Investigation of Pressure Distribution by Sloshing Effect for the Seismic Safety Assessment of the Spent Fuel Pool

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1. Introduction

A spent fuel pool (SFP) is a storage for the spent fuel assemblies after using in the reactor core. The spent fuel assemblies are put in the storage rack, submerged in approximate 12 m depth of boron-infused water, which is coolant and shielding material, and stored in the SFP until it cools down enough. When a seismic vibration is applied on the SFP, both SFP and inner structures including racks and fuel assemblies are excited not only seismic vibration (in another word, impulsive effect) but also by sloshing motion of the fluid (in another word, convective effect) [1-5]. Therefore, both impulsive and convective effects should be considered in the seismic safety assessment of the SFP.

Various computer simulation techniques, including finite element analysis (FEA) and computational fluid dynamics (CFD), are used for assessment of the nuclear power plant. It seems that fluid-structure interaction using both FEA and CFD would be the best way to consider both impulsive and convective effects in the seismic safety assessment of the SFP. However, that requires excessive computational resources to be used for seismic assessment of the SFP, thus simplified modeling techniques using beam-mass and spring-mass structure introduced by Housner and Epstein have been applied to consider both impulsive and convective effects [6, 7]. This study was performed as a preliminary study for validating and improving previously introduced simplified beam-mass and spring mass structure model to consider hydrodynamic effects, and investigated the pressure distribution by sloshing effect on the SFP wall.

2. Materials and method

Two dimensional CFD model of a rectangular pool, which was scaled down to 1/8 of the SFP in a Korean nuclear power plant was developed. The width and height of the pool, and water level were set to be 1,300 mm, 3,000 mm (to avoid overflow of the water, excessive height of the pool was used), and 1,525 mm, respectively (Model #3, Fig. 1). Four models with the different water level of 763 mm (Model #1), 1,144 mm (Model #2), 1,906 mm (Model #4), and 2,288 mm (Model #5) were, which are corresponding to 0.5, 0.75, 1.25, and 1.5 times of the initial water height, also.

The temperature of the water and air was set to be 25 ℃. Thus, corresponding densities and viscosities of water and air, 997 kg/m^3 and 1.185 kg/m^3, and 8.899 e-04 kg/m-s and 1.831 e-05 kg/m-s, were used. Surface tension of water was set to be 0.07199 N/m. Standard k-epsilon turbulence model was used. Nonslip boundary conditions were applied for all contact surface, and opening static pressure of 0 Pa was applied to the superior plane of the air.

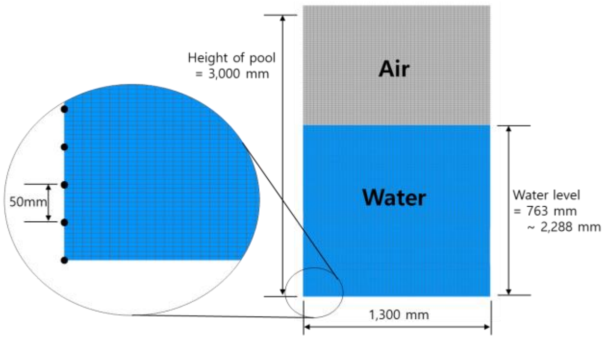


Fig. 1 Two-dimensional CFD model of a rectangular pool

The pool was horizontally excited with an amplitude of 5 mm and a frequency of 10 Hz for 5 seconds. Static pressure was measured at the left wall of the pool, every 50 mm of distance from the bottom surface. The data was analyzed using fast Fourier transform (FFT) to separate impulsive and convective effects. A commercial software, Ansys/Fluent (Ansys Inc., Canonburg, PA, US) was used for modeling and CFD analysis. Matlab (MATLAB 2018a, MathWorks, Inc., Natick, MA, USA) was used for investigating pressure distribution in frequency domain.

3. Results and discussion

Prior to investigating predicted pressures, natural frequency of the fluid in the tank were predicted using the following equation.

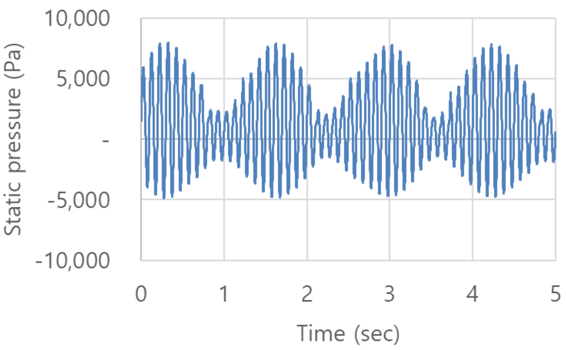
$$\omega_n^2 = g \cdot k_n \cdot \tanh(k_n h), \quad k_n = \frac{n}{L}\pi$$

Here, ω_n, g, k_n, h, and L are *nth* natural frequency, gravity acceleration, wave number, height of water level, and width of the pool, respectively. The natural frequency of the first mode were predicted approximately 0.8 Hz in all models (Table 1). Because the first mode of the fluid natural frequency is dominant in sloshing motion of a fluid [4], we could expect that the changes in pressure with approximate 0.8 Hz is owing to convective effect of the fluid.

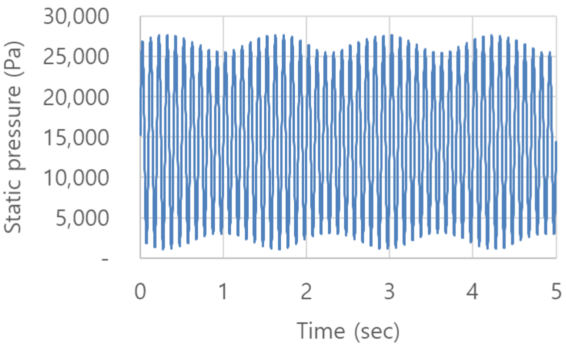
Table 1 Natural frequencies for first five modes of the fluid in developed models (Hz).

Model (Relative height)	MODE				
	1	2	3	4	5
#1 (H = 0.50)	0.76	1.10	1.34	1.55	1.73
#2 (H = 0.75)	0.77	1.10	1.34	1.55	1.73
#3 (H = 1.00)	0.77	1.10	1.34	1.55	1.73
#4 (H = 1.25)	0.77	1.10	1.34	1.55	1.73
#5 (H = 1.50)	0.77	1.10	1.34	1.55	1.73

The predicted static pressures at 50 mm height and 1,400 mm height of the initial model with water height of 1,525 mm during excitation were shown in Fig. 2. At both pints, ten peak points for a second, caused by impulsive effect, and wave shape of those peak points, caused by convective effect, were predicted.



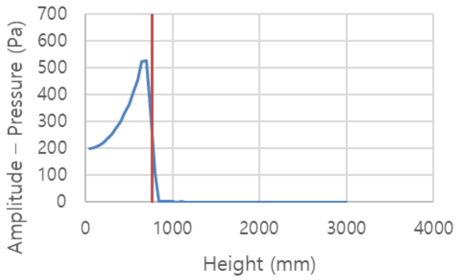
(a) Predict pressure at 1,400 mm height



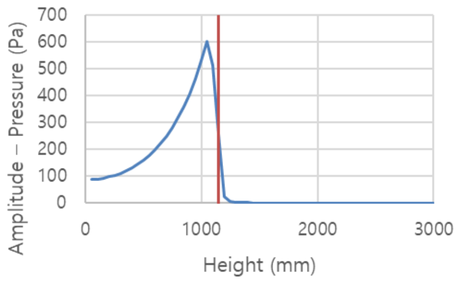
(b) Predict pressure at 50 mm height

Fig. 2 Changes in predicted pressure during excitation in the initial model with 1,525 mm water height

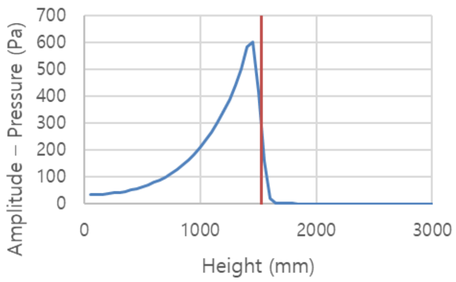
Predicted pressure data at all measuring points were analyzed using FFT to study changes in pressure in the frequency response. Then, the pressure amplitude around 0.8 Hz, which is the first natural frequency of the fluid, at all measuring points were gathered according to the measuring height (Fig. 3). We could obtain pressure distribution caused by sloshing effect, and guess the centroid of the integration of the graph can be the location of equivalent force.



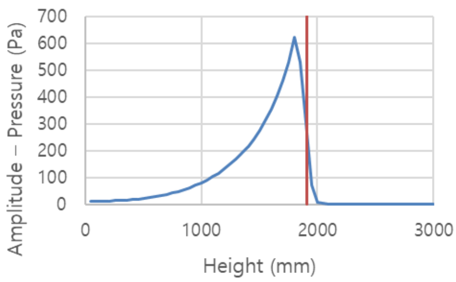
(a) Model #1



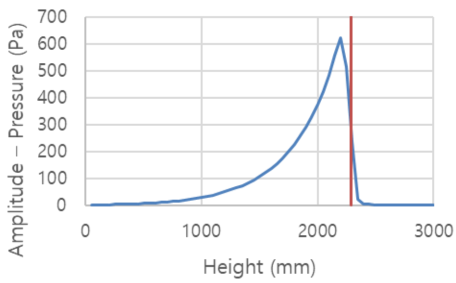
(b) Model #2



(c) Model #3



(d) Model #4



(e) Model #5

Fig. 3 Pressure amplitude of the initial model around the first mode natural frequency according to height. The red line indicates free surface height in each model.

The heights of centroid were 473 mm, 787 mm, 1,141 mm, 1,514 mm, and 1,905 mm for model #1 to #5, respectively. The heights for the convective mass in Housner model are 171 mm, 627 mm, 1,022 mm, 1,405 mm, and 1,788 mm for model #1 to #5, respectively [6]. In the future study, we plan to develop a new model using the obtained data. Then, the model will be compared to the previously introduced simplified model on the aspect of stress on the wall.

4. Conclusions

This study investigated pressure distribution on the SFP wall caused by sloshing effect. This study is a preliminary study as mentioned in the introduction. Thus, there are still many factors should be found to develop a new simplified model. However, the results found in this study provide fundamental information to develop a new model and validate previously introduced simplified model for considering sloshing effects.

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