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Numerical estimation of overflowed liquid for a partially filled rectangular container under seismic excitation

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1. Introduction

Sloshing phenomena occurred by external excitation always has been a problem for partially filled containers, such as fuel storage tanks, elevated water tanks, propellant tanks for spacecraft, liquefied gas tanks for ships and so on. In case of nuclear industry, partially filled rectangular containers, such as SFP(spent fuel pool), could be affected by sloshing phenomena.

Coolant in SFP which are rectangular shape without top cover and contain spent fuel assemblies could be overflowed by external excitation. Linear sloshing resonant frequencies are defined in accordance with height of liquid and width of a partially filled rectangular container, so, in condition of small wave amplitude at low resonant frequencies, linear sloshing wave height by sloshing could be estimated by linear sloshing theory. Whereas, in case of overflowed liquid condition, resonant frequencies of liquid continuously changes in accordance with amount of overflowed liquid.

In this study, estimation of amount of overflowed liquid of a partially filled rectangular container under seismic excitation was performed with numerical simulation.

2. Methods and Results

Numerical simulation was performed by OpenFOAM(Open Source Field Operation and Manipulation) C++ libraries of version 5.0 and interDyMFoam solver and VOF(Volume of Fluid) for interface capturing method were applied to simulate free surface shape and overflowed liquid.

2.1 Theoretical background of linear sloshing

Graham & Rodrigues [1] investigated linear sloshing phenomena for partially filled rectangular tanks of aircraft and suggested exact solution of velocity potential of liquid via Laplace equation and equivalent mechanical model. Housner [2,3] suggested approximated solution with laminated volume and Hamilton's principle and equivalent mechanical model.

$$\omega_n = \sqrt{g(2n+1)\frac{\pi}{a}\tanh\left[(2n+1)\pi\frac{h}{a}\right]}, n = 0, 1, \cdots \quad (1)$$

In accordance with Graham & Rodrigues, nth odd harmonic resonant frequencies (1) of free surface oscillation are determined by width of a rectangular container (a) and height of liquid (h). For scale-down model of a partially filled rectangular container, ratio of h/a has to be same as full-scale model. Nevertheless, resonant sloshing frequencies of scale-down model according to the equation (1) are somewhat higher than full scale model. Therefore, investigators must consider that discrepancy for investigating effect of external excitations of scale-down model of rectangular containers. Whereas, the effect of this discrepancy is beyond the scope of this paper.

2.2 Numerical simulation

A partially filled rectangular container and additional side tanks were applied to estimate amount of overflowed liquid and to simulate free surface of overflowed liquid. Size of the liquid tank is 1.6m x 1.3m (height x width) and the ratio of water level (h) to width (a) of liquid tank is 1.173.

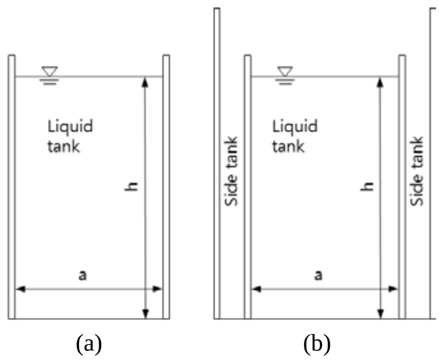

Fig. 1. Typical geometry of a partially filled rectangular container without side tank (a) and with side tank (b).

Rigid body motion of dynamic mesh library was used for translation of meshes according to seismic excitation input which consists of tabulated displacement-time history data. For free surface capturing accuracy, 5mm x 5mm structural grids and 0.5 of Max. Courant Number were applied [4].

Displacement-time history of the seismic input (Fig.2) for the numerical simulation is time history data of x-axis of the horizontal seismic testing system located in KAERI for testing beyond design based accident (PGA 0.3g) of 1/8 scale-down SPF which is primary design type of the national nuclear power station (OPR1000) [5]. Fig.2 shows that from 5s to 8s, maximum displacement occurred and it is about 95mm and after 11s, displacements are less than 10mm.

Entire simulation time is 30 sec. and after t = 20s, that container is stationary condition.

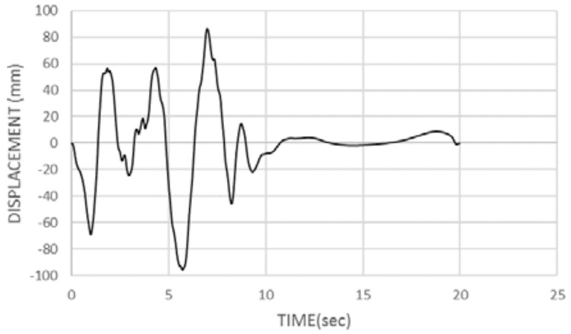

Fig. 2. Displacement-time history of seismic excitation.

(a) t =2.0s (b) t = 2.8s (c) t = 9.54s (d) t=20.0s

Fig. 3. Time-history of sloshing and overflowed liquid.

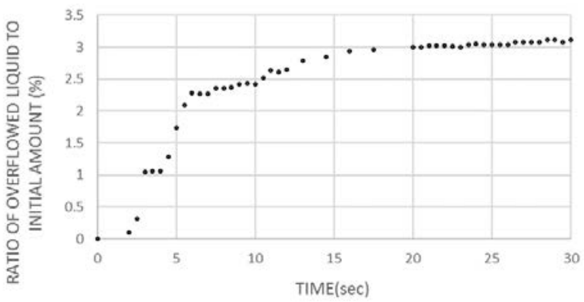

Fig. 4. Ratio of overflowed liquid to initial amount under seismic excitation.

Free surfaces of overflowed liquid are presented in Fig.3. At t = 2.0s, the container shifted about 54mm to right direction and liquid overflowed in the same direction. At t = 2.8s, the container shifted about 14mm to left direction and liquid overflowed in the same direction. At t = 9.54s and 20.0s, liquid was not overflowed.

Fig.4 shows that ratio of cumulated overflowed liquid to initial amount of liquid. Sloshed liquid started overflowing from t = 2s and from t = 2s to t = 6.5s, the amount of overflowed liquid is 2.3% of total amount of liquid. After t = 6.5s, overflow rate of liquid decreases rather than before t = 6.5s and at t = 30.0s, total amount of overflowed liquid is converged to 3.1% of initial amount of liquid in liquid tank

3. Conclusions

Time history of free surface of overflowed liquid and time history of the ratio of cumulated overflowed liquid to initial amount of liquid in a partially filled rectangular container were estimated under seismic excitation. Total overflowed liquid was approximately 3.1% of total amount of liquid. Time history of free surface of overflowed liquid shows that overflowed liquid did not fly far away horizontally. Besides, maximum height of overflowed free surface is about 150mm above the top of the liquid tank and maximum flying distance from side of the liquid tank horizontally at the level of top of the tank is about 160mm. As dominant sloshing mode for causing overflow is first mode, to regulate and control 1st sloshing mode is essential for reducing overflow. So, these results could be used for designing certain equipment or devices to capture and control overflowed liquid in a partially filled rectangular container under seismic excitation.

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