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BAFFLE EFFECTS OF THE SEISMICALLY-ISOLATED NUCLEAR TANKS ON SLOSHING REDUCTION BASED ON FSI ANALYSIS

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ABSTRACT

This paper focuses on investigating the baffle effects on sloshing/overflow reduction of the seismically-isolated nuclear tank systems based on Fluid-Structure Interaction (FSI) analysis. In the event of an earthquake, structural performance of the seismically-isolated nuclear tanks is typically improved due to the reduced seismic forces by the period shift. However, fluid motion may be rather amplified. For this reason, sloshing assessment of those structures has to be conducted. In an effort for preventing unanticipated sloshing damage, the inclusion of baffles can be taken into account. This is because sloshing height can be effectively reduced due to the damping effect provided by baffles. Sloshing analyses of the seismically-isolated nuclear tanks with various baffles are herein performed. FSI modeling is first developed to consider influence of fluid motion on tank structure by coupling ANSYS with CFX for structural and fluid analyses, respectively. Various baffles according to their sizes and locations for a given shape are then modeled in order to find a most effective baffle based on the FSI outputs including sloshing height, overflow and hydro-dynamic pressure. Floor acceleration time-histories, which are produced from the preliminary dynamic analysis for a full modeling of the nuclear auxiliary building, are applied to the tank base at each of the directions. The approach is illustrated on a nuclear tank, Spent Fuel Pool (SFP), which is located in the auxiliary building.

INTRODUCTION

To date, effectiveness of seismic isolation systems for improving structural performance has been well demonstrated in many important structures (e.g., buildings, bridges). In recent years, application of the technology has been applied more and more to nuclear liquid storage tanks. For these tank systems, violent sloshing is one of the most common failure mechanisms. Accurate sloshing assessment and prediction are required to establish effective management activities for preserving structural and environmental safety. Numerous experimental and numerical studies have been conducted to investigate liquid sloshing as well as the effect of baffles on sloshing reduction (Silveira et al. 1961, Gedikli & Ergüven 1999, Chen et al. 2007, Angelis et al. 2010, Biswal & Bhattacharyya 2010). However, these studies have been generally applied to sloshing assessment for the seismically non-isolated systems or moving structures (i.e., trucks and ships transporting liquids). Fluid motion in the seismic isolation systems can be rather amplified and overflowed due to a long-period shift, and the overflowed fluid in nuclear tanks (e.g., SFP) can often cause critical damages to humans and environments. Therefore, it is necessary to (i) assess the time-variant liquid sloshing in the seismically-isolated nuclear tank systems under potential seismic loading; and (ii) make an effort to reduce the amplified sloshing (overflow). For this purpose, FSI analyses considering interaction of structural elastic deformation and fluid motion are performed for more reliable sloshing assessment of the seismically-isolated nuclear tanks, while various baffles models are developed considering its shape, location, and size in order to reduce the total cumulative overflowed water volume. The proposed approach is illustrated on a nuclear liquid storage tank, SFP, under seismic isolation condition.

SLOSHING ASSESSMENT BASED ON FSI ANALYSIS

In many engineering fields, sloshing assessment has always been an important engineering concern. In particular, assessing sloshing behavior in the seismically-isolated nuclear tanks that sloshing is expected to be more amplified is considerably essential since sloshing is a significant phenomenon even at very small amplitude excitations. Assuming that water containing radioactive material is overflowed under earthquake, thereby unexpected damage can happen.

In the sloshing assessment, FSI effects on nuclear tanks have to be included to obtain more reliable outputs. Typically, FSI analysis is to solve a multiphysics problem where the interaction between deformable structures and fluid flow filled internally or surrounded externally is taken into account. As shown in Figure 1, two different analyses from each solver are simultaneously performed. Structural analysis is based on the mechanical application, while sloshing analysis is based on the computational fluid dynamics (CFD) approach associated with multiphase flow phenomena of gas (air) and liquid (ANSYS, 2010). In the sloshing analysis, volume of fluid (VOF) model that is suitable for the free surface analysis is employed. Output data at each time step from structural analysis is transferred to the CFD analysis as a load effect (i.e., mesh displacement). Conversely, individual step outputs from CFD analysis are imposed to the structural analysis as a force.

In this study, a two-way FSI analysis is performed by using common FE software ANSYS and CFX for structural and fluid analyses, respectively. It is assumed that fluid motion is ideally irrotational, incompressible, and inviscid. All necessary boundary conditions are imposed and acceleration excitations (e.g., SSE, OBE) are applied to the base of the seismically-isolated nuclear tank.

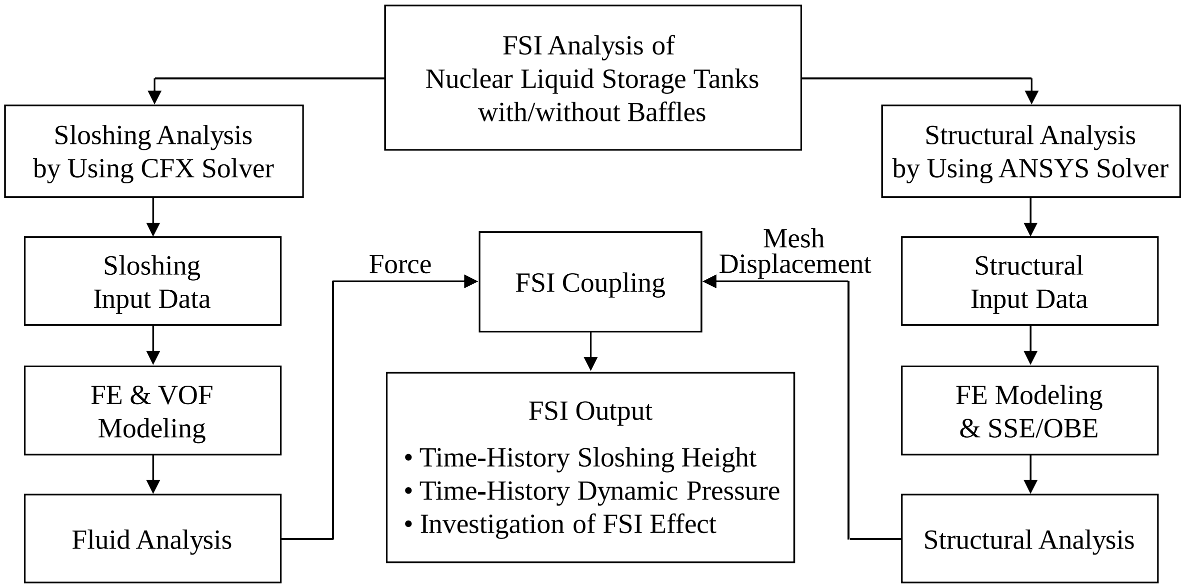


Figure 1. Schematic for FSI analysis.

The 3D FSI approach adopted in this study is herein validated by comparing (i) the computed results for flexible and rigid wall conditions with (ii) the simulated sloshing time-history of a 2D liquid storage steel tank (i.e., 9.14 m x 6.10 m in width and height) conducted by Chen et al. (1996; see Figure 2). Potential flow equations with rigid wall condition were used in the previous work, while east-west component of El Centro earthquake was used as a loading condition. The predefined liquid free surface is 4.57 m. As indicated in Figure 2, three sloshing profiles are almost similar except the difference in the peak sloshing height. Such an increase in the peak sloshing is reasonable because fluid motion can be more amplified due to the included FSI effect with flexible wall condition. In other words, it implies that the results can be underestimated when assuming rigid wall condition in sloshing assessment.

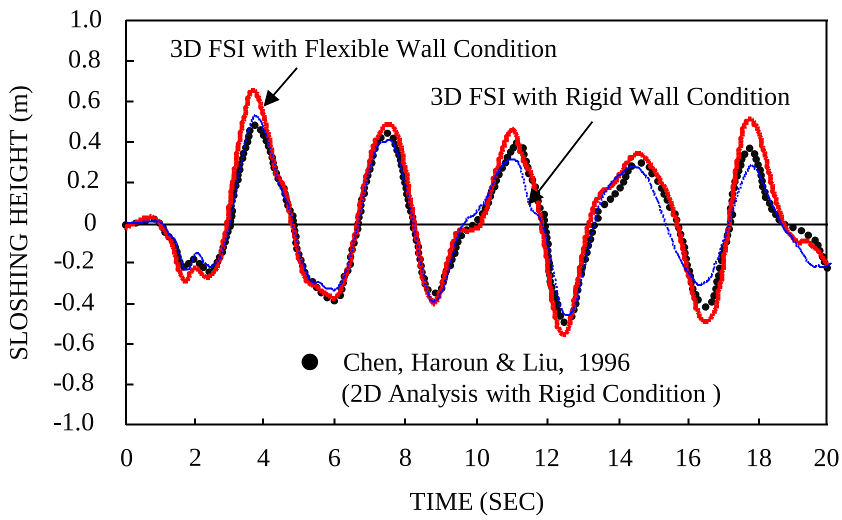


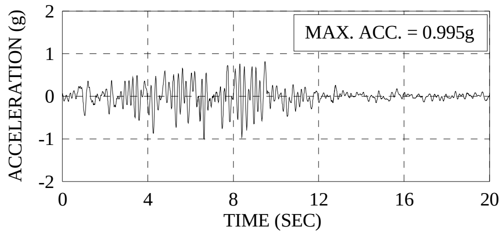
Figure 2. Time-history sloshing profiles for FSI verification.

APPLICATION

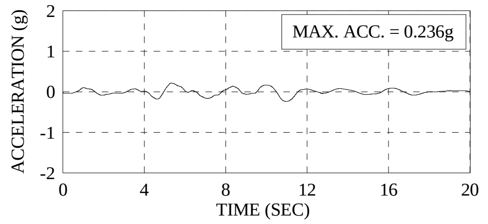
SFP Description and Seismic Loading

The proposed approach is illustrated on a nuclear tank, SFP, which is a pool-type rectangular reinforced concrete structure located in the auxiliary building. This SFP is typically operated to store spent fuel from nuclear reactors: (i) for allowing the fuel to cool as its decay heat decreases; and (ii) for shielding the emitted radiation. The SFP inner dimensions (i.e., VOF modeling of water and air) considered in this study are 10.52 m in width and 12.80 m in length and height. Fluid filled in SFP is assumed to be water and free surface of 12.24 m. Its material properties are Young's modulus E = 27.8 GPa, Poisson's ratio ν = 0.17, and density ρ = 2,403 kg/m^3.

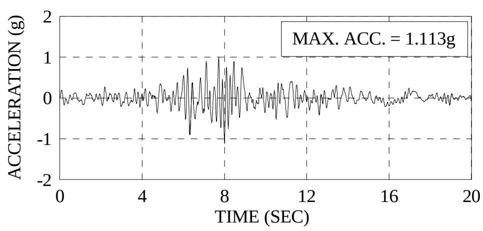
For horizontal and vertical directions, peak ground acceleration (PGA) of 0.5g at bed rock level is herein assumed as a target value of the isolated system that is much higher than the allowable design PGA (e.g., 0.2g, 0.3g), in a conservative way. The associated acceleration time-history inputs for the isolated and non-isolated SFP are presented in Figure 3, while the acceleration response spectra in east-west (EW) and vertical (VT) directions are plotted in Figure 4. As shown in Figure 4, the horizontal acceleration response spectrum in the isolation system increases in low-frequency, whereas it decreases significantly in high-frequency. The vertical acceleration response spectra for the isolated and non-isolated systems show almost similar trends. The acceleration excitations presented in Figure 3 are applied to the base of SFP in FSI analysis.



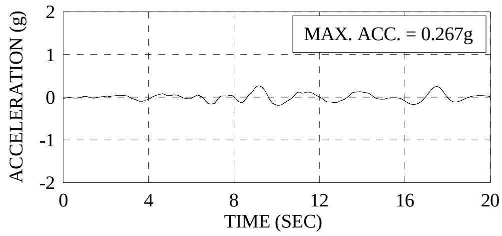
(a) non-isolated EW direction



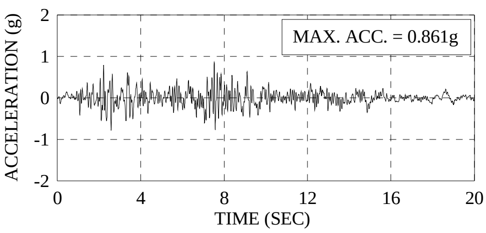
(d) isolated EW direction



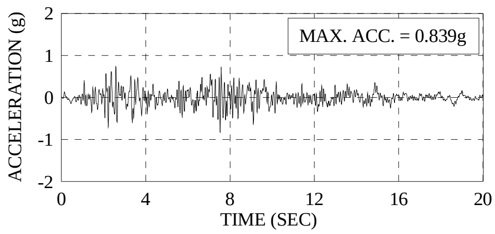
(b) non-isolated NS direction



(e) isolated NS direction

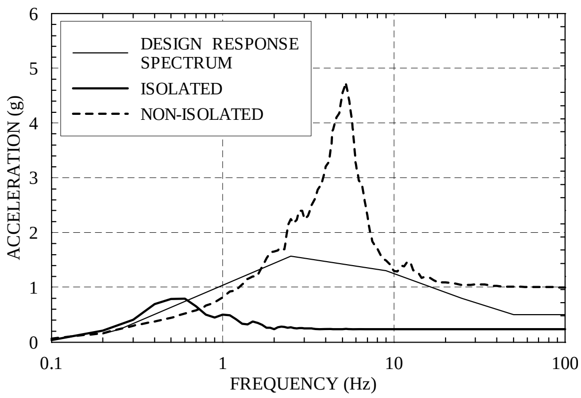


(c) non-isolated VT direction

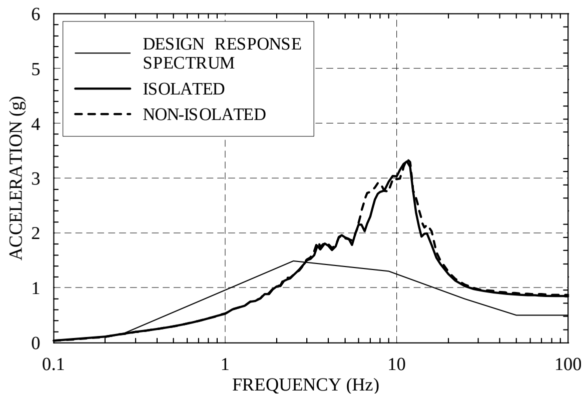


(f) isolated VT direction

Figure 3. Isolated and non-isolated acceleration time-histories for FSI analysis.



(a) EW direction



(b) VT direction

Figure 4. Acceleration response spectra for the isolated and non-isolated SFP.

FE Modeling of SFP and Baffle

3D FE modeling for SFP and fluid (i.e., water) is developed with the software ANSYS and CFX, respectively (ANSYS, 2010). Figure 5 presents the relevant information on all dimensions of SFP and fluid, including baffle size and location (i.e., width, depth). It is noted that positive x and z indicate east and south directions, respectively. As described previously, VOF model consisting of air and water regions is used in liquid sloshing modeling, while a solid element type (i.e., solid185) is used in SFP structural modeling.

Various baffle models are created to investigate its effect on sloshing (overflow) reduction (see Table 1 and Figure 6). As indicated in Figure 6, three different rectangular baffle shapes at SFP corner are identified as: (i) continuous rectangular baffle (CRB); (ii) rounded rectangular baffle (RRB); and (iii) spaced rectangular baffle (SRB). It is noted that any vertical baffle models are not considered in this study since any interference in SFP top region should not be made for handling SFP crane.

For a given shape of baffle (i.e., CRB, RRB), different sizes and locations are selected to investigate its size and location effects on sloshing reduction. To find the most effective baffle shape, different shape models are developed for given size and location. It is noted that two void regions in baffle modeling are made since two gates exist in north and south side walls of SFP (see Figure 6).

Table 1: FSI baffle models.

Type of baffle		Size and location of baffle		
		Depth, D	Width, W	Baffle Area, A_B
Continuous Rectangular Baffle (CRB)	CRB1	3ft (0.914 m)	1ft (0.305 m)	16.35 m^2
	CRB2		2ft (0.610 m)	24.53 m^2
	CRB3		3ft (0.914 m)	32.33 m^2
Rounded Rectangular Baffle (RRB)	RRB4	3ft (0.914 m)	1ft (0.305 m)	16.39 m^2
	RRB5		2ft (0.610 m)	24.69 m^2
	RRB6		3ft (0.914 m)	32.69 m^2
	RRB7	5ft (1.829 m)	3ft (0.914 m)	32.69 m^2
	RRB8	10ft (3.048 m)		32.69 m^2
	RRB9	at free surface		32.69 m^2
	RRB10	at SFP top		32.69 m^2
Spaced Rectangular Baffle (SRB)	SRB11	3ft (0.914 m)	3ft (0.914 m)	27.31 m^2

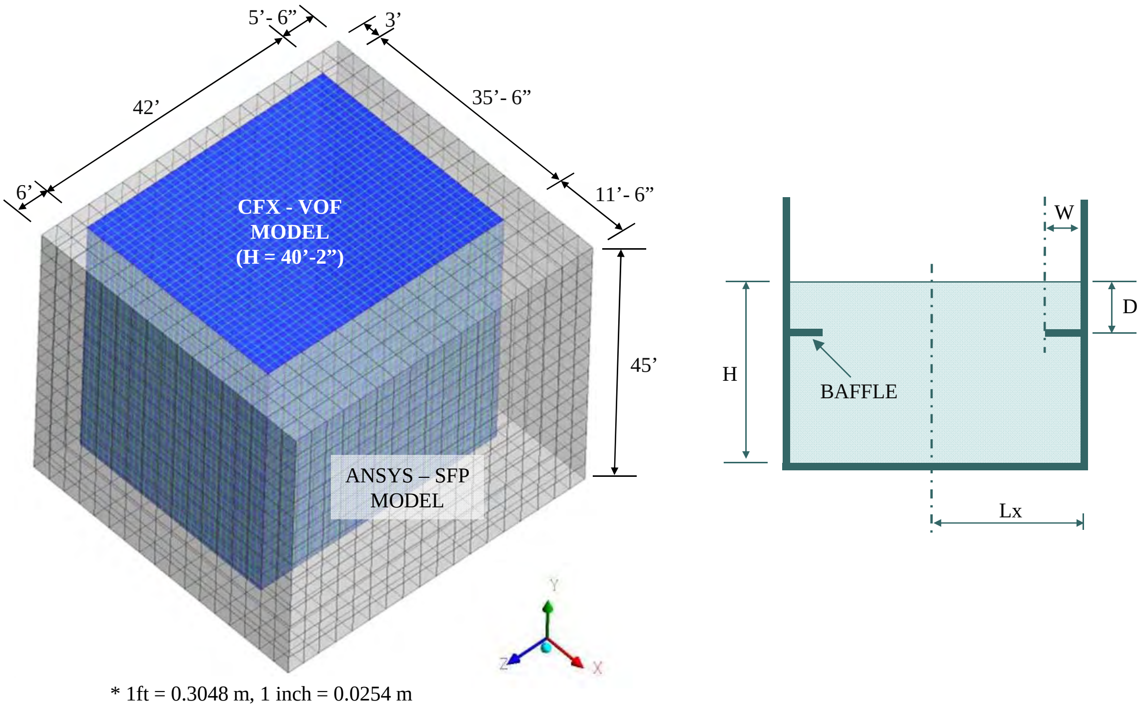


Figure 5. FE modeling and dimensions for FSI analysis.

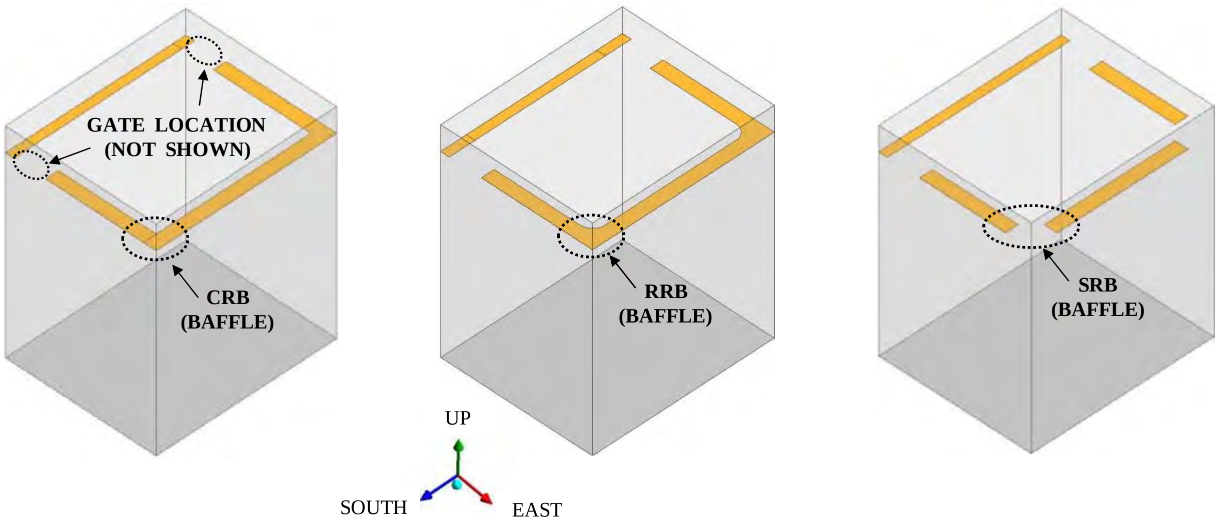
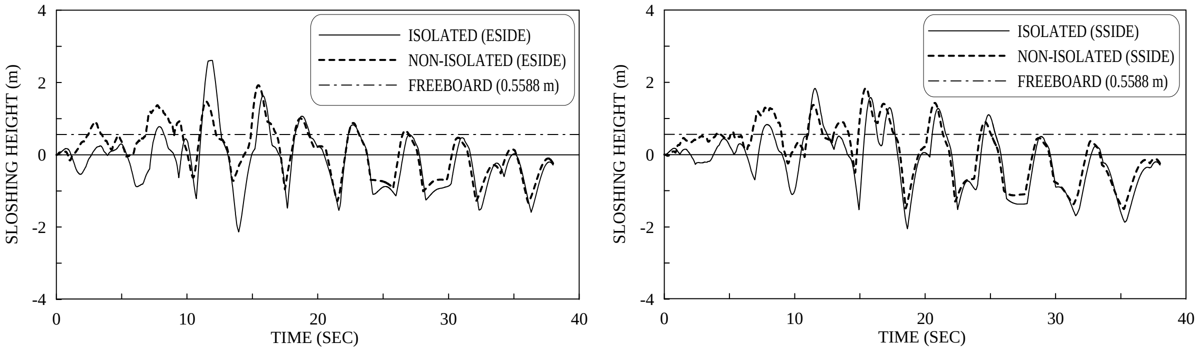


Figure 6. Baffle models for sloshing reduction.

Baffle Effect on Sloshing (Overflow) Reduction

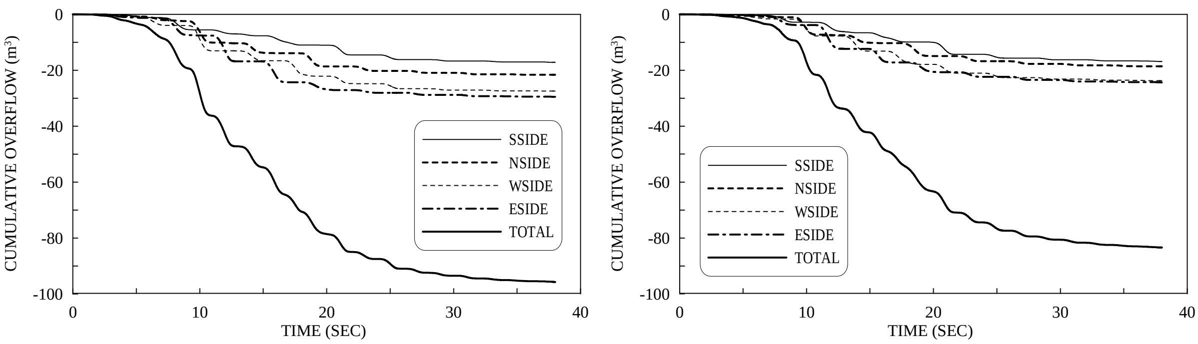
As a preliminary study, the time-variant sloshing height is first investigated for the seismically isolated and non-isolated SFP, without any baffles. The total cumulative overflowed water volumes are then investigated. Two-way FSI analyses for the structural and fluid FE models are carried out with the applied acceleration excitations in all directions (see Figure 3). It is noted that the acceleration excitation lasts t = 38 sec such that sloshing behavior is converged stably.



(a) at east side

(b) at south side

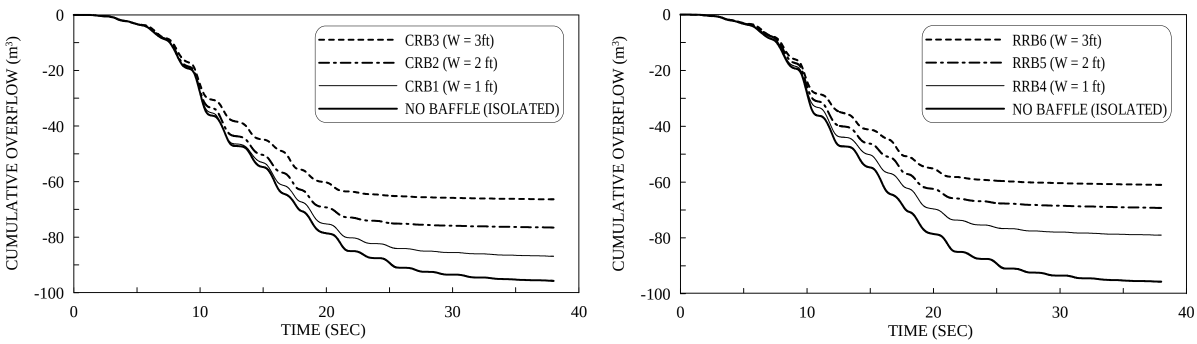
Figure 7. Time-history sloshing profiles of the isolated and non-isolated SFP.



(a) isolated SFP

(b) non-isolated SFP

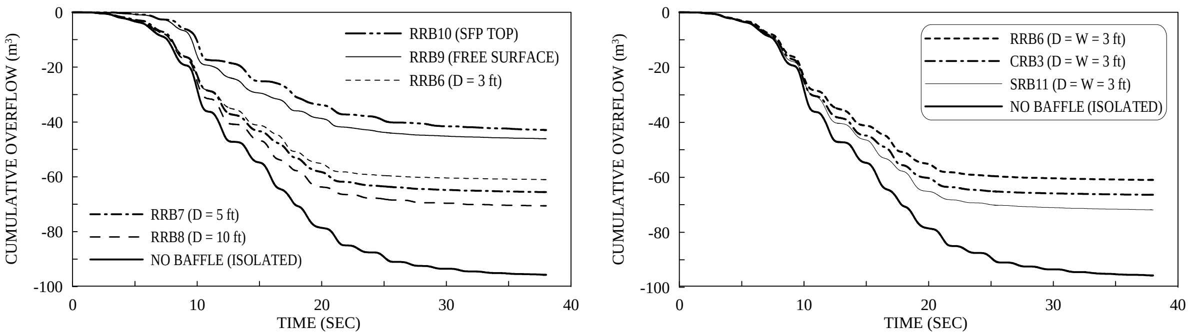
Figure 8. Cumulative overflowed water volumes of the isolated and non-isolated SFP.



(a) CRB

(b) RRB

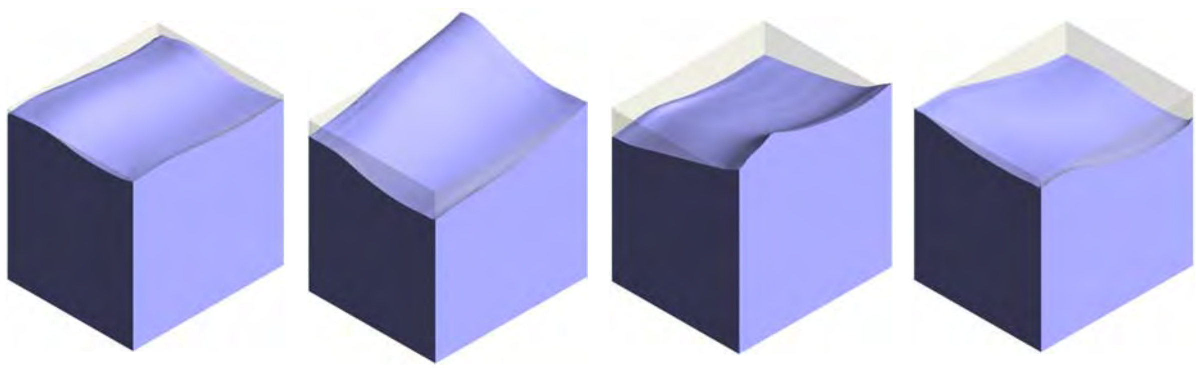
Figure 9. Cumulative overflowed water volumes according to the baffle sizes
for a given shape in the isolated SFP.



(a) different RRB locations

(b) different baffle shapes

Figure 10. Cumulative overflowed water volumes according to the baffle locations and shapes in the isolated SFP.



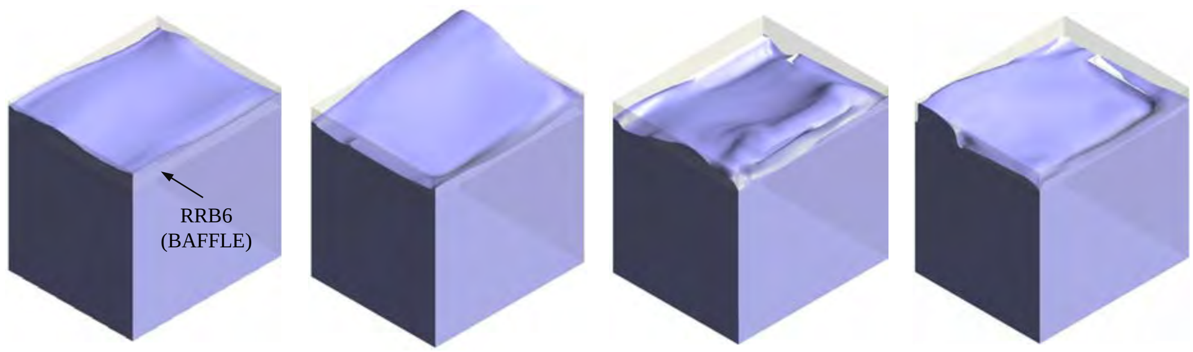
(a) t = 5 sec

(b) t = 9.74 sec

(c) t = 11.88 sec

(d) t = 20.48 sec

Figure 11. Time-variant free surface profiles of the isolated SFP without baffle.



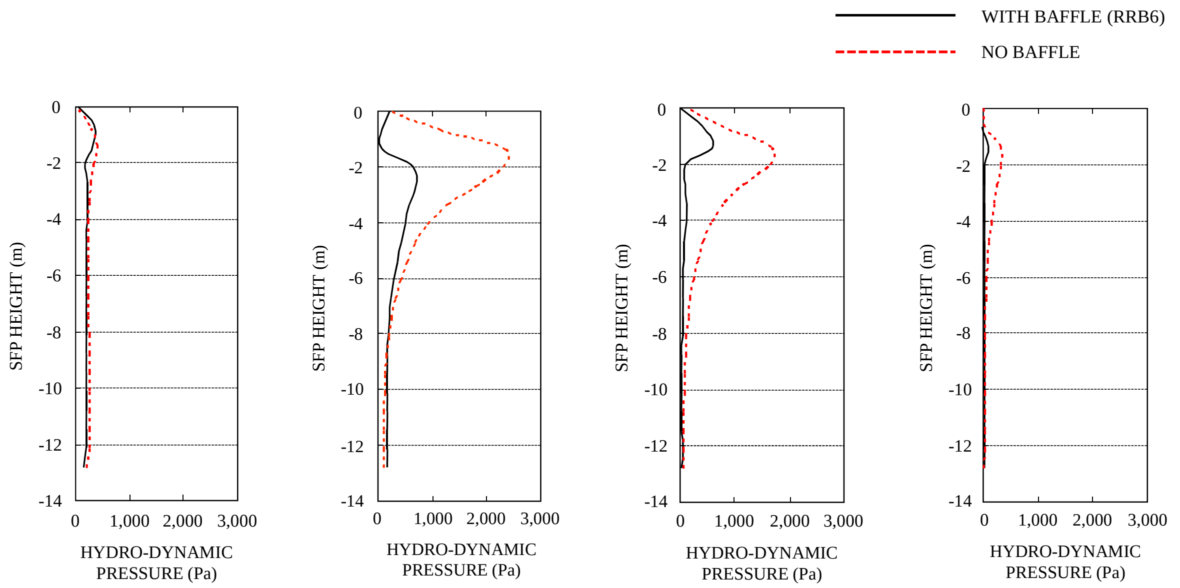
(a) t = 5 sec

(b) t = 9.74 sec

(c) t = 11.88 sec

(d) t = 20.48 sec

Figure 12. Time-variant free surface profiles of the isolated SFP with baffle, RRB6.



(a) t = 5 sec (b) t = 15 sec (c) t = 20 sec (d) t = 38 sec

Figure 13. Hydro-dynamic pressure distributions in east side wall.

As expected, sloshing height in the isolation system (i.e., east side wall of SFP) is more amplified than that in the non-isolated system (see Figure 7(a)), but sloshing difference in south side wall is not significant (see Figure 7(b)). It is also observed that in both systems sloshing behavior exceeds overly the predefined freeboard of 0.5588 m. At east side, the peak sloshing heights in the isolated and non-isolated systems are around 2.61 m and 1.92 m at different times, respectively.

For both systems, the total overflows accumulated in each side wall are plotted in Figures 8 (a) and (b). After approximately t = 30 sec, liquid sloshing becomes stabilized. The total overflowed water volumes in SFP are about 96 m^3 and 83 m^3 in the isolated and non-isolated systems, respectively. This small increase of 15% can be rational since relatively big acceleration inputs are applied to the non-isolated SFP (see Figure 3).

For the identified baffle models in the isolated SFP (see Table 1), FSI analyses are performed. As shown in Figures 9 and 10, it is found that the inclusion of baffle is effective to reduce sloshing/overflow of SFP as compared to the total cumulative overflows in no baffle model. For given baffle shape and location, its size effect (i.e., width is variable) on sloshing reduction is investigated based on FSI analysis. As shown in Figures 9 (a) and (b), the increases in baffle size lead to more decreases in the total cumulative overflowed water volumes without regard to baffle shapes. It is also examined that liquid sloshing according to different baffle locations is influenced for given shape and size. As shown in Figure 10 (a), as vertical location of baffle is closer to the SFP top, the total cumulative overflows are more reduced. It should be noted that this result associated with the location effect of baffle may be applicable for reducing sloshing/overflow only not hydro-dynamic pressures. In addition, the most useful baffle type among the three different shapes is found. As presented in Figure 10 (b), the total overflows in RRB and CRB models (i.e., RRB6, CRB3) are 61 m^3 and 66 m^3 at t = 38 sec, respectively, while that in SRB model (i.e., SRB11) is 72 m^3. Consequently, RRB model can be effectively used as a best solution for minimizing liquid sloshing of SFP.

Time-variant free surface profiles are presented in Figures 11 and 12, including sloshing behavior of the seismically-isolated SFP without baffle and with baffle (i.e., RRB6), respectively. During the earthquake event, the peak sloshing height without baffle is occurred in east side wall away from its corners where t = 11.88 sec. On the contrary, the peak sloshing with baffle at t = 9.74 sec is occurred in the corner between west and north walls. Especially, it is well observed that fluid motion due to baffle becomes much gentler (see Figure 12).

In the oscillating process, hydro-dynamic pressures are usually distributed along SFP wall depth. The time-variant hydro-dynamic pressure distributions are plotted in Figure 13. As shown in Figures 13 (a) to (d), the maximum hydro-dynamic pressures occurred near the free surface of SFP are significantly reduced in baffle model although the pressure values are not big in comparison of them with hydro-static pressures.

CONCLUSIONS

From the investigation of the baffle effects on sloshing/overflow reduction of the seismically-isolated SFP based on FSI analysis, the following conclusions are drawn: (i) FSI analysis can be possibly conducted to investigate influence of fluid motion on nuclear tanks, based on 3D FE modeling which can be developed by linking ANSYS to CFX in terms of a tank structure and fluid, respectively; (ii) for a given baffle shape at the same location, the peak sloshing as well as the total cumulative overflowed water volumes can be significantly reduced with increases in its width; (iii) for given baffle size and shape, its better location for reducing overflow-induced sloshing is near the SFP top; (iv) as a best solution for minimizing liquid sloshing of the rectangular tank, a rounded baffle at corner (i.e., RRB) can be effectively used; (v) the maximum hydro-dynamic pressure can be significantly reduced due to the damping effect provided by baffles; and (vi) further research associated with various seismic inputs (e.g., PGA) is needed for implementation purposes.

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