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Validation of an Equivalent Test Condition for a Scaled-down Model of the Spent Fuel Pool for Seismic Safety Assessment

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1. Introduction

A spent fuel pool (SFP) is a temporary storage for the spent fuel assemblies which are put in the storage racks. Each nuclear power plant has different size of a SFP, but typically a SFP is a large pool with the area larger than 8 m X 8 m and height taller than 16 m. Even though experimental studies using a real scaled storage rack have been performed on the world largest vibration table in Japan [1], it is very hard to perform an experimental study using a real scale model because of its excessive size and weight.

Experiment using a scaled-down model is a widely used research method in engineering fields, including mechanical engineering, civil engineering, and nuclear engineering, when experiment using a real scale model is impossible or difficult. It is very important to develop an equivalent scaled-down model in the experiments. Besides, it is also very important to select equivalent test condition which can satisfy the similarity of the experimental results.

A SFP is filled with boron-infused water, which is used for coolant as well as shielding material. Thus, sloshing motion of the filled fluid is expected in case that an external excitation is applied on the SFP. This sloshing motion of the fluid is very important because it could cause overflow and affect motion and deformation of inner structures including spent fuel assemblies and storage racks. This study suggested an equivalent test condition for differently scaled models on the aspects of aspect of fluid behaviors. Then, the similarity of the results was validated using computational fluid dynamic (CFD) analysis.

2. Equivalent test condition

The first mode natural frequency of the fluid in a rectangular pool like a SFP is mainly affect sloshing behaviors. It can be calculated using the following equations Eq. 1 and 2 [2].

$$\omega_n^2 = g k_n \tanh(k_n h) \qquad \text{Eq. 1}$$

$$k_n = \frac{2n+1}{L}\pi \qquad \text{Eq. 2}$$

where,

n = 0, 1, 2, 3 ….,
k_n = Wavenumber
L = Width of the spent fuel pool
H = Water level

The square of natural frequency is inversely proportional to width of the pool L. Sloshing motion occurs with resonating with excitation frequency, thus, we could expect that frequency of the external excitation should be also the same relationship with the natural frequency for the similarity of two models which have different scales.

Thus, relationship between external excitation frequency (ω) and scale factor (Scale) could be induced as Eq. 3~5.

$$\omega^2 \propto \frac{1}{L} \qquad \text{Eq. 3}$$

$$L \propto Scale \qquad \text{Eq. 4}$$

$$\omega \propto \frac{1}{\sqrt{Scale}} \qquad \text{Eq. 5}$$

In addition, when a sine wave external excitation is applied to the rectangular pool, sloshing height (ξ) is directly proportional to the amplitude of excitation (A). Thus, the relationship between the amplitude and scale can be found as shown in Eq. 6.

$$\xi \propto A \qquad A \propto Scale \qquad \xi \propto Scale \qquad \text{Eq. 6}$$

If external excitation is applied using acceleration, accelerations of the real scale model (a) and scale-down model (a_{Scale}) are calculated using Eq. 7.

$$a = -A \cdot \omega^2 \cdot \sin(\omega \cdot t)$$

$$a_{Scale} = d''_{Scale} = A \cdot Scale \cdot (-1) \cdot \left(\frac{\omega}{\sqrt{Scale}}\right)^2 \cdot \sin(\frac{1}{\sqrt{\mathrm{Scale}}}\,\omega \cdot t)$$

$$= -A \cdot \omega^2 \cdot \sin(\frac{1}{\sqrt{Scale}}\,\omega \cdot t) \qquad \text{Eq. 7}$$

where, d_{Scale} and t is displacement of external excitation and time, respectively.

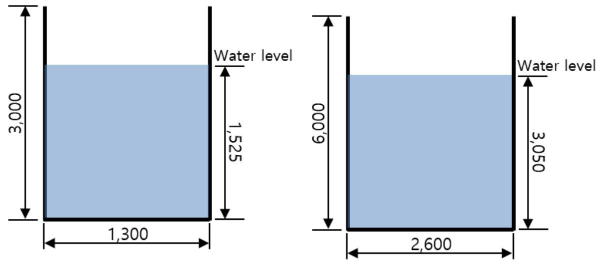
Therefore, amplitude of the excitation acceleration for the scale-down model is same with that for the real scale model. However, duration of excitation time for the scale-down model should be changed because frequency of external excitation was changed.

$$t_{Scale} = \sqrt{S_f} \cdot t_{\mathrm{Original}} \qquad \text{Eq. 8}$$

where, $t_{Original}$ and t_{Scale} are duration in which external excitation applied on the real and scaled models, respectively.

3. CFD analysis for validating the similarity

Two two-dimensional CFD models (model 1 and 2) of fluid filled rectangular pools were developed (Fig. 1). For the model 1, the width and height of the pool was set to be 1,300 mm and 3,000 mm, and water level was set to be 1,525 mm. The model 2 was developed to be two times bigger than the model 1.



(a) Model 1 (b) Model 2

Fig. 1 Developed two-dimensional CFD models of the fluid filled rectangular pools with different scales

The model 1 was horizontal vibrated with a frequency of 1 Hz, an amplitude of 5 mm for 5 seconds (case 1); with a frequency of 10 Hz, and an amplitude of 5 mm, for 5 seconds (case 3), and with the design-based earthquake (DBE) along east-west direction for 5 seconds (case 5). Equivalent test conditions for case 1, 3, 5 were obtained using Eq. 5 ~ 8 and applied to model 2 (case 2, 4, 6, Table 1).

Sloshing behaviors in the model 1 and 2 were predicted using a commercial CFD, code Ansys/Fluent (Ansys Inc., Canonburg, PA, US). For CFD analysis, finite volume method was used; the convection term was used for the upstream scheme; the Pressure Implicit with Splitting of Operators (PISO) algorithm was used for the pressure-velocity coupling; the volume of fluid (VOF) model and the standard k-ε model were used [3].

Table 1 Test conditions for the model 1 and 2

Case #	Model	Frequency [Hz]	Amplitude [mm]	Total analysis time [sec]
1	1	1	5	5
2	2	0.7071	10	7.071
3	1	10	5	5
4	2	7.701	10	7.071
5	1	DBE		5
6	2	DBE		7.071

4. Results

Predicted sloshing height and pressure on the left wall of the pool were used to validate similarity of the equivalent test conditions for the model 1 and 2. Because excitation time for the model 1 and 2 is different, the predicted results were compared in the normalized time. Furthermore, the sloshing height of the model 2 should be two times higher than that of the model 1, so half of the sloshing height predicted in the model 2 was compared to that of the model 1 (Fig. 2 and 3).

Sloshing heights in case 1 and 5 showed very good agreement with those in case 2 and 6. While overall sloshing motion in case 3 showed good agreement with that in case 4, slight differences were shown between two cases. Nonlinear features of fluid behaviors including splash would cause the differences (Fig. 2). Not only predicted sloshing height, but also fluid behaviors showed good agreement (Fig. 3) between two models.

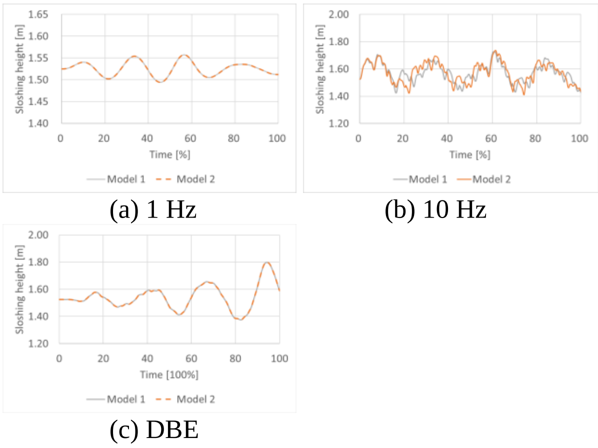


Fig. 2 Sloshing height at the left wall of the spent fuel pool

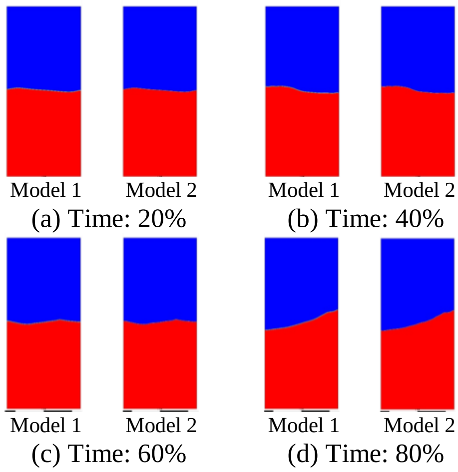
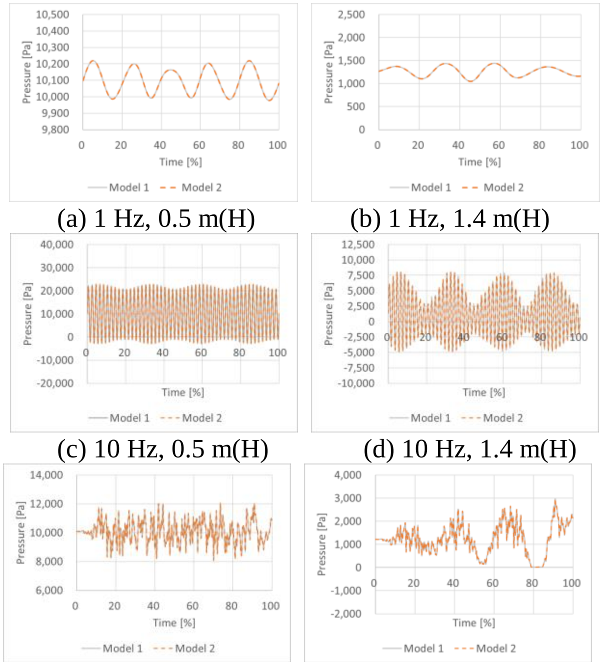


Fig. 3 Comparison of sloshing motion under DBE excitation (Case 5 and 6)

The pressures on the left wall were predicted at two different height, which are 0.5 m and 1.4 m from the bottom plane of the pool of the model 1. The pressures in the model 2 were also predicted at the corresponding locations. While the impulsive effect is strongly shown at the deep position of the pool, the convective effect is well shown around the free surface [4, 5]. Based on force equation, the pressure of the model 2 should be twice of those of the model 1. The half of the predicted pressure in model 2 was compared to that in model 1 and the results showed good agreement with each other in all test conditions (Fig. 4).



(a) 1 Hz, 0.5 m(H) (b) 1 Hz, 1.4 m(H)
(c) 10 Hz, 0.5 m(H) (d) 10 Hz, 1.4 m(H)
(e) DBE, 0.5 m(H) (f) DBE, 1.4 m(H)

Fig. 4 Pressure at the left wall of the spent fuel pool

5. Conclusions

In this study, equivalent test conditions for the scaled model on the aspect of fluid behaviors were proposed and similarity of the predicted results were validated using CFD analysis. Fluid behaviors including sloshing motion and pressure on the wall in two models, which have different scales, showed very good agreement with each other. Therefore, the authors believe that the proposed test condition could be used in the experimental studies using the scaled-down model for the seismic safety assessment of the SFP.

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