Variation in Seismic Behaviour of R.C Shaft Supported Elevated Water Towers with Change in Proportion of the Shaft Staging

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1 Introduction

Structurally elevated tanks are constructed either on frame or shaft type of staging system and such structures may be classified as top heavy inverted pendulum structures, and they have a tendency to overturn under the influence of lateral forces including wind and earthquakes. But it is found that the elevated water tank is generally more sensitive to seismic forces than wind forces. R.C shaft supported water tanks are more vulnerable towards damage or complete collapse due to seismic forces which has been reported in literature elsewhere [1]. Elevated water tanks are integral part of piped water supply schemes, and they are very significant structures from disaster management point of view. After a severe earthquake, generally grid power is out due to uprooting of electric poles and there are also events of break out of fire due to short circuit or rupture of gas pipelines. Under such inclement situation if the elevated water tank is standing erect without failure then water supply can be ensured for emergency firefighting and drinking water supply to the relief camps by water tanker until the grid power is restored. Structurally frame supported water tanks are more earthquake resistant due to the superior structural ductility in comparison to cylindrical shaft supported tanks. However it is found that shaft supported water tanks are popularly constructed in comparison to frame supported tanks because shaft supported water tanks are constructed with relatively lesser time using slip formwork and is also economic with respect to material consumption than frame supported tanks. Shaft supported tanks are also more aesthetic in comparison to frame supported tanks. Design and construction of R.C elevated water tank is covered in the Indian Standard code of practise IS 11682-1985, whereas seismic design of water tanks are covered in details in BIS code IS 1893 (part 2).

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The safety against overturning of elevated water tanks may be ensured through the provision of adequate factor of safety of the structure against overturning moment induced about the base of the tank support under lateral forces. If the diameter of the hollow cylindrical shaft support is small, the structure being slender is likely to have more lateral deflection at the tank level. Again if the diameter of the shaft is large it shall provide sufficient restoring couple against the lateral load induced overturning moment. More the diameter of the shaft supported tank, more is the material consumption and area of shuttering required for construction of the same. Thus it is required to strike a balance to the diameter of the shaft support which if adopted shall not make the structure unnecessarily costly and also prevent excessive lateral deflection. An important dynamic parameter of a structural system is the time period of the structural system. The fundamental period is dependent on the mass and the lateral stiffness of the structural system. Any variation in the structural proportions influences both the mass and the structural stiffness of the system. As the natural period of the system changes, the seismic behaviour of the structural system gets affected accordingly. This paper deals with the effect of change of structural proportion on the seismic behaviour of shaft supported elevated water tanks. Seismic force induced Bending Moment at the base of shaft staging shall be varied with the ratio of diameter of the tank to the shaft and the height of the shaft staging system. The outcome of this study is to understand the structural behaviour of the shaft supported elevated tank due to variation in the structural proportion of the shaft.

2 Study of Failure

The shaft support of elevated water tank is a thin cylindrical shell. From damage surveys of earthquakes [2–4], it has been revealed that thin shell shaft supports has generally failed by development of circumferential flexural tension crack approximately within a zone of about 1/3rd height from the base of the staging system. The shaft support deflects like a cantilever beam, and the maximum B.M due to lateral load is found to develop near the shaft base. The possibility for crack development near the base is further aggravated due to door opening in the shaft, which structurally weakens the shaft near the base location. Generally the height of the jumping formwork used to construct the shaft wall is 1.2 m height, for a 20 m height shaft staging about 18 nos. of subsequent casting operations are required. Thus 18 numbers of construction joints are formed at each lift of the slip form. These joints are the weakest points of the shaft staging. If adequate precautions are not taken while casting the shaft staging, under repetitive seismic jolts these joints opens up circumferentially under the influence of flexural tension leading to development of cracks in the shaft. The shaft is subjected to the combined effect of axial load from retained water and dead load of the tank, the seismic force induces B.M in the shaft cross-section. Under vertical load the thin shell shaft has a buckling tendency. While under lateral seismic load the shaft is subjected to severe bending stress near the base region. The flexural tension crack developed near the base zone of the shaft drastically reduces the load carrying capacity of the shaft and may cause collapse of the shaft staging. The strength of the shaft cross-section to accommodate bending stress is dependent on the shell thickness and the diameter of shaft staging. The tendency of the shaft to buckle under vertical load shall be studied with respect to the slenderness ratio (l_{eff}/r_{min}) of the staging. It is well known that there is paucity of literature and books on aseismic design of shaft supported water tanks. The BIS code IS 11682 is age old and requires immediate revision. As state of the art guideline is limited, consultants mostly design elevated water tank structures from their personal judgement and age old design provisions. Thus it is essential to re-examine seismic design aspects of R.C shaft supported water tanks in light of current research and development. If optimum diameter of the shaft of the elevated water tank is provided, it shall ensure adequate lateral stiffness to the shaft preventing excessive side sway and development of large bending stress in the shell concrete. The existing literature in this field does not enlighten this uncharted domain, although the matter is of great practical significance.

3 Structural Model

Different structural models have been studied by researchers for dynamic analysis of elevated water tanks against seismic forces. The erstwhile Indian seismic code IS 1893-1984 [5] vide cl no. 5.2 has recommended in favour of adoption of Single Degree of Freedom (SDOF) model. The SDOF model assumes that during seismic sway the water retained in the tank moves as a rigid body with the tank and causes the development of impulsive pressure and convective pressure, but since the convective pressure is meagre, it is neglected. The impulsive pressure is resisted by the support system of the elevated tank, it generates bending stress in the shaft cross-section, causing combined action of compressive and bending stress. G.W Housner in 1963 [6] propounded the two mass model for seismic analysis of water tanks this theory assumes that the portion of the liquid which moves with the tank container causes development of impulsive pressure and a portion of the liquid near the free board of the tank sloshes and causes the development of convective pressure. These two different modes of vibration are modelled as a two degree of freedom model. The current version of IS 1893-part 2 [7] has absorbed the two mass model as it is more rational and accurate in comparison to SDOF model, where convective component of vibration is totally neglected. Researchers have also modelled shaft supported elevated water tank using Multi Degree of Freedom Model (MDOF) [8] (lumped mass model) and Finite Element Model (FEM) [9]. While SDOF and Two DOF models are approximate models which hails from pre computer age, MDOF model and Finite Element Analysis of elevated water tank are done using structural analysis software, which are now easily accessible to the researcher. The MDOF model gives a better idea of the various higher modes of vibration of the tank. The Finite Element Model may be considered as a relatively most accurate structural model, which gives a more comprehensive idea of deflected shape in the structure with different load combinations. In this paper Finite Element Analysis of shaft supported elevated water tank shall be performed in SAP 2000 software [10]. This software has been particularly used, as the dynamic analysis module of the software is very comprehensive. However as there is no effective tool to model the sloshing behaviour of water, the philosophy of the two mass model has been incorporated in the analytical model. In absence of any finite element which may effectively model the sloshing behaviour and impulsive vibration of the water under seismic forces, the impulsive mass is approximately assumed to be attached with the tank wall as a rigid link and the convective stiffness K_c has been adopted as per formula given in IS 1893 (Part-2) 2014, such modelling philosophy has been used by researchers elsewhere [11].

4 Problem Studied

An Intze type R.C water tank of 2250 CuM capacity supported on thin shell cylindrical shaft, having structural details as tabulated in Tables 1 and 2, of this paper (it is mentioned that the dimensions are adopted from practical water tank design, but the wall thickness of shaft staging has been kept as 150 mm to simulate the worst effect of forces on the tank structure.) The elevated tank is constructed with M30 grade concrete and Fe415 grade of steel. Keeping the capacity of the tank same the diameter of the shaft staging has been varied. The height of the staging is also varied as 20 m, 30 m and 40 m, respectively, the slenderness ratio of the shaft cross-section is accordingly modified. The tank structure is subjected to modal time history analysis in the elastic range of forces in SAP 2000 software using three different time histories of past earthquakes including (i) 1940 El-Centro Earthquake time history N-S component, (ii) San Fernando Earthquake time history of 1971 and (iii) Bhuj

Table 1 Dimensions of elevated tank

Sl. no.	Tank portion	Dimensions
1	Top dome	Diameter = 17.0 m, Rise = 1.5 m, Thickness = 100 mm
2	Top ring beam	Section 450 mm × 450 mm
3	Shell wall	450 mm average thickness
4	Bottom ring	Section 750 mm × 1200 mm
5	Conical dome	650 mm thickness of slab
6	Bottom dome	300 mm thickness slab
7	Circular ring girder	Section 500 mm × 2000 mm
8	Thickness of shaft wall staging	150 mm thick
9	Staging height	Varied by 20 m, 30 m and 40 m respectively
10	Diameter of shaft (d)	Varied by 14.9 m, 12.0 m, 10.0 m, 9.0 m, 7.5 m and 6.0 m respectively

Table 2 Details of water tank models

Model no.	Shaft height (m)	Tank dia (m)	Dia of staging (m)	d/D	Thk. of shaft (mm)	l_{eff}/R_{min}	Mass (KN)	Moment of inertia (m^4)	Stiffness (KN/m)
1	20	17	14.9	0.876471	150	3.10	13,576	9.6E+13	899,795,786
	30	17	14.9	0.876471	150	4.66	15,329	9.6E+13	266,606,159
	40	17	14.9	0.876471	150	6.21	17,081	9.6E+13	112,474,473
2	20	17	12.0	0.705882	150	4.80	15,800	5E+13	468,318,242
	30	17	12.0	0.705882	150	7.21	17,208	5E+13	138,760,961
	40	17	12.0	0.705882	150	9.61	18,620	5E+13	58,539,780
3	20	17	10.0	0.588235	150	6.94	17,352	2.88E+13	270,000,817
	30	17	10.0	0.588235	150	10.42	19,462	2.88E+13	80,000,242
	40	17	10.0	0.588235	150	13.89	20,675	2.88E+13	33,750,102
4	20	17	9.0	0.529412	150	8.59	16,007	2.09E+13	196,337,870
	30	17	9.0	0.529412	150	12.89	17,065	2.09E+13	58,174,184
	40	17	9.0	0.529412	150	17.19	18,250	2.09E+13	24,542,234
5	20	17	7.5	0.441176	150	12.44	14,312	1.21E+13	113,053,085
	30	17	7.5	0.441176	150	18.66	15,200	1.21E+13	33,497,210
	40	17	7.5	0.441176	150	24.88	16,100	1.21E+13	14,131,636
6	20	17	6.0	0.352941	150	19.58	15,455	6.13E+12	57,449,120
	30	17	6.0	0.352941	150	29.37	16,200	6.13E+12	17,021,961
	40	17	6.0	0.352941	150	39.17	16,900	6.13E+12	7,181,140

Earthquake time history of 2001. The ground acceleration time history plots are shown in Fig. 1a, b and c respectively. Details of ground acceleration time histories of earthquakes such as Magnitude, PGA value, duration of strong ground motion, depth of focus, intensity and place of occurrence are tabulated in Table 3 only for reference. Time History Analysis (THA) is the most accurate method of dynamic analysis, by adopting different earthquake time histories it is possible to check the seismic response with different PGA values and durations of earthquakes. For the

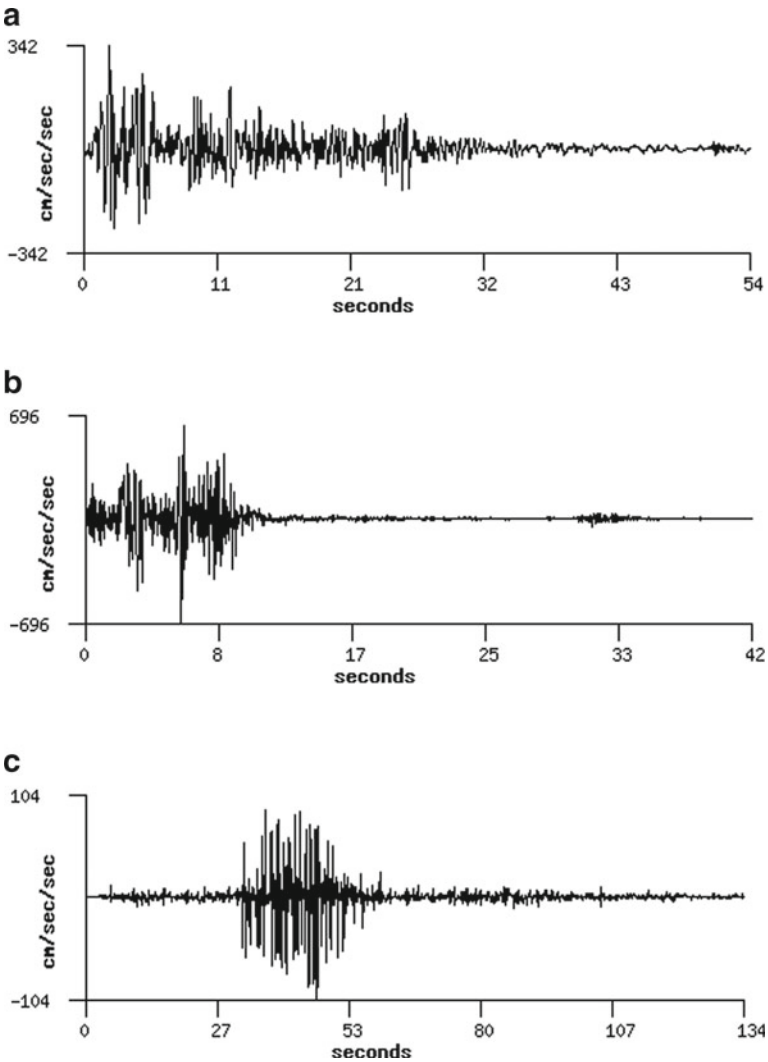


Fig. 1 Ground acceleration related data of time histories of earthquake. **a** El-Centro Earthquake 1940, N–S component. **b** San Fernando earthquake 1971. **c** Bhuj earthquake 2001

Table 3 Relevant information of earthquakes time history analysis

Sl. no.	Name of the earthquake	PGA of earthquake (g)	Strong motion duration (s)	Focal depth (KM)	Magnitude (Mw)	Intensity (MMI scale)	Location of earthquake
1.	El-Centro 1941	0.32	29	16	6.9	X	California
2.	San Fernando, 1971	1.25	12	8.4	6.5	X	California
3.	Bhuj, 2001	0.11	22	16	7.9	X	India

purpose of modelling the tank wall and shaft 4 noded quadrilateral shell element has been used. This type of shell element combines both the membrane action and plate bending behaviour which is observed in the shaft staging of the elevated tanks under the impact of vertical and lateral load. Modelling of the axisymmetric elevated water tank structure has been done with radial replication of the mesh of shell element. The Finite Element mesh size has been kept 1 m × 1 m, such mesh size is kept in many real life structural design problems. If the mesh size is made smaller it takes appreciable time for the desktop computer system to analysis the structure. The retained water in the tank container has been approximately modelled adopting the two mass model philosophy. As there is no available finite element to simulate impulsive and convective vibration of the retained water, so the retained water has been classified into two modes of vibration under seismic shaking as per guideline of the current BIS code IS 1893 (part-2) the impulsive mass and the convective mass respectively. The impulsive mass is assessed to be attached to the tank body with a linear rigid link while the convective mass is connected with convective springs whose stiffness value was obtained from Fig. 2a of IS 1893 (part 2). The impulsive mass is located at the height h_i from the base of the tank, and the convective mass is located at the height h_c from the tank base, the value of impulsive and convective height respectively may be obtained from the graph vide Fig. 2b of IS 1893 (part 2) depending on h/D_t ratio, where h = tank height and D_t = diameter of tank. The relative placement of the impulsive and the convective masses has been shown in Fig. 2 of this paper. The parameters of two mass model as given in IS 1893 (part 2) 2014 are valid for circular tanks with flat bottom. As the tank is of INTZE type the dimensions of impulsive height (h_i) and convective height (h_c) given in the paper are equivalent dimensions for cylindrical tanks. The elevated tank is assumed to be supported on fixed support. The shaft diameter has been varied from 14.9 m, 12.0 m, 10.0 m, 9.0 m, 7.5 m and 6.0 m respectively to change the structural proportion. Six different shaft diameters are given six model nos. whereas 14.9 m diameter shaft is model no. 1, 12.0 m diameter shaft is model no. 2, similarly 10.0 m diameter shaft model no. 3, 9.0 m diameter shaft is model no. 4, 7.5 m diameter shaft model no. 5 and 6.0 m diameter model no. 6 respectively. Structural data of different diameter shafts are given in Table 2. Shaft staging height has been changed through 20 m, 30 m, 40 m respectively. Shaft wall

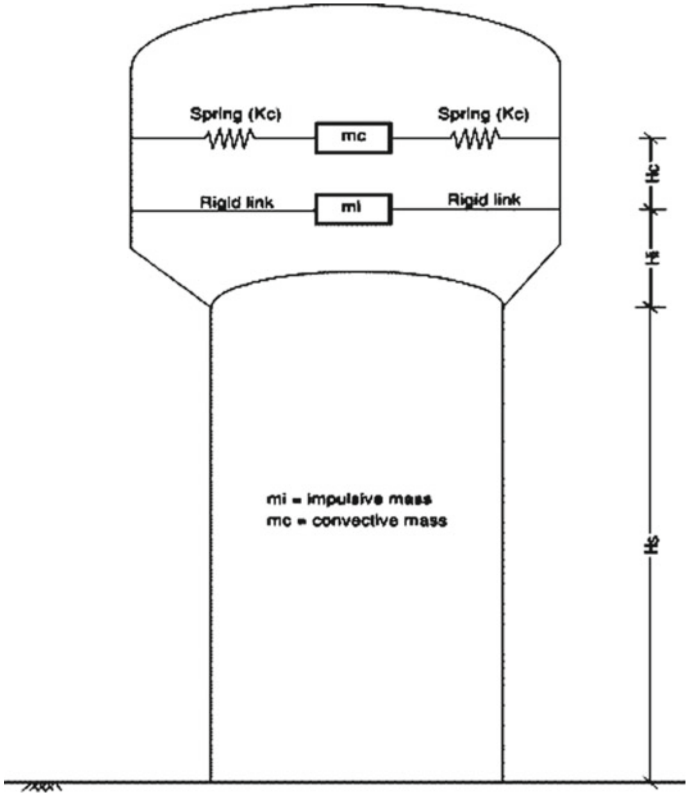


Fig. 2 Schematic sketch showing the impulsive and convective masses within the tank as modelled in SAP 2000 (the dimensions h_i and h_c are equivalent dimensions of two mass model for flat bottom water tank)

thickness has been kept at 150 mm, which is the minimum thickness as per provisions of cl no. 8.2.1 of IS 11682 [12]. The shaft thickness has been kept at minimum, i.e., 150 mm, in a pursuit to study the worst effect of seismic force on the structure. The slenderness ratio (l_{eff}/r_{min}) of the shaft staging has been calculated for all the cases, the effective length is assumed to be 1.2 l, i.e. (the shaft staging is considered as a hollow compression member which is effectively held in position and restrained against rotation at one end, while restrained against rotation but not held in position at the other end). Such an end restraint has been conceived for Shaft support elevated water tank under lateral seismic force, as the deflected profile under lateral load for a large R.C elevated tank on shaft staging shall exhibit much stiffness against rotation. The analysis has been performed both for tank empty and tank full conditions (as per provisions of cl. no. 4.7.4 of IS 1893 (part-2)). The ratio of diameter of tank shaft staging (d) to that of tank container (D) i.e. (d/D) has been plotted along X-axis and the variation in seismic force induced B.M in the tank shaft has been plotted against Y-axis. Separate graphs (vide Fig. 3a–f of this paper) are plotted for tank empty and

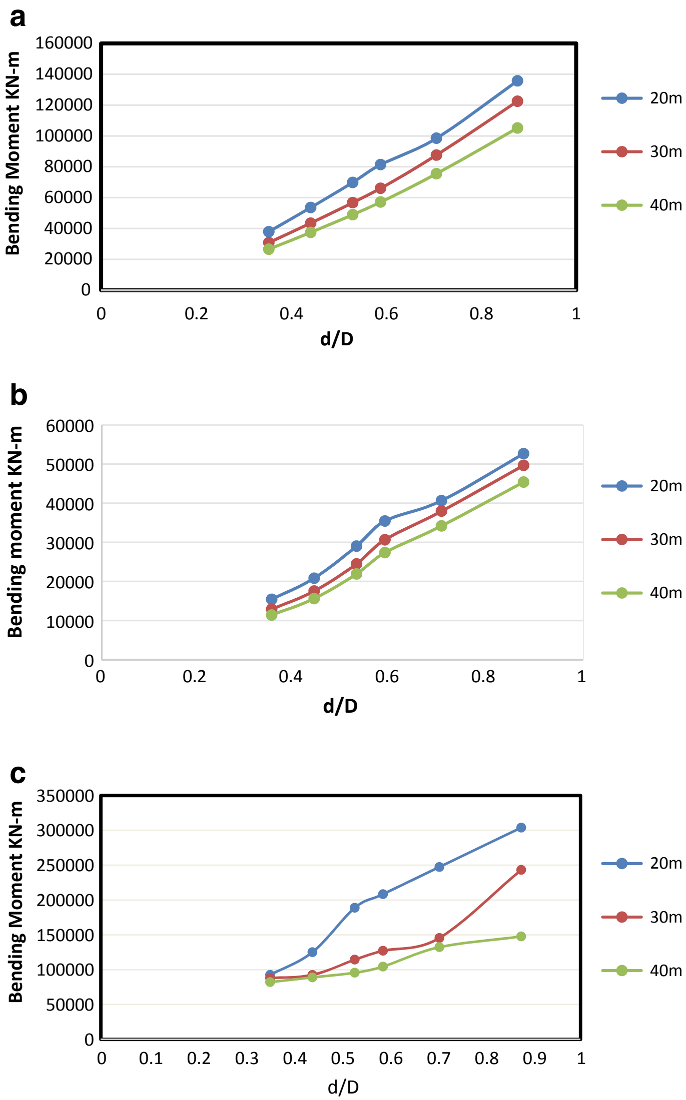


Fig. 3 **a** Variation of bending moment at shaft base with change in d/D ratio in tank full condition for El-Centro earthquake time history. **b** Variation of bending moment at shaft base with change in d/D ratio in tank empty condition for El-Centro earthquake time history. **c** Variation of bending moment at shaft base with change in d/D ratio in tank full condition for San Fernando earthquake time history. **d** Variation of bending moment at shaft base with change in d/D ratio in tank empty condition for San Fernando earthquake time history. **e** Variation of bending moment at shaft base with change in d/D ratio in tank full condition for Bhuj earthquake time history. **f** Variation of bending moment at shaft base with change in d/D ratio in tank empty condition for Bhuj earthquake time history

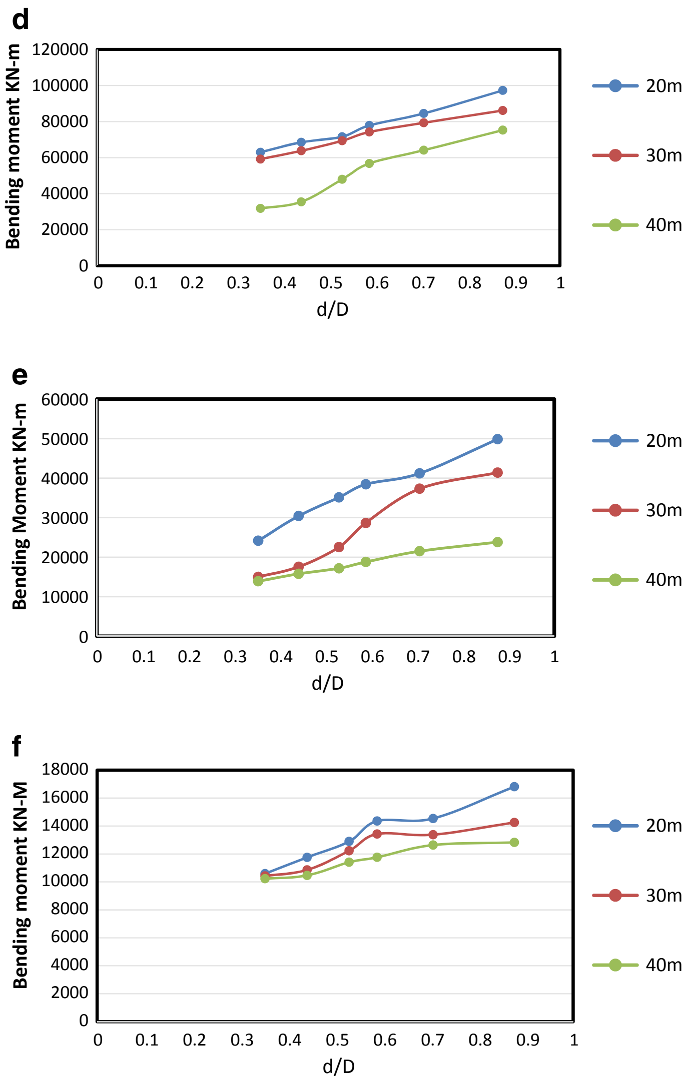


Fig. 3 (continued)

tank full condition for all the three time histories. Trend-line plots are obtained for 20 m, 30 m, and 40 m high shaft staging respectively. Mode shapes for first three modes of vibration for tank full condition (as the worst case) of the shaft supported tank for shaft diameters 14.9 m, 9.0 m and 6.0 m respectively are shown side by side (vide Fig. 4 of this paper) with the respective time period of vibration to compare between the mode shapes with change in shaft diameter.

5 Results and Discussion

A study of the graph showing the variation of B.M at the base of shaft (along y-axis) versus d/D ratio (along x-axis) both for tank full and tank empty condition under the effect of all the three seismic time histories, the following general observations are indicated:

(i) The value of B.M at the base of the shaft increases continuously with increase in d/D ratio.
(ii) The maximum B.M at the base of the shaft is observed for tank full condition under San Fernando earthquake time history excitation in comparison with other earthquake time histories.
(iii) The B.M at the base of the shaft is higher for tank full condition than tank empty condition.
(iv) As the diameter of the shaft is reduced progressively the lateral drift of the tank increases under the same seismic excitation.

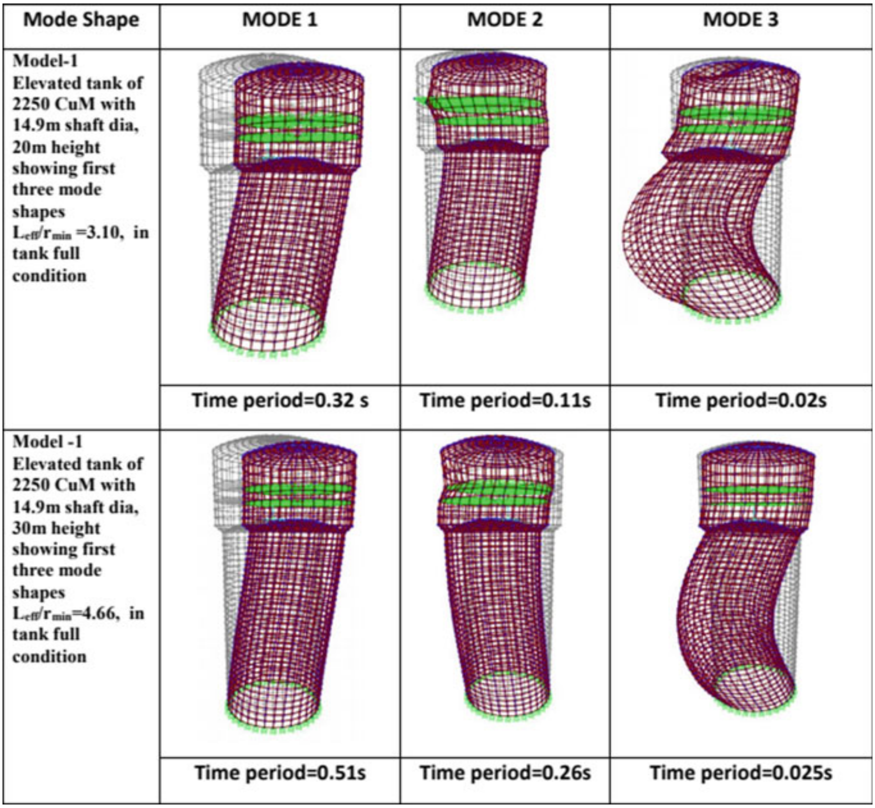


Fig. 4 First three modes of vibration of the shaft supported tank in tank full condition, for diameters of the shaft staging of 14.9 m, 9.0 m and 6.0 m respectively in SAP 2000 software

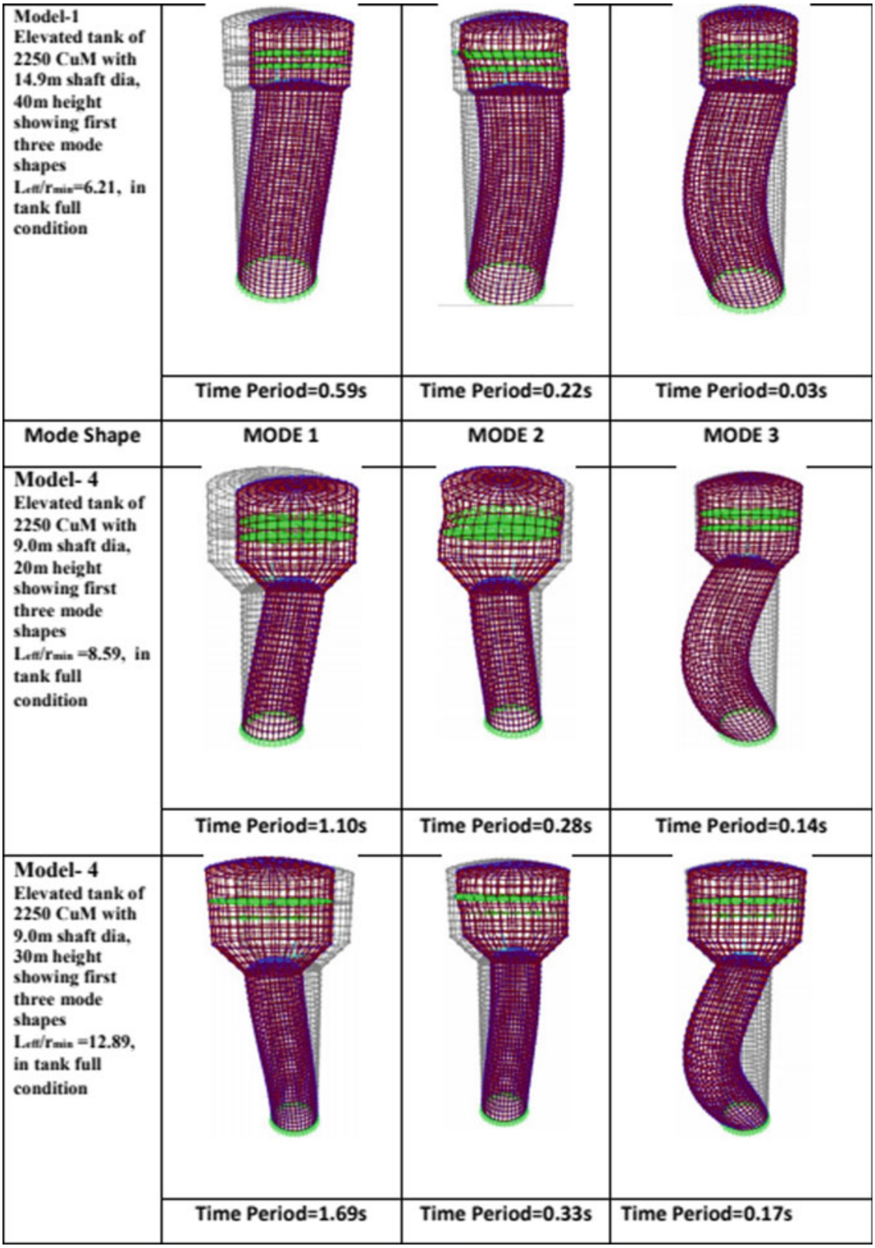


Fig. 4 (continued)

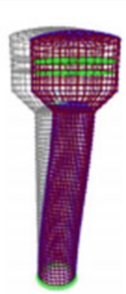
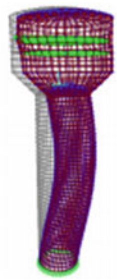
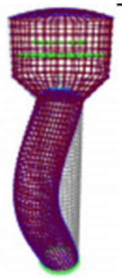
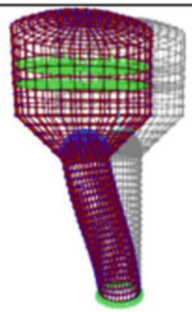
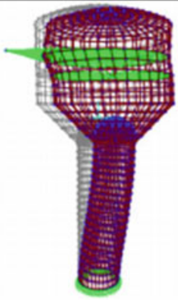
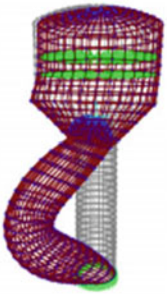
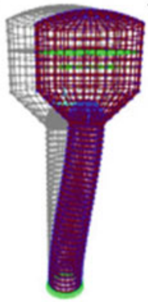
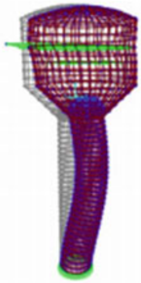
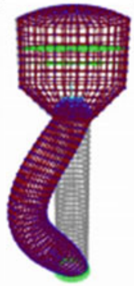
Model- 4 Elevated tank of 2250 CuM with 9.0m shaft dia, 40m height showing first three mode shapes L_{eff}/r_{min} =17.19, in tank full condition	 Time Period=2.35s	 Time Period=0.40s	 Time Period=0.20s
Mode	**MODE1**	**MODE 2**	**MODE 3**
Model- 6 Elevated tank of 2250 CuM with 6.0m shaft dia, 20m height showing first three mode shapes L_{eff}/r_{min} =19.58, in tank full condition	 Time Period=1.92s	 Time Period=0.47s	 Time Period=0.18s
Model- 6 Elevated tank of 2250 CuM with 6.0m shaft dia, 30m height showing first three mode shapes L_{eff}/r_{min} =29.35, in tank full condition	 Time Period=2.94s	 Time Period-0.58s	 Time Period=0.25 sec

Fig. 4 (continued)

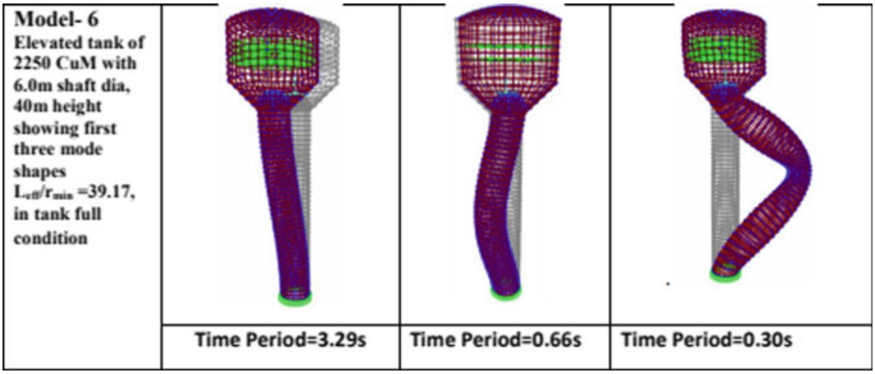


Fig. 4 (continued)

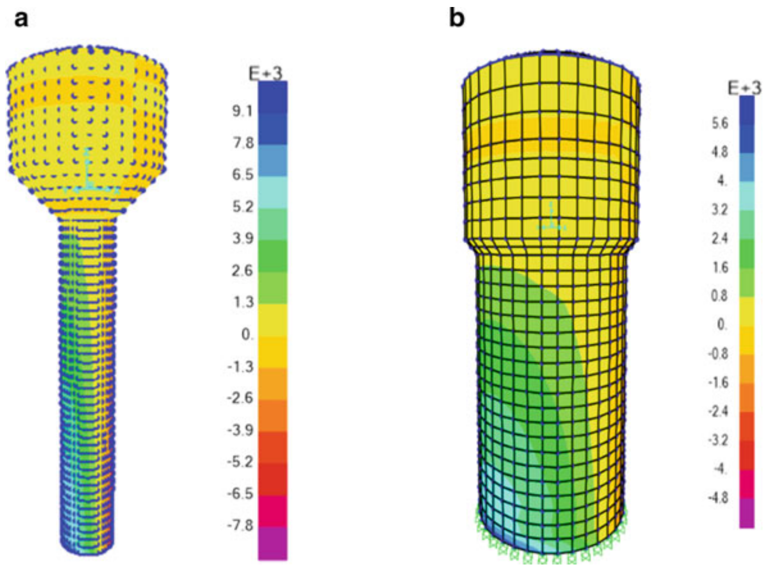


Fig. 5 **a** Bending stress contour of the shaft staging of 40 m height and 6 m diameter of shaft (unit KN/m^2) under the effect of San Fernando earthquake time history. **b** Bending stress contour of the shaft staging of 20 m height and 14.9 m diameter of shaft (unit KN/m^2) under the effect of San Fernando earthquake time history

(v) The fundamental period of vibration of 14.9 m diameter shaft of 20 m height in tank full condition is 0.32 s whereas for the 6.0 m diameter shaft with 20 m staging height in tank full condition the fundamental period is 1.92 s under San Fernando excitation. So it is found that the lateral flexibility of the system changes remarkably with the variation in shaft diameter.

Table 4 Lateral drift at the tank level of a 40 m high shaft supported elevated water tank under San Fernando time history

Sl. no.	Shaft diameter (m)	Staging wall thickness (mm)	Lateral stiffness of shaft (KN/m)	Base shear (KN) f	Lateral drift at tank level (mm)
1.	14.9	150	112,474,473	10,452	0.09
2.	9.0	150	24,542,234	6380	0.26
3.	6.0	150	7,181,140	4263	0.59

(vi) Bending stress contour (refer Fig. 5a, b) indicates that the maximum bending stress due to lateral seismic jolt occurs approximately in the area near 1/3rd distance from the base of the shaft staging. But with the increase in shaft diameter the bending stress intensity reduces and the zone of stress concentration also reduces.

(vii) Lateral drift of elevated water tank on shaft for the most severe San Fernando is shown in Table 4 for three shaft diameters of 6.0 m, 9.0 m and 14.0 m respectively.

Within the limited scope of available data it is found that the seismic force induced B.M at the base of the shaft staging is maximum for the earthquake time history with greater PGA value than others (such as San Fernando time history). The BM increases with the increase in diameter of the shaft staging. With increase in the shaft diameter the lateral stiffness of the water tank structure increases attracting more seismic force inducing greater B.M in the shaft. The B.M increases gradually; however, from the graph a trend is observed that beyond the shaft diameter 0.65D the BM value increases significantly requiring thicker shaft section which makes shaft construction relatively un-economical. Normally if the height of the shaft staging increases the B.M should increase due to increase in lever arm for the lateral load induced B.M. But as the natural period of the structure increases with an increase in the shaft height and the structure becomes more flexible and attracts less seismic force, resulting in less B.M in the shaft cross-section with an increase in shaft height. As the shaft diameter decreases the lateral drift increases, which is evident from relative study of the mode shapes. Increased lateral drift induces additional B.M at the shaft aggravating overturning tendency of the elevated water tank. However from Table 4 it is found that even under the impact of severe base shear of San Fernando earthquake no significant lateral drift has been obtained.

6 Conclusion

From the above study, it may be concluded that if the d/D ratio of the shaft is kept low then consumption of construction material for casting the shaft is on the lesser side but it may increase lateral drift endangering the stability of the elevated water tank on shaft with respect to collapse. If d/D ratio is kept relatively large lateral stiffness of the shaft increases and lateral displacement is reduced, but material consumption for shaft construction also becomes high. A stiffer system attracts more seismic force thus B.M in the shaft base increases. Thus from experience it may be stated that optimally for construction of elevated water tank on shaft a preferable d/D ratio should be kept around 0.55–0.75 (about 55–75% of the tank diameter) for safer and economic design. Beyond these values construction material consumption tend to increase and seismic induced BM is found to be on the higher side. Construction joints at the subsequent lift of the slip formwork are the weakest points. If this joints especially those within 1/3rd height of the base of the shaft are not properly cast, they are likely to open up under flexural tension and circumferential crack may badly undermine the strength of the shaft portion near the base aggravating tendency of collapse.

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