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REVIEW OF BUCKLING CAPACITY OF REINFORCED CONCRETE THIN SHELL SHAFT STAGING OF ELEVATED WATER TANKS.

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Abstract- Reinforced concrete elevated water tanks supported on thin shell shaft staging are subjected to buckling under vertical compression from axial loads due to tank container and retained water. Buckling is further aggravated under the action of lateral forces of earthquakes. Existing codes of practise recommends for checking the shaft cross-section against buckling, to prevent crippling of the shaft staging in buckling. In this paper a critical study has been made on the design provisions of R.C shaft staging of elevated water tanks against buckling induced due to combined effect of vertical and lateral seismic loads by varying simultaneously capacity of the tank and thickness of the shaft staging.

Keywords-Elevated water tanks, shaft staging, buckling failure, thin shell, buckling strength.

I. INTRODUCTION

In the present scenario, Intze or conical type R.C elevated water tanks supported on circular shaft type of staging system are widely constructed due to swiftness in construction of the staging and pleasing architectural appearance. Such structures in practise are built by contractor firm on the basis of turnkey/lump sum tenders. Although there is a clause for peer review of designs submitted by the contractors by universities and institutes but generally such designs are done with a view for economy. It has been observed that many elevated water tanks on shaft are very prone to collapse and several such structures have collapsed during the Chilean (1960) [1] and Bhuj (2001)[2] earthquakes. At other locations shaft failure has been observed even during construction phase. Failure of R.C shaft staging may be attributed to the following factors by authors elsewhere[3]:-

(i) Top heaviness of the elevated water tank structures in tank full condition aggravates tendency of buckling of the shaft.
(ii) Flexural stresses due to lateral loads such as wind and earthquake in combination with existing axial load of the tank container and water loads aggravates buckling of shaft. Elevated water tanks being structurally inverted pendulum structure under lateral load they tend to overturn. Circumferential flexural tension is developed at the base of shaft which may further aggravate buckling.
(iii) Heterogeneity of R.C.C during construction may also be a causative agent of buckling of shaft due to variation of material strength in different direction.
(iv) Constructional defect, honey combing, non-concentricity and ellipticity of shaft during construction may aggravate tendency of shaft buckling.
(v) Opening in the shaft staging for entrance door and ventilators causes stress concentration increasing tendency of shaft buckling.

In this paper it shall be studied that what variation is observed in the buckling strength of the shaft staging, simultaneously changing the capacity of tank, thickness of shaft staging and internal diameter of the shaft support, so an optimum thickness for the shaft staging system may be arrived at for elevated water tanks of different capacities supported on shaft under the influence direct and bending stress due vertical load and lateral seismic forces.

II. BEHAVIOUR OF THIN SHELLS UNDER AXIAL COMPRESSION

If a Cylindrical shell is uniformly compressed in axial direction it causes buckling of the shell. Theoretically[4] the critical stress at which buckling of axially compressed thin cylinder takes place is given by the expression

$$f_{cr} = \frac{1}{\sqrt{(3(1-\vartheta^2)}} X \,\frac{E\,t}{R}, \qquad \text{(i)}$$

t= Shell thickness of shaft,

R= Radius of the shaft shell,

ϑ= poisson's ratio,

E= Modulus of elasticity of concrete.

Experiments on long reinforced concrete shells subjected to axial compression indicates that the critical stress for reinforced concrete shells may be taken as,

$$f_{cr}= 0.20\, X \frac{E\, t}{R}. \quad \text{(ii)}$$

for shells with Aas Jackobsen's Parameter in the range $\rho < 7$ & $\kappa < 0.12$.

Permissible buckling stress[5] in cylindrical shell is given as,

$$f_{ac}= \frac{0.25\, X\, f_{ck}}{1+\frac{f_{ck}}{f_{cr}}} \quad \text{(iii)}$$

f_{ck} = Characteristic strength of concrete at 28 days.

The above mentioned formula shall be used for checking the safety of thin shells against buckling.
An inspection of the expression indicates that the critical stress for buckling of axially loaded thin shells depends on the ratio of shell thickness to the diameter of the thin shell.
Permissible buckling stress f_{ac} is also dependent on the grade of R.C used in casting the annular shaft. The current version of the Indian Earthquake code for design of liquid retaining tanks IS 1893 part-2 (2014) [6] indicates under clause no. 6.2 that the safety of shaft type of staging of elevated water tank against buckling should be ensured.
The BIS code IS-11682[7] recommends that the minimum thickness of concrete shell for shaft staging shall 150mm. The minimum shell thickness is chosen as 150mm as this is the shell thickness which permits the slip form to be moved without causing tears in the concrete[8]. However with increase in diameter of the shaft staging beyond 6000mm, the codal, provisions of the thickness of the shaft in mm is given by the formula,

$$t = 150 + \frac{D-6000}{120} \ .$$

The requirement for thickness of the shaft staging of the R.C elevated water tank has been adopted similar to that of R.C concrete chimney as per BIS code IS 4998[9]. The shaft staging and R.C chimney both have comparable structural configuration. The shaft may be thought to be structurally like a chimney of low to moderate height, but surmounted with a heavy load of tank retaining liquid. Whereas chimney is very slender cantilever structure fixed at the base, which functions as a smoke stack, it generally has a longer fundamental period. While elevated water tank on shaft staging is a relatively short period system and attracts more seismic forces. Naturally the design seismic co-efficient of elevated water tank on shaft staging is generally on higher side in comparison to a chimney. Higher lateral forces, induces in the shaft greater seismic shear, causing higher B.M at the base of the shaft staging.

III. STRUCTURE STUDIED

In a pursuit to study the buckling behaviour of shaft staging of R.C elevated water, Intze type R.C elevated water tanks of seven different capacities generally on the higher side are studied. The capacities of the tanks studied are varied from 700 CuM to 3000 CuM capacity. The elevated tanks are supported on R.C annular shaft type of staging and founded on annular raft type of foundation. It is assumed that the underlying soil is hard rock type of foundation soil and located in Zone-IV seismic zone of the Indian earthquake code. As per codal requirement the water retaining container of the water tank is to be constructed with M30 grade of concrete whereas the shaft support may be constructed of M20 grade of concrete. It is also assumed for simplicity of calculation that the shaft has no opening. By varying the capacity of the tank the vertical load on the shaft has been gradually increased as well the seismic behaviour has been studied by modelling the tank as a two mass model (as recommended by G.W Housner, for tank full condition below free board) considering the retained water to vibrate in two different modes of vibration such as the impulsive mass and convective mass as per requirements of the present Indian seismic code. Elevated water tank with its liquid content is 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 (see fig.1). For calculation of the design seismic forces response spectrum method has been adopted. Seismic base shear has been calculated using the formula,
$V= A_h\, X\, W$, where A_h = design seismic coefficient, W=Seismic weight, design seismic coefficient is defined as, $A_h = \frac{Z\, I\, S_a}{2R\, g}$, again Z= Seismic Zone factor (considering seismic Zone IV), I = importance factor (taken as 1.5), R= response reduction factor (which is taken as 2.5), S_a/g is obtained from the design spectra of the code IS 1893-2016 (part-1)[10], as per the impulsive and the convective period (also refer [6]) of the water tank both in tank empty and tank full conditions respectively.
The time period for the impulsive mode of vibration is given by

$$T_i = 2\pi\left(\sqrt{(m_i + m_s)/K_s}\right) \quad \text{(iv)}$$

Where m_i + m_s = impulsive mass including portion of the liquid affected in impulsive mode and structural mass of the tank container and 1/3rd mass of the shaft staging system lumped together.
K_s = Lateral stiffness of the Shaft staging = $\frac{3EI}{l^3}$,
I= Moment of Inertia of annular shaft, E= $5000\sqrt{f_{ck}}$, where $f_{ck} = 20$ N/mm^2,
l= staging height = 21.5m (20 m height of staging and 1.5 m depth of foundation).
Time period should be calculated for tank full and tank empty condition of the water tank.
In case of the convective mode of vibration for circular tank the time period is

$$T_c = C_c\sqrt{\frac{D}{g}} \text{ ,} \qquad \text{(v)}$$

where C_c =co-efficient of time period for convective mode, D= inner diameter of the tank
However for the purpose of the present paper, only the results for the tank full conditions have been considered, as in the tank full condition the tendency of shaft buckling under the effect of vertical loads are the most significant. R.C shaft being a thin shell the permissible buckling stress in the thin shell is checked with respect to the BIS code for shells IS 2210. The expression for permissible buckling stress is already reproduced in equation (iii).
The study involves observing the buckling behaviour of the shaft staging, as the capacity of the tank container in increased, with simultaneous variation in the thickness of the shaft wall and also with increase in the diameter of the shaft staging. The other parameters which are varied includes, the ratio of the Depth/ internal dia (H/D) of the tank container. The shaft thickness has been varied three times, once it is taken as 150mm, increased to 200mm and then the shaft thickness has been varied as per the empirical formula given in the BIS code IS 11682 cl no. 8.2.1, the said formula is already mentioned in the previous section 2 of this paper. As the shaft staging is subjected to direct and bending stress due to vertical load and lateral seismic forces, the tendency of shaft buckling is checked with respect to the buckling strength of the shaft. Calculations are based on working stress methods. The representations are made in tabular fashion. Table no.1 gives the data of the various structural portions of the tank container and shaft. While table no.2 represents the stresses in 150 mm thick shaft staging and table 3 & 4 represents the stress conditions in the shaft with 200mm thick shaft and thickness as per IS 11682 codal formula. The stresses developed at the shaft base in buckling under the combined action of vertical load and uniaxial bending due to seismic forces are also checked against permissible stresses given in IS 456 [11]table no.21. as per clause B-2.3 under the action of seismic force permissible stresses are increased by $33\frac{1}{3}$ percent. Check against wind load is not done as elevated water tanks are generally more vulnerable against seismic loads than wind loads.

IV. RESULTS AND DISCUSSION

From critical study of table 2, 3 &4 following trends are observed which are indicated below:-
(i) As the internal diameter of the shaft staging increases, permissible stress in buckling of shaft reduces.
(ii) With increase of shaft thickness permissible stress in buckling increases.
(iii) For all the three cases of shaft thickness, as the value of eccentricity (e) of forces increases the overturning moment increases, the ratio of (e/r) (eccentricity to internal radius of shaft) increases. When e/r is greater than 0.5, tension is induced in shaft section aggravating possibility of the tension crack. If the dia of the shaft staging system is 0.7D or more generally tension shall not be observed in the shaft under the action of lateral bending stress, optimum dimensions of Intze type of tank may be obtained elsewhere[12].
(iv) As the height to dia ratio of the water tank (H/D) increases beyond 0.6 it is found that compressive stress is on the higher side. Tendency of development of tension in shaft cross section increases. The stress values for 1000 CuM capacity water tank may be cited as an example in all the three tables.
(v)From table 2 it is found that with 150 mm thick shaft of M20 grade concrete buckling failure is observed in 1800, 2250 & 2500 CuM capacity water tanks, in tank full condition. Although 1000 CuM capacity water tank in tank full condition has much lesser vertical load but as the diameter of the shaft staging is less the bearing area of the shaft for surmounted tank is also lesser hence the load per unit area is large. Thus buckling strength of the shaft approaches the direct stress due to vertical load for 1000 CuM tank in tank full condition. Failure has been observed with respect to buckling strength for 2500 & 3000 CuM shaft with 200 mm shaft thickness and M20 grade concrete.
(vi) Table 2 shows stress values only upto 2500 CuM capacity water tank as it clearly fails in flexural compression under the influence of seismic force induced B.M. so it is evident that in seismic Zone-IV it is not possible to construct elevated tank on 150mm thick shaft staging of 2500 CuM capacity in M20 grade concrete.
(vii)If the grade of concrete in the shaft staging is increased to M25 grade and the formula for shaft thickness as per IS 11682 is adopted then sufficient safety is obtained against buckling in tank full condition for all the higher capacity water tanks beyond 1500CuM upto 3000 CuM (refer table 5).
(viii) The codal formula basically appears to be a linear interpolation formula which assumes from a practical point of view a minimum thickness of 150mm for a shaft wall of an internal diameter of 6000mm, beyond that the shaft thickness is increased linearly as the diameter increases an additional thickness is added per 120mm increase in shaft diameter beyond 6000mm. The formula is much like a thumb rule based on practical observational of chimney shell thickness.
(ix)Although the formula mostly yield safe design of shaft from buckling point of view but there appears to be no rational approach on arriving at the formula, because the parameter that is load from the tank is totally absent, which mainly aggravates buckling.

(x) It may further be indicated that from the perspective of improving seismic resistance, ductility of elevated water tanks on shaft supports, the IS-1893 (part-2), vide clause no. 8.2.1 has enhanced the minimum thickness requirement for shafts. Upto a shaft dia of 4m, the minimum wall thickness of shaft is 150mm, for dia beyond 4m upto 8m, minimum thickness is given by,

$$t = 150 + \frac{D-4000}{80}\,. \qquad \text{(vi)}$$

Again for shaft dia beyond 8m, minimum shaft thickness is given by,

$$t = 200 + \frac{D-8000}{120}\,. \qquad \text{(vii)}$$

However still there is no rational derivation of the above formulae from first principal, the expressions are mostly from experience of the structural designer.

(xi) A rational approach for approximating the initial thickness of the shaft staging is indicated.

Dia of tank= D (say), the dia of shaft staging = 0.7D (approx., or any other suitable value), weight of tank, liquid and shaft = W (say). From observation of tabulated data vide table 2, 3 &4, it is found that an average direct stress of, $\boldsymbol{\sigma}$ = 4N/mm^2 may be safely allowed (please refer [12]) in the shaft staging from the criteria of vertical load in tank full condition so that no crippling may occur in the shaft.

Thus shaft thickness $t_{initial} = \frac{\boldsymbol{W}}{\pi\, XDX\sigma}$, for lateral load such as earthquake, the shaft staging is subjected to bending stress in addition to direct stress. For additional thickness requirement from bending stress criteria increase, thickness of shaft wall by 15% for seismic zone II, 20% for seismic Zone III, 25% for seismic Zone IV and 30% for seismic Zone V (as severity of seismic forces increase from Zone II to Zone V). For each seismic Zone increase the overall thickness thus obtained by 5% to accommodate for stress concentration due to opening kept in the shaft wall for doors and ventilation. Check if the shaft thickness so arrived is at least150mm if D<= 4m, greater than or equal to 175mm if 4m<D<8m, greater than or equal to 200mm if D>=8m. Check the section of shaft wall thus obtained from bending stress criteria at the critical section. If the section fails increase overall thickness by 5% and redesign.

A sample calculation for first approximation of shaft thickness for an elevated water tank with 1500 CuM capacity, dia of the tank container 17.0m, h/D ratio of tank container 0.38, centre to centre dia of shaft type staging is 14.9m, the tank is located in seismic Zone IV, the shaft portion is constructed of M20 grade concrete, is shown below for ready reference.

Shaft Thickness from direct stress criteria, considering an average stress of $\boldsymbol{\sigma}$ = 4N/mm^2 , $t_{initial} = \frac{\boldsymbol{W}}{\pi\, XDX\sigma} = \frac{\mathbf{28822.67\ X\ 10\hat{}3}}{\pi\, X14900X4.0}$ = 153.9 mm, for seismic Zone –IV, increase thickness by 30% as a requirement from bending stress criteria for lateral seismic load, t = 153.9 X 1.3 = 200.07mm, providing say 200mm thickness of the shaft. If the shaft has opening for ventilation increase, thickness by further 5%, say, 200 X 1.05mm = 210mm say. The value thus obtained may be used as a logical guess for thickness of the shaft staging. Now it should be checked against the actual direct and bending stress values, if section fails increase thickness by 5% and retry. As per sl no. 3 of table 3,for 200mm thick shaft wall, Maximum bending stress = 4.47 N/mm^2 (compressive) and Minimum bending stress = 1.35 N/mm^2 (compressive), permissible stress for M20 grade concrete under transient seismic load = 1.33 X 7.0 N/mm^2 = 9.31 N/mm^2.

V. CONCLUSION

It is generally observed that from buckling point of view the t/r (ratio of shaft thickness to shaft staging radius) value is very important parameter. As the internal dia of the shaft staging increases, permissible buckling stress reduces, while increase in buckling strength is observed when the shaft wall thickness is increased. As capacity of tank increases, in tank full condition, under direct and bending stress due to vertical load and seismic base shear buckling in shaft staging is aggravated.

Thus in this paper, on the basis of limited study of seven relatively higher capacities of water tanks, with different shaft thickness the formula for shaft thickness as it appears in the IS code is studied in critical details from buckling point of view, and it reveals that although it is not derived from buckling strength point of view but practically it yields a shaft wall thickness which generally gives safe design against buckling of thin shell under axial compression. An alternative approximate approach for arriving at the thickness of the shaft wall staging of R.C elevated water tank from vertical and lateral load consideration has also being shown in the paper.

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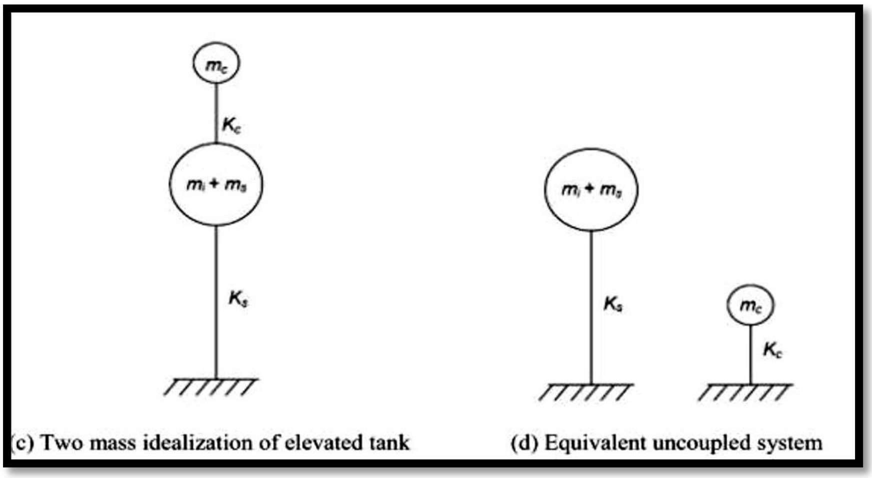

(c) Two mass idealization of elevated tank (d) Equivalent uncoupled system

Fig 1 Two mass idealization of elevated water tank

Tables:

Table No.1 Dimensions of various structural parameters of Intze type water tank

Sl no.	Capacity of tank (CuM)	Dia of tank (D) (m)	Top dome Thk(mm)	Top ring Beam sectional area	shell wall avg thk (mm)	bottom ring beam sectional area	conical dome thk (mm)	Bottom dome thk (mm)	sectional area of Bottom circular Girder
1	700	12.5	100	300 x 300	200	500 x 650	350	150	600 x 1100
2	1000	12	100	300 x 300	300	600 x 1200	600	300	600 x 1200
3	1500	17	100	450 X 450	325	750 x 800	500	200	500 x 1500
4	1800	17	100	450 X 450	350	750 x 1000	500	250	500 x 1800
5	2250	17	100	450 X 450	450	750 x 1200	650	300	500 x 2000
6	2500	18.5	100	450 X 450	500	800 x 1200	650	350	550 x 2000
7	3000	18.5	100	500 x 500	600	800 x 1500	800	450	650 x 2000

Table No.2 Variation of earthquake induced Bending stresses in R.C shaft support of OHR, with 150mm thick shaft wall with 20m height and 1.5 m depth of foundation with M20 grade Concrete

Sl No.	Tank Capacity (CuM)	c/c Shaft Dia (mm)	Shaft thickness (mm)	Tank Height/Dia (h/D)	Mass of Water (Kg)			Time period (S)		Seismic base shear (KN)		Seismic force induced Base Moment (KN-m)		Vertical Load (KN) (tank full)	Direct stress (N/sqmm) (tank full)	Permissible stress in buckling (N/ Sq mm)	e=M/P (m)	e/r	Bending stress at Tank Base in full condition (Compression / Tension) (N/sq mm)	Permissible stress (N/ Sq mm)
					Tank full (impulsive + structural mass/ convective mass)	% of liquid mass excited in impulsive / convective mode	Tank empty	Tank full (impulsive mode/ convective mode)	Tank empty	Tank full	Tank empty	Tank full	Tank empty							
1	700	8500	150	0.5	mi + ms =841581.11	55	ms =423663.6	0.37	0.26	1068	531.98	27222.1	13054.9	13385.9	3.35	4.44	2.03	0.48	6.61 (comp)	1.33 x 7 = 9.31
					mc= 341932.5	45		3.84											0.08 (comp)	
2	1000	8000	150	0.67	mi + ms =1251548.29	67	ms =645346.5	0.49	0.35	1291.1	810.35	34387.5	21474.25	16897.6	4.47	4.47	2.04	0.51	9.04 (comp)	
					mc= 298577.0	33		3.76											0.1 (tension)	
3	1500	14900	150	0.38	mi + ms =1630257	45	ms = 966340.5	0.22	0.17	2054	1213.4	52239.1	30274.68	26819.8	3.82	4.09	1.95	0.26	5.84 (comp)	
					mc= 767192.4	55		4.6											1.80 (comp)	
4	1800	14900	150	0.47	mi + ms =2041178.69	52	ms = 1096941.9	0.25	0.18	2569.7	1377.4	68085.9	35123.9	31440.5	4.48	4.09	2.17	0.29	7.11 (comp)	
					mc= 817128	45		4.6											1.85 (comp)	
5	2250	14900	150	0.6	mi + ms = 2926746.5	62	ms = 1519469.9	0.29	0.21	2827.9	1907.9	101073	50561.15	39389.1	5.59	4.09	2.57	0.34	9.50 (comp)	
					mc= 839826.4	37		4.5											1.68 (comp)	
6	2500	15500	150	0.51	mi + ms = 3278452.48	55	ms = 1873972.5	0.3	0.22	4124.8	2353.1	113003	61769.1	46023.9	6.3	4.06	2.46	0.32	10.29 (comp)	
					mc= 1149120	45		4.7											2.31 (comp)	

Table no. 3 Variation of earthquake induced Bending stresses in R.C shaft support of OHR, with 200mm thick shaft wall with 20m height and 1.5 m depth of foundation with M20 grade Concrete

Sl No.	Tank Capacity (CuM)	c/c Shaft Dia (mm)	Shaft thickness (mm)	Tank Height/Dia (h/D)	Mass of Water (Kg)			Time period (S)		Seismic base shear (KN)		Seismic force induced Base Moment (KN-m)		Vertical Load (KN) (tank full)	Direct stress (N/sqmm) (tank full)	Permissible stress in buckling (N/ Sq mm)	e=M/P (m)	e/r	Bending stress at Tank Base in full condition c (Comp / Tension) (N/sq mm)	Permissible stress (N/ Sq mm)
					Tank full (impulsive + structural mass/ convective mass)	% of liquid mass excited in impulsive / convective mode	Tank empty	Tank full (impulsive mode/ convective mode)	Tank empty	Tank full	Tank empty	Tank full	Tank empty							
1	700	8500	200	0.5	mi + ms =865966.43	55	ms =448048.93	0.32	0.23	1095.9	567	27902.8	13806.35	14103.56	2.64	4.57	1.98	0.47	5.15 (comp)	1.33 x 7 = 9.31
					mc= 341932.5	45		3.84											0.13 (comp)	
2	1000	8000	200	0.67	mi + ms =1274499.45	67	ms =668297.66	0.43	0.31	1487.8	839.17	39682.5	22237.95	17573.04	3.49	4.59	2.26	0.56	7.44 (comp)	
					mc= 298577.0	33		3.76											0.46 (tension)	
3	1500	14900	200	0.38	mi + ms =1673004.17	45	ms = 1009087.67	0.19	0.15	2107	1267.1	53562.3	31360.51	28077.85	2.91	4.29	1.91	0.26	4.47 (comp)	
					mc= 767192.4	55		4.6											1.35 (comp)	
4	1800	14900	200	0.47	mi + ms =2083930.99	52	ms = 10139694.19	0.15	0.16	2623.2	1431	69451.5	37923.92	32698.55	3.39	4.29	2.12	0.29	5.41 (comp)	
					mc= 817128	45		4.6											1.37 (comp)	
5	2250	14900	200	0.6	mi + ms = 2969488.6	62	ms = 1562212	0.26	0.19	3733.5	1961.64	102493	51983.4	39389.1	4.22	4.29	2.60	0.35	7.20 (comp)	
					mc= 839826.4	37		4.5											1.24 (comp)	
6	2500	15500	200	0.51	mi + ms = 3278452.48	55	ms = 1937195.72	0.26	0.2	4196	2493	115083	63853.1	47332.58	4.86	4.26	2.43	0.31	7.95 (comp)	
					mc= 1149120	45		4.7											1.77 (comp)	
7	3000	15500	200	0.65	mi + ms = 4723201.8	65	ms = 2626542.30	0.31	0.23	5930.8	3298.1	166439	90697.66	60900	6.25	4.26	2.733	0.35	10.72 (comp)	
					mc= 1128970.5	35		4.67											1.78 (comp)	

Table No. 4 Variation of earthquake induced Bending stresses in R.C shaft support of OHR, with thickness of shaft wall as per IS 11682 with 20m height and 1.5 m depth of foundation with M20 grade Concrete

Sl No.	Tank Capacity (CuM)	c/c Shaft Dia (mm)	Shaft thickness (mm)	Tank Height/Dia (h/D)	Mass of Water (Kg)			Time period (S)		Seismic base shear (KN)		Seismic force induced Base Moment (KN-m)		Vertical Load (KN) (tank full)	Direct stress (N/sqmm) (tank full)	Permissible stress in buckling (N/ Sq mm)	e=M/P (m)	e/r	Bending stress at Tank base in full condition f (Comp / Tension) (N/sq mm)	Permissible stress (N/ Sq mm)
					Tank full (impulsive + structural mass/ convective mass)	% of liquid mass excited in impulsive / convective mode	Tank empty	Tank full (impulsive mode/ convective mode)	Tank empty	Tank full	Tank empty	Tank full	Tank empty							
1	700	8500	180	0.5	mi + ms =856245.74	55	ms =438328.74	0.34	0.23	1083	552.86	27587.5	13567.11	13816.51	2.87	4.52	2.00	0.47	5.57 (comp)	1.33 x 7 = 9.31
					mc= 341932.5	45		3.84											0.17 (comp)	
2	1000	8000	170	0.67	mi + ms =1260729.82	67	ms =654528.03	0.46	0.33	1382	825.55	38565.1	21876.99	17167.81	4.02	4.52	2.25	0.56	8.53 (comp)	
					mc= 298577.0	33		3.76											0.49 (tension)	
3	1500	14900	230	0.38	mi + ms =1034799.19	45	ms = 1009087.67	0.18	0.14	2149.3	1305.18	54590.3	32303.14	28822.67	2.68	4.6	1.89	0.25	4.04 (comp)	
					mc= 767192.4	55		4.6											1.32 (comp)	
4	1800	14900	230	0.47	mi + ms =2109584.4	52	ms = 1165347.6	0.2	0.15	2666.9	1469	70576.4	37480.83	33443.36	3.11	4.6	2.11	0.28	4.87 (comp)	
					mc= 817128	45		4.6											1.35 (comp)	
5	2250	14900	230	0.6	mi + ms = 2995175.2	62	ms = 1587898.6	0.24	0.18	3782.3	2002.79	103800	53074.04	41701.95	3.87	4.6	2.49	0.33	6.46 (comp)	
					mc= 839826.4	37		4.5											1.29 (comp)	
6	2500	15500	230	0.51	mi + ms = 3402999	55	ms = 1998519	0.24	0.19	4299.7	2520.7	117605	66168.47	48669.75	4.35	4.35	2.42	0.31	7.05 (comp)	
					mc= 1149120	45		4.7											1.64 (comp)	
7	3000	15500	230	0.65	mi + ms = 4749881.9	65	ms = 2653222.4	0.29	0.21	5996.1	3346.47	168097	92027.97	61684.8	5.51	4.35	2.73	0.35	9.38 (comp)	
					mc= 1128970.5	35		4.67											1.64 (comp)	

Sl no.	Tank capacity (Cum)	C/C dia of Shaft (mm)	Shaft thickness (mm) as per IS Code	Direct Stress (Tank full) (N/mm^2	Permissible Buckling stress (N/mm^2)	
					M20 grade	M25 grade
1	700	8500	180	2.87	4.52	5.59
2	1000	8000	170	4.02	4.52	5.59
3	1500	14900	230	2.68	4.60	5.37
4	1800	14900	230	3.11	4.60	5.37
5	2250	14900	230	3.87	4.60	5.37
6	2500	15500	230	4.35	4.35	5.34
7	3000	15500	230	5.31	4.35	5.34

Table 5 Showing variation in direct stress in shaft due to vertical load and permissible stress