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Seismic Test of a Scaled-down Model for Spent Fuel Racks in NPP Spent Fuel Pool

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1. Introduction

The OPR-1000 was designed based on a safety shutdown earthquake (SSE) of 0.2 g, while the APR was based on a 0.3 g SSE. Recently, there have been severe earthquakes on the Korean peninsula. It should be mentioned that the locations of Korean NPPs are not far from the epicentres of earthquakes that occurred in 2016 and 2017. The SSE of OPR-1000 (a Korean NPP) is even lower, although most OPRs and APRs are also near the epicentres of the earthquakes. From this point of view, seismic safety evaluation of OPRs is considered to be much more essential.

When a water-filled SFSP (Spent Fuel Storage Pool) is subjected to dynamic excitation by an earthquake, hydrodynamic forces arise from water oscillation (called sloshing) in the storage pool. It has been reported that, at times, such hydrodynamic forces cause severe permanent damage to the wall structures of the storage pool [1]. In addition to structural damage, when severe sloshing occurs in the SFSP of an NPP, coolant contaminated by radioactivity could flow over the wall of the SFSP. When designing an SFSP in regards to seismic incidents, several issues must be considered. These include such as overflows of contaminated water, the structural integrity of the spent-fuel assemblies and spent-fuel storage racks, and the damage that might result from impacts between racks, as well as between racks and the walls of the SFSP.

This is a report on a seismic simulation test as a follow-up study on a scalability method (similitude law) for the experimental evaluation of SFSP [2].

2. Seismic Experiment

2.1 Scaled-down model

All of the structures in the experimental SFSP were made maintaining a one eighth (1/8) scale. In the pool, there are twelve spent-fuel racks each of which actually contains seventy to one-hundred-fifty-eight spent-fuel assemblies. For this experiment, total weight of spent fuel assemblies in each rack is just added to the rack as a dead weight.

Dynamic pressure sensors were installed on two sides of the 1/8 SFSP to measure the dynamic fluid pressure during sloshing induced by the seismic input. Because impact between the walls of the SFSP and the racks inside in it was expected during the test, six force transducers were mounted on the interior walls of the SFSP, which is shown in Figure 1. It was desirable to measure the movement and acceleration of each rack during the tests.

Water-proof accelerometers installed on t top of the racks were used to record movements as well as accelerations of the racks in two dimensions.

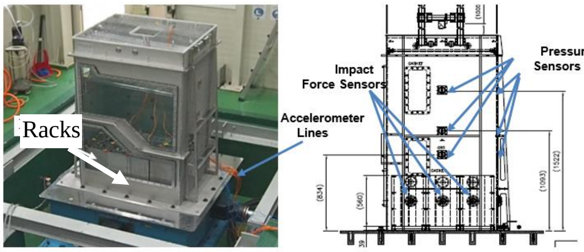

Fig. 1. One-eighth model of a SFSP and racks

2.2 Seismic Input

The input seismic signals in the time domain were made according to the US NRC Reg-guide 1.60 [6]. In this study, the safety-shutdown earthquake (SSE) and beyond-design-basis earthquake values were set as 0.2 g and 0. 3 g, respectively. Total seismic duration was set for 15 s, and for the period, the strong seismic period was set for 9 s. Once the seismic input was determined, it was modified according to the similitude law in Table 2. Figure 2 shows the east-west and north-south seismic acceleration for the 1/8 test model made according to similarity laws presented in the previous section.

The output of the detector model is input to the cable model. The cable is modeled using the code PSpice and includes the cable characteristics of capacitance, resistance, characteristic impedance, and length. Although the effect of cable on the shape of the output signal of a detector is usually negligible, in our application to high-rate counting, its effect is significant. For our application, we found a distributed parameter model was necessary for accurate modeling of the cable.

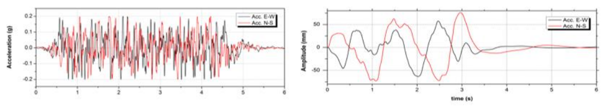

Fig. 2 Seismic acceleration in g and amplitude for test

2.3 Experimental Results

Dynamic pressures during fluid oscillation measured from the two side walls are shown in Figure 3 for SSE and BDBE. The BDBE of 0.3 g was produced by scaling up from the SSE of 0.2 g. As shown in Figure 3, for dynamic pressures at OBE, the measurements from the sensor at the highest position turned out to be no good. That happened because sensors might be exposed to air and then submerged in water as the free surface of the water rose and fell due to the fluid wave oscillation called sloshing. The pressure was stronger with depth beneath the free surface of the fluid. The maximum pressure at SSE was approximately 2.5 kPa from the deepest sensor, and approximately 5.4 kPa from the same sensor at BDBA. As shown in Table 2, using the 1/8 scale law to convert to a full-scale value, the dynamic pressure at full size might be higher than 20 kPa for SSE and 43.2 kPa for BDBE.

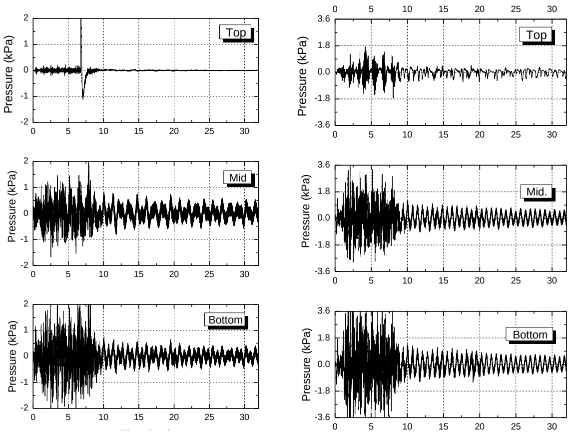

Fig. 3. Dynamic pressure measurements on the walls of SFSP at 0.2g (three left column) and 0.3g (three tight column) seismic input.

Unlike the response signals during the first six seconds, a certain periodic oscillation was observed after six seconds, which anyone could assume was sloshing information. Response pressure signals after the first six seconds reveal lower sloshing frequencies, which were obtained from the bottom and middle height sensors. The frequencies measured in the west direction were 0.75 Hz and 1.468 Hz, while those in the north direction were 0.843 Hz and 1.468 Hz, respectively. The frequencies obtained from this experiment are the first and the third (or fourth) sloshing frequencies produced by an analytical method based on linear potential theory. The equation for sloshing frequency [3] is written as

$$\omega_n = \left\{ \frac{(2n+1)\pi g}{L} \cdot tanh\left(\frac{(2n+1)\pi h}{L} \right) \right\}^{1/2} \quad (1)$$

In equation (1), L, h, and g denote the reservoir width, fluid height, and gravitational acceleration, respectively. It is well known that the sloshing frequency can be estimated precisely by linear theory, which provided the sloshing frequencies in Table 1. As seen in Table 1, the frequency difference between each mode is very small. We believe that the small difference is the reason why the experimental results gave just two frequencies. Two neighbor modes may have collided and merged into one. As seen in Table 3, the water height from the bottom of the reservoir was 1.525 m, and that from the top of the spent-fuel racks was 0.965 m. We believe that our experimental results are more comparable with the latter (water height of 0.965 m). This is very reasonable because the active water height might have been reduced by spent-fuel racks if they had actually filled in the reservoir.

Table 1: Sloshing frequency obtained by a potential flow linear theory [3]

Mode No.	East-West Direction (Width =1.3 m)		North-South Direction (width =1.075 m)	
	Water H=1.525 m	Water H=0.965	Water H=1.525 m	Water H=0.965
1	0.774 Hz	0.768 Hz	0.852 Hz	0.849 Hz
2	1.096 Hz	1.096 Hz	1.025 Hz	1.205 Hz
3	1.342 Hz	1.342 Hz	1.476 Hz	1.476 Hz
4	1.550 Hz	1.550 Hz	1.704 Hz	1.704 Hz

3. Conclusions

Spent fuel storage pool of OPR1000 was designed and manufactured in 1/8 scale, and then, tested for SSE of 0.2g and beyond SSE up to 0.3g as applied a dynamic similitude rule to scaled model. The maximum pressures were measured at the lowest sensors, just above the spent fuel storage rack, which were 2.5 kPa for SSE and 5.4 kPa for beyond SSE. As considered similitude law, pressures could be equivalent to 20kPa and 43.2 kPa. Sloshing was observed from all three different water heights that were from the free surface of water to just above fuel rack.

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