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FSI-based Overflow Assessment of Liquid Storage Tanks

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Abstract - *Overflow assessment of liquid storage tanks are carried out based on the fluid-structure interaction (FSI) analysis. Typically, liquid storage tanks under earthquakes or any external vibration may experience violent sloshing-induced overflow. In case of that the contents are from nuclear environments and any isolation systems are imposed at base, the overflow issue becomes more important. This is because it can cause serious damage. For this reason, it is necessary to assess and predict sloshing-induced overflow especially in seismically-isolated tanks subject to seismic loading. A FSI-based analysis, which is useful for solving implicit problems in nature, is herein adopted. The overflow assessment is illustrated on a nuclear liquid storage tank.*

***Key Words*: Sloshing, Overflow, FSI analysis, Isolation**

1. INTRODUCTION

Liquid storage tanks can be inevitably exposed to an aggressive environment with unexpected earthquake. Due to these seismic loading, violent sloshing-induced overflow can be occurred. Assuming that radioactive material is contained in a seismically-isolated nuclear tank, the overflow occurrence exceeding its allowable capacity will cause serious damages to human and environment. Accordingly, liquid overflow has to be considered as one of critical failure mechanisms in design and/or assessment. In this study, a FSI-based overflow analysis is performed to assess reliable overflow.

To date, many sloshing problems focusing on its behavior not liquid overflow have been investigated from numerous experimental and numerical studies [1-3]. In a nuclear environment, assessing and predicting sloshing-induced overflow are important to prevent potential accidents. In this study, overflow assessment based on FSI approach is addressed. The interaction between structural elastic deformation and fluid motion is basically considered in FSI analyses.

In the overflow evaluation, there are three key factors to be considered. Free surface level is one of important parameters affecting initial sloshing behavior. Liquid density and amplitude of seismic loading are also taken into account importantly in the total cumulative overflow assessment. In this study, free surface level and water density are fixed, while two different Peak Ground Accelerations (PGAs = 0.3g, 0.5g) are imposed. The overflow assessment is illustrated on a rectangular tank.

2. FSI-based Overflow Assessment

In engineering fields, application of the isolation systems to liquid storage tanks is challengeable to dramatically improve seismic performance. However, these isolation systems may rather allow fluid motion under earthquake to be amplified and even overflowed. Assuming that a seismically-isolated nuclear tank containing radioactive material is vibrated, overflow event can happen inevitably. Fig-1 shows the schematic for overflow damage stages of the seismically-isolated nuclear tank according to different water levels. As shown in Fig-1, its safety in normal condition is more preserved in high water level, whereas that in seismic condition is not guaranteed due to the relatively more occurrence of liquid overflow. Unfortunately, nuclear tanks like Spent Fuel Pool (SFP) have to contain sufficient water volume for their operation purpose: (i) to allow the spent fuel to cool as its decay heat decreases; and (ii) to shield the emitted radiation. Therefore, the sloshing-induced overflow event has to be well managed in design or assessment.

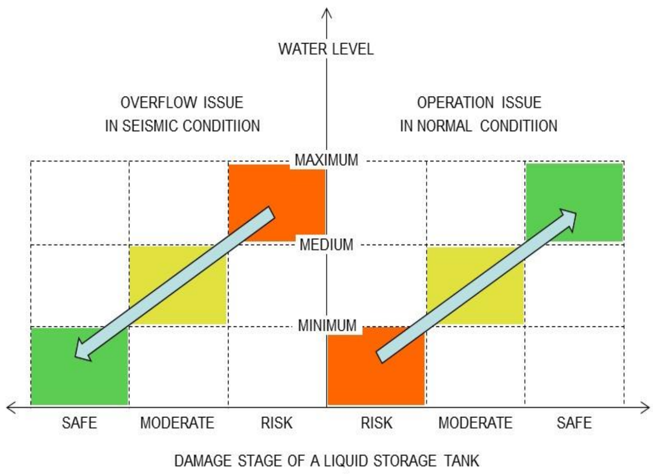

Fig -1: Schematic for overflow damage stage

As described previously, liquid overflow in the seismic isolation tank systems can be occurred due to violent sloshing in an earthquake event. This is possible because sloshing is a significant phenomenon caused even at very small amplitude excitations. In these tank systems, liquid overflow can be well quantified by sloshing assessment based on FSI analysis. The inclusion of FSI effects is necessary to produce more reliable outputs. Typically, FSI analysis is used to solve a multiphysics problem associated with the interaction between deformable structures and flow of fluid where it is filled internally or surrounded externally [4]. The computational fluid dynamics (CFD) approach is also used to consider multiphase flow phenomena of gas/air and liquid. As shown in Fig-2, FSI analysis is conducted by coupling two analytical solvers [5-6]: (i) fluid solver for liquid sloshing analysis; and (ii) structural solver for mechanical application. In structural analysis, all necessary boundary and loading conditions are imposed at the base of a tank, while volume of fluid (VOF) method in sloshing analysis is employed due to its suitability for determining the shape and location of free surface [7]. In the FSI coupling process, individual outputs including mesh displacement and force are continuously transferred to the structural and fluid solvers, respectively.

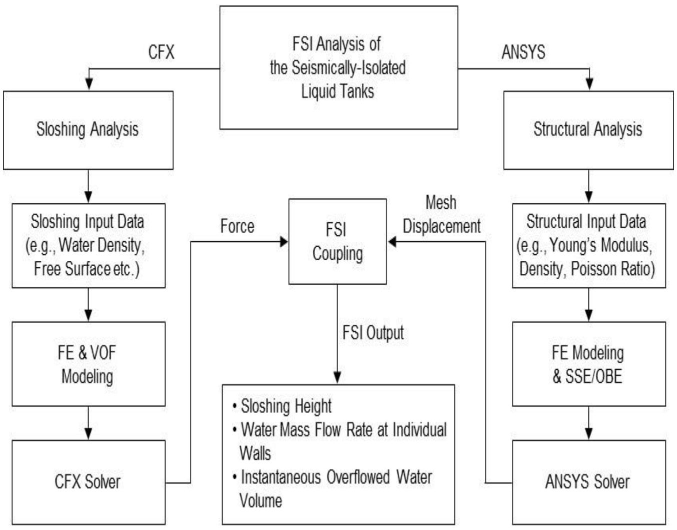

Fig -2: Flowchart for FSI analysis

To estimate sloshing-induced overflow, mass flow rate, $\dot{m}$ (kg/sec), is necessary to be first computed from FSI analysis. It indicates the mass of a substance (e.g., fluid) that passes through an identified surface per unit time. $\dot{m}$ at the opening boundary is calculated as [5]:

$$\dot{m}_i = \rho \cdot A_i \cdot V_i \tag{1}$$

where ρ is the mass density of the fluid; A is the cross-sectional vector area/surface; V is the flow velocity of the mass elements; and i indicates the individual side walls in a rectangular tank (e.g. east, west, north, south). Sloshing-induced overflow is then estimated by dividing the computed $\dot{m}$ in Eq. (1) into the fluid mass density. The total cumulative overflowed liquid volume, V_{tot} (m^3), measured in four-side walls is given by:

$$V_{tot}(t) = \int_0^t \frac{\dot{m}_E(t) + \dot{m}_W(t) + \dot{m}_N(t) + \dot{m}_S(t)}{\rho} \cdot \mathrm{d}t \tag{2}$$

where $\dot{m}_E$, $\dot{m}_W$, $\dot{m}_N$, and $\dot{m}_S$ are the mass flow rate in each side wall.

In this study, a two-way FSI analysis is performed to estimate liquid overflow by using common finite element (FE) software programs Ansys and CFX for structural and fluid analysis, respectively. It is assumed that fluid motion is ideally irrotational, incompressible, and inviscid.

3. APPLICATION

A nuclear SFP, which is a pool-type rectangular reinforced concrete structure located in the nuclear auxiliary building, is employed for performing the sloshing-induced overflow assessment. As shown in Fig-3, its inner dimensions (i.e., VOF modeling of water and air) are 10.82 m in width and 12.80 m in both length and height. Fluid filled in the SFP is assumed to be water with water density, ρ = 997.0 kg/m^3. Its design free surface is assumed to be 12.2428 m. Structural material properties are given by: Young's modulus, E = 27.8 GPa; Poisson's ratio, ν = 0.17; and concrete density, ρ_c = 2,403 kg/m^3.

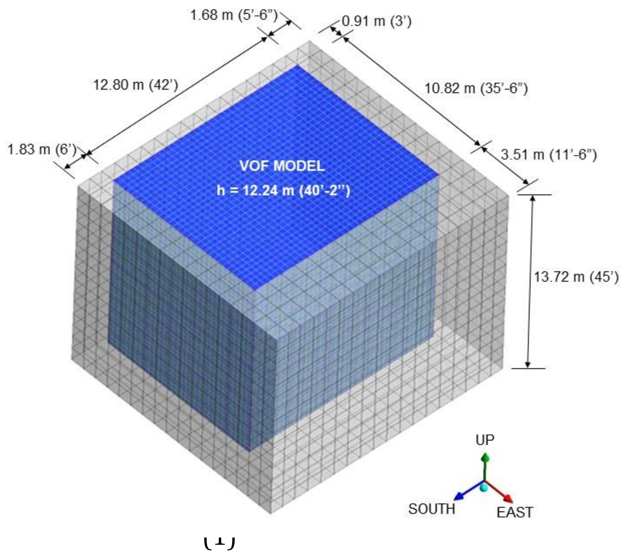

Fig -3: Details of the rectangular SFP

A 3-D FE modeling for the SFP and fluid (i.e., water) is developed with the software Ansys and CFX, respectively.

Fig-3 presents the relevant information on all dimensions and mesh sizes of SFP and fluid. To develop liquid sloshing modeling, VOF technique consisting of air and water regions is used, while a solid element type (i.e. solid185) is used in the SFP structural modeling.

Three sloshing-related parameters (i.e., free surface, water density, seismic loading) are determined from the preliminary FSI analyses. Three acceleration excitations in two horizontal and vertical directions are simultaneously imposed to the base of the SFP up to t = 20.48 sec in every 0.005 sec. After the excitations, additional zero excitations up to t = 40 sec are lasted in order to make sloshing behavior to be converged stably.

For two loading cases of target PGAs of 0.3g and 0.5g, the total cumulative overflow time-histories are plotted in Fig-4 and Fig-5, respectively. After approximately t = 30 sec, it is observed that the liquid sloshing in both cases becomes stabilized. The maximum and minimum overflows happen in east and south side walls, respectively, while the total overflowed water volumes at t = 40 sec are about 51 m^3 and 101 m^3 for PGAs of 0.3g and 0.5g, respectively. Such a significant difference is made in the excitation time intervals between 10 sec and 20 sec.

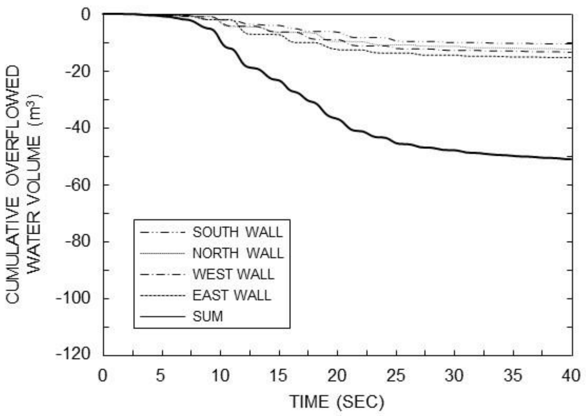

Fig -4: Cumulative overflow time-history for a PGA of 0.3g

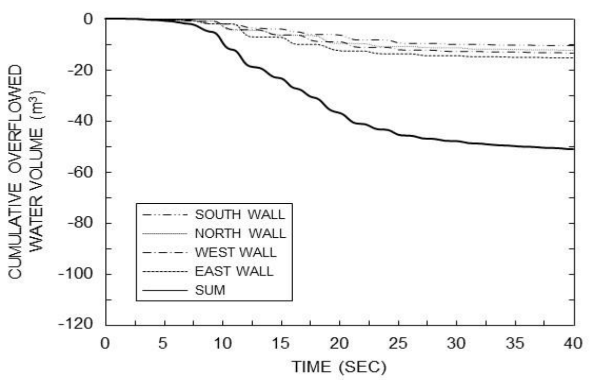

Fig -5: Cumulative overflow time-history for a PGA of 0.5g

Fig-6 and Fig-7 show the sloshing profiles for PGAs of 0.3g and 0.5g, respectively. Due to the amplitude variation and frequency shift dependent on the input PGAs, two different peak sloshing is occurred at different times. For PGAs of 0.3g and 0.5g, the maximum amount of instantaneous overflowed water are about 7.66 m^3 and 18.29 m^3 at different times t = 9.92 sec and 10.18 sec, respectively, as indicated Fig-6 and Fig-7. From this, it is demonstrated that seismic loading uncertainty for the amplitude and frequency can be well considered by using floor acceleration responses produced from the SSI analyses for various PGAs. Fluid motion in PGA of 0.3g becomes converged more stably than that in PGA of 0.5g when the excitations at t = 40 sec are completed.

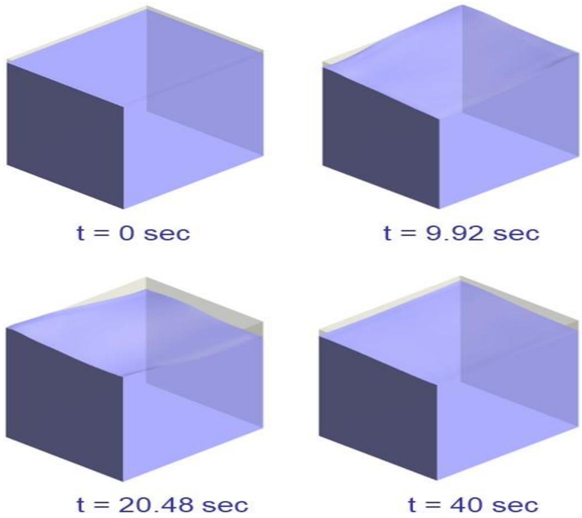

Fig -6: Sloshing profiles for a target PGA of 0.3g

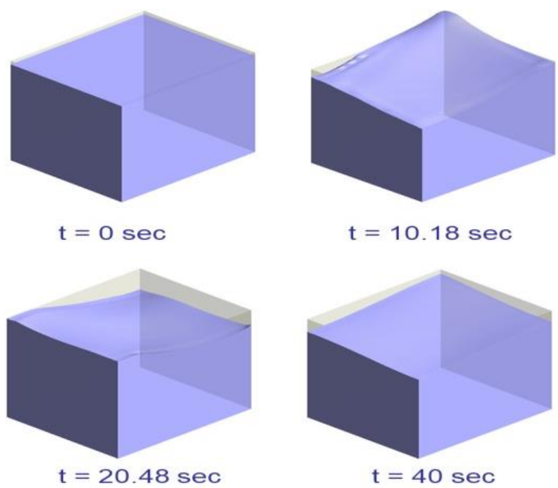

Fig -7: Sloshing profiles for a target PGA of 0.5g

In addition, the instantaneous and total cumulative overflowed water volumes are investigated for the PGAs from 0.2g to 0.6g, as shown in Fig-8 and Fig-9. As expected, the more increases in the excitation amplitude are, the more overflows are occurred. At t = 40 sec, the complete overflows for PGAs of 0.2g and 0.6g are about 33 m^3 and 137 m^3, respectively. Again, the significant increase exceeding about four times can be occurred under uncertainty associated with excitation amplitude.

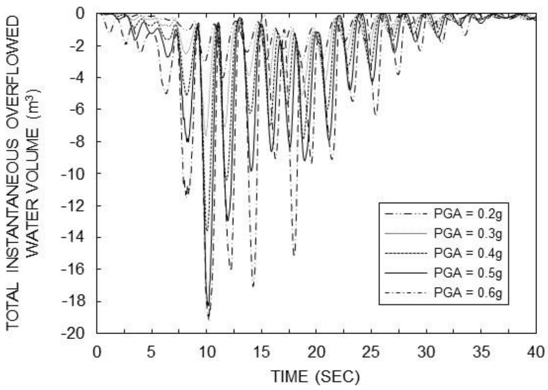

Fig -8: Instantaneous overflowed water volume

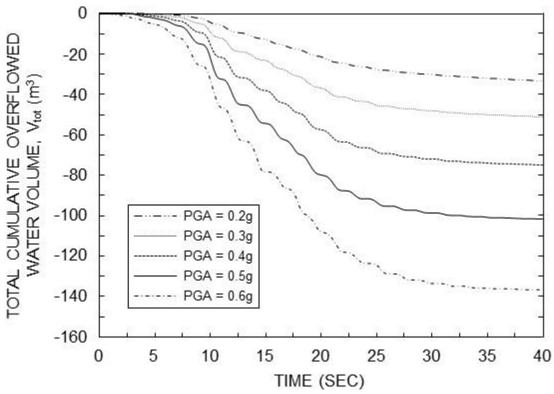

Fig -9: Total cumulative overflowed water volume

3. CONCLUSIONS

This paper presented a FSI-based approach for estimating the time-variant overflow assessment of liquid storage tanks which sloshing behavior can be more amplified in the seismically-isolated system, by imposing potential seismic loading. The proposed approach was illustrated on the seismically-isolated nuclear tank.

The following conclusions are drawn:

1. Sloshing-induced overflow in the seismically-isolated liquid tanks under earthquake can be possibly identified as a crucial failure mode since violent sloshing in those isolation systems can be caused due to the increased relative displacement between the base and superstructures by a long-period shift.

2. The time-variant overflow deterioration models associated with the three sloshing-related parameters (i.e., free surface, water density, seismic loading) can be developed by employing FSI approach which offers efficient opportunities to define an explicit solution for overflow.

3. Assuming that the seismically-isolated nuclear SFP has a drain system to store temporary overflowed water volume under potential dynamic events, an allowable drainage capacity can be reliably identified for preventing overflow-induced damages to human and environment.

4. Future effort is needed to find optimal design solutions to prevent unexpected liquid overflows in any liquid storage tanks including the seismically-isolated nuclear tanks, and furthermore to establish a risk-based methodology dealing with various uncertainties associated with liquid overflow.

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