

## A Scalability Method for the Seismic Test of a Spent Fuel Storage Pool

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### 1. Introduction

Korea had built OPR-1000 Nuclear Power Plants (NPPs) in 1995 between 2012 in Kori, Younggwang, and Ulchin. After success in OPR-1000 design, Korea developed APR-1400 NPP of which standard design was recently approved by USNRC. Shinkori-3&4, ShinHanwool-1&2, and even Baraca in UAE are APR-1400 NPPs. OPR-1000 NPP is designed based on Safety shutdown Earthquake (SSE) of 0.2g while APR-1400 NPP based on 0.3g of SSE. It is worthy to mention that Korea NPPs are not far from the epicenter of Kyungjoo and Poohang earthquake, in 2017, and 2016, respectively. Although most of OPR-1000 NPPs and APR-1400 NPPs are near the epicenter of big earthquakes, the seismic design base of OPR-1000 NPPs are low. From this point of view, seismic safety evaluation of OPR-1000 NPPs is much more important.

After Fukushima accident, most people get worried about Spent Fuel Storage Pool (SFSP) as being aware that fuel assemblies exist not only in reactor core but also in the SFSP. Especially, since the disposal policy on spent fuels is not decided yet, lots of fuels in SFSP are stacked much more than in reactor.

With regard to this study, several studies may be referred such as IAEA technical document [1], Lu's similarity study on Fast Breed Reactor [2], and recent japan researcher's study on seismic experiment[3].

In this study, we describe a scalability method for the experimental evaluation of the SFSP of OPR-1000.

### 2. Similarity law of fluid and fluid-structure interaction

#### 2.1 Geometric similarity

The SFSP of OPR-1000 may be considered as tall tanks. The pool height is taller than two-side widths. Water depth is approximately 2.7 times longer than fuel assembly height. The spent fuels are standing freely in the cells provided in the spent fuel racks, which was shown in Figure1. There are twelve (12) spent fuel racks in SFSP. Each spent fuel rack contains seventy (70) to one-hundred fifty-eight (158) spent fuels.

We decided one-eighth (1/8) scale for the test model. The scale was determined considering the table size and performance of shaker, respectively, 2m x 2m and 9.8m/s<sup>2</sup> at payload of 5 tons. Every structures in the SFSP reduced by 1/8 in length and by 1/512 in mass. Masses and dimension of the reduced model for the rack are summarized in Table 1. Total weight difference between scaled model and as-built model is less than 1%.

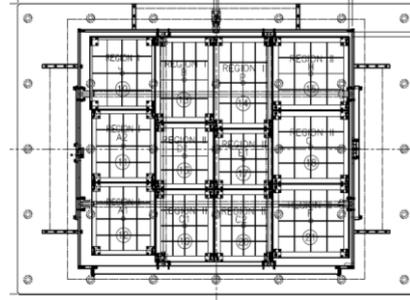


Fig. 1 Concept drawing for the spent fuel racks in spent fuel storage pool of OPR-1000

Table 1 Scaled dimension and weight of Fuel rack models

Module	Dimension		Scaled weight (kg)	As-built Weight (kg)	Error (%) (as-built-scale)/scale
	N-S	E-W			
A1	333.8	299.8	137.95	135.33	-1.9
A2	333.8	299.8	137.95	135.33	-1.9
J	333.9	310.7	109.76	108.25	-1.4
C1	333.5	277.8	171.06	171.83	0.4
C2	334.2	278.1	170.97	172.28	0.8
D1	306.0	277.9	156.89	151.92	-3.2
E1	278.3	277.9	143.10	142.0	-0.8
B	394.1	281.6	199.53	197.45	-1.0
P	422.4	281.6	212.92	206.1	-3.2
H	338.1	365.9	220.92	216.1	-2.2
G	338.1	365.9	221.33	211.87	-4.3
F	338.3	366.4	221.33	236.0	6.6
Total			2103.70	2084.46	-0.9

#### 2.2 Dynamic similarity

A dynamic similarity importantly involves various forces such as pressure, fluid inertia, gravity, elastic forces. A model is dynamically similar to the prototype if a constant force ratio is remained between model and prototype.

The Buckingham Pi theorem allows the derivation of a complete set of dimensionless parameters for a given problem. As the theorem, a problem of n variables in r fundamental dimensions can be fully described by m (m=n-r) dimensionless parameters. For the seismic excitation-induced sloshing problem, the wall pressure may be expressed as:

$$p = f(\rho_f, L, H, q_0, \omega_g, g, t, \rho_s, E_s) \quad (1)$$

Where L and H are the width and height of SFP, and  $q_0$  and  $\omega_g$  are seismic displacement amplitude and frequency, t is time, and  $\rho_s$  and  $E_s$  are density and Young's modulus of structure, respectively.

Fluid density ( $\rho_f$ ), pool length ( $L$ ) and gravity ( $g$ ) may be selected as base parameters as required by Pi theorem. Then, one may have the following equation for the dimensionless pressure.

$$\frac{p}{\rho_f L g} = f\left(\frac{H}{L}, \frac{q_0}{L}, \omega \sqrt{\frac{L}{g}}, t \sqrt{\frac{g}{L}}, \frac{\rho_s}{\rho_f}, \frac{E_s}{\rho_f L g}\right) \quad (2)$$

By using dimensionless frequency and time in eq. (2), similitude between model and prototype would be set as follows:

$$\frac{(\omega)_m}{(\omega)_p} = \frac{(\sqrt{L})_p}{(\sqrt{L})_m} \quad (3)$$

$$\frac{(t)_m}{(t)_p} = \frac{(\sqrt{L})_m}{(\sqrt{L})_p} \quad (4)$$

Where, subscript m and p stand for model and prototype, respectively. One may determine acceleration and velocity scalability once model scale is fixed, which are as follows:

$$\frac{(a)_m}{(a)_p} = \frac{(L)_m}{(L)_p} \cdot \frac{(t^2)_p}{(t^2)_m} \quad (5)$$

$$\frac{(V)_m}{(V)_p} = \frac{(L)_m}{(L)_p} \cdot \frac{(t)_p}{(t)_m} \quad (6)$$

The scalability of pressure in eq. (2) may be expressed as follows:

$$\frac{(p)_m}{(p)_p} = \frac{(\rho_f L g)_m}{(\rho_f L g)_p} \quad (7)$$

Since dimension scale was set as one-eighths (1/8), physical quantity for a scale model test may be summarized in Table 2 as follows:

Table 2 Parameters for 1/8 test model

Parameters	Prototype	Scale model
Length	1	1/8
Mass	1	1/512
Frequency	1	$\sqrt{8}$
time	1	$1/\sqrt{8}$
Acceleration	1	1
Velocity	1	$1/\sqrt{8}$
pressure	1	1/8
Force	1	1/512

Fluid motion induced by seismic excitation would be involved several important forces that must be considered for some dynamic similarity as follows:

- 1) Inertia force of fluid:  $\rho L^2 V^2$
- 2) Gravity force:  $\rho g L^3$
- 3) Pressure force:  $p L^2$

4) Structure elastic force:  $EL^2$

When it comes to a sloshing problem, the relation between the gravity and inertia forces is very important, which was quantified by the Froude Number defined as:

$$Fr = \frac{v}{\sqrt{Lg}} \quad (8)$$

In addition, the relation between the pressure and inertia force is important for the FSI problem, which may be quantified by the Euler Number defined as:

$$Eu = \frac{p}{\rho V^2} \quad (9)$$

Regarding FSI problem, the other important relation is structural elastic force to inertia force, which is quantified by the Cauchy Number defined as:

$$Cy = \frac{\rho V^2}{E} \quad (10)$$

The three important relations mentioned above are preserved once the similarity laws that were derived in section 2.

### 3. Conclusion

In this study, a scalability method for the seismic experiment on PWR (OPR-1000) spent fuel storage pool were developed. Once the dynamic as well as the geometric similarity keep according to this study, three important force relations such as Froude Number, Euler number and Cauchy Number were preserved. It is believed that the developed scalability method can be used for a scale-down model of a big structure involved in FSI phenomenon.

### ACKNOWLEDGEMENT

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