IOSR Journal of Engineering (IOSRJEN) **www.iosrjen.org**
ISSN (e): 2250-3021, ISSN (p): 2278-8719
PP 45-53

Analysis of Elevated Circular Storage Reservoir of High Capacity with Different Staging Height Using IS 1893(Part II):2014

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Abstract— *The main aim of this study is to understand the behavior of elevated circular storage reservoir of large capacity for different staging height, so as to get better performance of structure during any climatic conditions. Normal type of bracing is applied to the staging of elevated circular water tank for earthquake zone II of India. Analysis is carried using Staad Pro. Software. Nine models are used for calculating base shear and displacements for different H/D ratios of 0.4, 0.5, and 0.6. Variation of staging height is 14m, 18m, 22m i.e. at 4m interval each. Sloshing forces and base shear was calculated from IIT Kanpur GSDMA and IS 1893(Part II):2014. Hydrodynamic pressure for impulsive and convective mode was calculated. An attempt has been made to study the effect of variations in staging height on the seismic behavior of elevated water tank.*
Keywords: *Circular water tank; Convective pressure; Impulsive pressure; sloshing height*

I. Introduction

Liquid tanks are important public utility and industrial structures [1]. ESRs are major structures in any water distribution system. Water is stored in the container at a certain height above ground level and further distributed by gravity. Several towns have water supply system which depends on overhead water tanks for life. Water distribution systems use ground supported and elevated tanks of RC & steel. Petrochemical industries use ground supported steel tanks.

These structures are especially vulnerable to an earthquake because of a large amount of mass concentrated at top of the slender supporting structure [2]. Because of a large amount of mass of tank and smaller exposed area, earthquake forces govern the lateral force design criteria [2]. Therefore out of the total cost of the structure, the major cost goes in constructing the structure as earthquake resistant. Specifications, designs and construction method in reinforced concrete structures are influenced by the already existing construction practices, physical properties of the material and the environmental condition [2]. Design criteria for elevated water tanks require a careful consideration and compromise between economy and importance for ensuring the safety of these structures [2].

Design of Water retaining structures is governed by following BIS codes
1) IS 3370 (I):1965 /2009– “General Requirements”
2) IS 3370 (II):1695/2009–“Reinforced Concrete Structures”
3) IS 3370 (III):1965 - “Prestressed Concrete Structures**”**
4) IS 3370 (IV):1967 - “Design tables”.
IS 3370 takes care of making structure water leak proof.

Design of water retaining structure has to be based on avoidance of cracking in concrete. Additionally the calculated tensile stress on water retaining face of equivalent concrete section shall not exceed limits specified or as per limit state method. Crack width shall not exceed 0.2/0.1 mm. Members of the container of elevated water tank are always in contact with water. It is therefore mandatory to design them by uncracked theory of concrete as per IS 3370(Part I, II & IV)-2009-1967. Crack widths are minimized by using higher grade of concrete and limiting the tensile stress in concrete within the permissible level. Permissible stresses in steel are suitably reduced to achieve the above purpose. Thus the leakage of water is prevented.

1. Analysis of Elevated Water Tank According to IS 1893:2014 (Part II)

Modeling of liquid as a two-mass model is the main modification in IS 1893(Part II):2014. Total liquid mass, m, gets divided into two parts: Impulsive liquid mass, m_i, Convective liquid mass, m_c [5]. The liquid in a bottom portion of the container moves with wall [5]. It is called impulsive liquid [5]. The liquid in top portion undergoes sloshing and moves relative to the wall [5]. It is called convective liquid or sloshing liquid [5]. The impulsive liquid moves with wall and is rigidly attached to it [5]. It has same acceleration as the wall [5]. The convective liquid which is also called sloshing liquid moves relative to the wall [5]. It has different acceleration than the wall. Impulsive & convective liquid exerts pressure on the wall [5].

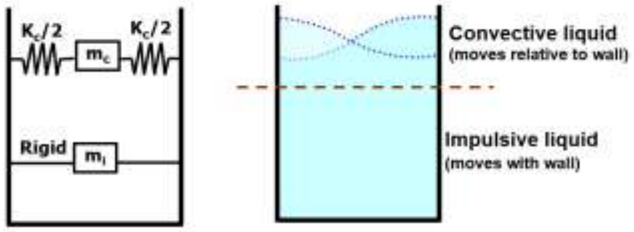


Fig. 1: Convective and Impulsive mass of liquid

In seismic design, a mechanical analog of tanks are used, wherein, the liquid is replaced by impulsive & convective masses [5]. These masses and their points of application depend on aspect ratio [5]. Graphs and expressions are available to find all these quantities [5]. These are based on work of Housner (1963). Impulsive and convective masses have different time periods and hence, have different S_a/g values. Sometimes, the summation of m_i and m_c may not be equal to total liquid mass, m. This difference may be about 2 to 3 % [5]. If the difference is of concern, then first, m_c is observed from the graph or expression and then $m_i = m - m_c$ is obtained. Mechanical model based on rigid wall assumption is considered adequate for design [5]. Elevated tank consists of container and staging [5]. Lateral stiffness, K_s, of staging is considered [5]. This makes it a two-degree-of-freedom model which is also called two mass idealizations [5].

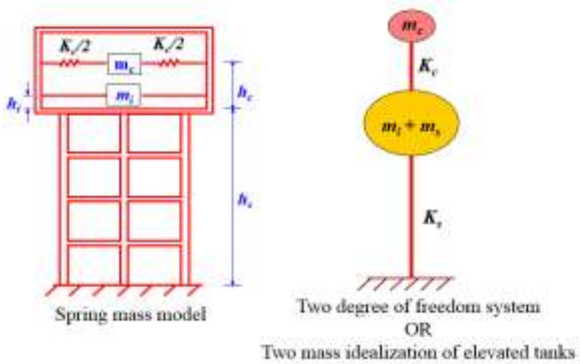


Fig. 2: Two mass idealization of the elevated tank

Based on mechanical models, the time period for impulsive and convective modes is obtained for elevated tanks [5]. Seismic force is obtained by $V = (A_h) \times (W)$ where A_h is base shear coefficient [5].

Seismic force in impulsive mode (impulsive base shear)

$V_i = (A_h)_i$ x impulsive weight

Seismic force in convective mode (convective base shear)

$V_c = (A_h)_c$ x convective weight

Where,

$(A_h)_i$ = impulsive base shear coefficient

$(A_h)_c$ = convective base shear coefficient.

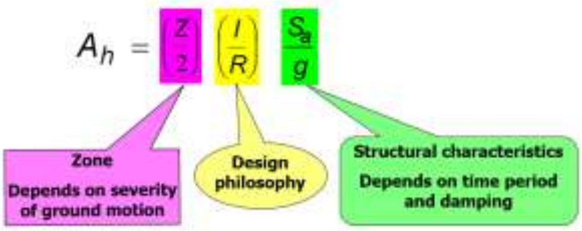


Fig. 3: Base Shear Coefficient

Impulsive and convective base shear are combined using Square Root of Sum of Square (SRSS) rule [5]. In elevated tanks, base shear at the bottom of staging is of interest and M_s is structural mass [5].
Base shear in impulsive mode,

$$V_i = (A_h)_i (m_i + m_s) g$$

Base shear in convective mode,

$$V_c = (A_h)_c m_c g$$

Total base shear, V is obtained as:

$$V = \sqrt{V_i^2 + V_c^2}$$

Structural mass, m_s comprises of the mass of empty container and 1/3rd mass of staging whereas the mass of container includes the mass of roof slab, the mass of the wall, the mass of floor slab and beams [5]. m_s is assumed to act at CG of the empty container and CG of the empty container shall be obtained by considering roof, wall, floor slab and floor beams [5].
Bending moment at the bottom of staging,

$$M_i^* = (A_h)_i \left[m_i \left(h_i^* + h_s\right) + m_s h_{cg} \right] g$$

$$M_c^* = (A_h)_c m_c \left(h_c^* + h_s\right) g$$

Where,
h_s = staging height (Measured from top of footing to bottom of wall)
h_{cg} = distance of CG of empty container from bottom of staging.
Total bending moment,

$$M^* = \sqrt{M_i^{*2} + M_c^{*2}}$$

Elevated tanks are analyzed for tank full as well as tank empty conditions and design is done for the critical condition [5]. In empty condition, no convective liquid mass is considered and hence, the tank will be modeled using a single degree of freedom system [5]. Mass of empty container and 1/3rd staging mass shall be considered [5]. Lateral stiffness of staging, K_s will remain same in full and empty conditions [5]. In full condition, mass is more and therefore in empty condition mass is less [5]. Hence, the time period of an empty tank will be less [5]. Hence, S_a/g will be more [5]. Usually, tank full condition is critical, however, for tanks of low capacity, the empty condition may become critical [5].
For frame staging consisting of columns and braces, IS 11682:1985 suggests that horizontal seismic loads shall be applied in the critical direction (IS 11682:1985, "Criteria for Design of RCC Staging for Overhead Water Tanks", Bureau of Indian Standards, New Delhi) [6].
Clause 7.1.1.2 Horizontal forces – Actual forces and moments resulting from horizontal forces may be calculated for critical direction and used in the design of the structures. The analysis may be done by any of the accepted methods including considering as space frame [6].
Clause 7.2.2 Bending moments in horizontal braces due to horizontal loads shall be calculated when horizontal forces act in a critical direction. The moments in braces shall be the sum of moments in the upper and lower columns at the joint resolved in the direction of horizontal braces [6].

II. Methodology

In the present paper different staging height for constant capacity is studied with the help of IS codes namely IS 1893:2002, IS 1893(Part I):2016, (Part II):2014 and with the help of computer software Staad Pro. It deals with the analysis of elevated water tanks. The behavior of hydrodynamic pressure is understood. The hydrodynamic pressure is acting due to division of water into convective and impulsive masses respectively [6]. The portion of the tank fluids that act in impulsive mode largely depends on the aspect ratio (height/diameter) of the tank [6]. For tanks of very low aspect ratio, a very little of tank fluids acts in the impulsive mode [6]. Spring-mass idealization as per IS 1893(Part II):2014 has been used to evaluate the seismic base shear.

The capacity of the tank is kept constant as 1800 m^3 for the study. In total nine models are made having different staging heights and different H/D ratios so as to optimize the structure. Different H/D ratios are 0.3, 0.4, 0.5 and different staging heights are 18m, 22m, 26m. The tank is analyzed in zone II with wind speed 44 m/sec. A grade of concrete and steel is M30 for container and Fe500 respectively. Before taking up designs, the designer should decide the most suitable configuration of the tank and staging. The configuration for the economy does depend on a method of constructions, a number of tanks, reusing formwork and experience of construction of a particular structure, and hence cannot be governed by general rules [2]. Most optimization studies do not consider the parameters influenced by construction and hence results have limited applications [2].

Table 1: Dimension details of tank

Elevated Circular Tank (Constant Capacity - 1800 m^3)			
Staging height	18m, 22m, 26m		
H/D Ratio	0.3	0.4	0.5
Dia of container	20	18	17
Height of container	6	7.2	8.5
C.G of container	3	3.6	4.2
No. of columns	21	21	21
Bracing Levels	4	4	4
Free Board	0.4	0.4	0.4

Table 2: Loads Applied

Loads on Staad Pro. , Staging height 18 m			
H/D Ratio	0.3	0.4	0.5
Sloshing Forces			
Impulsive (kN)	256	221	192
Convective (kN)	159	126	98.5
Water Pressure on base slab			
WL=9.81 X H kN/m^2	58.86	70.63	83.38

Table 3: Loads Applied

Loads on Staad Pro, Staging height 22 m			
H/D Ratio	0.3	0.4	0.5
Sloshing Forces			
Impulsive (kN)	210	196	189
Convective (kN)	146	98	95
Water Pressure on base slab			
WL=9.81 X H kN/m^2	58.86	70.63	83.38

Table 4: Loads Applied

Loads on Staad Pro, Staging height 26 m			
H/D Ratio	0.3	0.4	0.5
Sloshing Forces			
Impulsive (kN)	164	152	148
Convective (kN)	101	96	93
Water Pressure on base slab			
WL=9.81 X H kN/m^2	58.86	70.63	83.38

Along with above loads, a 10 kN loads is applied to obtain defection of the C.G of the tank. The total mass of structure according to IS 1893(Part II):2014 is taken as the mass of container plus one-third mass of staging. Weights of floor finish and plaster is accounted, wherever applicable [3]. Live load on roof slab and gallery is not considered for seismic load computations as per IS 1893:2014 [3]. Water load is considered as dead load [3]. For seismic analysis, freeboard is not included in the depth of water [3]. The arrangement of water load is such as to cause the most critical effects [1]. The term water load includes the effect of water pressure [1]. Imposed loads or live loads are in accordance with IS 875(Part 2):2015 [1]. Wind load is estimated as per IS 875(Part 3):2015. Load combinations consider both the tank empty and tank full conditions. Wind and seismic loads are not being assumed to act together [1]. Effect of sloshing or convective mass of liquid is considered for the design of staging [1]. Both impulsive and convective effects are considered simultaneously, which results in two mass model idealization which is technically more appropriate, and also gives an economical design of staging [1].

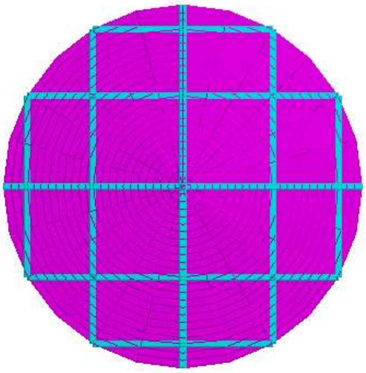


Fig. 4: Plan

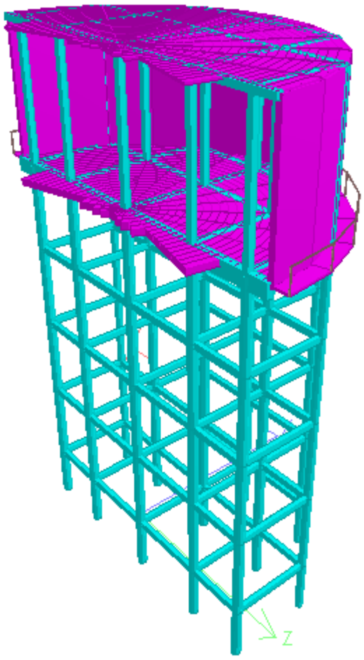


Fig. 5: Isometric view of the elevated circular water tank

Wind forces acting on the structure are calculated as per IS 875 (Part III):2015. It has introduced various factors such as a) K_d = Wind directionality factor [The factor recognizes the fact of (i) reduced probability of maximum winds coming from any given direction (ii) reduced the probability of the maximum pressure coefficient occurring for any given wind direction. (This factor has not been included in the 1987 version of the Code.)]. b) K_a = Area averaging factor: the Surface area from which the wind forces get transferred to the part of the structure being designed. This area is defined as the tributary area for the part of the structure. c) K_c = Combination factor. Already existing parameters are Risk Coefficient (k1), Terrain and height factor (k2), Topography (k3), Importance Factor for Cyclonic Region (k4).

Design Wind Speed (Vz), $Vz = V_b\ k1\ k2\ k3\ k4$

Design Wind Pressure (Pz), $Pz = 0.6\ V_z^2$.

Since a huge mass is accumulated at a great height, lateral analysis and design are done for earthquake forces and wind forces are ignored because they are most of the times critical when compare with earthquake forces. The Design wind pressure induces the forces on members according to the shape and size of the member.

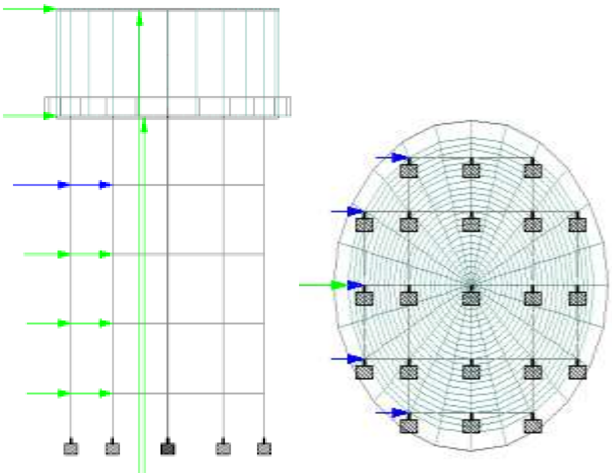
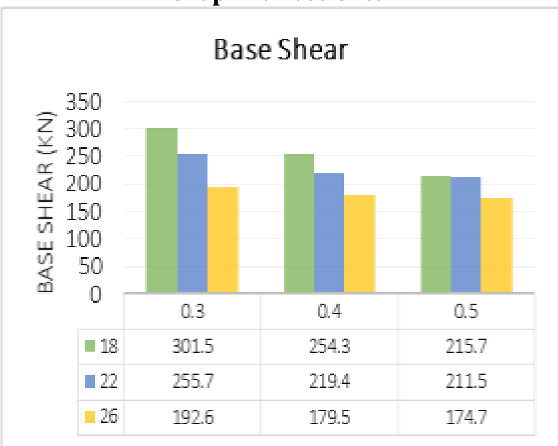


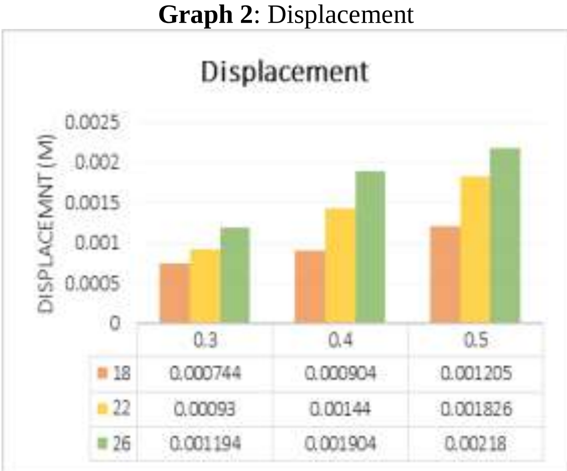
Fig. 6: Vertical and horizontal wind forces

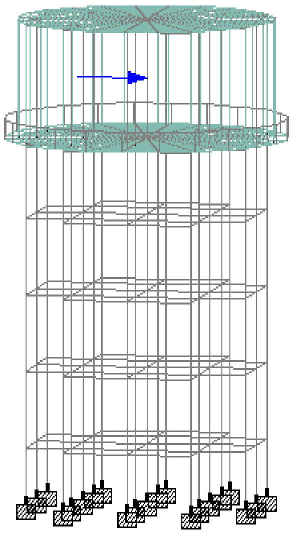
III. Analysis and Results

Graph 1: Base Shear



Graph 2: Displacement



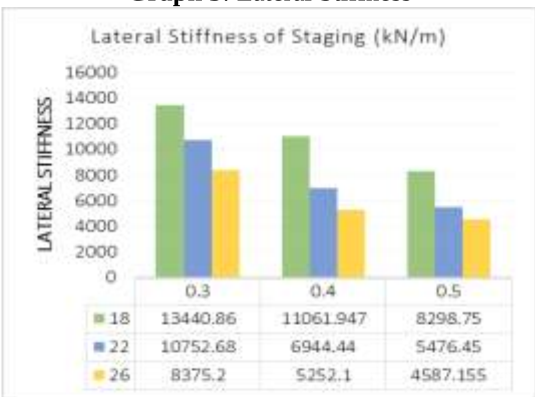


Deflection of CG of tank due to an arbitrary 10 kN force is obtained. Lateral stiffness of staging is defined as the force required to be applied at the CG of tank so as to get a corresponding unit deflection. CG of tank is taken as CG of empty container.

Fig. 7: 10 kN Applied At CG of Tank

Under design wind load or designed seismic load, the lateral sway at the top should not exceed Ht/500, where Ht is the total height of the tower (including container) according to Bureau of Indian Standards (BIS) [1].

Graph 3: Lateral Stiffness



Lateral stiffness of the staging is the horizontal force required to be applied at the center of gravity of the tank to cause a corresponding unit horizontal displacement [4].

Graph 4: Mass of Structure

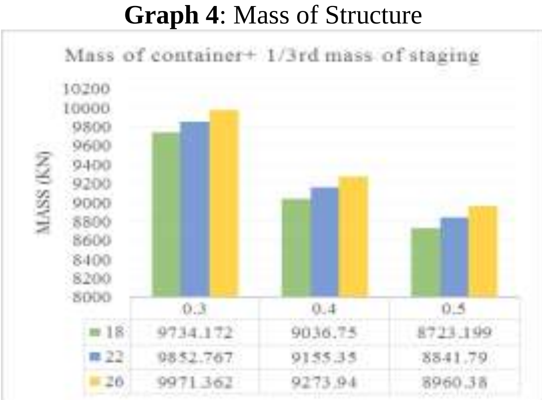


Table 5: Column Optimization

Optimized Dia Of Column (mm)			
H/D Ratio	0.3	0.4	0.5
Staging Height			
18 m	450	450	450
22 m	500	500	500
26 m	500	500	500

Table 6: Bracing Optimization

Optimized Section Of Bracing (mm)			
H/D Ratio	0.3	0.4	0.5
Staging Height			
18 m	250 X 350	250 X 350	250 X 350
22 m	300 X 450	300 X 450	300 X 450
26 m	300 X 450	300 X 450	300 X 450

Table 7: Shear Force in Bracing

Shear Force In Bracing (kN)			
H/D Ratio	0.3	0.4	0.5
Staging Height			
18 m	213.95	253.61	301.7
22 m	196.46	244.92	282.16
26 m	188.12	216.54	263.45

Table 8: Axial Force in Column

Axial Force In Column (kN)			
H/D Ratio	0.3	0.4	0.5
Staging Height			
18 m	1610.3	1696.4	1721.4
22 m	1724.8	1782.1	1811.9
26 m	1859.1	1874.3	1909.2

Table 9: Base Moment

Base Moment (kN-m)			
H/D Ratio	0.3	0.4	0.5
Staging Height			
18 m	18411.15	21484.41	24600.93
22 m	19999.70	23300.73	26647.75
26 m	21981.48	25558.78	29179.54

IV. Conclusion

1) As staging levels increases, the deflection increases and stiffness decreases.
2) Time Period is found to be varying between 3.8 sec to 16.5 sec for convective mode. For medium soil Sa/g is calculated by 1.36/T formula, resulting in very low values of Sa/g.
3) Natural time period in impulsive mode of liquid is directly proportional to height of supporting system**.** As the height of supporting system increases staging stiffness decreases and time period is inversely proportional to the stiffness.
4) The natural time period in the convective mode of liquid remains constant even if the height of supporting system increases because it depends upon the value of the coefficient of convective mode (Cc) which depends on h/D ratio which is constant for all the tanks.
5) Time period for impulsive mode of vibration is much less than that for convective mode.
6) The base shear in impulsive mode slightly increases with increase in staging height while for convective mode it remains constant.
7) Hence, base shear in impulsive mode increase with increase in h/d ratio while for convective mode it is reversed.
8) It is the impulsive mode which dominates the loading on the tank wall.
9) Base moment for elevated water tank is directly proportional to height of supporting system for tank full condition and also for tank empty condition
10) Base moment in impulsive mode increase with increase in h/d ratio while for convective mode it is vice versa.
11) A total base moment in impulsive and convective mode increases with increase in staging height.
12) Hydrodynamic pressure acts due to:

- Vertical Excitation – Due to vertical ground accelerations

- Wall Inertia – Uniformly distributed along the wall height
- Impulsive Hydrodynamic Pressure – at Base of Wall and on the base Slab
- Convective Hydrodynamic Pressure – At Base of the wall (y = 0, y = h) and on-base slab.

13) Total hydrodynamic pressure is obtained by combining these pressures as per SRSS.
14) Hydrodynamic pressure variation in impulsive mode increases with increase in h/d ratio whereas the hydrodynamic pressure variation in convective mode decreases with increase in h/d ratio and same is observed with variation of the height of staging.
15) The maximum hydrodynamic pressure increases with increase in h/d ratio.
16) Sloshing wave height remains constant for a given h/D ratio.
17) Sloshing wave height result represents that, it's necessary to provide free board for partially filled tanks or else the roof of tanks should be designed to resist the uplift pressure of liquid. The sloshing wave height of the above models is obtained from the formula introduced in IS 1893(Part II):2014. It is within the freeboard assumed initially for different cases. The sloshing occurs due to convective mass only.
18) Lateral stiffness of staging, K_s remains same in full and empty conditions.
19) As H/D ratio and staging height increases concrete and steel cost increases.
20) The total of impulsive mass and convective mass is equal to the total mass of water. However, in some cases, there may be a difference of 2 to 3%.
21) The base shear and overturning moment depends on the stiffness of staging system.
22) As the staging height increases the displacement of CG tank increases.
23) As H/D ratio and staging height increases, the axial force in columns increases.
24) Time period of empty tank is less. Hence, S_a/g will be more.

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