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Seismic Analysis and Optimization of RC Elevated Water Tank Using Various Staging Patterns

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ABSTRACT
As known from very upsetting experiences, poorly designed elevated water tanks were heavily damaged or collapsed during earthquakes. This might be due to the lack of knowledge regarding the behaviour of supporting system of the tank, and also due to improper selection of geometry of staging patterns. For certain proportions of the tank and the structure, the sloshing of the water during earthquake may be one of the dominant factors.Dynamic analysis of tank containing liquid is complex involving fluid-structure interaction.In this paper, the seismic behavioural effect of circular elevated water tank is studied for specific capacity of tank for various staging arrangements in plan, variation in number of periphery columns and variation in number of stages in elevation. Two mass idealizations suggested by Gujarat State Disaster Management Authority are considered here. Under earthquake loads; a complicated pattern of stresses is generated in the tanks. Total 36 combinations were analysedwith SAP2000 using Response Spectrum Method (RSM) and results are presented. It is observed that increase in number of columns, does not assure the increase in the improvement of structural responses. Radial arrangement with six staging levels is found to be best for the number of columns used. To suggest number of columns with suitable diameter cost optimization is done for the radial staging arrangement with six staging levels consideringcritical direction of seismic force, quantity of concrete and steel required. It is found that eight numbers of columns gives less cost as compared to six, ten and twelve with optimized diameter of 300mm.

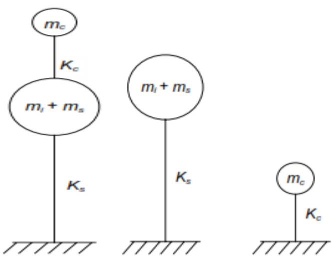
Keywords: Inadequate design, Elevated Circular Water Tank, Two mass model, Frame Staging, RSM, Optimization of Columns.

I. INTRODUCTION

An elevated water tank is a large water storage container constructed for the purpose of holding water supply at certain height to pressurise the water distribution system. There are different ways for the storage of liquid such as underground, ground supported and elevated used extensively by municipalities and industries. Thus water tanks are very important for public utility and for industrial structure. Elevated water tanks consist of huge water mass at the top of a slender staging which is most critical consideration for the failure of the tank during earthquakes. Elevated water tanks are critical and strategic structures; and damage of these structures during earthquakes may endanger drinking water supply,fail in preventing large fires and may cause substantial economic loss. Due to the lack of knowledge of supporting systems,many of the water tanks were collapsed or heavily damaged. In comparison with shaft staging, the reinforced concrete elevated water tanks with frame staging have shown better seismic resistance against lateral loads, because of having more degree of determinacy and seismic energy absorption capacity through the non-linearbehaviour.There are also various modes of failures such as buckling, sloshing damage to roof, inlet/outlet pipe breaks and impulsion due to rapid loss of contents. So there is need to focus on seismic safety of lifeline structure with respect to alternate supporting system. The present work is an effort to study the structural responses of circular elevated water tank using Response spectrum Method (RSM) considering different staging arrangements, staging levels and different sizes of columns, using SAP2000. For modelling, impulsive and convective water mass is considered. After study of structural responses optimization of diameter and number of columnsis done. Considering cost parameter; the best suitable number of columns required for the structurally adequate staging arrangement and staging levels were found out.

II. MODEL PROVISIONS

Most elevated tanks are never completely filled with liquid. Hence two mass idealization of the tank is more appropriate as compared to one mass idealization (IS 1893:1984).Two mass model is proposed by Housner (1963) and is being commonly used in most of the international codes including draft code IS 1893 (Part-II). The pressure generated within the fluid due to the dynamic motion of the tank can be separated into impulsive and convective parts. When a tank containing liquid with a free surface is subjected to horizontal earthquake ground motion, tank wall and liquid are subjected to horizontal acceleration. The liquid in the lower region of tank behaves like a mass that is rigidly connected to tank wall, this mass is termed as impulsive liquid mass which accelerates along with the wall and induces impulsive hydrodynamic pressure on tank wall. Similarly liquid mass in the upper region of tank undergoes sloshing motion. This mass is termed as convective liquid mass; and it exerts convective hydrodynamic pressure on tank wall and the base. Thus total liquid mass gets divided into two parts, impulsive mass and convective mass. The two degree of freedom system shown in Figure 1(a) can be treated as two uncoupled single degree of freedom systems shown in Figure 1(b). Figure 1 (b) represents the impulsive plus structural mass behaving as an inverted pendulum withlateral stiffness equal to that of the staging, k_s and Figure 1 (a) representing convective mass with k_c.



a) Two mass idealization b) Equivalent uncoupled system

Figure 1: Two mass idealization for elevated tank

Structural mass m_s, includes mass of container and one third mass of staging. Mass of container comprises of roof slab,container wall, floor slab, floor beams and gallery (if any). The response of the two-degree of freedom system can be obtained by elementary structural dynamics. However, form ostelevated tanks it is observed that the two time periodsare well separated. Hence, the two mass idealizations can betreatedas two uncoupled single degree of freedom systems. For circular tanks, maximum hydrodynamic force per unit circumferential length for convective and impulsive mode, is given by

$$q_i = \frac{(A_h)_i .m_i .g}{(\pi D/2)};\ and\ q_c = \frac{(A_h)_c .m_c .g}{(\pi D/2)}$$

(1)

Where,

q_i = Impulsive hydrodynamic force per unit length of wall, kN/m

q_c = Convective hydrodynamic force per unit length of wall, kN/m

$(A_h)_i$ = Design horizontal seismic coefficient for impulsive mode

$(A_h)_c$ = Design horizontal seismic coefficient for convective mode

m_i = Impulsive mass of liquid, kg

m_c = Convective mass of liquid, kg

g = Acceleration due to gravity, m/s^2; and

D = Inner diameter of circular tank, m

III. FLUID-STRUCTURE INTERACTION

During lateral base excitation seismic ground acceleration causes hydrodynamic pressure on the tank wall which depends on the geometry of tank, height of liquid, properties of liquid and fluid-tank interaction. Proper estimation of hydrodynamic pressure requires a rigorous fluid-structure interaction analysis. In the mechanical analogue of tank-liquid system, the liquid is divided in two parts as impulsive liquid and convective liquid. The impulsive liquid moves in unison with the tank wall in its fundamental mode of vibration and the convective part which represents sloshing action of the liquid in its fundamental mode of vibration. This mechanical model is quantified in terms of impulsive mass, convective mass, and flexibility of convective liquid. Housner (1963) developed the expressions for these parameters of mechanical analogue for circular and rectangular tanks. Fluid- structure interaction problems can be investigated by using different approaches such as added mass West ergaard approach, Lagrangian approach (Wilson and Khalvati), Eulerian approach (Zienkiewicz and Bettes), or the Eulerian-Lagrangian approach (Donea). Added mass approach is the simplest method as shown in Figure 2, which can be investigated by using some of the conventional Finite Element Method software such as SAP2000, STAAD Pro and LUSAS.

The general equation of motion for asystem subjected to an earthquake excitation can be written as,

$M\ddot{u} + C\dot{u} + Ku = M\ddot{u}_g$

In which M, C and K are mass, damping and stiffness matrices respectively; $\ddot{u}$, $\dot{u}$ and u are the acceleration, velocity, displacement and $\ddot{u}_g$ is the ground acceleration. In the case of added mass approach the equation (2) takes the form:

$M^* \ddot{u} + C \dot{u} + K u = M^* \ddot{u}_g$

In which M* is the new mass matrix after adding hydrodynamic mass to the structural mass, while the damping and stiffness matrices are same as in equation (2).

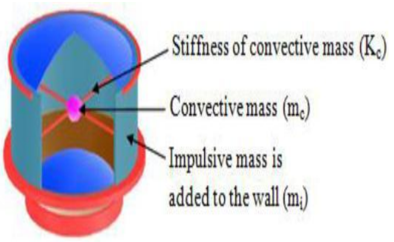


Figure 2: FEM model for Fluid-Structure Interaction added mass approach

IV. OPTIMIZATION OF SUPPORTING TOWER

In optimization of a design, the design objective could be simply to minimize the cost of structure or to maximize the efficiency of the structure. An optimization algorithm is a procedure which is executed iteratively by comparing various solutions till an optimum solution is found. With the advent of computer software's like STAAD Pro, SAP, ETABS optimization has become a part of computer-aided design activities. The purpose of optimization is to achieve economy by saving concrete and steel along with safety.

From the output of structural responses, the type of staging arrangement and staging levels having maximum base shear and minimum roof displacement is finalized as best combination. To decide the diameter and number of columns, the optimization considering full tank condition only is carried out.

Then, considering prevailing market rates of concrete and steel as per CSR 2013-14 (manual); PWD division, Nagpur total cost required for the optimized diameter for particular number of columns is obtained. Critical direction of shear force in columns and bracings is considered as per IITK GSDMA guidelinesfor design of columns.

V. NUMERICAL SIMULATION OF THE TANK

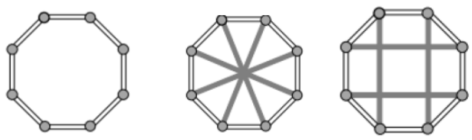
The frame type is the most commonly used staging in practice. The main components of frame type of staging are columns and braces. In frame staging, columns are arranged on the periphery and it is connected internally by bracing at various levels. The staging is acting like a bridge between container and foundation for the transfer of loads acting on the tank. In elevated water tanks, head requirement for distribution of water is satisfied by adjusting the height of the staging portion. A reinforced elevated circular water tank having*(3)*different staging arrangements, column sizes and staging levels has been considered for the present study. Total 36 combinations are studied for tank full and tank empty condition. The storage capacity of water tank is 500 m^3. The configuration of staging is the arrangements of columns and bracings in particular pattern. In the present study,three frame types of staging arrangements – normal, radial and cross have been considered as shown in Figure 3.Finite element model of tank is prepared in SAP2000. The results with respect to variation in stiffness are provided in fig.5.

Table 1(a): Design Data

Capacity of tank	500 m^3
Staging height	16 m
Unit weight of concrete	25 kN/m^3
Grade of steel	Fe415
Grade of concrete	M25
Earthquake Zone	III
Type of soil	Medium soil
Staging levels	Four, Five, Six

Table 1(b): Estimated Sizes of various components ofWater tank

Roof slab		320 mm
Wall		350 mm
Floor slab		350 mm
Floor Beams		400× 750mm
Braces		300× 500
Columns	**Six**	520 mm
	Eight	450mm
	Ten	350mm
	Twelve	300mm
Inner Diameter		9.50m
Outer Diameter		10.20m
Height		7.15m
Freeboard		0.30m



Normal **Radial** **Cross**

Figure 3: Different types of staging arrangements

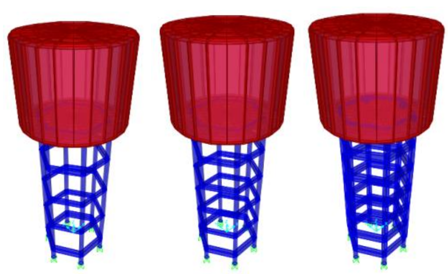


Figure 4: 3D FE models of various staging levels forNormal arrangement; six columns

VI. ANALYSIS RESULTS

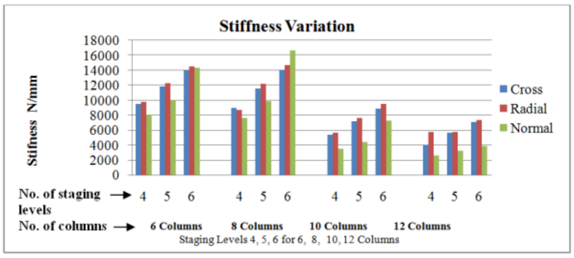


Figure 5: Stiffness variation for different staging arrangements

From Fig. 5, it is observed that with increase in number of columns, the overall stiffness of staging reduces. Conversely with the increasing of staging levels, the overall stiffness increases. This is due to the fact that the total cross sectional area of columns required to resist vertical loads is calculated by considering the permissible axial load for short columns in 'Working Stress Method'. Since the cross sectional area required is constant, the diameter decreases with increase in number of columns. This also reduces the moment of inertia of columns. The stiffness of staging is directly proportional to moment of inertia.

Figure 6 through 11 provides graphical representation for various parameters as Base Shear, Base Moment and Displacement with the number of columns and staging levels; for full and empty tank condition.

It is observed that with increase in number of columns, base shear increases while displacement reduces for both tank empty and tank full condition.

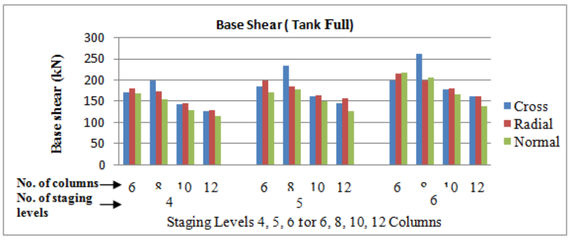


Figure 6: Base Shear variation for tank full condition

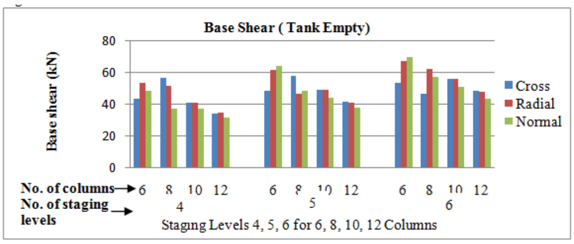


Figure 7: Base Shear variation for tank empty condition.

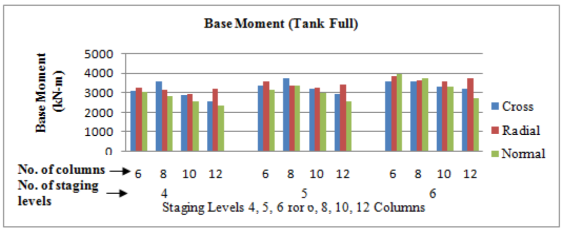


Figure 8: Base Moment variation for full tank condition

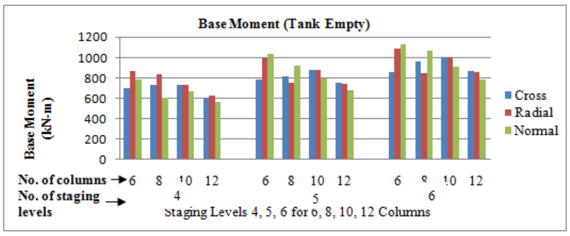


Figure 9: Base Moment variation for empty tank condition

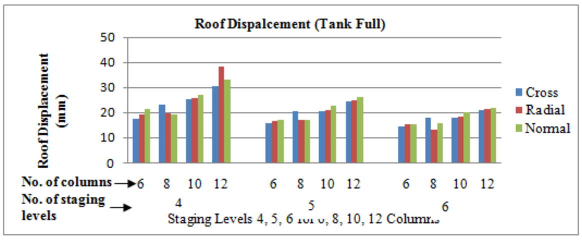


Figure10: Roof Displacement for full tank condition.

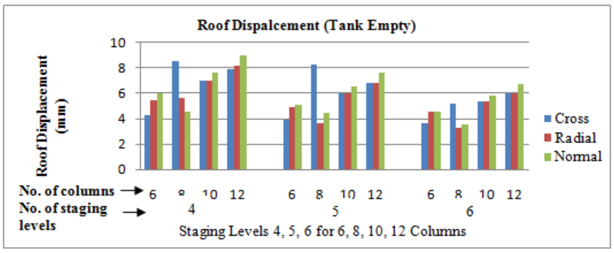
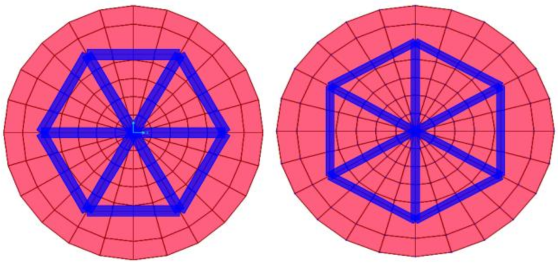


Figure 11: Roof Displacement for empty tank condition.

Optimization Considering Radial Arrangement, Six Staging Levels and Full Tank Condition only-

It is observed that for bracing width below 300 mm, design is inadequate and so 300mm is optimized value. Six, eight, ten and twelve number of columns is optimized considering, radial arrangement and six staging levels for full tank condition. For thisl, column diameters are decreased with increasing ratio of 0.15 till the design is adequate using SAP2000 software. After this based on the quantity of concrete and steel of designed columns, cost required for the optimized diameter and number of columns is obtained. For seismically designed of columns critical direction of shear force in columns and bracings is considered as per GSDMA guidelines.



(i) (ii)

(i) Critical direction for shear force in column (ii) Critical direction for shear force in brace

Figure12: 3D FE models showing critical direction of seismic force for typical frame type staging profiles for six columns

Table 2: Optimized diameters for various numbers of columns and corresponding quantity of steel

SN	**Number of columns**	**Optimized diameter of columns (mm)**	**Quantity of steel (mm^2)**
(1)	**(2)**	**(3)**	**(4)**
1	Six	520	1698.97
2		450 (ratio 1:15)	1324.37
3		390 (ratio 1:30)	1675.59
4		350 (ratio 1:45)	2719.97
5	Eight	450	1272.34
6		390 (ratio 1:15)	989.4
7		350 (ratio 1:30)	831.01
8		300 (ratio 1:45)	655.55
9	Ten	350	789.43
10		300 (ratio 1:15)	617.22
11	Twelve	300	565.48

(Ratio indicates the proportions by which diameters decreased)

Table 3: Cost of concrete and steel in INR for optimized diameters

SN	**Number of columns**	**Optimized diameter of columns**	**Quantity of concrete**	**Cost of concrete**	**Quantity of steel**	**Cost of steel**	**Total cost includes cost of concrete and steel**
		(mm)	**(m^3)**	**(Rs.)**	**(tones)**	**(Rs.)**	**(Rs.)**
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**
1	Six	450 (ratio1:15)	15.27	88535.5	0.998	54570.64	143106.14
2	Eight	300 (ratio1:45)	9.04	52413.92	0.658	35979.44	88393.36
3	Ten	300 (ratio1:15)	11.3	65517.40	0.775	42377	107894.4
4	Twelve	300 (ratio1:00)	13.57	78678.86	0.852	46587.36	125266.22

Table 3 gives a close loop of the finalized optimized diameter of number of columns. For this optimally designed number of columns quantity of steel and concrete is converted in terms of Rupees. Finally the total cost for the particular optimized diameter of number of columns is shown (column No. (7)).

For rate of concrete and steel CSR manual 2013-14, PW Division Nagpur is used as per CSR.

(i) Rate of concrete for M25 is taken as 5798/cum as per item no. 3, pp 14.

(ii) Rate of steel for Fe 415 is taken as 54680/tonne as per item no. 20, pp 23.

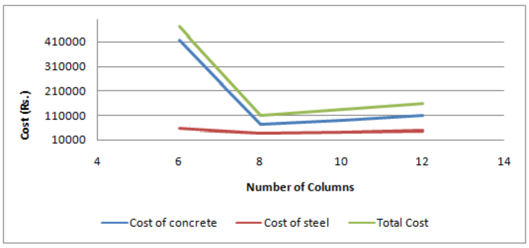


Figure13: Cost Optimization curve for six, eight, ten andtwelve columns for radial arrangement.

It is observed from the Figure 13 that the cost of steel and concrete is more for six numbers of columns. It decreased for eight number of columns drastically then found increasing linearly with increase in number of columns.

VII. OBSERVATIONS

- Normal type of arrangement has more deflection than cross and least in radial, and vice versa is the stiffness.
- For tank full and tank empty conditions, as staging levels increases; Base Shear with Base Moment increases and Roof Displacement decreases.
- For tank full and tank empty conditions, as number of columns increases; Base Shear with Base Moment decreases and Roof Displacement increases.
- For tank full and tank empty conditions, Base Shear and Base Moment is more for radial arrangement then cross and least for normal type of arrangement.
- Tank Empty condition has less Base Shear and Base Moment compared to tank full condition.

For Roof Displacement the condition is vice versa.

- Roof Displacements of all models are within permissible limits as per IS 1893 (PartI): 2002.
- For Eight columns quantity of concrete and steel required is less compared to six, ten and twelve columns for the respective optimized diameters.

VIII. CONCLUSIONS

Radial arrangement with six staging levels is best suited for six, eight, ten and twelve number of columns followed by cross and normal.Full tank condition shows critical responses than empty tank conditions. But we cannot neglect the structural responses of empty tank condition.Eight columns with 300mm optimized diameter are giving less cost (quantity of steel and concrete) than six, ten and twelve columns optimized diameter for radial arrangement, six staging levels and full tank condition only. It can be said that sometimes instead of increasing number of columns for the stiffened of structure or safety, it is better to optimize after assuring proper structural responses.

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