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Sloshing Behaviour of Water in Water Tanks and Swimming Pools Subjected to Earthquake

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Abstract—Most swimming pools in multi-storeyed buildings are constructed without considering the consequences that might occur during the event of an earthquake. The sloshing and overtopping of the large volume of water can lead to additional damages. The objective of this study is to model a swimming pool and the sloshing movement of the water retained in it using ANSYS 16. The swimming pool will be modelled as a rectangular flat bottom constant depth concrete water tank. A comparison between the stresses developed when water is modelled as a static body and the stresses developed when sloshing is permitted is also carried out. The effect of variation in positioning the pool at various storeys of the building on the magnitude of stresses developed is also studied.

Index Terms—Sloshing of water, elevated water tank, sloshing in swimming pools, guidelines regarding position of swimming pools, effect of earthquake on open water tanks.

1 Introduction

SLOSHING refers to the movement of the free surface of a liquid due to the movement of its container. Liquid sloshing is an important factor to be considered in various areas such as aircraft fuel tank designs, tankers transporting water and other liquids, sloshing of cargo in ships etc. a swimming pool is another such container of large volume of water where sloshing forces can be significant when subjected to lateral deflections. The large liquid movement during sloshing can result in high impact stresses in the walls of the pool. And in extreme cases can cause sufficient moment to negatively affect the stability of the supporting structure. This paper investigates the additional stresses developed in the additional stresses developed in structures due to sloshing.

2 LITERATURE REVIEW

V.S.Bachal (2006) confirms the need to adopt the new approach of analyzing and designing the water tank by considering it as a two degree of freedom system to make its design economical and safe against additional hydrodynamic pressure due tosloshing of water. Gaikwad Madhurar V and MangulkarMadhuriN(2013) has recognized that during the earthquake, impulsive pressure is always greater than convective pressure for small capacity tanks, but it is vice-versa for tanks with large capacities. Wakchaure ,BesekarSonal (2014) concluded that most of the failures of large tanks after earthquakes are suspected to have resulted from the dynamic buckling caused by overturning moments of seismically induced liquid inertia and surface slosh waves. It was found that if the water tank is excited due to earthquake ground motion the displacement of water in the tank depends upon the volume of water contained in it. The critical response of elevated tanks does not always occur in full condition, it may also occur under half condition. The critical response of the elevated tank in half condition as compared with the full condition is higher.

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3 PROBLEM FORMULATION

To study the effects of sloshing, a constant depth rectangular concrete water tank is modelled. The water in the tank is modelled initially as a static body and the stresses developed on the supporting structure and the tank walls are determined. The sloshing of water is then modelled and the increase in stresses developed due to sloshing is determined. The effect on sloshing on deflection of the structure, critical fill level, and direction of application of the earthquake acceleration is also studied. This investigation is further extended to the effects of sloshing in a constant depth rectangular swimming pool modelled in a symmetric building. Modelling and analysis is done using ANSYS software.

4 STRUCTURAL MODELLING

The pool is modelled as a constant depth concrete rectangular tank of dimensions 20m x 10m, modelled using Solid 187 elements. The tank is supported on four concrete columns of length varying from 4m to 116m (table 1). The tank has been modelled with a depth of 3.5m. The water in the tank is modelled using FLUID 220 elements. Fluid structure interaction is considered by assigning fluid structure interface at the inner walls and base of the pool. Acoustic fluid free surface is assigned at the top face of the fluid to permit sloshing. Acceleration due to gravity is assigned in the vertical direction and earthquake load is assigned along the longer dimension of the pool. Acceleration data of El-Centro earthquake is assigned as lateral earthquake load to the supports.

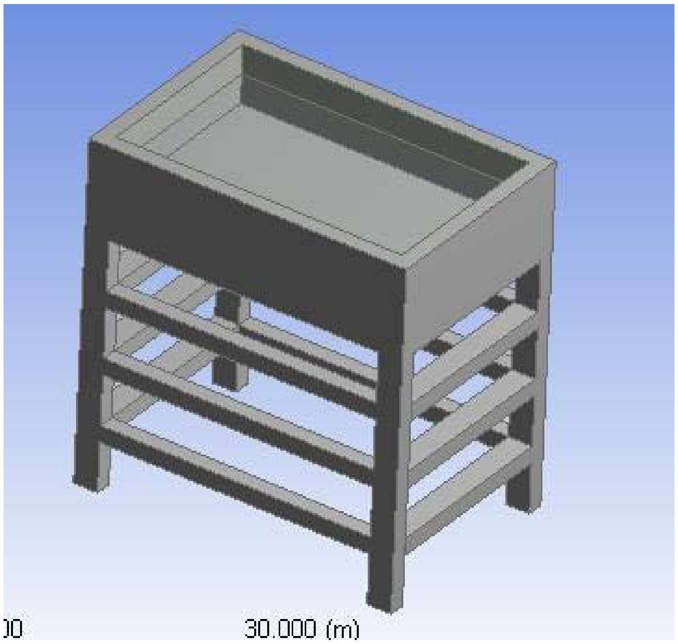

Fig1: Model of tank

Table 1: Dimension of framework

Dimension of the tank	20m X 10m
Depth of the tank	3.5m
Thickness of tank walls	0.8m
Dimensions of columns	1.2m X 0.8m
Dimension of beams	1m X 0.8m
Bay spacing of building in z direction	10m
Bay spacing of building in x direction	10m
Storey height	4m

5 RESULTS AND DISCUSSION

5.1 Comparison between static and dynamic behaviour of water

The stresses on the structure due to the sloshing of water in the pool is compared to the stresses developed when water is modelled as a static body. In the case where sloshing is required, water is modelled as an acoustic body. The fluid-structure interfaces are assigned (along the four inner side faces of the tank walls and the inner base of the tank). The top face of the water is assigned as acoustic free surface. For the case where sloshing is not considered, the weight of water in the tank is assigned as pressure on the inner bottom slab of the tank (density x height).

From table2, it is evident that both shear stress and axial forces have increased as a result of sloshing. The increase in shear stress is more significant as compared to that of normal stress. The increase in shear stress is seen to increase significantly as the staging height increases.

distance from ground level	increase in shear stress (Pa)	increase in axial force (KN)
4m	0.43%	0.13%
12m	0.96%	0.36%
20m	1.36%	0.75%
28m	1.88%	1.13%
36m	2.39%	1.72%
44m	3.05%	2.46%
52m	3.82%	3.25%
60m	5.02%	4.11%
68m	6.45%	5.23%
76m	7.80%	6.49%
84m	9.88%	7.61%
92m	12.36%	8.98%
100m	15.46%	10.48%
108m	18.78%	12.45%
116m	22.65%	14.79%

Table 2: Increase in stresses developed due to sloshing

5.2 Critical water depth

Critical water depth refers to the fill level in a water container at which the stresses developed due to sloshing are maximum. To determine the critical water depth, the fill level in the tank is varied and the equivalent (von mises stress), normal and shear stress is determined for each fill level (table 3). It is observed that the maximum stresses occur when the tank is near half filled. Equivalent stress, normal stress and shear stress were determined in each case. In all cases the maximum stresses were depicted when the tank is filled with 1.75m water depth (50% fill).

5.3 Effect of direction of application of earthquake load on sloshing

Dynamic stresses differ based on the direction of application of the lateral load. The earthquake acceleration was applied along the x direction (along longer span of the tank) and along the z direction (along the shorter span of the tank) and the results were compared. The water fill level was variedfrom empty tank to full tank and the shear stresses for each case was recorded.

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Water depth (m)	Equivalent stress (Pa)	Normal stress (Pa)	Shear stress (Pa)
0h	1.10E+06	1.97E+06	5.60E+05
0.1h	1.14E+06	1.97E+06	5.61E+05
0.2h	1.24E+06	1.99E+06	5.61E+05
0.3h	1.57E+06	2.30E+06	5.97E+05
0.4h	1.89E+06	2.57E+06	6.81E+05
0.5h	1.90E+06	2.59E+06	6.82E+05
0.6h	1.88E+06	2.51E+06	5.71E+05
0.7h	1.57E+06	2.37E+06	5.63E+05
0.8h	1.34E+06	1.98E+06	5.61E+05
0.9h	1.12E+06	1.97E+06	5.61E+05
H	1.12E+06	1.97E+06	5.61E+05

Table 3: Variation in stresses with change in water depth

Water depth (m)	Shear stress (Pa) along x	Shear stress (Pa) along z
0h	5.60E+05	8.42E+05
0.1h	5.61E+05	8.43E+05
0.2h	5.61E+05	8.47E+05
0.3h	5.97E+05	8.61E+05
0.4h	6.81E+05	9.31E+05
0.5h	6.82E+05	9.42E+05
0.6h	5.71E+05	9.30E+05
0.7h	5.63E+05	8.62E+05
0.8h	5.61E+05	8.51E+05
0.9h	5.61E+05	8.43E+05
h	5.61E+05	8.43E+05

Table 4: Variation of stresses with change in direction of application of earthquake acceleration

It can be observed from the results (table 4)that the shear stresses are greater when thesloshing is significant along the shorter spanof the tank.

5.4Effect of sloshing on deflection of the structure

The change in deflection of the structure with the increase in staging height is determined for both cases where sloshing is permitted and for the case where water is assumed static (table5). This analysis was done to provide insight into the idea wherein the sloshing of water can act as a damper to dissipate the energy transferred to the structure during the earthquake via the supports.

The sloshing of water helps dissipate energy transferred to the building during an earthquake. As a result there is a decrease in lateral deflection of the structure.

distance from ground level (m)	deflection without sloshing (m)	deflection with sloshing (m)	decrease in deflection
4	0.0002	0.000170	1.16%
12	0.0004	0.000346	2.21%
20	0.0006	0.000549	3.68%
28	0.0009	0.000850	4.29%
36	0.0014	0.001260	6.64%
44	0.0021	0.001890	8.39%
52	0.0032	0.002829	12.77%
60	0.0048	0.003994	16.26%
68	0.0072	0.005607	22.49%
76	0.0110	0.007895	28.38%
84	0.0179	0.011567	35.44%
92	0.0202	0.011293	44.02%
100	0.0310	0.014198	54.20%
108	0.0500	0.015930	68.14%
116	0.0621	0.012012	80.66%

Table 5: Variation of deflection with position of tank from ground level

5.4 Effect of sloshingwhen water is modelled in intermediate storeys of building

The tank was further modelled inside the building at intermediate storeys. The maximum normal and shear stressesdeveloped on the surrounding beams are tabulated. The stresses developed on the beams supporting the tank when water is modelled as a static body is determined (table6). These stresses are compared to the stresses developed when sloshing is permitted (table7).

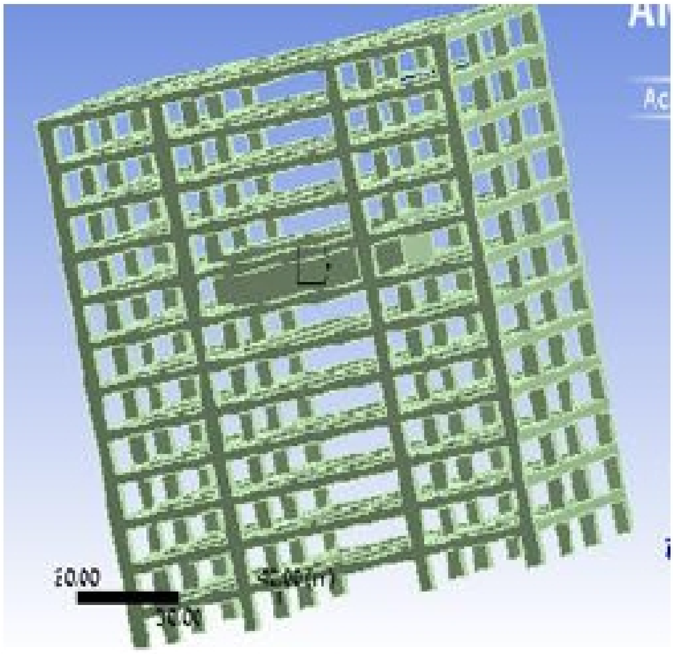

Fig2: Pool modelled inside a symmetric building

position of pool above ground level (m)	water is static	
	normal stress (Pa)	shear stress (Pa)
4	1.31E+06	9.57E+05
12	1.37E+06	9.59E+05
20	1.44E+06	9.61E+05
28	1.49E+06	9.67E+05
36	1.56E+06	9.73E+05
44	1.62E+06	9.78E+05
52	1.74E+06	9.83E+05
60	1.85E+06	9.87E+05
68	1.98E+06	9.93E+05
76	2.12E+06	9.97E+05
84	2.37E+06	9.85E+05
92	2.56E+06	9.92E+05
100	2.77E+06	1.04E+06
108	2.94E+06	1.11E+06
116	3.22E+06	1.27E+06

Table 6: Stresses developed when water is modelled as a

position of pool above ground level (m)	with sloshing	
	normal stress (Pa)	shear stress (Pa)
4	1.31E+06	9.58E+05
12	1.37E+06	9.63E+05
20	1.45E+06	9.69E+05
28	1.50E+06	9.80E+05
36	1.58E+06	9.91E+05
44	1.65E+06	9.99E+05
52	1.78E+06	1.01E+06
60	1.91E+06	1.02E+06
68	2.07E+06	1.05E+06
76	2.24E+06	1.07E+06
84	2.53E+06	1.08E+06
92	2.76E+06	1.11E+06
100	3.00E+06	1.18E+06
108	3.23E+06	1.29E+06
116	3.59E+06	1.50E+06

static body in the building

Table 7:Stresses developed due to sloshing when pool is placed inside building

Table 8: Increase in axial force and shear stress with change in height of pool from ground level

6 CONCLUSION

The conclusions drawn based on the study are:

- Increase in shear and normal stress in a structure due to the sloshing of the water in the pool increases significantly with the increase in staging of the pool above 80m.
- Maximum stresses on the pool walls and supporting structure due to sloshing occur when the pool is about half filled with water.
- Stresses developed due to sloshing when the load is applied along the shorter span is higher than the stresses developed when the load is applied along the longer span of the pool.
- There is a significant decrease in the deflection of the structure due to the sloshing of water retained in the pool. This decrease in deflection increases with the increase in staging height of the pool.
- When the pool is modelled inside a building the effect of sloshing is found to be significant above a height of 90 m from the ground level (table8).

7 FUTURE SCOPE

- The effect of change in earthquake intensity on sloshing in the pools and water tanks can be studied.
- The transient analysis of the building with swimming pool when subjected to both horizontal and vertical excitation can be evaluated.
- The analysis can be extended to pools with sloped bottoms. .

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position of pool above ground level (m)	increase in axial force (KN)	increase in shear stress
4	0.00%	0.10%
12	0.05%	0.42%
20	0.40%	0.83%
28	0.83%	1.34%
36	1.15%	1.85%
44	1.85%	2.20%
52	2.30%	2.99%
60	3.24%	3.75%
68	4.55%	5.64%
76	5.66%	7.10%
84	6.75%	9.14%
92	7.81%	11.90%
100	8.35%	13.46%
108	9.86%	15.77%
116	11.49%	17.87%