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Division III

Sloshing in a Large Water Tank of a Non-standard Configuration Subjected to Seismic Loading

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ABSTRACT

Conceptual design for a new nuclear power station integrates a Passive Containment Cooling (PCC) tank with the upper head of a free standing steel containment structure. The PCC tank configuration is toroidal when viewed in plan, and since supported by the containment structure, the tank base follows the convex elliptical profile of the containment head. This innovative configuration provides passive safe shutdown cooling while allowing containment access through the head and improving the modularity of the power plant. The tank structure must withstand sloshing loads generated during a design-basis safe shutdown earthquake (SSE). Sloshing in a tank with this unique configuration is significantly different than a cylindrical flat-bottom tank, so established sloshing analysis methods are not applicable. A computational fluid dynamics (CFD) analysis is performed to characterize sloshing response in the PCC tank. The resulting slosh frequency, slosh height and structural loads (base shear, and overturning moment) are presented. In addition, the non-linear effects of tank geometry on sloshing are investigated by comparing results to a cylindrical tank having similar dimensions and agitated with the same acceleration time history.

INTRODUCTION

Conceptual design for a new nuclear power station integrates a Passive Containment Cooling Tank (PCCT) with the upper head of a free standing steel containment structure. The PCCT configuration is toroidal when viewed in plan. Because the tank is supported by the containment structure, the tank base follows the convex elliptical profile of the containment head. This innovative configuration provides passive safe shutdown cooling while allowing containment access through the head and improving modularity of the power plant.

Understanding earthquake loading, specifically free surface sloshing behavior of water inside the tank is critical for design of the PCCT and the containment structure below to withstand a safe shutdown earthquake (SSE) and ensure safety of the station. The unique configuration of the PCCT prevents using conventional sloshing height and pressure calculation methods that are applicable to flat bottom cylindrical tanks. Therefore, a computational fluid dynamics (CFD) analysis is used to determine the fluid sloshing response under one of the two lateral acceleration time histories associated with the SSE.

Conventional methods for calculating sloshing response in flat bottom tanks to an earthquake are found in design standards ASCE 4, API 650 and AWWA D100. The theoretical underpinning of these methods can be traced to the linear sloshing model proposed by Housner (1963) and the extensive work of Abramson (1966). The theoretical model is based on linear potential flow (i.e., inviscid and irrotational flow) and assumes small amplitude sloshing heights. Enhancements gained through the work of Valestos (1993) and Haroun (1981) have been incorporated in ASCE 4.

Liepins (2008) investigated sloshing in circular tanks with not-flat bottoms using finite element analysis (NASTRAN) to determine whether Housner"s two-mass model can be approximated with an equivalent cylindrical flat-bottom tank of the same volume and free surface area as a not-flat-bottom tank. None of the not-flat-bottom configurations considered by Liepins was convex in shape.

Sumner (1966) investigated sloshing in a tank with a similar convex elliptical bottom as the PCCT. For small depth to diameter ratios, the experimentally observed slosh frequency was lower than that calculated for an equivalent flat-bottom cylindrical-tank, with the difference getting more pronounced for „shallower" depth/diameter ratios. They also point out that slosh frequency increases with the depth to diameter ratio until the bottom shape has little or no effect on sloshing characteristics.

This paper presents an analysis of free surface sloshing behavior of water inside the PCCT subjected to a 46 second lateral seismic acceleration time-history with peak accelerations as high as 0.58g. The CFD model employs finite volume discretization and the volume of fluid (VOF) multiphase model to characterize the free surface. The focus of the investigation is to determine the sloshing height, associated structural loads and the dominant oscillation frequency.

For validation purposes, a separate CFD simulation of a cylindrical flat-bottom tank with the same diameter and liquid depth as the PCCT is performed. Results are compared to predictions using ASCE 4 guidelines. Although, ASCE 4 addresses only the dominant/primary sloshing mode, the contribution of higher modes is considered by including the response of single-degree-of-freedom (SDOF) oscillators modeled to capture the first three sloshing modes of the flat-bottom cylindrical tank. CFD and modal results of cylindrical flat-bottom tank sloshing are compared with CFD results for sloshing in the PCCT to investigate the contribution of non-linear effects.

CYLINDRICAL FLAT-BOTTOM TANK SLOSHING ASCE 4 (SPECTRUM ANALYSIS)

The maximum sloshing amplitude occurs at the fundamental vibration mode of the tank/water system. The fundamental sloshing circular frequency (ω) for a flat-bottom cylindrical tank is a function of tank radius (R) and fluid depth (H) as in Equation 1 below, Housner (1963):

$$\omega^2 = \frac{1.84g}{R}\tanh\frac{(1.84H)}{R} \tag{1}$$

Sloshing height is a function of tank radius, and spectral acceleration (S_a) at the fundamental natural frequency (f) with 0.5% damping. Equation 2, ASCE 4 (1998), defines the maximum slosh height (d), where (g) is gravity acceleration 32.17 ft/s^2. Damping of liquid sloshing is considerably lower than structural damping.

$$d = R\frac{S_a}{g} \tag{2}$$

Methods for computing the higher mode frequencies and associated mode shapes representing the modal free-surface movements are well established; see Velestos (1993). The contribution of higher mode sloshing response is evaluated by applying the spectral acceleration at the applicable higher mode frequency.

SINGLE-DEGREE-OF-FREEDOM (SDOF) OSCILLATOR (TIME-HISTORY RESPONSE)

A SDOF oscillator mass-spring-damper model representing sloshing in a flat-bottom cylindrical tank/water system is shown Figure 1. The model has similar dynamic characteristics as the flat-bottom cylindrical water tank used in the CFD model.

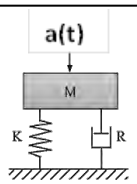


Figure 1. Mass-spring-damper model of sloshing water

The spring constant (K) are derived from Equation 3 for a given mass, where (f) equals the frequency for the mode of interest. Damping ratio is 0.5% of critical damping (per ASCE 4).

$$f = \frac{1}{2\pi}\sqrt{\frac{K}{M}} \tag{3}$$

GENERATION mPOWER PASSIVE CONTAINMENT COOLING TANK (PCCT) DESIGN

The Babcock and Wilcox (B&W) Generation mPower nuclear power plant is a Generation III++ integral pressurized water reactor (light water reactor) with a modular design. The reactor and steam generator are located in a single integrated reactor vessel located in an underground containment facility, and are designed to be factory-made and railed to the site.

The Generation mPower LLC modular reactor nuclear power station integrates a passive containment cooling tank (PCCT) with the upper head of a free standing steel containment structure. Having the tank on top of containment allows cooling of the hottest region of the containment, with the tank acting as a simple passive heat sink for long term cooling in the event of a loss of coolant accident. The PCCT configuration is toroidal when viewed in plan with the base of the tank following the convex elliptical profile of the containment upper head (see Figure 2). The toroidal tank configuration provides relatively easy access to the power plant through the crown of the containment upper head.

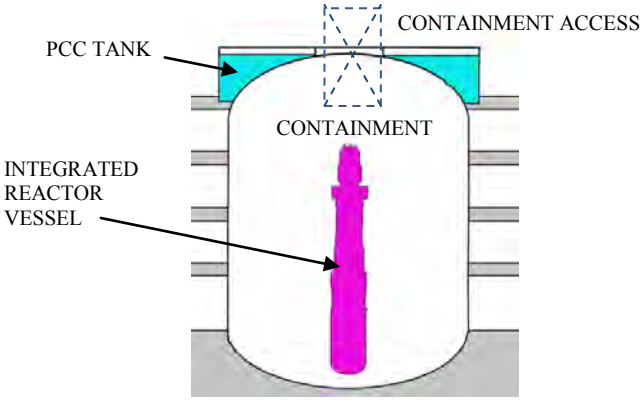


Figure 2. Generation mPower Schematic.

COMPUTATIONAL FLUID DYNAMIC NUMERICAL SIMULATION

The governing Navier-Stokes equations of fluid flow are solved over discrete control volumes using the Computational fluid dynamics (CFD) computer program FLUENT Version 13.0. The finite volume spatial discretization approach is used. Mass and momentum conservation equations are solved in separate volume domains of water and air. The interface between phases is established by solving the continuity equation for volume fraction of each phase. Flow field in the water and air phases in the tank is simulated in response to the prescribed acceleration time history. The computer workstation is a

Hewlett-Packard Z800, with dual Intel E5670 HC CPUs, 96 GB RAM, running Red Hat Enterprise Linux 5.5.

mPOWER PCC TANK SOLUTION DOMAIN AND MESH

The tank outer diameter is 90.5 feet. The diameter of the inner toroidal opening is 24 feet. The tank water level is 17 feet deep at the outer diameter, with three feet of freeboard for a tank height of 20 feet at the outer diameter. The tank bottom profile is that of a 2.2:1 elliptical head, 85.55 feet in diameter. Figure 3 provides an elevation and plan view of the PCC tank, as well as the associated 3D solution domain. The initial fluid depth is shown with the water colored red.

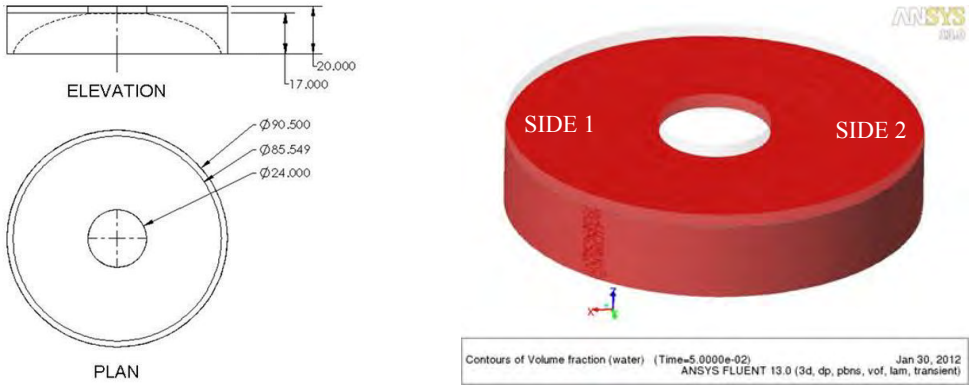


Figure 3. Solution domain and initial conditions

Figure 4 shows a cross-section of the mesh through the tank center. The mesh is a hexahedral mesh made up of 884,584 cells

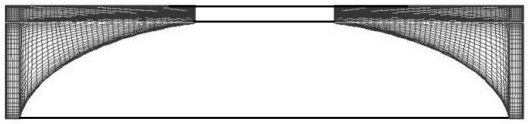


Figure 4. Cross-section of computational mesh

BOUNDARY CONDITIONS AND PHYSICAL MODELS

The tank solid boundaries are an enclosed system. Therefore, all boundaries are modeled as walls with no-slip shear conditions. The two phases in the model have material properties of water and air at 60°F.

The Volume of Fluid (VOF) model simulates two or more immiscible fluids by solving a single set of momentum equations and tracking the volume fraction of each fluid throughout the domain. The water free surface is calculated using the VOF model with the implicit volume fraction scheme and implicit body forces activated. The water phase has a surface tension coefficient of 0.072 N/m, and wall contact angle effects are not modeled.

The VOF model employs the phase localized compressive scheme with a defined constant water/air slope limiter of 2. This scheme setting is used to achieve diffuse modeling of dispersed phases (e.g., splashing) while maintaining sharp modeling of continuous phases.

ACCELERATION

The acceleration time histories are derived from the site seismic design response spectra. Time history accelerations are scaled-up to account for soil/structure interaction, and amplification due to seismic response of the containment structure which supports the tank.

The time history is approximately 46 seconds in duration with acceleration values provided at 0.005 second time intervals. Two horizontal acceleration time histories and one vertical time history were evaluated, but results for only one of the horizontal acceleration time histories is presented in this paper. The scaled horizontal acceleration time history and the associated spectra are shown in Figure 5.

To apply accelerations over time, a user-defined-function (UDF) updates acceleration in the x, y and z directions every 0.005 seconds. UDFs are written in the C programming language and executed by FLUENT allowing the user to enhance standard FLUENT features.

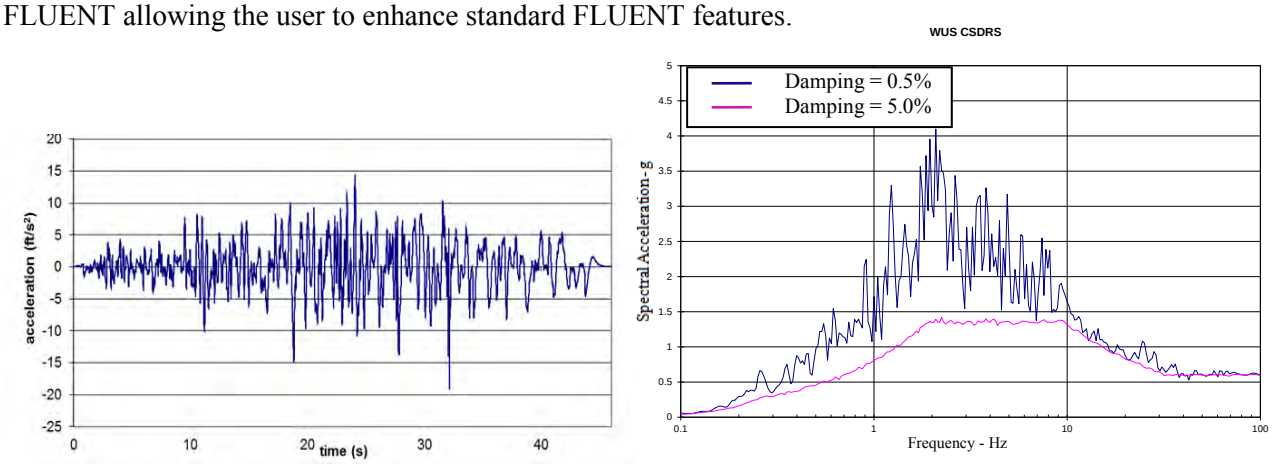


Figure 5. Horizontal acceleration time-history (left) and associated spectra (right)

CFD MODEL ASSUMPTIONS

1. Acceleration is applied as an inertia force equally to both the tank walls/floor and the contained water. That is, accelerations (u_g) are applied to the tank and water (system) and the CFD model simulates the water velocity response relative to the tank walls (u_r) as depicted in Figure 6.
2. Water velocity at the tank walls is zero (no-slip condition).
3. The tank walls are infinitely stiff with no structural bending.
4. The effects of wall adhesion angle are ignored.
5. Flow within the tank is primarily laminar.

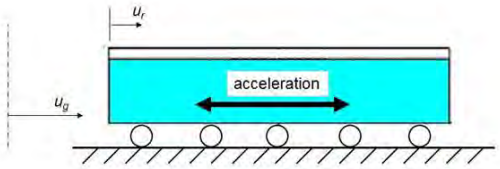


Figure 6. Tank acceleration schematic

GENERATION mPOWER PCC TANK DESIGN SLOSHING

An animation of the water free surface allows a qualitative assessment of the resulting sloshing. The animation indicates sloshing height frequently exceeds the three foot freeboard at the inner wall of the toroidal ring, but exceeds freeboard height at the outer wall only once. The animation suggests the toroidal configuration combined with the elliptical convex bottom profile encourages sloshing and water

run-up at the inner wall of the toroidal ring. However, since water level in this region is fairly shallow the sloshing produces negligible structural loads.

Resulting outer wall slosh height at the two tank ends aligned with the acceleration direction (side 1 and side 2 as shown in Figure 3) are recorded during the transient analysis. To capture the free oscillation sloshing response after the 46 second duration of acceleration time history, the analysis continues for an additional 74s with no acceleration. The free sloshing oscillation exhibits a period of around 17s. Figure 7 plots outer wall sloshing height over time at the two sides aligned with the acceleration direction. The outer wall slosh height (side 2) exceeds the three feet of freeboard at around 40s.

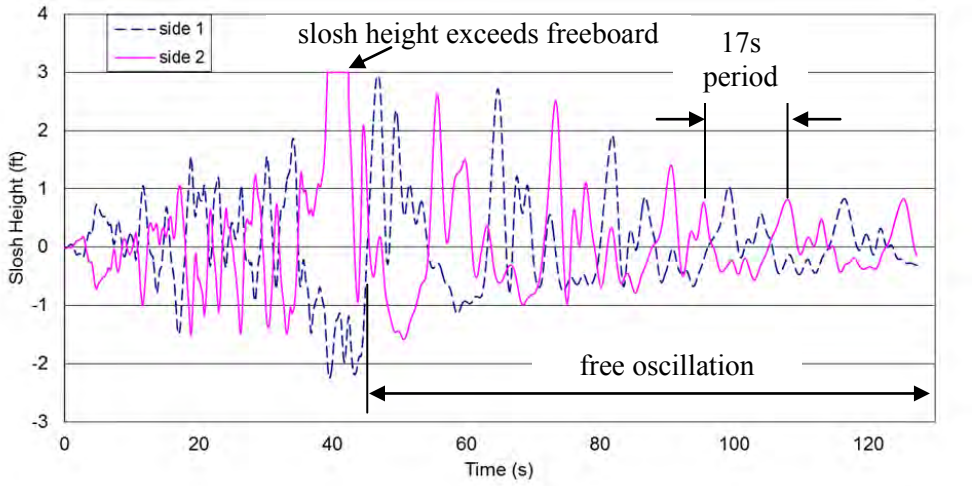


Figure 7. PCC tank design sloshing height

Figure 8 shows the water free surface at 47 and 40 seconds, the time of peak sloshing height for sides 1 and 2 respectively. The figures plot water free surface and water volume fraction at the walls and tank roof (red is 100% water). At 40s, side 2 contours indicate air present as water runs-up the tank roof.

Figure 8. PCC tank design free surface plots at peak sloshing heights at each side (t = 47s & 40s)

Figure 9 plots resulting forces due to pressure on the tank outer wall, inner wall, and roof surfaces over time. The plots suggest the tank experiences the greatest structural loads at approximately 40s, which is the time sloshing height at the outer wall (side 2) is at its highest.

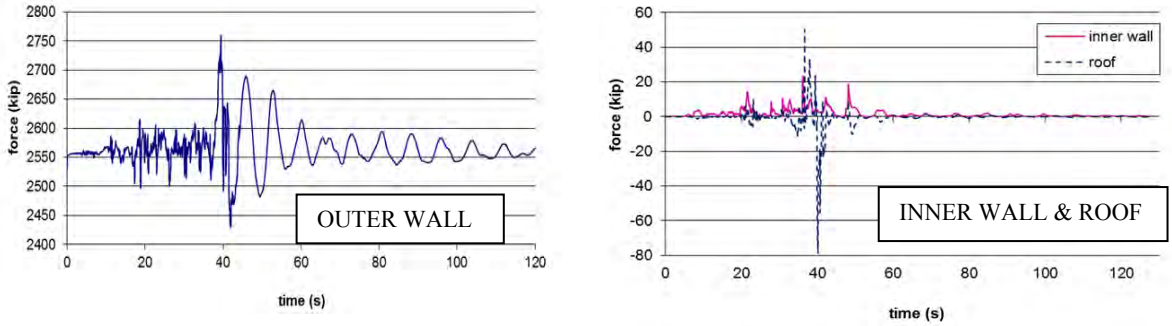


Figure 9. Forces on tank surfaces over time

The resulting base shear force and overturning-moment at the time of maximum structural loading (40s) are illustrated in Figure 10. The base shear force is the sum of all resulting surface forces (walls, roof and bottom) in the direction of the lateral accelerations (x direction). The overturning-moment is the resulting moment about the y-axis (i.e., normal to lateral acceleration direction) at the tank base. It is worth noting the base shear is primarily due to sloshing induced pressure on the outer wall, while the overturning-moment is due to an imbalance in hydrostatic pressure on the tank bottom as water accumulates in one region of the tank.

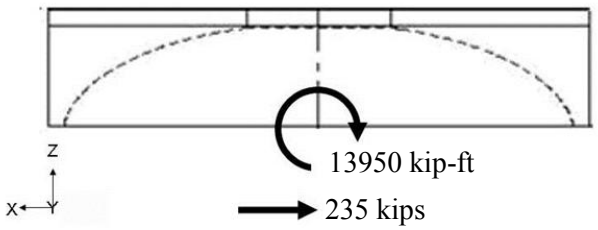


Figure 10. Resultant shear and over-turning moment at 40s

CYLINDRICAL FLAT-BOTTOM TANK CONFIGURATION SLOSHING

In order to validate the above CFD simulation for the PCCT, a separate CFD analysis calculates sloshing in a cylindrical flat-bottom tank with similar dimensions as the PCCT, and subjected to the same acceleration time history. Results of this analysis are compared to sloshing predictions using ASCE 4 guidelines.

Figure 11 plots sloshing height at the two opposing tank ends aligned with the acceleration direction. The maximum sloshing height occurs at approximately 35s and is 6.2ft. This maximum sloshing peak occurs only once, with smaller subsequent amplitudes measuring approximately 4.6 ft.

Measuring the time between peak slosh heights during free sloshing (with no acceleration) indicates a sloshing period of 7 seconds, considerably less than the 17s period observed with the PCC tank.

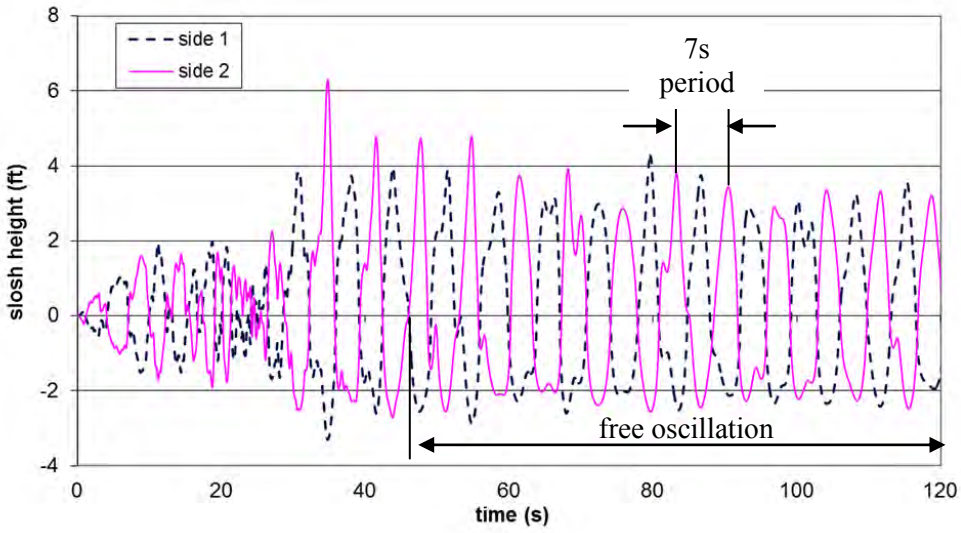


Figure 11. Cylindrical flat-bottom configuration sloshing height

Figure 12 shows an isometric view of the water free surface and an elevation view of the water volume profile along the XZ plane through the tank center at 48s. Note the presence of non-linear secondary surface features near the tank center. These non-linear effects contribute to the sloshing height measured at the tank wall.

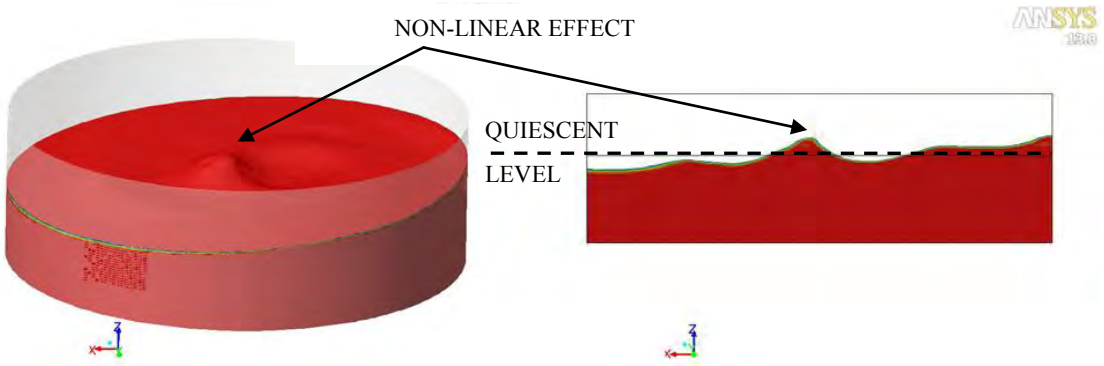


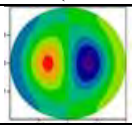
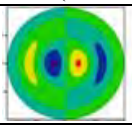
Figure 12. Cylindrical flat-bottom sloshing at 48s – isometric and XZ cut-plane views

ASCE 4 MODAL RESULTS

Using the methodology of ASCE 4 to predict sloshing in a cylindrical flat-bottom tank results in an oscillation period of seven seconds, which equals the period observed in the CFD analysis of the cylindrical flat-bottom tank. The maximum slosh height associated with the first sloshing mode is 4.1 feet, which is approximately two feet less than the maximum observed CFD slosh height, but close to the subsequent CFD amplitudes of 4.6 ft.

Based on Velestos (1993), Table 2 lists sloshing periods and resulting slosh heights, along with the associated spectral accelerations (at 0.5% of critical damping), for the first three sloshing modes. Using the higher sloshing modes, it is possible to estimate the cumulative sloshing height. Summing the heights of the first three modes produces a sloshing height of 6.5 feet, which is slightly higher than the CFD maximum of 6.2 ft. Considering the possible contribution of higher modes one can understand how the first-mode alone may under-predict sloshing height.

Table 2: Theoretical sloshing results summary of the first three modes

Sloshing Mode	Mode-1	Mode-2	Mode-3
Period	7 s	3.3 s	2.5 s
Spectral Acceleration*	0.09 g (0.13g)	0.37 g (0.38 g)	0.87 g (0.9 g)
Maximum Slosh Height*	3.4 ft (4.1 ft)	1.2 ft (1.25 ft)	1.1 ft (1.13 ft)
Mode Shape			

*Displacement based on pseudo-spectral acceleration - $S_A = \omega^2 S_d$
Values in parenthesis are for velocity based pseudo-acceleration - $S_A = \omega^2 S_v$

SDOF OSCILLATOR TIME HISTORY RESULTS

Time history response of a SDOF oscillator representing the primary sloshing mode of the cylindrical flat-bottom tank accelerated with the same time-history produces a maximum displacement of 3.6 ft. Computing the time history response of the two oscillators representing the tank second and third modes, and summing the response of all three modes leads to the combined response shown in Figure 13, where the combined oscillator response is compared to the CFD slosh height. The resulting maximum sloshing height of 6.2 feet at 35s in the CFD model is similar in magnitude to the combined oscillator amplitude of 6.2 ft at 42s.

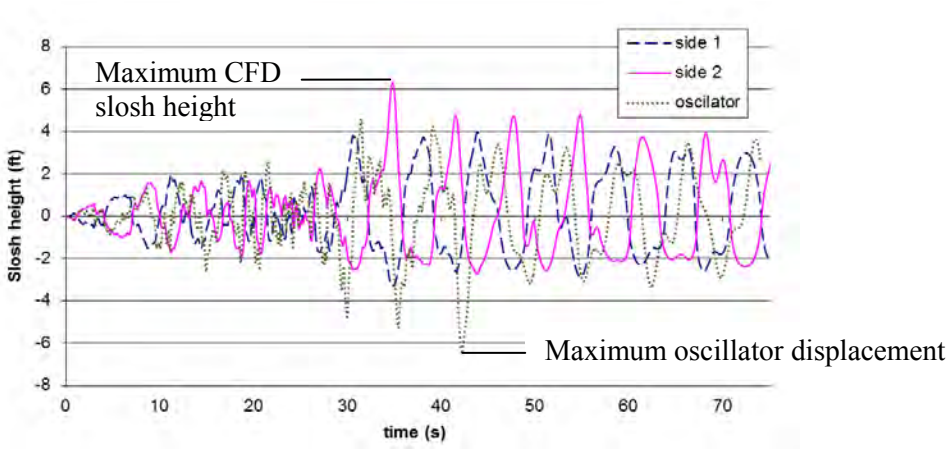


Figure 13. Comparison of SDOF oscillator combined modes to CFD sloshing results

PCC TANK AND CYLINDRICAL FLAT-BOTTOM TANK COMPARISON

Table 3 provides a summary of the cylindrical flat-bottom tank modal and time-history results.

Table 3: Cylindrical flat-bottom tank comparison of CFD and oscillator model results to ASCE 4 sloshing

Method	Period (s)	Maximum Slosh Amplitude (ft)
CFD Model	7	6.2
SDOF Model (primary mode)	7	3.8
ASCE 4 (primary mode)	7	4.1
SDOF Model + Higher Modes	N/A	6.2
ASCE 4 + Higher Modes	N/A	6.5

The PCCT sloshing oscillation period of 17 seconds is more than twice as long as the 7 second period observed for the cylindrical flat-bottom tank. Sloshing frequency is a function of water depth and

therefore, water volume. Consequently, it is not surprising to see a lower frequency (longer period) in the PCCT where the total water volume is significantly less than in a cylindrical tank of the same diameter. This is consistent with Sumner‟s (1966) experimental findings.

Since the PCCT CFD model has only three feet of freeboard, comparing slosh height beyond three feet is not possible. The tank‟s toroidal configuration, coupled with a water depth varying with radius (due to the elliptical contour of the tank bottom), likely enhances the non-linearity of flow within the tank and, therefore, the non-linear contributions to sloshing. This is particularly evident when observing sloshing at the wall defining the inner ring of the tank‟s toroidal profile.

CONCLUSION

CFD is used to investigate structural loads attributed to earthquake induced sloshing within an unusual water tank design for the Generation mPower small modular reactor. Results indicate the toroidal tank geometry and the elliptical convex contour of the tank bottom encourages sloshing and water run-up at the inner wall of the toroidal ring. However, since the water level in this region is shallow, sloshing in this area produces negligible structural loads.

CFD is also used to simulate the sloshing response of a cylindrical flat-bottom tank with similar dimensions to the PCCT. The sloshing results are compared to ASCE 4 predictions for the same cylindrical tank geometry.

The fundamental sloshing oscillation frequency from the CFD model and the ASCE 4 predicted value are very similar. ASCE 4 predictions of slosh height, based on the fundamental mode, is significantly less than the maximum slosh height observed in the CFD simulation. However, when the first three modes are considered, both the ASCE 4 modal approach and the SDOF oscillator time-history response produce amplitudes similar to the maximum slosh height observed in the CFD simulation. This suggests the contribution of higher sloshing modes is significant in a tank of this size and level of acceleration (0.58g).

The PCCT sloshing oscillation period of 17 seconds is more than twice as long as the 7 second period observed for a cylindrical flat-bottom tank with similar diameter and water depth. The PCCT geometry likely enhances the non-linearity of flow and sloshing within the tank. Therefore, capturing the non-linear effects is prudent when assessing sloshing in a tank with unusual geometry.

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