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SCALED POOL AND STORAGE RACK MODEL EXPERIMENT FOR SIMULATING SEVERE EARTHQUAKE ACCIDENTS WITH EQUIVALENT SIMILARITY

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ABSTRACT

The spent fuel and storage racks are susceptible to slides and can impact each other in the spent fuel pool due to the seismic base excitation that compromises their seismic safety. In addition, a strong earthquake can lead to the overflow of contaminated water and pressure loads to the storage pool by sloshing. These issues have been highlighted in recent years in nuclear regulations and industries, as the magnitude and frequency of earthquakes has increased in Korean peninsula. To satisfy the growing needs of estimating realistic spent fuel assembly dynamics and to assess the seismic safety of the real spent fuel pool, a reliable prediction model should consider the sloshing of the water surface and fluid-structure interactions between the racks, plus fuel and water, in the deep end of the pool. In this respect, the joint experimental test program on the scaled model and analysis model development project were funded by the Korean government. A scaled pool model with simplified racks, that were submerged in the filled pool, was mounted on the hydraulic shaking table and excited by a frequency-variated sinusoidal force to simulate typical dynamic events and earthquake accidents. According to the excitation condition and level of water, the amount of overflow, dynamic pressures on the wall, the sloshing wave profiles of the free surface were measured and compared with the analysis results. The residual response of the internal submerged structures, measured by accelerometers, showed natural sloshing modes of vibration for the filled water. The test results will show the validity of the numerical model for the seismic safety evaluation of the spent fuel and be used to predict full scale pool behaviours.

Keywords: Spent fuel pool, seismic safety evaluation, similarity rule, scale model, seismic simulation, vibration shaking table, sloshing, wave pressure, sliding rigid body motion, impact force, overflow.

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1. INTRODUCTION

Since the first commercial operation of the Kori nuclear power plant started in 1978, South Korea has been producing stable and environmentally-friendly electric power through nuclear power generation for 40 years. The reactor core that generates enormous heating power by the fission chain reaction consists of stacked piles of around 200 fuel assemblies. After three cycles of an in-reactor fuel burnup, the spent fuels were temporarily stored in the wet storage facilities for years or decades. With a 40-year history of nuclear power generation in Korea, the total amount of spent fuels accumulated in the wet storage facilities of each power stations has now reached 18,500 bundles (PWR basis), which is 70% of the total storage capacity in Korea, thereby approaching the national capacity limit. However, the storage facilities of some old-aged power plants, such as the Kori Power Station, are already saturated and are now transporting their spent fuels to neighboring storage facilities within the site [1].

Meanwhile, the magnitude and frequency of earthquake accidents on the Korean Peninsula are on the rise, and earthquake accidents are one of the major incidents that could seriously affect the safety of nuclear power plants, as in the case of the East Japan Earthquake in 2011[2, 3]. The magnitude of the earthquakes on the Korean Peninsula is relatively weak compared to Japan, but it is not possible to predict at what time and in what magnitude the earthquakes will occur in the future. Thus, the seismic safety analysis of the nuclear power station should be carried out on a sufficiently conservative basis and the real physical phenomena that may occur in the actual reactor core or storage facility should be sufficiently reflected in the analysis conditions. In addition, the spent fuel has material deterioration of increasing brittleness due to long-term in-reactor operations and wet storage in low temperatures, and it has a structural weakness particularly vulnerable to impact loads[4, 5].

The key part of the technology for evaluating seismic safety of spent fuel storage tanks is to predict the structural behavior of spent fuels in each cell of the storage rack and to determine the magnitude of the anticipated impact load. However, there are still many challenges with the current numerical techniques because the pool and spent fuel are in water and interacts with adjacent gap fluids. This is due to arbitrary factors such as complicated rigid body motions due to the friction condition with the floor, discontinuity such as the rattle oscillation of the fuel in it, and the gap with the neighboring storage rack[6-8].

Herein, in order to develop the safety evaluation technology of spent fuel pools and spent fuels for severe seismic accidents, a seismic accident simulation test was performed using a 1/8 scale model pool. Mass-embedded free standing racks seated over the pool floor were excited by the seismic input force in air and mostly under-water filled with different water levels. The scale pool was linearly scaled from the real spent fuel pool. The seismic input for the test was artificially deduced from the US-NRC REG-

Guide 1.6[9] on the basis of the time history generation rule. Time and frequency spans in the target control input seismic records were properly scaled to meet the similarity rule between the real and scale models. Two cases of the seismic excitation, design based accident (PGA 0.2g) and beyond design based accident (PGA 0.3g) for the primary design type of the national nuclear power station (OPR1000), were considered in the test program. Various tests were performed using test parameters such as air/water, level of water, excitation direction, level of excitation, and full and partial loading of the racks. The time history of the free surface fluid motion including the wave pressure, and the acceleration responses of the submerged racks in the pool were measured during the accidental seismic excitations of the pool base.

2. Scale Model Experiment

A scale model pool was constructed in a rectangular open pool with a 35% higher height than the actual pool to avoid an unexpected overflow. The model pool had a visualization window in the front to record the water movements during the seismic excitation. All of the spent fuel masses were assumed to be attached to the model storage racks, reflecting the domestic situation where the national storage facilities are saturated. The model racks also prevented random rattling noise in the response measurements from vibrating the nuclear fuel within each cells of the racks. The seismic excitation to the model pool was determined by dimensional analysis so that the water motion and the response of the structure can be reproduced with a real pool in a real earthquake condition. It was assumed that the non-dimensional numbers Fr and Eu, as well as the dimensionless variable corresponding to the structure acceleration, were set to 1.0. In addition, the correlation and the dimensional constants for the remaining dimensionless variables were derived, respectively. These scaling correlations and methodologies were validated through 2D fluid structure interaction model simulations. Fig. 2 shows a scale model pool and test configurations.

Each test case to simulate severe seismic accidents in the Korean peninsula was based on following control parameters such as the direction and magnitude of excitation, water level (e.g., 100 %, 85 %, 60 %; the water level in the spent fuel pool can decrease by evaporation and leakage), and waveform (e.g., earthquake, sinusoidal wave, random). The waveform of the seismic accident simulation was based on the standard earthquake input spectrum used in the seismic design of a nuclear power plant. However, in each test case, because the acceleration response of the model racks can vary depending on the interfacing gaps with the neighboring racks, each test case was performed after the initial re-positioning of the model racks.

The hydraulic shaker (MTS biaxial shaking table) with 1 g maximum acceleration and 60 Hz maximum excitation frequency with 5 tons full loaded condition was used for the seismic accident simulation test of the model spent fuel storage pool. In order to reproduce the target history of the standard seismic input waveforms, the system dynamic characteristics of the shaking table, including the weight of the pool specimen, were reflected during the iterative tuning process to make the resulting input force (scaled) before the seismic accident simulation test operation.

The free surface water motion and model rack acceleration during the seismic base excitation were measured using a high speed camera (250 fps ~ 500 fps, fps: frame per second) and underwater accelerometers, respectively. Uni-axial accelerometers were mounted on the selected racks of interest in three perpendicular directions each, close to the center of the rack mass. In order to measure the wave pressure onto the pool wall by free surface water motions, a dynamic pressure sensor (3 elevations along the centerline of the wall) was installed on the two perpendicular sides of the pool wall. Also, a 30 seconds time history of all instrumentations was recorded in the data acquisition device during the test operation. Each test operation consisted of a 10 second strong excitation period and 20 second naturally sloshed decaying periods.

The reference input of the seismic accident simulation test was based on the US-NRC Reg Guide 1.6[9]. A reference seismic acceleration input time history was created based on the Civil Engineering Derivation guideline of the input time history for the maximum amplitude value and one-degree-of-freedom model. After the reference acceleration input was made on the basis of 1g, then it was appropriately scaled to represent safety shutdown earthquake(SSE) accident for the seismic design evaluation of the OPR1000 Korean standard power plant.

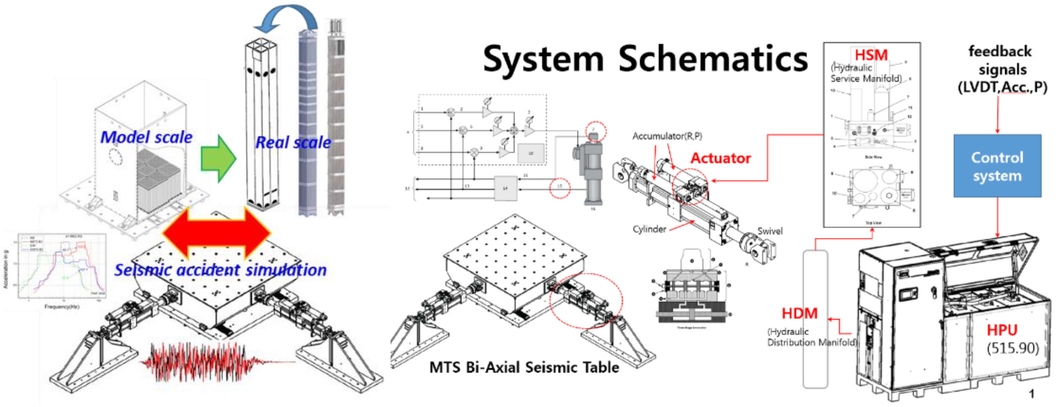

Fig. 1 Scale Model Pool, Test Configurations and Shaking System Schematics

3. Test Results

3.1 Free surface sloshing and wave pressure

Figure 2(a) shows the snap-shot images from typical free surface motion recorded by a high speed camera (250 fps). The water motions in the pool during the strong period of a seismic excitation are of a complex wave-form and an almost chaos motion, away from the local small linear motion, which accumulated with the flow separation, rise-up, and air-mixed two-phase (mixing) due to the wall impact and directional transition of the motion by the reversal excitation. The trends in motion slightly changed according to the magnitude of excitation and phase difference between the base excitation and fluid motion. The free-surface water behavior due to the seismic base motion showed a very different trend depending on the initial level of the pool. This can be understood that the difference in the potential kinetic energy of the water makes some discrepancies in the fluid motion and the lowering of the water level is caused by the interference near the upper part of the storage rack. If you trace out the movement history of water at the same time interval, you will notice that during the natural sloshing, the characteristics of the attenuation(damping) of the fluid motions depend on the initial water level and are the highest value at the lowest water level of 60%.

Fig. 2(b) shows the sloshing wave pressure time history measured at the three elevations in two perpendicular directions along the centerline of the pool wall. Since the kinetic energy of the fluid motion was relatively larger during the forced seismic excitation period, then the larger pressure wave acted on the wall during those periods. Thereafter, it gradually decreased and dissipated during the residual sloshed fluid motion. When attenuated by the natural sloshed motions, the frequencies of the two periodic components appearing in the spectrum (Fig. 3) indicate a fundamental frequency of natural sloshing mode in two perpendicular directions [10]. It is noted that the wave pressure time history acting on the wall during the sloshed motions showed a somewhat physical visualization about the waveform of free-surface fluid motions.

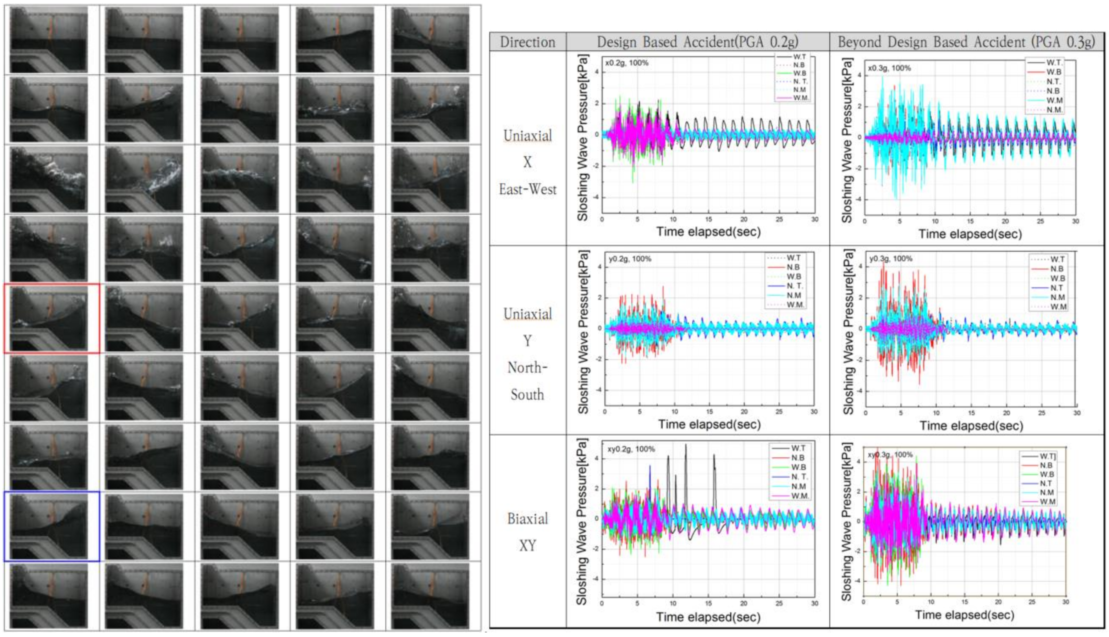

Fig. 2 (a) Snap-shot images from high speed camera measurement for free surface motion in the pool during the severe seismic simulation test (100% level, PGA 0.3g), (b) Typical time histories of sloshing wave pressure over the wall during the seismic excitation (PGA 0.2g, PGA0.3g, water level 100%)

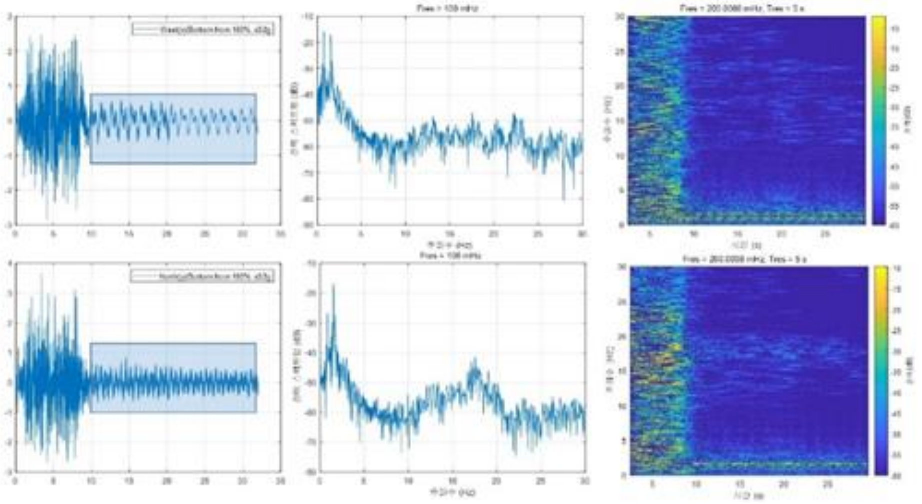

Fig. 3 Typical time histories of sloshing wave pressure over the wall during the seismic excitation (PGA 0.2g, PGA0.3g, water level 100%)

3.2 Frictional Sliding and Impact Motion of the Model Scale Racks

The measurement data from underwater accelerometers mounted on the model scale rack provide various useful information such as the frictional sliding motion, the impact force with neighboring racks, the type of dynamic motion, motional trajectories along the time duration, and after-shock scattered patterns of racks by additional events. Also, the irregular spike in the measured acceleration response was caused by the collision of the racks with the neighboring ones. Fig. 4 shows typical measured response of the scale racks and infrequent impact events. Contrary to the randomly-distributed spectrum of the seismic excitation during the first 10-seconds, two distinct frequency components, which correspond to the fundamental sloshing frequencies of the rectangular pool in each side of direction, dominantly appeared in the spectrum of the residual response during the natural sloshing period as shown in the Fig. 6(a). The 2D motional trajectory of the racks according to the initial position did not show any meaningful difference as shown in Fig. 5, but they can indicate the range of motion of the rack trajectory. If it crossed over the gap length of the racks, it may indicate that a shock to the neighboring rack can occur. Under the seismic base excitation, a unique force acting on the moving racks relative to the pool base was the friction force, except for the minor hydrodynamic force from fluid inertia. Since their kinetic energy decreased with the water depth, at the elevation of the rack, it was assumed that the fluid force was small and negligible, compared to the frictional force. The kinematic friction coefficient as shown in the Fig. 6(b) was obtained by subtracting the acceleration input of the shaking table from the measured acceleration of the rack and dividing it by the gravity. The resultant friction coefficient had a complicated waveform depending on the type of excitation and the corresponding rack motion. It also had a value in the range of about 0.2 to 0.8.

Finally, this study focused on the structural integrity evaluation of the submerged free-standing structures in the model scale pool under the event of a severe seismic accident. In particular, it measured the impact force acting on the storage rack while moving. Analytical studies related the storage racks' movements in the pool, reflecting nonlinear and discontinuous characteristics such as fluid-structure interactions and frictional sliding behaviors, were also carried out through the close cooperation with industry partners so that a realistic prediction model can be developed. In the future, we plan to conduct seismic accident simulation tests on the basis of the real-scale nuclear fuel assembly.

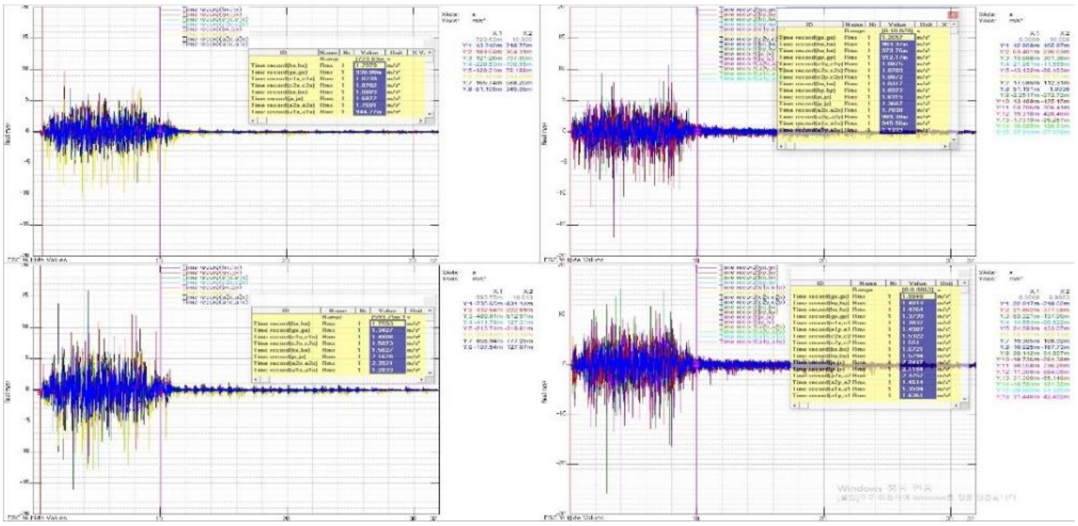

Fig. 4 Typical measured response of the scale racks and infrequent impact events.

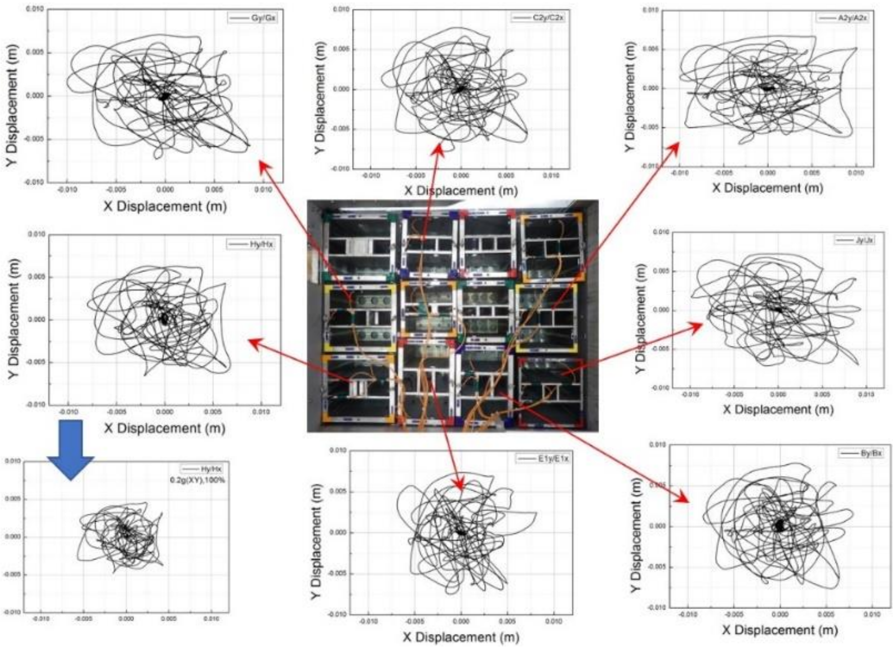

Fig. 5 Orbit Motional Trace of the Racks According to the Positions.

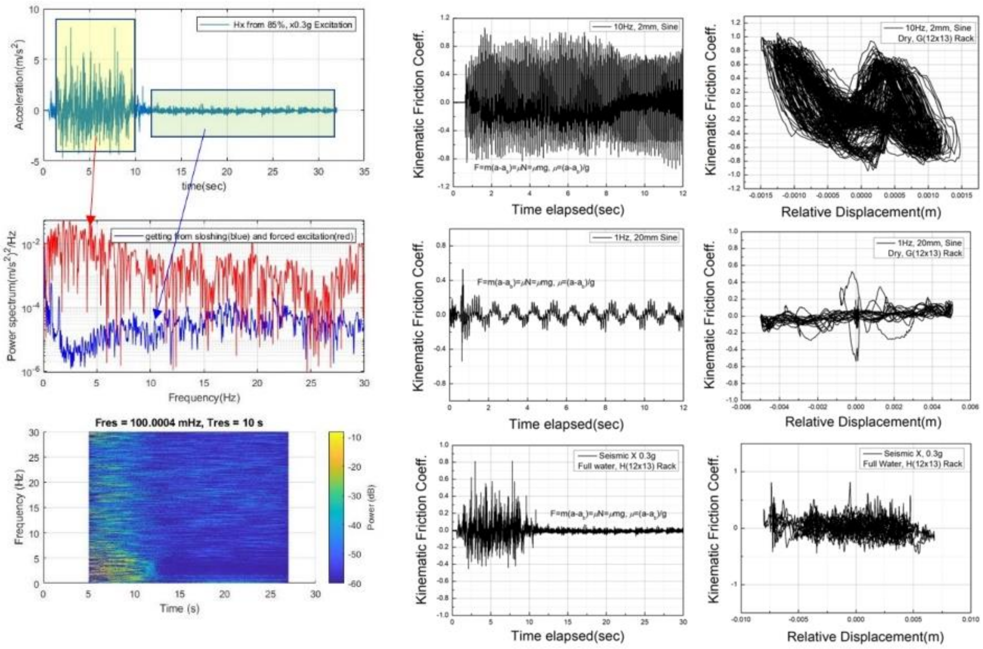

Fig. 6 (a) Time Frequency Spectrum of Scale Racks, (b) Kinematic Frictional Coefficient During the Base Excitation.

4. CONCLUSIONS

A 1/8 scale model spent fuel storage pool test was carried out in air and mostly under water filled with different water levels, to simulate severe seismic accidents in Korea. A free standing model scale rack was seated over the pool floor with 4 corner foots and embedded entire fuel mass. The seismic input for the test was artificially deduced from the US-NRC REG-Guide 1.6 on the basis of the time history generation rule. Various tests were performed using test parameters such as air/water, level of water, excitation direction, level of excitation, and full and partial loading of the racks. The time history of free surface fluid motions including wave pressure and, acceleration responses of submerged racks in the pool, were measured during the accidental seismic excitations of the pool base. The test results were consistent during the repeated test operations. This test was carried out to develop seismic safety evaluation technology for spent fuel pool and the spent fuel using a scale model. The test results will be primarily used as test data to verify the analysis model in related industries. In order to increase the usability of the results from this study, additional complementary experiments and analytical simulations should be conducted in the future.

5. ACKNOWLEDGEMENTS

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