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A critical review of comparative seismic behaviour of RC shaft supported elevated water tanks and chimney

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In event of severe earthquakes RC structures are subjected to lateral jolts. The behaviour of the structures towards seismic forces is dependent on the structural composition and lateral stiffness. Elevated water tanks supported on shafts are inverted pendulums with heavy mass suspended at the top. While chimneys are stack like structure whose structural composition is like a slender cantilever fixed at the base. In this paper an attempt shall be made to critically compare the lateral seismic behaviour of these two different structures using equivalent static and dynamic analysis procedure. The selection of the two classes of structures has been done from the logic that the RC shaft of an elevated water tank resembles a chimney of low height loaded with heavy load at the top. Whereas chimney being a more slender structure, both these structures falls in different natural period ranges of the design spectra and hence they attract different levels of seismic forces. The paper proposes to compare critically the variation in seismic behaviour of these two classes of structures, which is elevated water tank on shaft a relatively rigid period system and chimney a rather longer period system.

KEYWORDS: Shaft staging; elevated water tanks; inverted pendulum; slender chimney; seismic behaviour.

The behaviour of a structural system to lateral seismic forces is dependent on the portion of the mass of the structural system which participates during the seismic jolts and also the lateral stiffness of the structural system. Due to variation in the structural configuration the portion of participating seismic mass and the lateral stiffness of the structural system varies for various classes of structural composition. In this case elevated water tanks and chimney both have different structural compositions to suit the functional utility.

Elevated water tanks fall in the category of "inverted pendulums". The major mass which is affected by the lateral seismic forces is concentrated at the C.G. of the tank container. The location of the C.G. is affected with the depth of the water in the tank container. Housner[1] reported that the water contained in the tank container below the free board executes impulsive pressure and portion of the water near the free board executes convective pressure. This two different modes of vibration requires a two mass modelling to account for hydrodynamic pressure distribution in the tank container. The proposition put up by Housner was experimentally verified by Boyce[2]. The existing Indian Earthquake code IS 1893, however recommended a Single Degree of Freedom model (SDOF). Comparative study on the efficacy of single degree of freedom model, Two degree of freedom model, multi degree of freedom model and Finite Element (FE) model has been made by researchers elsewhere[3]. Chimneys are slender stack like structures used for discharging industrial waste gases at high enough elevation so that after dilution due to atmospheric turbulence, their concentration and that of their entrained solid particulates is within acceptable limit on reaching the ground. A tall chimney achieves simultaneous reduction in concentration of number of pollutants including Sulphur dioxide, fly ash etc. chimneys being slender cantilever structures, there behaviour against lateral forces such as earthquakes requires elaborate study. From observations of damage survey reports of 115 numbers chimney failures following the Tokyo earthquake 1923, Housner[4] developed empirical expressions for arriving at seismic base shear and earthquake induced Bending Moment (BM) at the base of the chimney. This expressions were adopted at the earlier version of the Indian earthquake code IS 1893-1984[5]. Researchers[6] indicated that the bending moment and shear force distribution along the height of the chimney is actually much lower than proposed by Housner. Thus a new distribution of the seismic induced BM and shear force along the chimney section was proposed. This later distribution has been adopted in the current version of IS 1893 (Part-4)[7]. Jain, et al.[8] has made critical study on IS codal provisions for seismic design of chimneys. Detailed analysis and design of Industrial chimneys using FE software STAADPRO has been done[9] elsewhere.

Elevated water tanks are nowadays constructed on shaft type of staging system for better architectural appearance and ease of construction. The shaft and the RC chimney both have comparable structural configuration. Thus the shaft may be thought to be a chimney of moderate height which is surmounted with a heavy load which varies with tank full and tank empty condition. But essentially there is variability in structural configuration due to distribution of mass and lateral stiffness along the height of the structures under study. Hence natural period of the structural system is also varied and it falls in the different range of the design spectra.

Thus a careful comparative study in the lateral seismic behaviour of this class of structures based on the available Indian earthquake codes of practice may effectively reveal the range of seismic forces wherein this particular group of structures may be sensitive.

Structural modeling and analytical approach:- Housner[1] proposed a two degree of freedom model where elevated water tank with its liquid content has been modeled as a two degree of freedom system. These types of tanks are categorized under “inverted pendulum” class of structure. When the surmounted tank filled with water is subjected to seismic shaking, hydrodynamic pressure develops. Broadly the hydrodynamic pressure may be classified in two categories (i) Impulsive pressure and (ii) Convective pressure respectively. The portion of the liquid in the inner part of the tanks acts with the body of the tank walls and creates the impulsive pressure. The other part of the liquid which is near the liquid surface exhibits a sloshing motion. The oscillatory motion develops convective pressure on the walls and base of the tank. The two classifications of hydro-dynamic pressures have been represented by a simple mechanical analogy which is represented in the Fig. 1 (a) - (d). The impulsive pressure is represented as a liquid mass rigidly fixed to the walls of the tank by rigid links as impulsive mass m_i and the convective pressure is represented by mass m_c attached with a convective spring to the impulsive mass of stiffness say K_C. For elevated water tanks the mass of the staging system is also to be taken into consideration as m_S. As per IS: 1893-1984[5] vide clause no.5.2.4 l/3rd of the staging mass should act together with the weight of the full tank container. The mass m_i is attached to the base of the staging system via a vertical member of stiffness that of the staging system. The expressions of m_i, m_c and K_c are given below[10].

$$m_i = \frac{\tan h\left(\frac{1.7R}{h}\right)}{\frac{1.7R}{h}} \tag{1}$$

$$m_c = 0.71m\frac{\tan h\left(\frac{1.8h}{R}\right)}{\frac{1.8h}{R}} \tag{2}$$

$$K_c = 4.75m_C^2\frac{gh}{mR^2} \tag{3}$$

Impulsive and convective masses are located at a distance h_i and h_c respectively from the bottom of the tank container, the expressions for which are as follows

$$h_i = \frac{3}{8}h\left\{1+\frac{4}{3}\left(\frac{m}{m_i}-1\right)\right\} \tag{4}$$

$$h_C = h\left\{1-0.21\frac{m}{m_C}\left(\frac{R}{H}\right)^2+1.1\frac{R}{h}\sqrt{(0.15\left(\frac{Rm}{hm_C}\right)^2-1)}\right\} \tag{5}$$

The time period for the impulsive mode of vibration is given by

$$T_0 = 2\,\pi(\sqrt{(m_i+m_s)/K_s}) \tag{6}$$

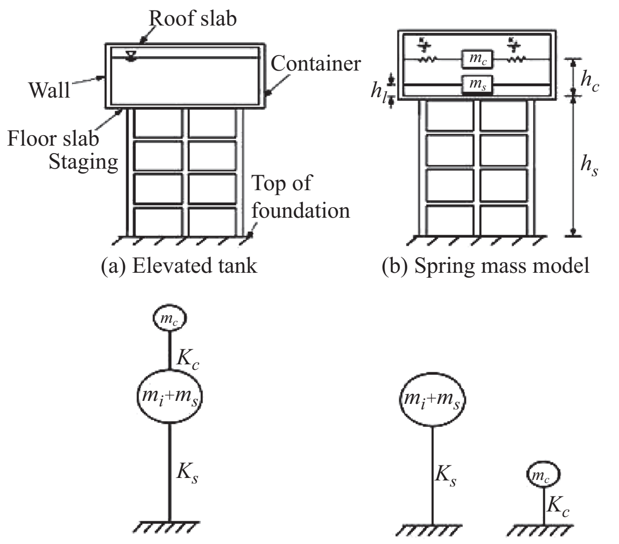


Fig. 1 Two mass idealization of elevated water tank[11]

Time period should be calculated for tank full and tank empty condition of the water tank.

In case of the convective mode of vibration the time period is

$$T_c = 2\pi(\sqrt{(m_c)} / K_c) \quad (7)$$

Analysis due to water sloshing induced impact on overhead liquid storage structures has been recently done by researchers[12] elsewhere.

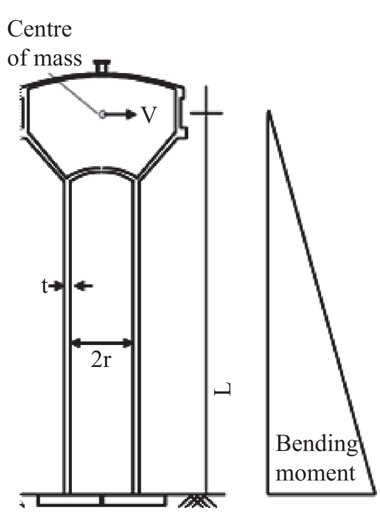


Fig. 2 BMD of elevated water tank on shaft[13]

The behaviour of the shaft staging system of the elevated tank under lateral earthquake force is like a flexural beam. Damage surveys have also revealed that the shaft staging system mainly fails by circumferential cracking near the base by tension flexure mode[13]. Researchers[14] have insisted upon modeling the shaft as a cantilever beam attached at the base (Fig. 2).

Thus Lateral stiffness of the shaft type staging

$$K_s = 3EI / l^3 \quad (8)$$

In case of annular section we have

$$I = \pi(D_1^4 - D_2^4) / 64$$

where D_1 and D_2 are the outside and the inside diameter of the annular shaft respectively.

The natural period for the SDOF model as suggested by IS: 1893-1984 vide clause no.5.2.3 is given by the formula

$$T = 2\pi\sqrt{(\Delta/g)} \quad (9)$$

where Δ= The static horizontal deflection at the top of the tank under a static horizontal force equal to a weight W acting at the centre of gravity of the tank.

The horizontal seismic force as per the IS: 1893-1984[5] is given by $a_h W$

which is given by

$$a_h = \beta I F o\, Sa/g \quad (10)$$

Natural period of the SDOF model should be assessed for tank full and tank empty condition.

However from the recent version of the Indian seismic code IS: 1893-2002 part-(l)[15] we have that design seismic base shear as

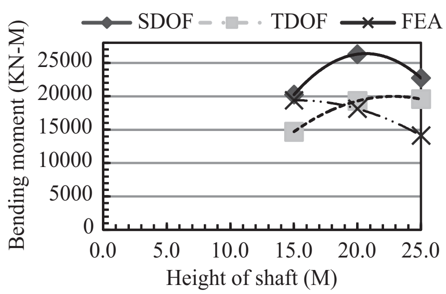
$$V_B = A_h W \quad (11)$$

Where horizontal Seismic co-efficient is given by

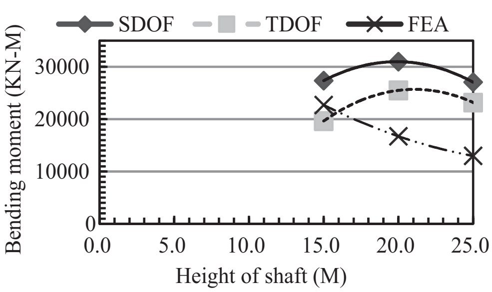
$$A_h = Z/2 \times Sa/g \times I/R \quad (12)$$

The importance factor selected I=1.5 which as per IS: 1893 part (l)-2002[15] is for important structures, which should remain in functional condition after an earthquake such as hospital, schools etc. Elevated water tanks being a lifeline facility and should remain in functional condition to ensure water supply by gravity during the power cut period has been classified under this class of importance factor.

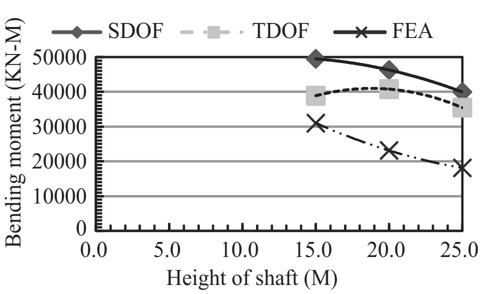
The parameter response reduction factor (R) represents the ratio of maximum seismic force on a structure during specified ground motion if it were to remain elastic to design seismic force. Thus actually (R) is used to reduce seismic force to obtain design force. It has been found[16] that the reduction is dependent on over strength, redundancy and ductility and it is identified that shaft type elevated reservoir have comparatively lower redundancy, than elevated water tanks with frame type of staging which is a highly redundant space frame structure. Seismic design codes have specified different values of Response reduction factors for elevated water tanks like structure. However there is no specific prediction regarding shaft type of staging so lower bound value has been suggested in view the lower redundancy value of the structure. In this connection various international codes are available regarding seismic design of water tanks. Works on comparative discussions on such codes are available in literature[16]. The IITK- GSDMA version of earthquake resistant design of water tanks[11], has suggested to adopt two mass model of the elevated water tank[1]. In the above method the two mass idealized model of the elevated water tank is represented as an equivalent uncoupled system[17]. Both of this system now becomes equivalent SDOF system, which are shown in Fig. 1. However such uncoupling is permitted when the period, for the impulsive and the convective modes differ by at least 2.5 Sec. IITK-GSDMA guidelines, for design of shafts for elevated water tanks recommended value of response reduction factor of Tank supported on RC shaft with two curtains of reinforcement, each having horizontal and vertical reinforcement as 1.8. Again for Tank supported on RC frame and the frame does not conform to ductile detailing, i.e., Ordinary Moment Resisting Frame (OMRF) response reduction factor is 1.8, for frames conforming to ductile detailing, i.e., Special Moment Resisting Frame (SMRF) the response



(a) Tank capacity 250 cum at tank full condition

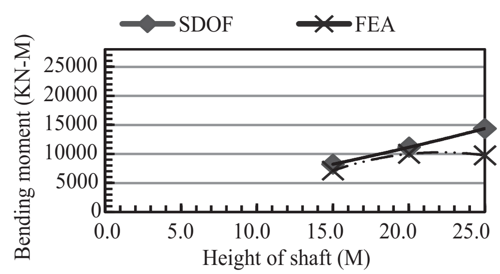


(b) Tank capacity 300 cum at tank full condition

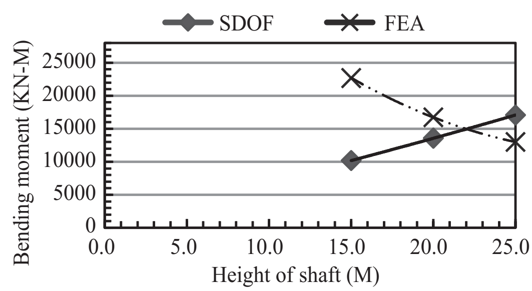


(c) Tank capacity 600 cum at tank full condition

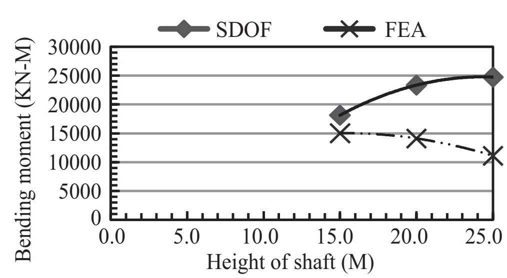
Fig. 3 (a), (b), (c) showing variation of BM at the base of shaft staging due to seismic base shear for elevated water tank full condition with variation in staging height considering IS 1893-2002[15] seismic loading



(a) Tank capacity 250 cum at tank empty condition

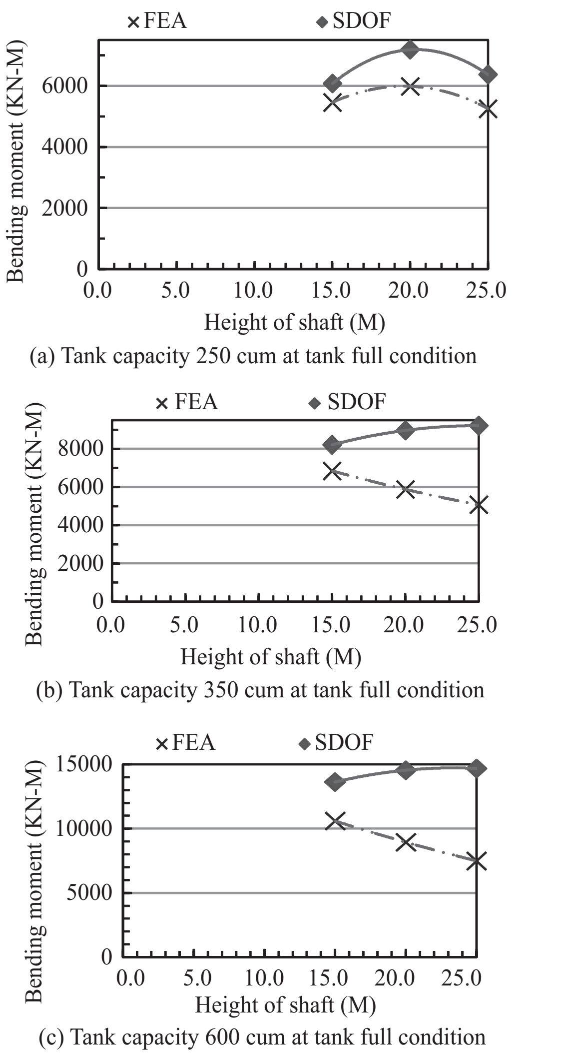


(b) Tank capacity 350 cum at tank empty condition



(c) Tank capacity 600 cum at tank empty condition

Fig. 4 (a), (b), (c) showing variation of BM at the base of shaft staging due to seismic base shear for elevated water tank empty condition with variation in staging height considering IS 1893-2002[15] seismic loading reduction factor is 2.5. The Indian seismic code recommends response spectrum analysis of a SDOF model as a cantilever fixed at the base. Stiffness of the shaft staging is relatively higher so it is expected that SDOF model as per IS: 1893-1984[5] version shall yield a relatively short period system. Such short period systems, generally pertains to acceleration sensitive region of the response spectra. Also IS: 1893-1984 neglects the convective component of hydrodynamic pressure. Again the Indian standard for staging system of elevated water tanks IS: 11682-1985[18] recommends the following for calculation of seismic forces "wherever required the effect of surge due to wave formation due to water should be considered" which is mutually contradictory. In the acceleration sensitive region of the spectrum lengthening of fundamental period of the structure may sometime cause increase in response, however in many other cases response may also reduce if the period lengthening is very large. Some researchers have suggested to adopt multi-degree of freedom model for seismic analysis of shaft supported elevated water tanks, where the contributions of the various higher modes of vibration has been taken into consideration. Dynamic analysis using response spectrum analysis has been assorted to and the contribution of various modes has been combined with SRSS method. Researchers[15]

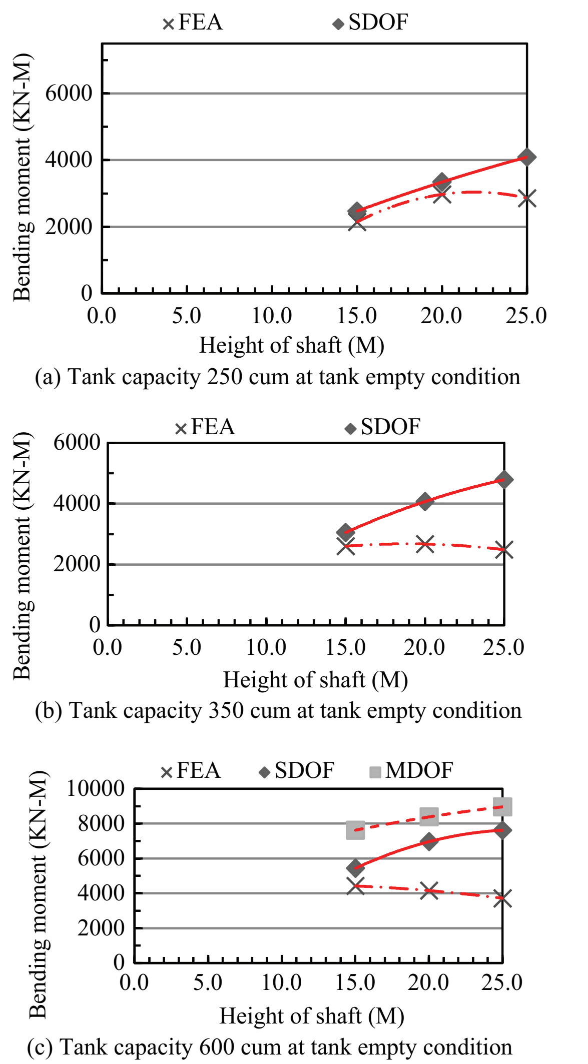


(a) Tank capacity 250 cum at tank full condition

(b) Tank capacity 350 cum at tank full condition

(c) Tank capacity 600 cum at tank full condition

Fig. 5 (a), (b), (c) showing variation of BM at the base of shaft staging due to seismic base shear for elevated water tank full condition with variation in staging height considering IS 1893-1984[5] seismic loading.



(a) Tank capacity 250 cum at tank empty condition

(b) Tank capacity 350 cum at tank empty condition

(c) Tank capacity 600 cum at tank empty condition

Fig. 6 (a), (b), (c) showing variation of BM at the base of shaft staging due to seismic base shear for elevated water tank empty condition with variation in staging height considering IS 1893-1984[5] seismic loading.

has also studied failure of shaft supported RC elevated water tanks during Manjil –Roudbar earthquake in 1990 Iran. They have studied the behaviour of water towers using FE method. Thus it appears that structural models of elevated water tanks supported on shaft should be studied through SDOF, TDOF and FEM models to get a comprehensive idea about the seismic behaviour and vulnerability of such structures.

Detailed studies on chimney designs against lateral forces such as wind and earthquake has been depicted elsewhere[19]. The modeling for the RC chimney for assessing the behavior under seismic forces shall be done as per provisions of the empirical formulae in the Indian earthquake code and also in F.E software STAADPRO. FE model shall be developed for dynamic analysis using response spectra, as has been done in the case of elevated water tanks. In each case as in the case of elevated tanks and chimney while studying the structures using response spectrum methods sufficient number of modes of vibration shall be considered to ensure atleast 90% mass participation.

Analysis shall be done as per provisions of IS 1893-2005 (Part-4)[7] the calculation of the design seismic coefficient shall be done as per above mentioned Eqs. (11) and (12) respectively. As per provisions of IS 1893-2005 (Part-4) the response reduction factor for RC chimney has been considered as 3.

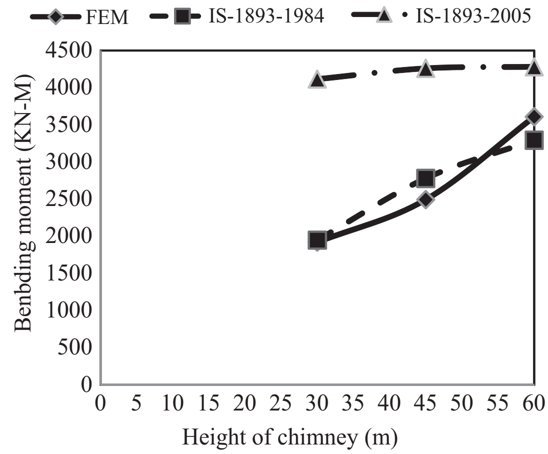


Fig. 7 Variation of BM at the base of Chimney due to seismic base shear for elevated water tank with variation in staging height considering both versions of IS 1893 seismic loading

The empirical formulae, for time period of chimney structure as given in IS 1893-1984 based on Housner's method is reproduced below:

$$\text{Time period, } T = C_T \sqrt{(W_t\, h/E_s\, Ag)} \qquad (13)$$

TABLE 1

SECTIONAL DIMENSIONS OF THE RC ELEVATED WATER TANKS OF THREE DIFFERENT CAPACITIES ON SHAFT TYPE OF STAGING

Component details		Component details		Component details	
Capacity of tank = 250 cum		Capacity of tank = 350 cum		Capacity of tank = 600 cum	
Shaft type staging		Shaft type staging		Shaft type staging	
Top dome	100 mm thick	Top dome	100 mm thick	Top dome	100 mm thick
Top ring beam	300 mm × 200 mm	Top ring beam	300 mm × 200 mm	Top ring beam	300 mm × 250 mm
Cylindrical wall	200 mm thick	Cylindrical wall	200 mm thick	Cylindrical wall	300 mm thick
Bottom ring beam	500 mm × 300 mm	Bottom ring beam	500 mm × 350 mm	Bottom ring beam	500 mm × 400 mm
Circular ring beam	400 mm × 300 mm	Circular ring beam	400 mm × 300 mm	Circular ring beam	500 mm × 500 mm
Bottom dome	150 mm thick	Bottom dome	150 mm thick	Bottom dome	200 mm thick
Conical dome	250 mm thick	Conical dome	250 mm thick	Conical dome	300 mm thick
Shaft wall	150 mm thick	Shaft wall	150 mm thick	Shaft wall	150 mm thick

TABLE 2

SECTIONAL DIMENSIONS OF THE RC CHIMNEY OF THREE DIFFERENT HEIGHTS

Height of chimney (m)	Inner top diameter (m)	Inner bottom diameter (m)	Shell thickness (mm)
30	2.0	3.0	0.3
45	2.0	3.0	0.3
60	2.0	3.0	0.3

The value of C_T is controlled against a quantity $k = h/r_e$. The variation in the values of C_T along with ratio k is given in Table 6 of IS 1893-1984[5]. An inspection of the table clearly indicates that as k increases the values of C_T also increases. Thus time period of the Chimney structure increases with the increase in the slenderness ratio of the chimney. The design shear force V for the chimney structures at a distance x from the top may be calculated by the formula:

$$V = C_v \alpha_h W_t \left[\frac{5}{3}\frac{x}{h} - \frac{2}{3}\left(\frac{x}{h}\right)^2 \right] \tag{14}$$

The design BM M at a distance x from the top shall be calculated from the formulae as below,

$$M = \alpha_h \; W_t \; h \left[0.6\left(\frac{x}{h}\right)^{0.5} + 0.4\left(\frac{x}{h}\right)^4 \right] \tag{15}$$

However the new version of the IS code IS 1893-2005 (part-4) has given different expressions of shear and BM for chimney as per the works of, Arya and Paul[6].

The general expression of design shear force V, is given by,

$$V = C_v A_h W_t D_v \tag{16}$$

and bending moment M is given by the general expression,

$$M = A_h W_t h D_m \tag{17}$$

The distribution of shear force and bending moment in the chimney is given in Table 10 of IS 1893-2005 (part-4)[7].

The values of the coefficients D_m and D_v are derived from the expressions given in Table 11 of IS 1893-2005 (part-4)[7], the values of the coefficients are dependent on the soil and foundation condition and are available in the current version of the code.

TABLE 3

SHOWING VARIATION IN TIME PERIOD FOR 250CUM CAPACITY OF TANK WITH BOTH TYPES OF STAGING SYSTEM, HEIGHT OF STAGING HAS BEEN CHANGED FROM 15m THROUGH 25m

Capacity of tank (cum)	Staging type	Height of staging (m)	Tank condition	Time period(sec)					
				SDOF model	TDOF model		FEA model		
					Impulsive mode	Convective mode	Mode 1	Mode 2	Mode 3
250	Shaft	15	Tank full	0.261	0.224	3.137	0.405	0.055	0.038
			Tank empty	0.167	0.166	-	0.222	0.058	0.040
		20	Tank full	0.406	0.349	3.137	0.568	0.066	0.050
			Tank empty	0.265	0.264	-	0.320	0.069	0.050
		25	Tank full	0.574	0.496	3.137	0.751	0.077	0.064
			Tank empty	0.381	0.380	-	0.438	0.080	0.063

TABLE 4

SHOWING VARIATION IN TIME PERIOD FOR 350CUM CAPACITY OF TANK WITH BOTH TYPES OF STAGING SYSTEM, HEIGHT OF STAGING HAS BEEN CHANGED FROM 15m THROUGH 25m

Capacity of tank (cum)	Staging type	Height of staging (m)	Tank condition	Time period(sec)					
				SDOF model	TDOF model		FEA model		
					Impulsive mode	Convective mode	Mode 1	Mode 2	Mode 3
350	Shaft	15	Tank full	0.293	0.249	3.334	0.468	0.064	0.040
			Tank empty	0.179	0.178	-	0.245	0.067	0.045
		20	Tank full	0.454	0.387	3.334	0.650	0.076	0.052
			Tank empty	0.282	0.281	-	0.348	0.079	0.054
		25	Tank full	0.639	0.548	3.334	0.855	0.087	0.066
			Tank empty	0.404	0.403	-	0.469	0.090	0.654

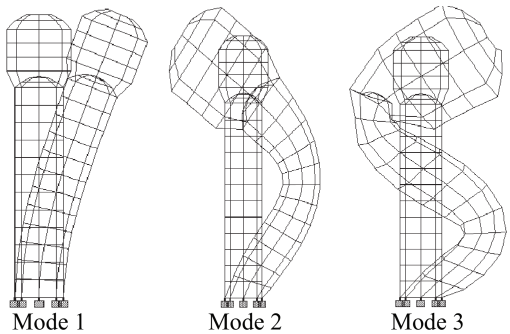


Fig. 8 Typical mode shapes of first three modes for elevated tank with FE model, modelled with shell elements in STAADPRO.

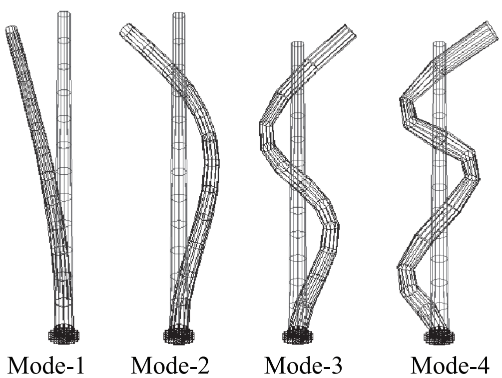


Fig. 9 Typical mode shapes of first four modes for chimney with FE model

These expressions for distribution of BM and shear force in chimneys[6] are indicated above. It is found that the distribution curves obtained using the expressions below are much lower than those obtained using Housner's expressions. For hard soil shear wave velocity was assumed as V_s = 600m/s whereas 150m/s for soft soil and pile foundation. It is found that the SF values are over estimated by Housner's expression between 0.2h and 0.95h height of the chimney shaft.

The current version of the IS code indicates that Reinforced Concrete Chimneys should be designed considering importance factor I=1.5 and response reduction factor R=3.0. The design seismic coefficient should be calculated using Eq. (12).

Structures studied

Three nos. RC elevated water tanks of Intz type construction has been studied in this paper. The capacity of the tank container varies from 250 cum, 350 cum and 600 cum. It is assumed that the tanks are constructed of M30 grade concrete to ensure water tightness and Fe 415 grade steel has been used. It is assumed that the tanks are constructed on shaft type of staging. The elevated water tanks are located in seismic Zone-IV, of 1984 and 2002 version of IS 1893. The heights of the staging are varied through 15m, 20m, and 25m respectively for all the tanks under study. SDOF model as suggested in the IS 1893-1984 version shall be studied. Simultaneously two degree freedom model as proposed by Housner and adopted by IITK-GSDMA guideline shall also be studied. For shaft type of staging the lateral stiffness of the shaft has been modeled as cantilever, $K_{stg} = 3EI/l^3$. The shaft staging elements are conceived as springs. The tanks are assumed to be founded on hard rock, for the purpose of the present study.

Three numbers RC chimney structures of 30m, 45m and 60m height (low to moderate height has been studied, to keep parity between the natural period of

TABLE 5

SHOWING VARIATION IN TIME PERIOD FOR 600 CUM CAPACITY OF TANK WITH BOTH TYPES OF STAGING SYSTEM, HEIGHT OF STAGING HAS BEEN CHANGED FROM 15m THROUGH 25m

Capacity of tank (cum)	Staging type	Height of staging (m)	Tank condition	Time period(sec)					
				SDOF model	TDOF model		FEA model		
					Impulsive mode	Convective mode	Mode 1	Mode 2	Mode 3
600	Shaft	15	Tank full	0.349	0.314	3.365	0.613	0.084	0.047
			Tank empty	0.211	0.211	-	0.324	0.087	0.057
		20	Tank full	0.538	0.484	3.365	0.836	0.098	0.059
			Tank empty	0.329	0.329	-	0.446	0.101	0.066
		25	Tank full	0.754	0.680	3.365	1.083	0.111	0.073
			Tank empty	0.467	0.466	-	0.586	0.114	0.077

TABLE 6 VARIATION IN TIME PERIOD FOR THREE NOS. CHIMNEY OF DIFFERENT HEIGHT 30m, 45m AND 60m							
Height of chimney (m)	Time period (sec)					Mass participation of modes	Percentage of mode participation for FE model
	Empirical formula of IS 1893	FE Model					
		Mode 1	Mode 2	Mode 3	Mode 4		
30	0.4	0.4583	0.09081	0.03654	0.03404	5	93.821
45	0.87	1.02617	0.19766	0.07654	0.05039	5	92.548
60	1.53	1.82128	0.34722	0.1324	0.06982	4	91.941

elevated water tanks and chimney structures) is also studied over here. The detailed structural parameter and sectional dimensions of the chimneys and also sectional dimensions of the tanks of three different capacities and staging systems are tabulated (Tables 1 and 2). It is also assumed that the chimneys are constructed of M30 grade concrete and with Fe 415 grade steel. Beside this tabular representation of fundamental time period of the various tanks with different height of the staging and chimneys of different height are given for all the various analytical models. The variation of BM at the base for all the three tank and chimney models, which the structure shall be subjected to due to the application of seismic shear, shall also be represented in a graphical form against height of the structure. The variation in time period of elevated water tanks on shaft of different capacity and different staging height are reproduced in Tables 3-5 and variation of time period for chimney is given in Table 6. FEM analysis has being done in STAADPRO software, the elevated water tank on shaft and chimney both has been modeled using axi-symmetric shell elements in STAADPRO. Whereas SDOF and TDOF models for water tank are studied with long hand calculations. The results are graphically represented showing variation in BM at the base of the tank and chimney with variation in height of the tank staging and chimney as given in figures (Figs. 3-7) respectively for tank full, tank empty condition and for Chimneys of all the three heights are considered. For Tank all the SDOF, TDOF, and FEA models are studied and for Chimney modeling has been done with respect to empirical formula as given in IS 1893 - 1984 and 2005 also FEM model has been made. Mode shapes for FM model analysis both for elevated water tanks and chimney model are shown in Figs. 8 and 9 respectively.

DISCUSSIONS

It is generally observed that for shaft type of staging system the period of the system increases with increase in height of the staging system and also with the increase in capacity of the tank container. The time period in tank full condition is more than that at the tank empty condition. The time period of the chimney increases with the height of the chimney. From the limited scope of study following discussions may be elaborated below.

- The shaft type staging system is a more rigid period system in comparison to the chimney. The shaft staging is a relatively shorter period system; however the period of the structural system lengthens with increase in vertical height of the shaft. Similarly the time period of the chimney increases with the increase in height of the chimney.
- As the shaft staging appears to be more rigid, the natural period of the system is in the acceleration sensitive zone of the response spectrum. A slight variation in the fundamental period may widely affect the design seismic coefficient values.
- As the tank container increases in capacity the fundamental period of the system also increases.
- With increase in height and mass of the tank container the fundamental period also increases. For longer period system, the seismic behavior is governed by the displacement sensitive character. Thus with lateral thrust of the seismic force there is significant lateral displacement inducing P-Δ effect.
- It has been found from the graphical representation of elevated water tanks and chimney represents that the response spectra of IS 1893-1984 version generates relatively lesser value of design seismic coefficient in comparison to that what is obtained

from IS 1893-2002 version.

- However of all the analytical model studied it is found from graphs that the SDOF model adopting 2002 codal provisions are generally on the higher side for all tank capacities in tank full condition. In most of the cases empty conditions yields lesser BM at the tank base than the tank full condition. As the height of the tank increases bending moment also increases at the tank base due to greater lever arm of the over turning couple.
- Seismic load induced bending moment at the base of the elevated water tank on shaft is relatively much higher than that of Chimney for comparable time period. The reason for same may be that seismic base shear is much dependent on the seismic weight of the structure concerned. As the weight of the tank container with liquid is lumped at the top the seismic weight of the elevated water tank is on the higher side. Also being a relatively rigid system the ordinate of design spectra is relatively higher to that of slender chimney.
- The empirical method for chimney given in the IS code IS 1893-2005 (part 4) yields a higher value of BM than IS 1893-1984 version and FEM analysis.
- In elevated water tanks first three modes of vibration yields more than 90% mass participation. Whereas for achieving 90% mass participation in case of Chimney at least 5 to 6 modes of vibration must be studied. Thus analysis by empirical method for chimneys are valid only for low height chimneys as for more slender chimneys the contribution of the higher modes become more significant. So modal analysis using FE software is a must for proper analysis of slender chimney structures.
- Current version of the Indian earthquake code IS 1893 (part-1)-2016[20], has the same seismic Zone factors as the 2002 version. The design spectra is also essentially the same as 2002 version except the 2016 version is defined upto a natural period of 6s, hence it is valid even for more slender structures of greater heights. But elevated water tanks on shaft staging is relatively shorter period system, where natural period of vibration seldom crosses 1s. Hence S_a/g values are same for both 2002 and 2016 version for hard rock type foundation soil. Thus design horizontal co-efficient calculated by both the codal versions would not affect the base shear values. The other factors for calculation of the horizontal seismic co-efficient values, remains essentially the same for elevated water tank structures.

CONCLUSION

The results obtained from such limited study though not exhaustive but may be considered as indicative of the following conclusions.

Elevated water tank on shaft is a more rigid structural system in comparison to chimney. Within comparable range of time period the BM at the base of the elevated water tank on shaft is much higher in comparison to Chimney structure. This is because the elevated water tank in the tank full condition has much higher seismic weight in comparison to chimney thus seismic base shear is more. However SDOF modeling as per provision of IS 1893[14] yields higher values of BM at the base of the elevated water tank out of all the models i.e. SDOF, TDOF and FE Model. Finite element model for chimney yields much lower BM at the base of the chimney shaft than in comparison to empirical formula as per IS 1893(part 4) 2005. It is hereby concluded that seismic design is more critical for top heavy elevated water tanks as seismic force induced moments are more prominent in case of the structure. Whereas for chimney check should be made between wind and seismic forces to evaluate the more critical force. The empirical formula for chimney yields conservative results. Modal analysis or finite element analysis considering sufficient nos. of modes are essential for proper evaluation of forces in chimneys. Under the effect of the vertical load from tank in tank full condition, membrane stresses are induced in the shaft which is a thin shell. Thin shell shaft are very susceptible to buckling due to vertical load from tank container and the retained water. Such study has been done previously elsewhere[21] wherein check against buckling of shaft of elevated water tank has been studied. Hence broadly in this paper we see that as structural composition changes the relative seismic behavior of the structure also changes significantly.

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NOTATION

α_h	=	Design seismic coefficient determined as per provision of IS 1893-1984.
β	=	A coefficient depending upon the soil-foundation system
A	=	Area of cross section at the base of the structural shell
C_T	=	Coefficient depending upon the slenderness ratio of the Chimney structure
C_v	=	Coefficient which is dependent on the slenderness ratio k as indicated
D_v	=	Distribution factor for shear force at a distance x from top
D_m	=	Distribution factor for bending moment at a distance x from top
E	=	Modulus of elasticity
E_s	=	Modulus of elasticity of the structural shell
F_0	=	Seismic zone factor for average acceleration spectra
I	=	Importance factor
I	=	Moment of inertia of the section
I	=	A factor dependent upon the importance of the structure = 1.5 for elevated water tanks
K_c	=	Convective stiffness
R	=	Response reduction factor
S_a/g	=	Average acceleration co-efficient as read from Fig.2 of the code for appropriate natural period and damping of the structure
W_t	=	Total weight of the structure at the base of the chimney
W_t	=	Total weight of the chimney structure
Z	=	Zone factor
a_h	=	Design horizontal seismic co-efficient
g	=	Acceleration due to gravity.
h	=	Height of the structure above the base.
h_c	=	Height of impulsive mass above tank bottom, respectively
h_i	=	Height of impulsive mass above tank bottom
l	=	Length of the shaft
m_i	=	Impulsive mass
m_c	=	Convective mass
r_e	=	Radius of gyration of the structural shell at the base section

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