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DEVELOPMENT OF PROBABILISITIC SEISMIC RISK ASSESSMENT METHODOLOGY FOR SEISMICALLY ISOLATED NUCLEAR POWER PLANTS

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ABSTRACT

Seismic isolation is one of the most effective methods for increasing the seismic safety of a nuclear power plant. The seismic isolation technique is already widely applied to conventional structures. However, it is not often applied to nuclear power plants. This is because a seismic isolation system can decrease the seismic ground motion dramatically, but in the case of nuclear power plants, only decreasing the seismic input motion is not enough. Even though the seismic input motion is reduced, the seismic risk also should be reduced. For the assessment of seismic risk of nuclear power plants, a probabilistic seismic safety assessment (seismic PSA, SPSA) should be performed. The SPSA method is already applied to non-isolated nuclear power plants for risk assessment. However, if we want to apply it to seismically isolated nuclear power plants, it requires more consideration than non-isolated nuclear power plants.

For the performance of an SPSA, there are three major steps. A seismic hazard assessment, seismic fragility assessment, and system analysis should be performed. The seismic hazard assessment is the same procedure of non-isolated nuclear power plants. The system analysis is very similar to the SPSA of non-isolated nuclear power plants, but it cannot be exactly the same as in non-isolated nuclear power plant cases; therefore, system analysis should be performed again. Fragility analysis is totally different from that of non-isolated nuclear power plants. The failure of the seismic isolation system and interface piping system should be considered. Also, because the whole floor response spectrum was changed, all fragility results for equipment located on the seismic isolation system should be re-assessed.

In this paper, a procedure of seismic PSA for seismically isolated nuclear power plants is proposed. For the fragility assessment of a seismic isolation system, the piping system and equipment, failure mode, and failure criteria were determined. Finally, using the proposed SPSA procedure, sample SPSA calculation was performed.

INTRODUCTION

Although seismic isolation is one of the most effective applications for the seismic safety enhancement of nuclear power plants, very few nuclear power plants have applied seismic isolation systems. However, in conventional structures, such as buildings and bridges, the application of seismic isolation systems is increasing more and more. The differences between nuclear power plants and conventional structures are the safety concepts. For conventional structures, reduction of acceleration is enough for seismic safety enhancement, but for nuclear power plants, reduction of acceleration is not sufficient for this purpose.

Because there are many pieces of important equipment inside a nuclear power plant, the safety of nuclear power plants is important. With the application of seismic isolation, the acceleration of the superstructure is reduced, but the relative displacement between the seismically isolated structure and the non-isolated structure is greatly increased, and the interface piping system is subjected to large displacement. This improves the safety due to the reduction of the acceleration as a result of the application of a seismic isolation device, but it increases the possibility of pipe breakage, which reduces safety. Therefore, the safety improvement effect of applying isolation devices to nuclear power plants can be confirmed through the probabilistic safety assessment of nuclear power plants.

Although there has been some research on the seismic isolation of nuclear power plants and many studies on probabilistic seismic safety assessment for nuclear power plants, there have been very few studies on the seismic risk assessment of seismically isolated nuclear power plants. Huang et al. (2010) performed seismic performance assessment of seismically isolated nuclear facilities. This research suggested a very important concept for the seismic risk assessment of seismically isolated NPPs and its application to nuclear power plants. Kumar et al. (2017) performed seismic PRA for seismically isolated nuclear facilities. Kumar provided seismic risk assessment concepts for seismically isolated nuclear facilities considering seismic hazard for each NPP site in the US. However, this research could not consider more practical approaches for real nuclear power plants.

Tanaka et al. (2015) performed seismic PRA for PWR- and BWR-type nuclear power plants and they provided core damage probabilities for seismically isolated NPPs using a practical approach. However, for security reasons, they did not openly provide all details of seismic fragility data.

SAFETY OF SEISMICALLY ISOLATED NUCLEAR POWER PLANTS

Seismic Isolation Terminology

The concept of seismic isolation of nuclear power plants and major terminologies are illustrated in Figure 1. As seen in Figure 1, a nuclear power plant is constructed in the same manner as non-seismically isolated nuclear power plants up to the basemat. Below the basemat, an isolation system is constructed, which includes a seismic isolator, pedestal, and foundation. Also, a moat wall or hard stop is one of the most important structures for seismically isolated nuclear power plants. For the design of the moat wall, the clearance to the hard stop should be determined by consideration of the ultimate capacity of the seismic isolators.

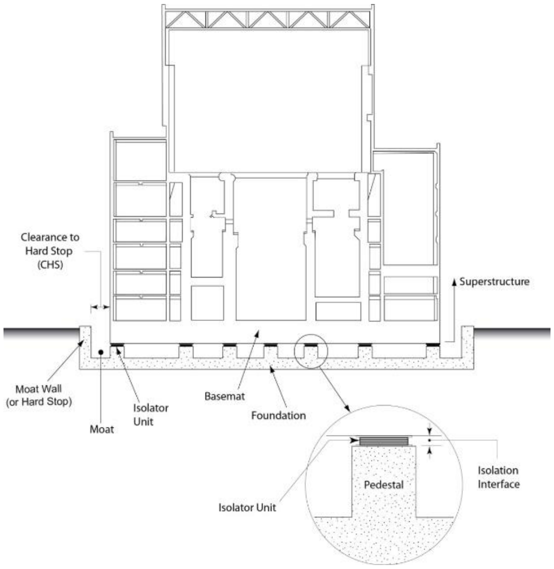


Figure 1. Schematic diagram of seismically isolated NPPs and major terminologies for seismic isolation system (NUREG/CR-7253)

With the application of a seismic isolation system to nuclear power plants, acceleration response can be decreased dramatically, but displacement should be increased. When we consider a seismic isolation system for nuclear power plants, other sources of risk should be considered in addition to those for non-isolated nuclear power plants. One is the failure of seismic isolators or the seismic isolation system, the second is an impact to the moat wall, and the other is failure of interface piping system.

Safety Goal of Nuclear Power Plants

The safety of a seismically isolated NPP is defined as follows: ‘Individuals do not receive significant additional risk to life and health and nuclear power plants do not pose a significant additional risk to other societal risks.’ The Regulatory Guide 1.174 defined derivative/surrogate goals for use with expanded applications of probabilistic risk assessments (PRA) for operating reactors are defined as follows:

- Large early release frequency (LERF) of 10 to 5 per reactor year
- Core damage frequency (CDF) of 4 to 10 per reactor year
- In conjunction with NRCʹs traditional defence-in-depth philosophy

The target for existing nuclear power plants consistent with the technical safety objective is a frequency of occurrence of severe core damage that is below about 4 to 10 events per plant operating year. Severe accident management and mitigation measures could reduce by a factor of at least ten the probability of large off-site releases requiring short term off-site response. The application of all safety principles and the objectives for future plants could lead to the achievement of an improved goal of not more than 5 to 10 severe core damage events per plant operating year.

Recently, in Korea, the Nuclear Safety Law has been amended, and it includes a plan to submit an accident management plan. The PSA evaluation results should be included in the submission of the accident management plan. Accident management includes consideration of design basis accidents, accidents caused by multiple faults, as well as natural and man-made disasters exceeding design standards. Therefore, even seismically isolated nuclear power plants should satisfied safety goals for nuclear power plants. For the verification of satisfaction of safety goal of nuclear power plants, a seismic PRA should be performed. For these reasons, a seismic PRA procedure for seismically isolated nuclear power plants is presented in this paper.

Seismic PRA for Seismically Isolated NPPs

The overall seismic PRA procedure for seismically isolated NPP structures considering a failure of the interface piping systems and equipment on the seismically isolated NPP is shown in Figure 2.

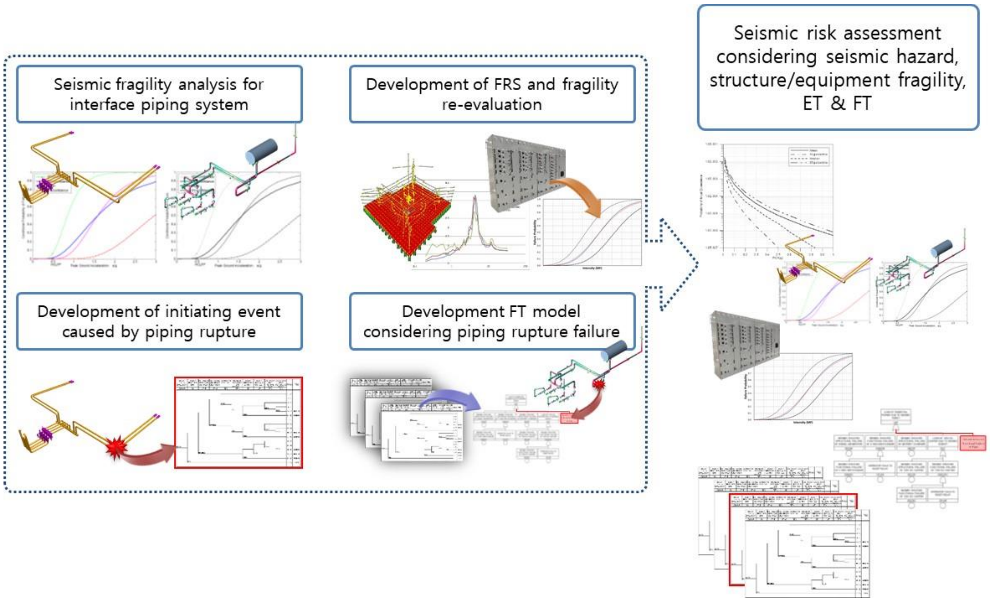


Figure 2. Overall SPRA procedure for seismically isolated NPP structures.

SEISMIC FRAGILITY OF SEISMIC ISOLATION SYSTEM

For the development of seismic PRA for seismically isolated NPPs, a seismic hazard analysis, seismic fragility analysis, and system analysis should be performed. We do not need to perform the seismic hazard analysis if the site has not changed. The system analysis should be performed again considering a failure of the interface piping system and equipment failure. One of the most important steps for seismic PRA is seismic fragility assessment for the seismic isolation system, interface piping system, and equipment on the seismically isolated NPP structures.

Failure Mode of Seismic Isolation System

A seismic isolator is a structural element that is simultaneously subject to shear, compression, and tensile forces. Therefore, the key failure modes and criteria of seismic isolators shall be determined and assessed by combining these three types of loads. The key failure modes can be classified into shear, compression, tensile, compression-shear, and compression-tensile. Failure criteria are determined based on the capacity to maintain the three critical functions of vertical load-bearing capacity, restoring force toward the origin, and damping. However, cases in which the limit-state is deemed to be affected by distortion are assessed under the assumption of the maximum possible distortion under the EDB load.

There are three general failure modes for rubber bearings: shear, compression-shear (buckling), and compression-tensile. All failure modes of seismic isolators are schematically shown in Figure 2. As an earthquake load involves shearing behavior, the possibility of pure compression or pure tensile force is negligible. In addition, as the structure of an NPP is designed for the greatest possible match between the stiffness center and the mass center in the superstructure of a seismic isolation system, as well as to have a large basemat, changes incurred by distortion in each seismic isolator are expected to be minor.

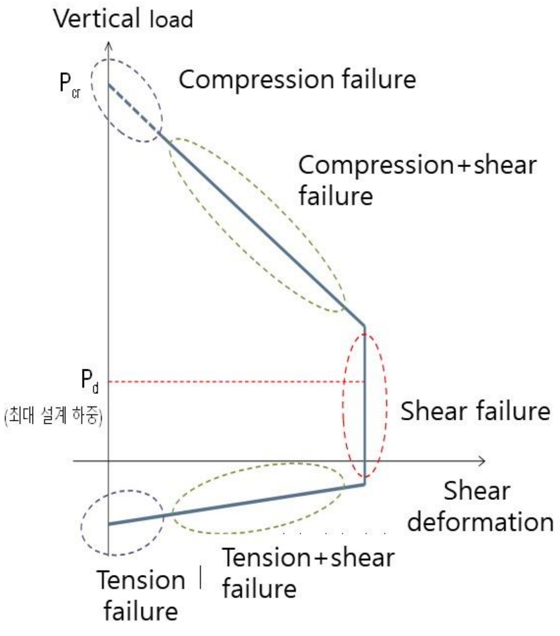
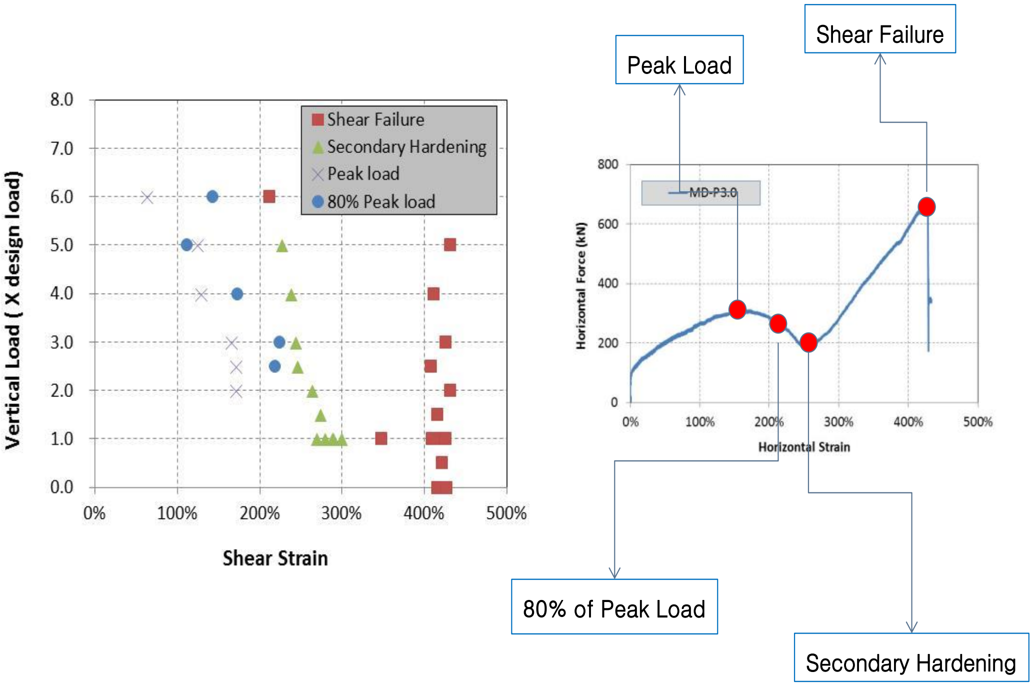


Figure 3. Schematic diagram of failure mode for seismic isolator

Failure Criteria of Seismic Isolation System

For the determination of the failure criteria of a seismic isolation system, failure tests for scale-model seismic isolators were performed. For the failure test of seismic isolators, 20 specimens were used. Through the test, failure mode and criteria can be determined according to the isolation unit and isolator devices. Even though the failure mode of seismic isolation unit was buckling failure, the global failure mode of the seismic isolation system might be shear failure. Figure 4(a) shows the relation between shear strain and vertical load for the shear failure test of a seismic isolator. As shown in Figure 4, the failure of an isolation device can be determined according to the failure mode. It can be determined for the peak load and 80% of the peak load after passing the peak load. Secondary hardening and shear failure can be determined as failure of a seismic isolator. It is interesting that even the peak load, 80% peak load, and second hardening points differ according to the vertical load cases, but shear failure capacities do not show many differences. The definition of each failure point is shown in Figure 4(b). The failure of a seismic isolator is shown in Figure 4(b).



(a) Relation between shear strain and vertical load for various seismic isolator tests (b) Relation between horizontal shear strain and force

Figure 4. Failure results of seismic isolator tests

SEISMIC FRAGILITY OF UMBILICAL LINES AND EQUIPMENT

Seismic Fragility Assessment Framework of Piping Elements

To evaluate the seismic fragility of the piping elements, the following procedure should be performed:

① Conduct sensitivity analysis of elbow component responses
② Sample random variables
③ Determine the input relative displacement motions
④ Undertake detailed modeling of critical elbow components

⑤ Perform numerical simulations of elbow components

For the sensitivity analysis of elbow component responses, selection of random variables and ranges, evaluation of the responses of elbows under cyclic loading (stress, strain, etc.), and the definition of the important random variables should be conducted. In the case of the sampling of random variables, a DB should be constructed for each random variable by coupon tests or measurement, and the probability distribution function of random variables should be defined. For determining the input relative displacement motions, the number of cycles is determined from the strong motion duration and the representative input relative displacement motions (sine-wave form). Afterward, detailed numerical modeling should be performed for elbow components.

Seismic Fragility Assessment Framework of Piping System

To evaluate the seismic fragility assessment of the piping system, the following procedure should be performed:

① Sample random variables
- Define important random variables
- Evaluate the probability distribution of random variables

② Produce simplified modeling of global piping system
- Best estimate model of piping system
- Construction of input model set considering random variables

③ Perform numerical simulations of piping system
- Selection of input ground motions
- Evaluate the relative displacements between the ends of critical elbow components

④ Undertake detailed modeling of critical elbow components

⑤ Perform numerical simulations of elbow components
- Evaluate the response at critical points (crowns, etc.)
- Compute the failure probabilities w.r.t. the load intensities

⑥ Estimate the fragility capacity of piping system
- Estimate the median capacities & uncertainty parameters at each critical component
- Condense the fragility curves at each critical point
- Compute the piping system level fragility parameters

Seismic fragility of seismically isolated equipment

The components of seismically isolated NPPs are not inclusive of the umbilical lines crossing the isolation interface, and they are divided into those located at the superstructure and other components. The components in the superstructure should be assessed by calculating the FRS of the seismically isolated structure, while the latter may be assessed with the same approach used for conventional NPPs. The FRS of the seismically isolated structure should be calculated by reflecting its characteristic in that its nonlinearity increases along with seismic intensity.

SEISMIC RISK ASSESSMENT FOR SEISMICALLY ISOLATED NPPS

Evaluating the seismic risk of a seismically isolated NPP first requires the consideration of a scenario for the failure of isolation systems and another for the failure of safety-related umbilical lines. To this end, a seismic fragility curve must be calculated with the same physical quantities as its parameters with regards to such elements and all safety-related components that are not screened out. The fragility of the system should also be calculated by considering that the response displacements experienced by all elements with failure criteria related to the displacement of the isolation system are almost identical under the same earthquake. The scenario based on the failure of non-isolated elements and the calculation of risk based on the convolutions of hazard and fragility should follow the seismic risk assessment method used for conventional nuclear power plants.

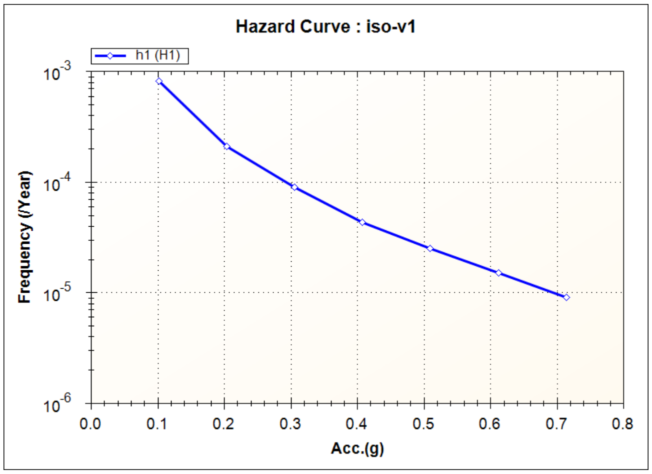


Figure 5. Artificial seismic hazard curve for seismic PRA of seismically isolated NPP.

For the determination of interface piping fragility, CCW and AFT are considered. The fragility results are assumed as 10% failure probability of EDB (1.0 g) loading. The randomness and uncertainty are assumed to be 0.2. Also, all equipment located on the seismically isolated NPP structure are assumed to be safe. However, it should be recalculated considering the floor response spectrum of the seismically isolated NPP structure. In the case of yard facilities, only loss of offsite power is considered as failure. Therefore, only the LOOP was considered as an initiating event for seismic risk. The fragility function of the LOOP was used as previous seismic PRA results in Korea. All assumed fragility values are shown in Table 1.

Table 1: Fragility values for SPRA of seismically isolated NPP.

Comp.	Am	Br	Bu	Bc	HCLPF
CCW	1.67	0.2	0.2	0.283	0.865
AFT	1.67	0.2	0.2	0.283	0.865
LOOP	0.3	0.22	0.2	0.298	1.50

For the performance of a seismic PRA, a very simple event tree was developed, and it is shown in Figure 6. CCW, AFT, and LOOP failures were considered, and all other failures were assumed to be screened out. Because of this assumption, these results might be very conservative. The seismic PRA results are shown in Table 2. As seen in Table 2, although the results CDF were slightly lower than those of a non-isolated NPP (2.0E-06), many assumptions were included in the calculation; hence, a more detailed analysis is needed.

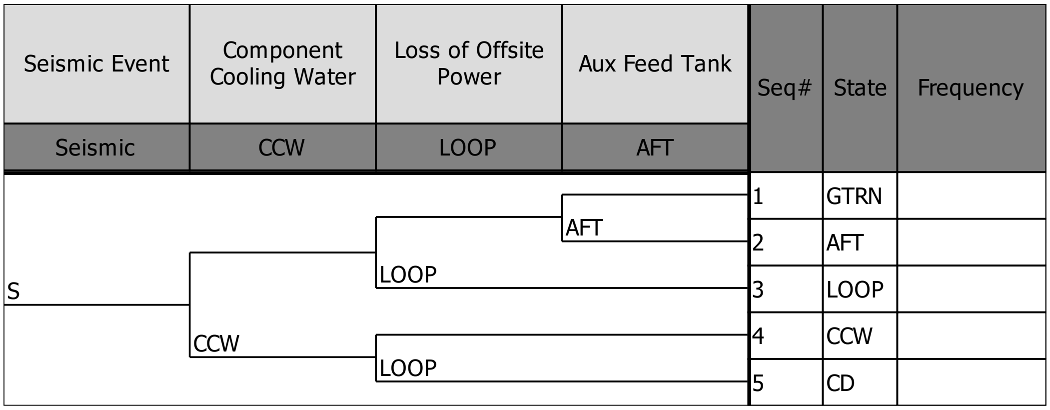


Figure 8. Figures should be centered and followed by a numbered caption.

Table 2: SPRA results for seismically isolated NPP.

event	HCLPF	1%HCLPF	5%-ile	50%-ile	95%-ile	Mean	IE to CDF	CDF
#GTRN	No_solution	No_solution	1.42E-03	1.54E-03	1.59E-03	1.53E-03	2.98E-06	4.55E-09
#AFT_only	No_solution	No_solution	3.42E-20	2.94E-15	2.06E-11	2.40E-11	0	0.00E+00
#LOOP_only	0.15	0.15	4.69E-05	1.04E-04	2.12E-04	1.15E-04	6.63E-03	7.61E-07
#CCW_woLOOP	No_solution	No_solution	6.23E-21	1.16E-14	2.16E-11	1.05E-11	0.00E+00	0.00E+00
#CCW_wLOOP	0.864	0.865	1.01E-08	1.79E-07	1.22E-06	3.51E-07	1.00E+00	3.51E-07
								1.12E-06

CONCLUSION

In this paper, a procedure of seismic PRA for seismically isolated nuclear power plants was proposed. For the fragility assessment of the seismic isolation system, piping system, and equipment, failure mode and failure criteria were determined. Finally, using the proposed SPRA procedure, sample SPRA calculation was performed.

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