Seismic Assessment of RC Framed Staging of Elevated Water Tanks

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1 Introduction

Seismic behaviour of elevated water tanks are very complex due to the coupled fluid–structure interaction. Past earthquakes have revealed the vulnerability of these structures under seismic excitation. Engineers study and learn from those disastrous experiences to increase the robustness of these complex structures. Seismic codes are evolving every day following the scientific contributions from different ideas throughout the globe. Present seismic codes of different countries including Indian Seismic Code on Liquid Retaining Tanks [1] follow the Housner model of spring-mass system [2–5]. Previous documented literatures suggest that according to Housner model if the ratio of the convective mode to the impulsive mode of time period (T_c/T_i) is greater than 2.5, then the coupled fluid–structure interaction can be uncoupled for simplified analysis [6–8]. Also, greater value will decrease the chance of forming coupled resonance condition between the fluid and the structure [9]. This ratio is strongly dependent on the number of panels and the height to diameter ratio of the RC framed staging (h_s/D_s). For some values of the staging aspect ratio (h_s/D_s), the value of T_c/T_i can be less than 2.5. Hence, the present study focuses on finding some optimal ranges or specific values of the staging aspect to satisfy the desirable criteria. Also, the study reveals some efficient remedies for the structures to come under that provision without major negotiation to the proposed aspect ratio.

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S. Kolathayar and S. C. Chian (eds.), *Recent Advances in Earthquake Engineering*, Lecture Notes in Civil Engineering 175,
https://doi.org/10.1007/978-981-16-4617-1_6

2 Methodology

2.1 Tank Models

Elevated circular concrete water tank with flat roof is considered for this seismic assessment study. Two models of small (80 m^3) and large (500 m^3) capacities are taken into account with different staging aspect ratio. Analysis of elevated intze tanks can be simplified by considering an equivalent cylindrical tank container of same capacity [6, 7]. Therefore, the present study can also be used for intze type tank of same capacity. The dimensional parameters of different structural elements are listed in Table 1.

The above-mentioned dimensions of structural elements are consistent throughout the entire analysis. Bracings of staging system are comprised of horizontal circumferential tie beams only. As the aspect ratio of staging (h_s/D_s) varies, the aspect ratio of the tank container (h_t/D) and the number of panels change. In consequence of that these parameters are not listed as constant dimensions in the Table 1.

2.2 Analysis of Tanks

Various seismic codes of different countries follow the analysis method proposed by Malhotra et al. [10] which is a generalized and simplified extension of Housner model. The present study also takes the path shown by Malhotra to assess convective time period (Tc) of the tank models. The lateral stiffness of the staging is calculated following a method proposed by Sameer and Jain [11] to evaluate the impulsive time period (Ti) of elevated tanks. The small tank is considered to be located in a low seismic zone, whereas the large tank is situated in high seismic zone. Both the tanks are built on a soft soil.

The variable parameters in this study are the height of staging (h_s), diameter of staging (D_s), diameter of tank container (D), height of water level (h), height of sloshing (h_{sl}), height of tank container (h_t), number of columns in plan and the number of panels. Among these parameters D is taken as approximately equal to D_s

Table 1 Detail of structural elements of tank models

Structural elements	80 m^3 tank	500 m^3 tank
Thickness of roof (tr)	0.12 m	0.2 m
Thickness of wall (tw)	0.2 m	0.25 m
Thickness of base slab (tb)	0.2 m	0.25 m
Dimension of floor beam	0.6 m × 0.25 m	0.7 m × 0.4 m
Diameter of staging column	0.45 m	0.8 m
Dimension of staging brace	0.45 m × 0.3 m	0.7 m × 0.5 m

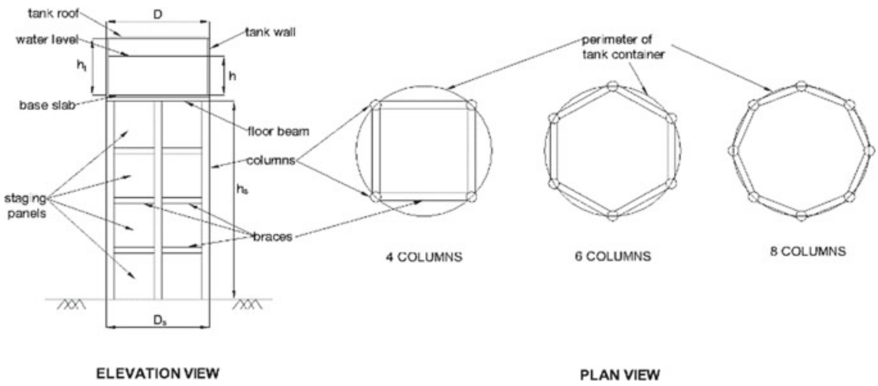


Fig. 1 Detail of structural elements and their corresponding notations

and h_t is considered as the upper limit approximate sum of h and h_{sl} where h_{sl} is also a dependent variable of h/D. Therefore, as long as the D_s is constant the value of D, h, h_{sl}, h_t will not vary. In case of both the tanks, variations of the results are carried out for four, six and eight numbers of columns in plan. All these notations and detail of structural elements are shown below (see Fig. 1).

The parameters h_s, D_s and number panels are taken for three different cases. In the first case, D_s and panel height are fixed with variation in h_s only. In the second case, h_s and D_s are fixed with variation in number panels only. And in the last case, h_s and panel height are fixed with variation in D_s. For the last case, the variation in D_s causes D, h, h_{sl} and h_t to vary also. And for all the cases, number of columns in plan are taken as three different values of 4, 6 and 8. These three cases for both the tanks are tabulated in Tables 2 and 3, respectively.

All the three cases are performed according to the above-mentioned methods to obtain the impulsive and convective mode of time periods and their ratio. For both the tanks in case 1 and 2, the aspect ratios of the tank containers are taken by considering h/D as nearly equal to 0.5 for finding rest of the parameters accordingly.

3 Results

The results obtained from the entire assessment of the tank models are discussed in this section. As the number of columns in the plan increases, the stiffness of the structure increases, subsequently, the impulsive time period gets reduced and the ratio T_c/T_i gets increased. This effect can be seen in all the data provided below (see Figs. 2, 3, 4, 5, 6 and 7). Our goal is to achieve the value of T_c/T_i greater than 2.5 and for any scenario this value should not lie below 2.5. For all the cases of both the tanks, it can be observed that 4 columns in plan is intuitively more vulnerable to

Table 2 Variation of parameters in 80 m^3 tank model

	$D_s = D$ (m)	h (m)	h_{sl} (m)	h_t (m)	Panel height (m)	No. of panels	h_s (m)	h_s/D_s
Case 1	6	2.85	0.25	3.2	3	2	6	1
						3	9	1.5
						4	12	2
						5	15	2.5
						6	18	3
						7	21	3.5
						8	24	4
Case 2	6	2.85	0.25	3.2	6	2	12	2
					4	3		
					3	4		
					2.4	5		
					2	6		
Case 3	12	0.71	0.33	1.1	3	4	12	1
	8	1.6	0.23	2				1.5
	6	2.85	0.25	3.2				2
	4.8	4.45	0.23	4.7				2.5
	4	6.4	0.21	6.7				3
	3.43	8.7	0.19	8.9				3.5
	3	11.4	0.18	11.6				4

generate coupled resonance between fluid and structure compared to 6 and 8 number of columns.

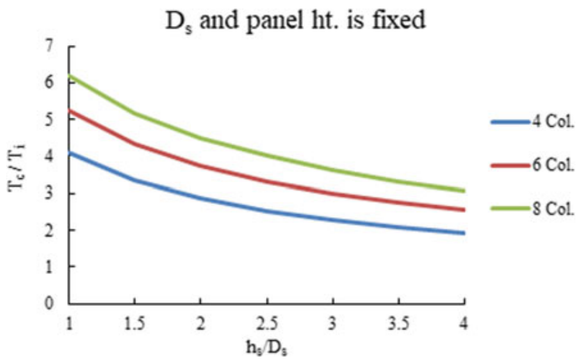
From Fig. 2, it can be seen that T_c/T_i value gets reduced as the number of panels as well as h_s increases. For 4, 6 and 8 number of columns in plan, it is safe to limit the h_s/D_s value to 1.5, 2.5 and 3.5, respectively, with 4 panels in each case. Comparing Figs. 3 and 4, it can be concluded that at least 3 panels should be provided when h/D and h_s/D_s is limited to 0.5 and 1.5, respectively. Also, from economic view-point if number of panels cannot be increased above 5 then h_t/D and h_s/D_s should be limited to 1 and 3, respectively. Hence, for any tank of capacity less than 100 m^3, the maximum value of h_s/D_s should be taken as 2 with 4 columns and 5 panels, 2.5 with 6 columns and 5 panels and 3 with 8 columns and 5 panels, by keeping the h_t/D value less than 1. Otherwise, if these values exceed, then either the dimensions of the columns and braces must be increased or the radial braces must be used.

From Fig. 5, it can be seen that T_c/T_i value gets reduced as the number of panels as well as h_s increases. For 4, 6 and 8 number of columns in plan, it is safe to limit the h_s/D_s value to 1.5, 2 and 2.5, respectively, with 4 panels in each case. Comparing Figs. 6 and 7, it can be concluded that at least 4 panels should be provided when h/D and h_s/D_s is limited to 0.5 and 1.5, respectively. Also, from economic view-point if

Table 3 Variation of parameters in 500 m^3 tank model

	$D_s = D$ (m)	h (m)	h_{sl} (m)	h_t (m)	Panel height (m)	No. of panels	h_s (m)	h_s/D_s
Case 1	11	5.26	1.21	6.5	5.5	2	11	1
						3	16.5	1.5
						4	22	2
						5	27.5	2.5
						6	33	3
						7	38.5	3.5
						8	44	4
Case 2	11	5.26	1.21	6.5	11	2	22	2
					7.33	3		
					5.5	4		
					4.4	5		
					3.67	6		
					3.14	7		
					2.75	8		
Case 3	22	1.315	2.17	3.5	5.5	4	22	1
	14.67	2.96	1.45	4.5				1.5
	11	5.26	1.21	6.5				2
	8.8	8.22	1.12	9.4				2.5
	7.33	11.84	1.02	12.9				3
	6.28	16.14	0.94	17.1				3.5
	5.5	21.05	0.89	22				4

Fig. 2 Variation of T_c/T_i with respect to h_s/D_s (Case 1) of 80 m^3 tank model



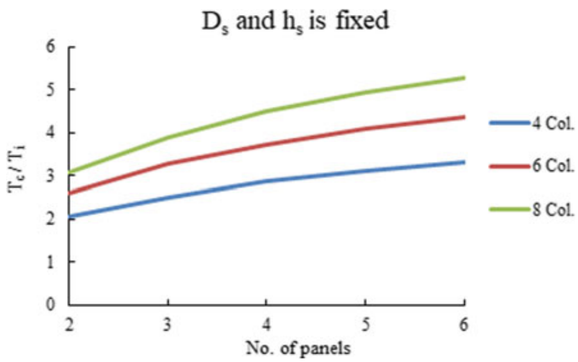


Fig. 3 Variation of T_c/T_i with respect to panel numbers (Case 2) of 80 m^3 tank model

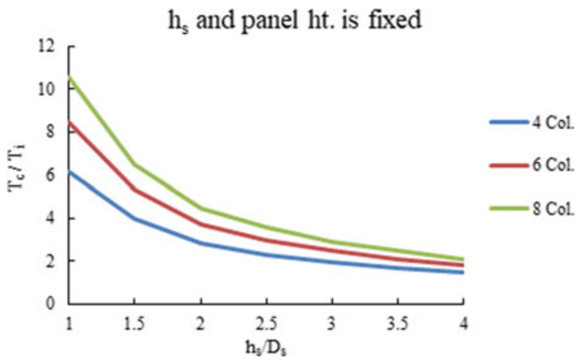


Fig. 4 Variation of T_c/T_i with respect to h_s/D_s (Case 3) of 80 m^3 tank model

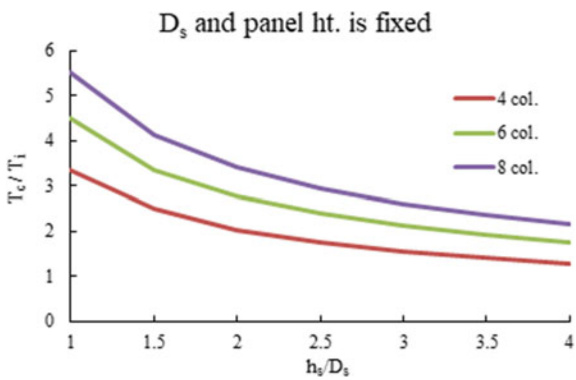


Fig. 5 Variation of T_c/T_i with respect to h_s/D_s (Case 1) of 500 m^3 tank model

number of panels cannot be increased above 6 then h_t/D and h_s/D_s should be limited to 1 and 3, respectively. Hence, for any tank of capacity up to 500 m^3, the maximum value of h_s/D_s should be taken as 1.5 with 4 columns and 6 panels, 2.5 with 6 columns and 6 panels and 3.5 with 8 columns and 7 panels, by keeping the h_t/D value less than 1. Otherwise, if these values exceed, then either the dimensions of the columns

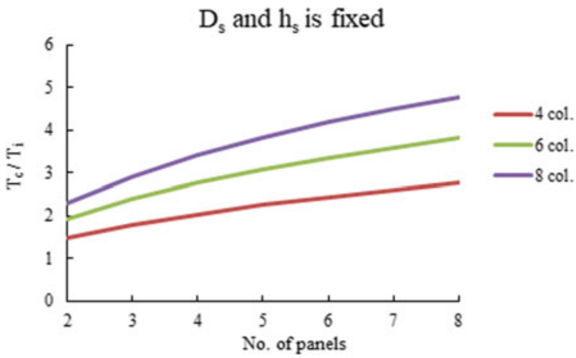


Fig. 6 Variation of T_c/T_i with respect to panel numbers (Case 2) of 500 m^3 tank model

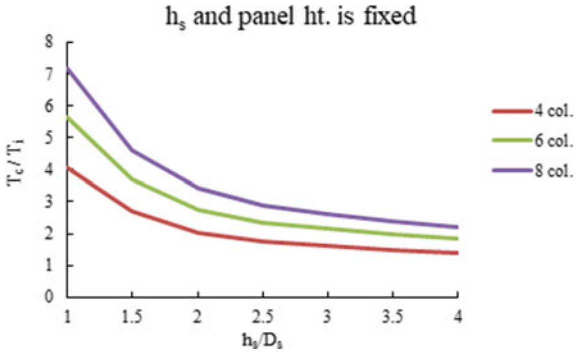


Fig. 7 Variation of T_c/T_i with respect to h_s/D_s (Case 3) of 500 m^3 tank model

and braces must be increased or another concentric staging with lesser diameter of circumference must be used.

4 Conclusion

Elevated water tanks are more vulnerable under seismic excitation than ground-supported tanks because of the elevated limped mass system. When the ratio of the convective mode to the impulsive mode of time period (T_c/T_i) lies below 2.5, the coupled resonance between fluid and structure generates which can cause detrimental damage or collapse of the structure. This study suggests some efficiently proportioned aspect ratio of staging (h_s/D_s) as well as container (h_t/D), number of columns and panels in the staging. In case of tanks having capacity of less than 100 m^3, the h_s/D_s value should be limited to 2 with 4 columns and 5 panels keeping h_t/D within 1 for economical design. If the value of h_s/D_s exceeds, then either the dimensions of staging elements can be increased or the number of columns can be increased with panel numbers by interpolating the above-mentioned graphical data. In case of tanks having capacity up to 500 m^3, the h_s/D_s value should be limited to 3 with 8 columns and 6 panels keeping h_t/D within 1 for economical design. If the value of h_s/D_s exceeds, then either the dimensions of staging elements can be increased or the number of columns can be increased with panel numbers by interpolating the above-mentioned graphical data. For extreme cases, the use of radial braces or extra concentric staging of lesser diameter can be used in large tanks.

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