as it is provided with 31 numbers columns and also horizontal bracing of three sets of ring beams. Similarly, the impulsive masses and convective masses are ranging from 45.52 tons to 227.6 tons and 55.05 tons to 712.5 tons respectively for tank 1 to tank 8. The height of all tanks is tantamount and is equal to 15.7 m.

Figure 6(a) shows the lateral stiffness variations from tank 1 to tank 8. Lateral stiffness is gradually increasing from tank 1 to tank 8 except tank 4, i.e., stiffness of tank 4 is maximum among all the tanks in case of impulsive mode. Tanks are numbered in ascending order according to their storage capacity. Gravity loads such as weight of the container, weight of water, and weight of staging are the main loads that are offering resistance to the lateral load applied. Even though the weight of tank 4 is less than that of tanks 5 to 8, the number of columns supporting the staging system is 31, which is the maximum among all tanks.

The lateral stiffness of tank 1 to tank 4 ranges from 3675.119 kN/m to 28409.09 kN/m and the stiffness of tank 5 to tank 7 is more or less equal to 16000 kN/m. Again, the stiffness of tank 8 is increased to 27548.2 kN/m.



(a) Lateral stiffness of tanks (b) Natural time periods of tanks

Figure 6: Dynamic properties of elevated water tanks.

It is understood that a greater number of columns increases the lateral stiffness of tank 4 compared to others. The horizontal bracing configuration is also influencing lateral stiffness to a certain extent. Figure 6(a) is a semi-log sheet which clearly shows that the lateral stiffness of convective mode is very less compared to that of impulsive mode.

Figure 6(b) shows that NTPs of the impulsive mode of filled tanks and that of empty tanks are almost concentrated on 1 second [33]. Meanwhile, NTPs of convective mode is ranging from 3 sec to 5.5 sec for tanks 1 to 8. It is to be noted that the spectral acceleration coefficient (Sa/g) is almost negligible for larger NTPs, so that the contribution of impulsive mode in the seismic performance of EWTs would be very maximum compared to that of convective mode.

5.3. Base shear

When interpreted, it is known that the total seismic response of the tank is obtained by the multiplication static and dynamic responses. The total weight of the tank leads to the static response while dynamic response represents the spectral acceleration coefficient which is obtained from individual ground acceleration. Spectral acceleration coefficient is the function of NTP which in turn is depending on stiffness as well as the mass of the tank. Lateral stiffness and mass of the impulsive mode of tank 4 are 28409.09 kN/m and 121889.14 kg respectively. The corresponding NTP of impulsive mode is 1.22 sec and Spectral acceleration coefficient is taken out from the individual response spectrum. For example, the Spectral acceleration coefficient value of the Bhuj earthquake for the NTP of 1.22 is 1.79 which is high among all other Spectral acceleration coefficient values. This dynamic response is the principal factor behind the increased total seismic response of the Bhuj earthquake.

Figs. 7(a) & (b) shows the base shear of filled as well as empty tanks for different GAs, in addition to ERS of IS 1893. Total base shear is obtained from the base shear due to the impulsive mode and convective mode using SRSS method. In the case of filled tanks, the contribution of Impulsive mode is much significant compared to the negligible convective mode. Although the mass of convective mode is more than that of impulsive mode, its lengthy NTP gives a very less spectral acceleration coefficient. In all the tanks, the base shear of IS 1893 is surpassed by that due to three ground acceleration and they are Bhuj, Gopeshwar, and Ghasiali. Base shear due to ground acceleration such as Ummulong and Mawphlang are very less compared to all other ground accelerations. Response contribution by Bhuj is maximum among all ground accelerations. Bhuj ground acceleration induces base shear of 904 kN & 937 kN respectively in tank 4 and tank 8, while ERS of IS1893 induces base shear of 419 kN & 413 kN in that two tanks respectively.

In the case of an empty tank, the maximum base shear is induced in tank 4 by Bhuj ground acceleration and is equal to 80.02 KN. In both cases, the base shear is gradually increasing due to all ground accelerations and attaining the maximum value at tank 4 and it is going to decreases upto tank 7 before attaining the sudden increment at tank 8. As far as ERS of IS 1893 is concerned, base shear is gradually increasing from tank 1 to tank 8 except tank 4.

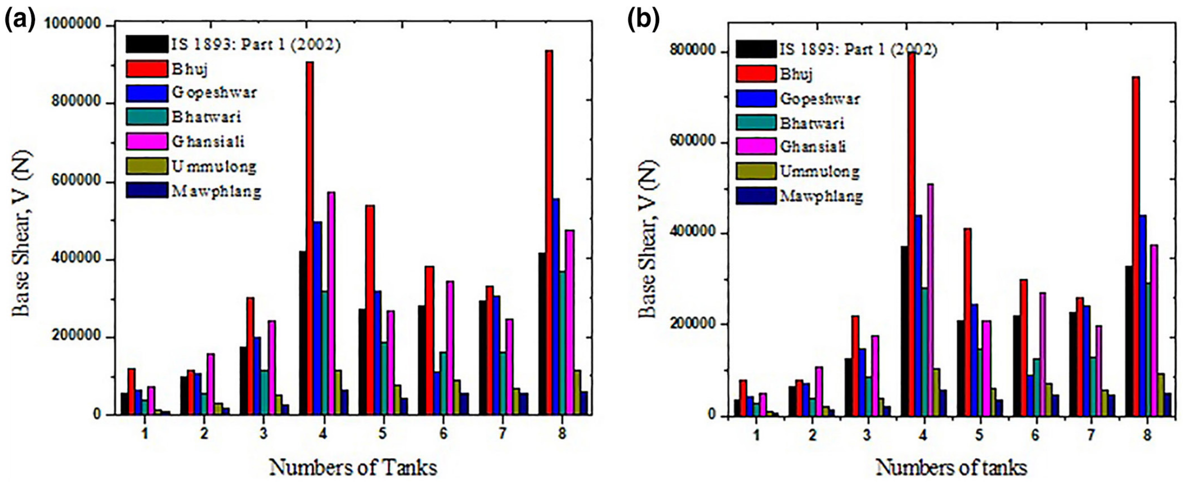


Figure 7: Variation of base shear with respect to ground accelerations. (a) Base Shear of filled tanks. (b) Base Shear of empty tanks.

5.4. Base moment

Figs. 8(a) & (b) shows the variation of the base moment with respect to ground accelerations for all the tanks. The base moment is obtained by multiplying the base shear and heights of relevant modes. The percentage of base moment induced in each tank is exactly equal to that of base shear as both are linearly proportional to each other. This is delineated in Figs. 8(a) & (b). In the case of an elevated tank with filled water, the maximum base moment has taken place in tank 8 by the Bhuj earthquake and is equal to 16941.15 kN. m, followed by tank 4 subject to the base moment of 15784.6 kN.m. Meanwhile, in the case of an empty tank, tank 4 is subject to the maximum base moment of 13276.536 kN.m. In both cases, base shear and base moment induced in all tanks by EDRS of IS1893: part 1(2016) is almost surpassed by three ground accelerations, namely, Bhuj, Gopeshwar, Ghansiali. Two ground accelerations such as Ummulong and Mawphlang are producing very less amount of base shear and base moment among the all tanks. It has left a question of constructing the number of elastic response spectra based on the severity of earthquake-prone regions instead of only one ERS [34, 35].

5.5. Hydrodynamic pressure

In addition to impulsive and convective hydrodynamic pressure, two more dynamic pressures are considered. Pressure due to wall inertia (p_{ww}) is significant for concrete tanks and its distribution is uniform along the height of the tank wall. It has to be added with impulsive hydrodynamic pressure, i.e., ($p_{iw}+p_{ww}$). Additional hydrodynamic pressure on the tank wall by effective weight of water because of vertical ground acceleration is (p_v). NTP of the vertical ground excitation is generally taken as 0.3 sec [23, 24] for all the ground acceleration. It is to be noted here that p_v is always greater than p_{iw}. The resultant hydrodynamic pressure (p) due to the horizontal as well as vertical ground acceleration is then calculated as per the Eq (16) and its variation with respect to tanks is delineated in Fig. 9(b). Spectral acceleration coefficient of Bhuj ground acceleration corresponding to the NTP of 0.3 sec is 3.457, compared to 2.5 of ERS of IS1893. It shows that resultant hydrodynamic pressure is almost equal in all tanks by all ground excitations except tank 4 & tank 8, where hydrodynamic pressure by Bhuj ground acceleration is more than that by other accelerations. They are equal to 5.035 kN/m^2 and 5.115 kN/m^2 for tank 4 and tank 8 respectively and for all other tanks, it is around 2.5 to 3 KN/m^2. Tanks analysed in the IITK-GSDMA guidelines shows the hydrostatic pressure of around 2.5 kN/m^2.

5.6. Height of sloshing wave

The height of the Sloshing wave is calculated using the Eq (17) and is necessary to fix the height of the freeboard. If the roof slab is not to be subjected to uplift pressure due to sloshing effects, the desirable height of the freeboard has to be provided based on the height of the Sloshing wave. Fig. 9(a) shows the height of the Sloshing wave distribution among all the tanks due to different GA. It is known from Fig. 9(a) that EDRS of IS 1893 and Bhuj GA are governing the height of the Sloshing wave and it is more than 200 mm for tanks 6, 7 and 8 by Bhuj ground acceleration and the effects of height of the Sloshing wave is negligible for all other ground accelerations.

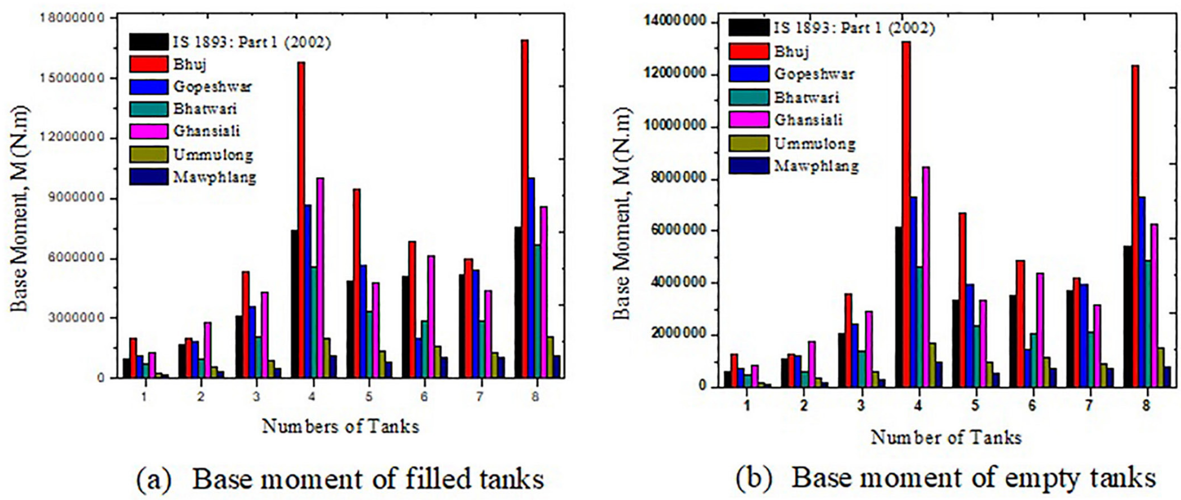


Figure 8: Variation of the base moment with respect to ground accelerations.

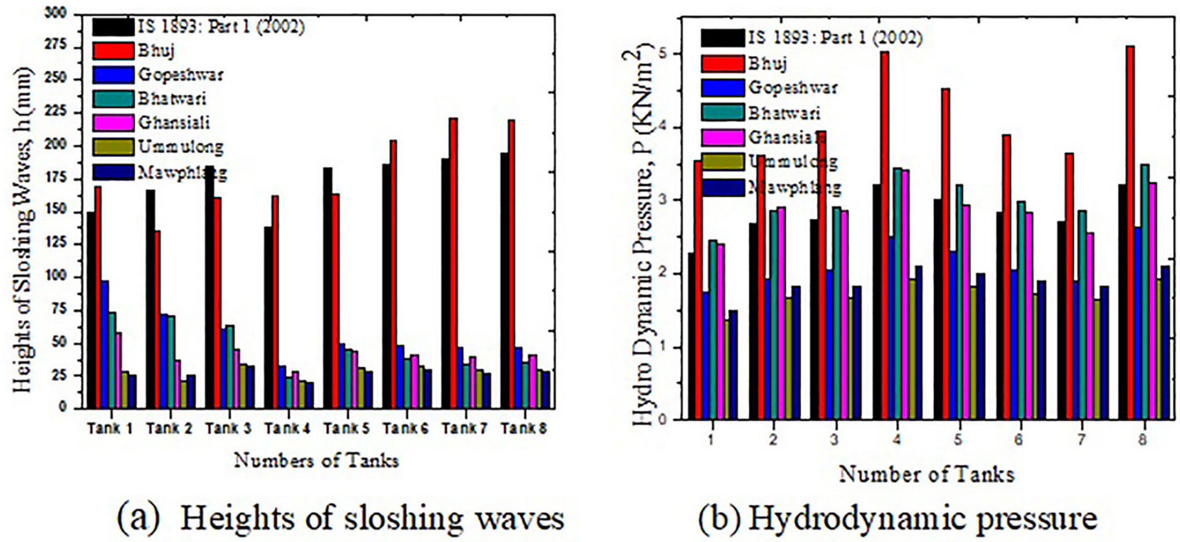


Figure 9: Variation of hydrodynamic pressure and height of sloshing wave.

5.7. Comparison of base shear of EWTs with filled and empty condition

Figs. 10(a) & (h) and Figs. 11(a) & (h) show the base shear distribution of tanks due to ground accelerations in terms of percentage of seismic weight of the tank. Figures from (a) to (h) have been drawn in the same scale to have a clear comparison. Total weight is ranging from 2464 kN for tank 1 to 21054.8 kN for tank 8 and in the case of empty tanks, it is from 1425.3 KN to 11346.5 kN. Maximum percentage of seismic weight is transferred as base shear in tank 4. The maximum base shear is induced by Bhuj GA, i.e., 5.23% followed by Ghansiali (3.32 %) and Gopeshwar (2.88%). EDRS of IS1893 gives 2.43% of percentage of seismic weight as the base shear in tank 4. Next to tank 4, tank 8 is attained maximum percentage of seismic weight as the base shear. Moreover, it is less than 1% of seismic weight, which is transmitted to all tanks by ground accelerations Ummulong and Mawphlang. Percentage of seismic weight transmitted as base shear is maximum for an empty tank compared to that of filled tanks. 6.55% of the seismic weight is transmitted as base shear for empty tanks 4 and 8 by Bhuj ground acceleration. EWTs analysed in the IITK-GSDMA guidelines shows 4 to 6 % of seimic weight as base shear for filled tanks and 3 to 4.5 % for empty tanks.

Figs. 10(a) & (h) and Figs. 11(a) & (h) show the base shear distribution of tanks due to ground accelerations in terms of percentage of seismic weight of the tank. Figures from (a) to (h) have been drawn in the same scale to have a clear comparison. Total weight is ranging from 2464 kN for tank 1 to 21054.8 kN for tank 8 and in the case of empty tanks, it is from 1425.3 KN to 11346.5 kN. Maximum percentage of seismic weight is

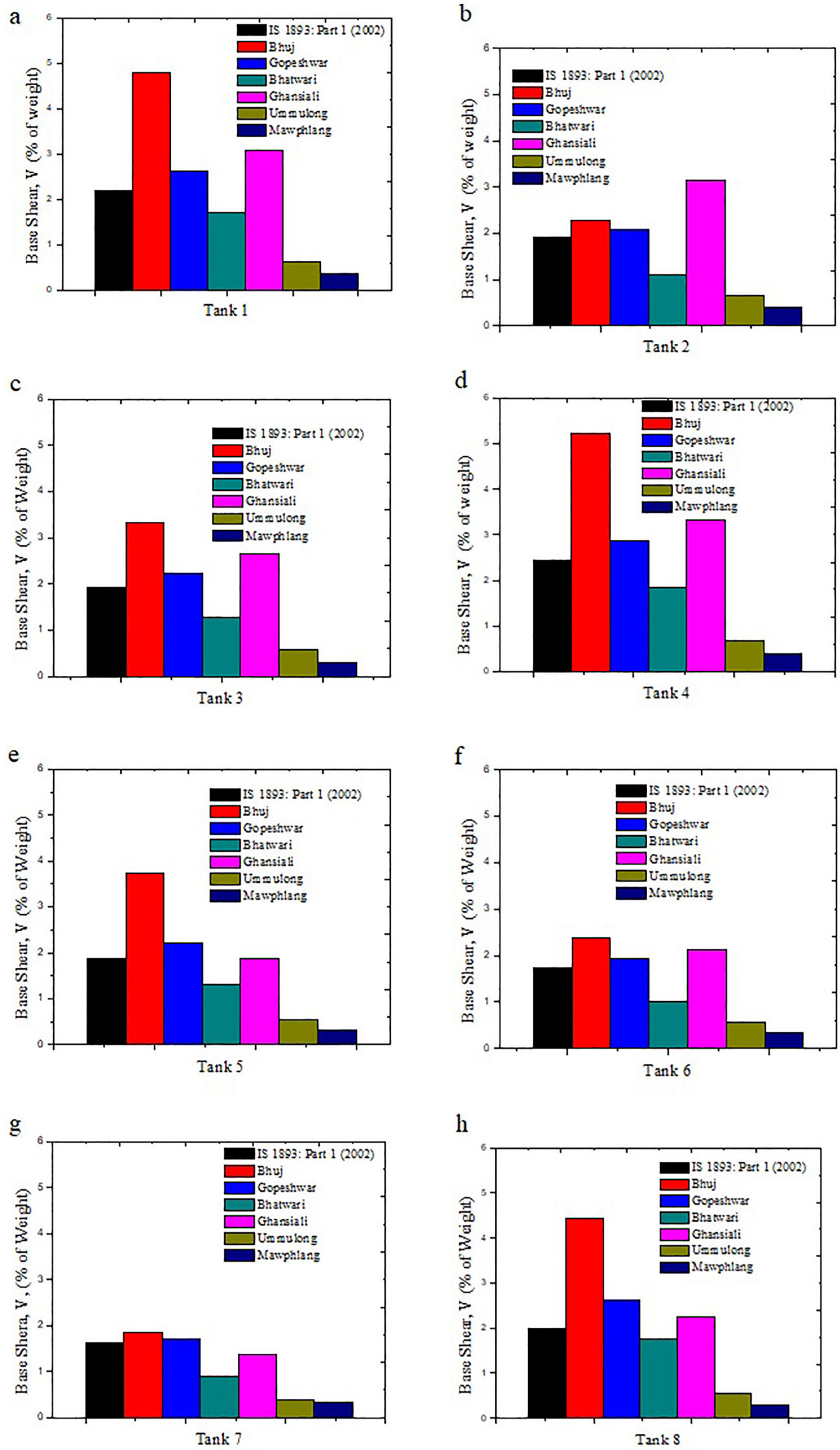


Figure 10: Variation of base shear as a percentage of the total weight of filled tanks.

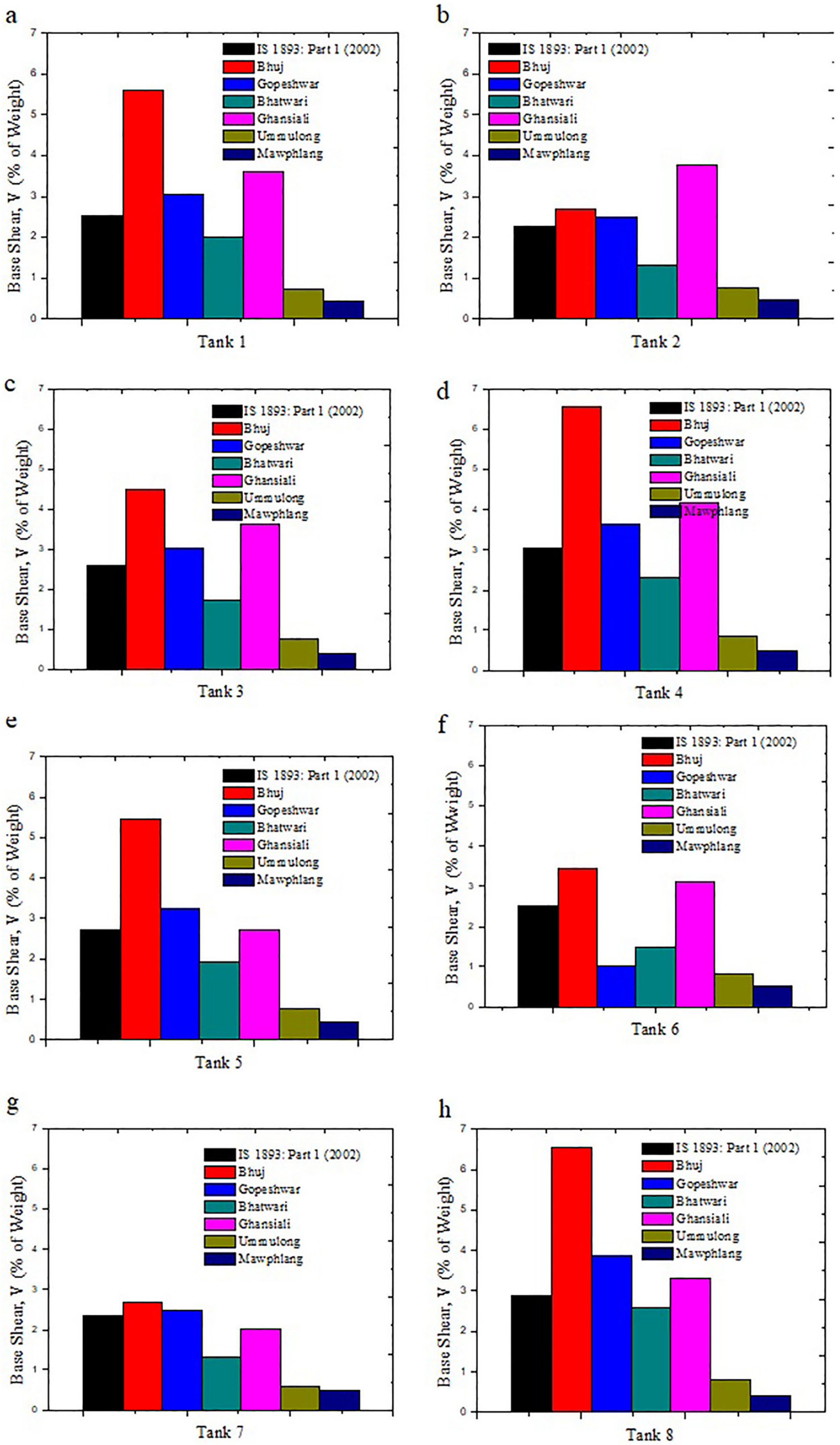


Figure 11: Variation of base shear as a percentage of the total weight of empty tank.

transferred as base shear in tank 4. The maximum base shear is induced by Bhuj GA, i.e., 5.23% followed by Ghansiali (3.32%) and Gopeshwar (2.88%). EDRS of IS1893 gives 2.43% of percentage of seismic weight as the base shear in tank 4. Next to tank 4, tank 8 is attained maximum percentage of seismic weight as the base shear. Moreover, it is less than 1% of seismic weight, which is transmitted to all tanks by ground accelerations Ummulong and Mawphlang. Percentage of seismic weight transmitted as base shear is maximum for an empty tank compared to that of filled tanks. 6.55% of the seismic weight is transmitted as base shear for empty tanks 4 and 8 by Bhuj ground acceleration. EWTs analysed in the IITK-GSDMA guidelines shows 4 to 6 % of seimic weight as base shear for filled tanks and 3 to 4.5 % for empty tanks.

Finally, it is understood that the GAs such as Bhuj, Gopeshwar, and Ghasiali are contributing maximum seismic response quantities such as base shear, base moment and hydrostatic pressure compared to ERS of IS1893: part1(2016), meanwhile the response contribution by remaining ground accelerations, Bhatwari, Ummulong, and Mawphlang are less significant in contributing seismic response compared to ERS of IS 1893: part 1(2016).

5.8. Experimental investigation

To substantiate the results obtained analytically, models of two tanks of storage capacity105.86 m^3 223.278 m^3 have been made. Tests have been conducted for both filled and empty conditions of EWTs. The readings of roof displacement of the model tanks are obtained by doing double-time integration of the acceleration values from the test conducted. It has been planned to adopt two tank models reflecting the configurations of tank 1 and tank 2 to determine the displacement as well as stiffness experimentally and to compare with the staad-pro analytical results of the tank prototypes. A scale of 1:10 is adopted for staging height, horizontal bracing interval, and height of container and a scale of 1:15 is adopted for diameter of container. The heights of the container and staging of the tanks are fixed at 0.35 m and 1.6 m respectively. The thicknesses of the base slab, roof slab, and wall were taken as 3 mm, 2 mm, and 2 mm respectively. The diameter of steel rods reflecting the tie beams and columns are taken as 8 mm and 10 mm respectively. The tank 1 and tank 2 models are differing based on the horizontal as well as vertical bracing configurations and storage capacity. The bracing interval along the height is taken as 0.4 m. Diameters of the container of 1^{st} and 2^{nd} tank models are fixed at 0.45 m and 0.6 m respectively. The tank 1 and tank 2 models and the experimental set-up are delineated in Fig. 12. Harmonic forced vibration is induced at a rate of 2 cycles per second in the base plate level. An accelerometer, a device used to measure motion of a structure along three mutually perpendicular directions x, y and z, consists of an Arduino Board with a micro controller. It is simply connected to a computer with a USB cable for gathering accelerometer values from the roof level of the tank. The load is being applied continuously up to 15 s and the acceleration response is readily plotted in numerical values as well as a graphical form in the computer system. Table 6 shows the readings of roof displacement of the tanks which are obtained by doing double time integration of the acceleration values from the test conducted.

The schematic representation of the calculation of lateral stiffness is shown in Figure 13. Here, the direct comparison is not made between the tank models and prototypes but between tank 1 of capacity 105.86 m^3 and tank 2 of 223.278 m^3. Roof displacement and lateral stiffness of staging are changing from tank 1 to tank 2 prototypes and these are substantiated by the results obtained from the tank models. While roof displacement decreases, lateral stiffness increases from tank 1 to tank 2 as additional number of columns and horizontal

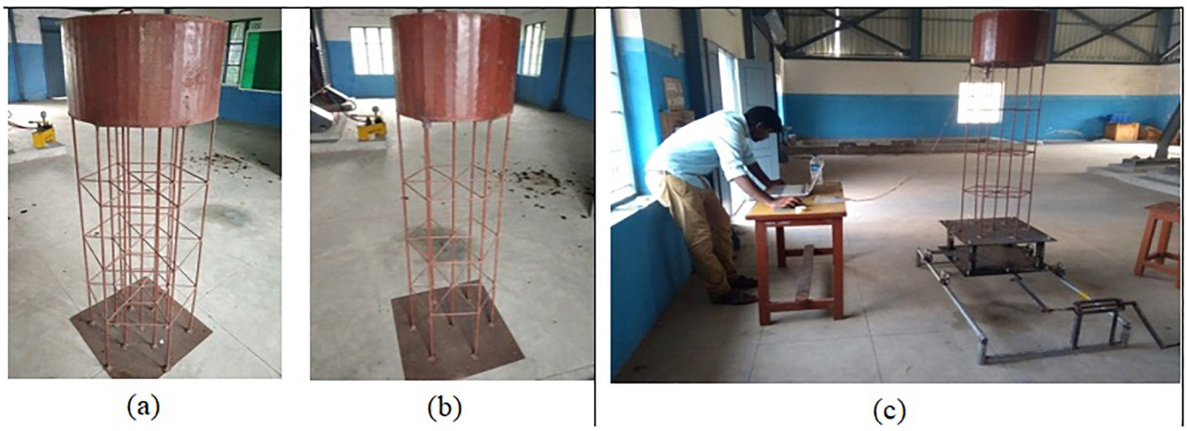


Figure 12: Tank models and experimental set-up.

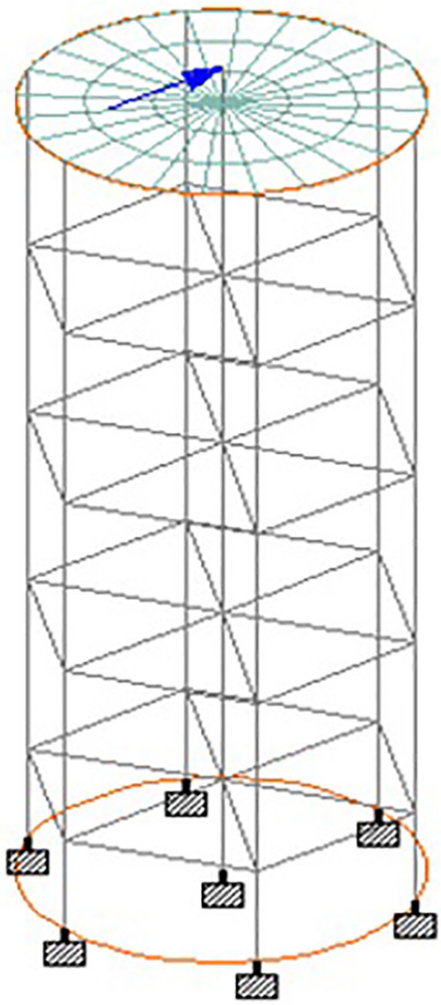


Figure 13: Lateral load application for stiffness calculation.

Table 6: Comparison of experimental results with analytical results of EWTs.

TANK NO.	ROOF DISPLACEMENT (mm)		LATERAL STIFFNESS (kN/m)	
	TANK PROTOTYPE (ANALYTICAL RESULTS)	TANK MODEL	TANK PROTOTYPE (ANALYTICAL RESULTS)	TANK MODEL
1	272.1	148.543	3675.119	673.2
2	182.0	121.655	5488.47	822.0

bracings are provided in tank 2. The rate of reduction of roof displacement from tank 1 to tank 2 for prototypes and models are 33.11% and 18.1% respectively. Similarly, the rate of increment of lateral stiffness of staging from tank 1 to tank 2 is 49.34% for prototypes and 22.1% for tank models. Table 6 shows comparison of experimental results with analytical results of EWTs.

Tank storage capacity, staging support system and ground accelerations are the main factors affecting the seismic response quantities such as base shear, base moment, hydrodynamic pressure and height of the sloshing wave. Among the three factors mentioned above, ground acceleration is the main factor affecting the seismic performance of EWTs. When comparing the seismic performances due to different ground accelerations, it is the Bhuj ground acceleration giving very high response quantities. Next to Bhuj ground acceleration, Gopeshwar and Ghansiali ground accelerations are giving seismic response quantities significantly higher than ERS of IS1893 (part1): 2016. So the structures may be susceptible to similar ground accelerations if they are analysed as per ERS of IS1893 (part 1): 2016.

6. CONCLUSIONS

Seismic performances of EWTs are studied by with respect to the variations of different parameters such as tank storage capacity, lateral resistance, and ground accelerations. Based on the above study, the following conclusions are made.

- Even though the storage capacity of tank 4, i.e., 522.456 m^3 is less than that of tank 5, tank 6, tank 7 and tank 8, seismic responses of tank 4 is greater than tank 5, tank 6, and tank 7 for all the ground accelerations. It was found that structural framing of tank 4 is responsible for the very high seismic response quantities. Therefore, it is concluded that design of structural framing of EWTs has to be done meticulously.
- Seismic response quantities in tanks with maximum storage capacity and lower NTPs are highest. To optimize EWT design, predominant natural periods should be located away from peak acceleration region, with periods exceeding 1.0 seconds.
- Indian earthquakes can cause significant damage to structures, such as chimneys, bridges, dams, and elevated buildings. The amplitude of ERS of ummulong ground acceleration is the highest, with a maximum of 4.8 g. These amplitudes are typically short-lasting, ranging from 0.02 to 0.4 sec. Therefore, adequate safety factors should be considered in the spectral acceleration coefficient of IS1893 part: 2016.
- IITK-GSDMA guidelines indicate that base shear, particularly in empty tanks, is maximum, with a PSW of 6.5%. This can lead to a significant reduction in NTP, potentially causing catastrophe. Steel tanks are lighter than reinforced concrete tanks, so empty condition should be considered when designing EWTs with reinforced concrete framed staging.

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