Probabilistic seismic safety assessment concept and application for seismic isolated NPP structures considering a clearance to hard stop

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Abstract: Seismic isolation is one of the most applicable solutions for increasing the safety of a nuclear power plant against moderate and strong earthquakes. Even though seismic isolation is a good alternative against an earthquake event and has also already been applied to many conventional structures, application to nuclear power plants needs more research than in other conventional structures. Nuclear power plants should be designed and constructed using severe seismic design criteria and satisfy certain safety goals. Based on IAEA INSAG, the target for existing nuclear power plants consistent with the technical safety objective is a frequency of occurrence of severe core damage of below about 10–4 events per plant operating year. In addition, the application of all safety principles and the objectives for future plants can lead to the achievement of an improved goal of not more than 10–5 severe core damage events per plant operating year. For verification of the safety goal of nuclear power plants, a probabilistic seismic safety assessment (SPSA) should be performed. Therefore, this paper considers a probabilistic seismic safety assessment methodology for a seismic isolated nuclear power plant. To conduct an SPSA of seismic isolated NPP structures, we assumed that all equipment and structures should not fail during an earthquake. We only considered the failure of seismic isolation systems and the moat wall. Through this study, we try to suggest an ultimate failure capacity of seismic isolation systems for satisfying the safety goal of a nuclear power plant.

Keywords: Seismic isolation, Safety goal, SPSA, Clearance hard stop (CHS), Ultimate failure capacity.

1. INTRODUCTION

Seismic isolation is one of the most applicable solutions for increasing the safety of a nuclear power plant against moderate and strong earthquakes. Although seismic isolation is a good alternative against an earthquake event and have already been applied to many conventional structures, application to nuclear power plants requires more researches than other conventional structures. The nuclear power plants should be designed and constructed using severe seismic design criteria and satisfy certain safety goals. Based on IAEA INSAG, 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 10–4 events per plant operating year. In addition, application of all safety principles and the objectives for future plants could lead to the achievement of an improved goal of no more than 10–5 severe core damage events per plant operating year. For verification of the safety goal of nuclear power plants, a probabilistic seismic safety assessment (SPSA) should be performed. Therefore, this paper considers a probabilistic seismic safety assessment methodology for a seismic isolated nuclear power plant. The main characteristics of seismic isolated nuclear power plants are as below:

1. Decrease of acceleration response and increase of relative displacement of seismic isolated NPP structures
2. The failure of a seismic isolation system is a key parameter of safety
3. A hard stop is one of the most important structures for the seismic safety of an NPP

To perform an SPSA of seismic isolated NPP structures, we assume that all equipment and structures should not fail during an earthquake. We only considered the failure of a seismic isolation system and moat wall. Through this study, we try to suggest the ultimate failure capacity of a seismic isolation system for satisfying the safety goal of nuclear power plants.

2. STATE OF THE ART

Even though a seismic isolation is one of the most effective methodologies for enhancing the seismic safety of NPPs, a seismic isolation system has not been applied to many commercial NPPs. Many researchers have studied the application of a seismic isolation system to commercial NPPs, but there have been very few researches on a risk assessment. Recently, many researchers have studied the risk assessment for seismic isolated NPP structures. Tanaka et al. (2015) presented seismic PRA researches for seismic isolated NPP structures. They performed a seismic PRA for seismic isolated BWR and PWR type NPP structures. Based on their research, the CDF value of a seismic isolated NPP was not decreased according to the application of a seismic isolation system. However, after they were applied to vertical springs for specific equipment, the CDF was dramatically decreased. Even though Takada et al. already performed a seismic PRA for a seismic isolated NPP structure, they did not open specific equipment, and there is a lack of information in the fragility results. Kumar et al. (2017) published a seismic PRA for seismic isolated safety related nuclear facilities. They performed a seismic risk calculation of eight NPP sites in the US when considering the failure of the seismic isolator and the effect of moat wall. Recently, Yu. et al. (2018) demonstrated that the seismic isolation of nuclear facilities has the potential to achieve both improved safety (lower risk) and reduced overnight capital cost. Sarebanha et al. (2018) proposed the structural behavior by the impact on the moat wall of a seismic isolated NPP structure using a numerical simulation.

3. GROUND MOTION FOR THE SEISMIC RISK EVALUATION OF NPP

All nuclear power plants should satisfy the safety goal. The safety goal of an NPP was defined in IAEA INSAG. To satisfy the safety goal of an NPP structure, particularly the seismic isolation, the performance goals of each isolator and umbilical line were proposed in the NUREG draft (Kammerer el al., forthcoming). The draft NUREG suggested two different seismic hazards according to the return period. One is the ground motion response spectrum (GMRS+) and the other is the extended design base (EDB) GMRS.

The ground motion response spectrum (GMRS) is defined based on the Regulatory Guide 1.208, and is associated with earthquake shaking that typically has a Mean Annual Frequency of Exceedance (MAFE) of no less than 1x10-4 (return period of 10,000 years), with additional Design Factors, as described in that document. The GMRS+ is a composite spectrum that envelopes the GMRS and the minimum foundation input motion required by Appendix S to 10CFR50 (i.e., an appropriate spectral shape, such as the RG1.60 spectral shape, anchored to a PGA of 0.1g). The Extended Design Basis (EDB) Ground Motion Response Spectrum (GMRS) associated with a MAFE of 1x10-5 (a return period of 100,000 years). The Extended Design Basis (EDB) ground motion represents beyond design basis shaking. The ordinates of the EDB spectrum cannot be taken as less than 167% of the GMRS+ spectrum, defined above (Kammerer el al., forthcoming).

4. DEFINITION AND ASSUMPTION FOR RISK ASSESSMENT

A schematic cross section of seismic isolated NPP structures is shown in Figure 1. As shown in Figure 1, the basemat and foundation are separate in the isolated NPP structures. To support the whole NPP structure and seismic isolator, pedestals are used. Pedestals are used to facilitate the inspection and possible replacement of an isolator. The most important aspects of seismic isolated NPP structures are the moat wall and clearance to hard stop. Seismic isolated NPP structures normally behave horizontally during an earthquake. Because of the seismic isolator, seismic isolated NPP structures should behave in a horizontal manner from the very small ground motion. Although a seismic isolator behaves mainly through shear motion, all seismic isolators have the ultimate capacity of shear behavior. The moat wall prevents an excessive horizontal behavior of a seismic isolated NPP structure. The clearance to the hard stop should be decided for a very low probability of impact between a seismic isolated structure and a moat wall, and to prevent a failure of the seismic isolator according to an excessive shear deformation. The forthcoming NUREG defined as the moat is sized such that there is less than 1% probability of the superstructure contacting the moat or the hard stop under GMRS+ loading. In addition, the CHS displacement must be equal to or greater than the 90th percentile isolation system displacement under EDB loading. A hard stop should be designed to survive impact forces associated with the 95th percentile EDB isolation system displacement. Limited damage to the moat or hard stop is acceptable, but the hard stop must perform its intended function (Kammerer el al., forthcoming).

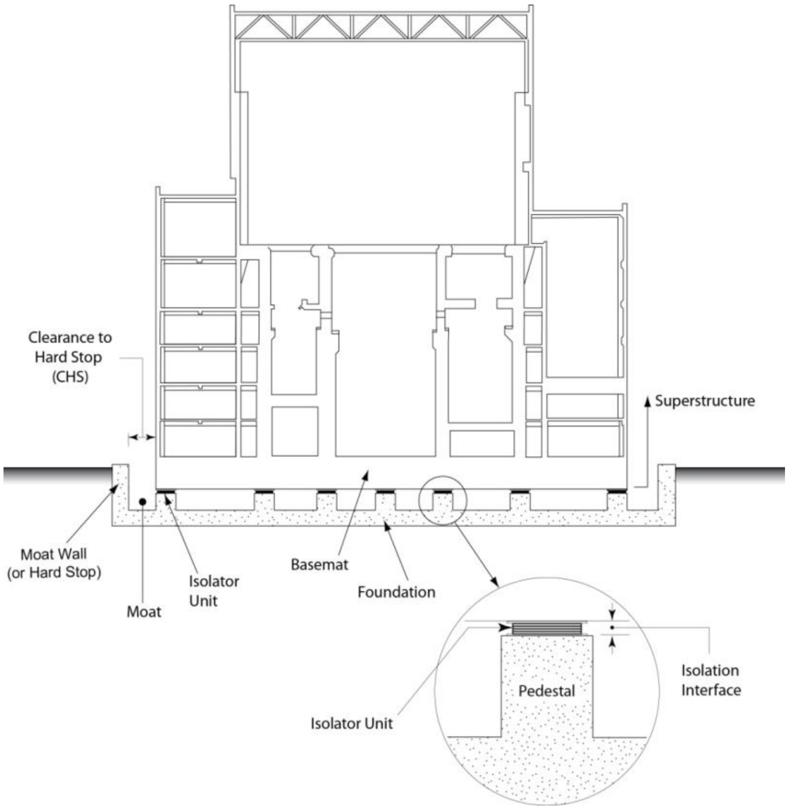
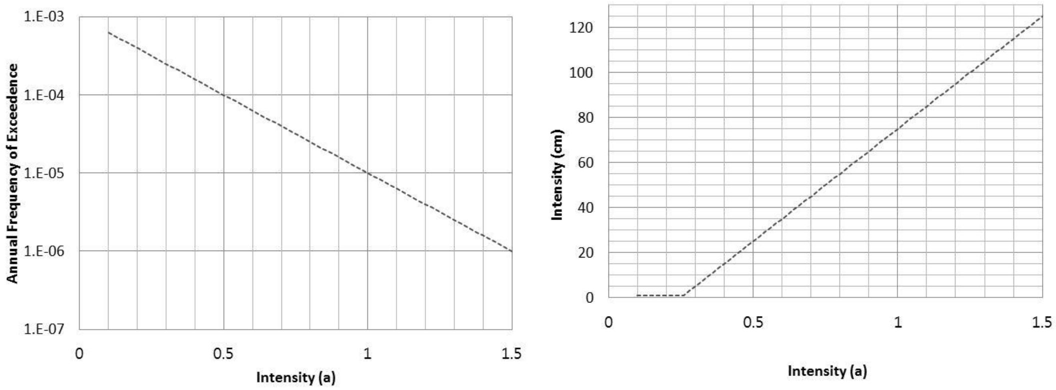


Figure 1: Schematic Diagram of Seismically Isolated NPPs (Kammerer el al., forthcoming)

To perform a seismic risk assessment for a seismic isolated NPP structure, the following assumptions are considered in this paper.

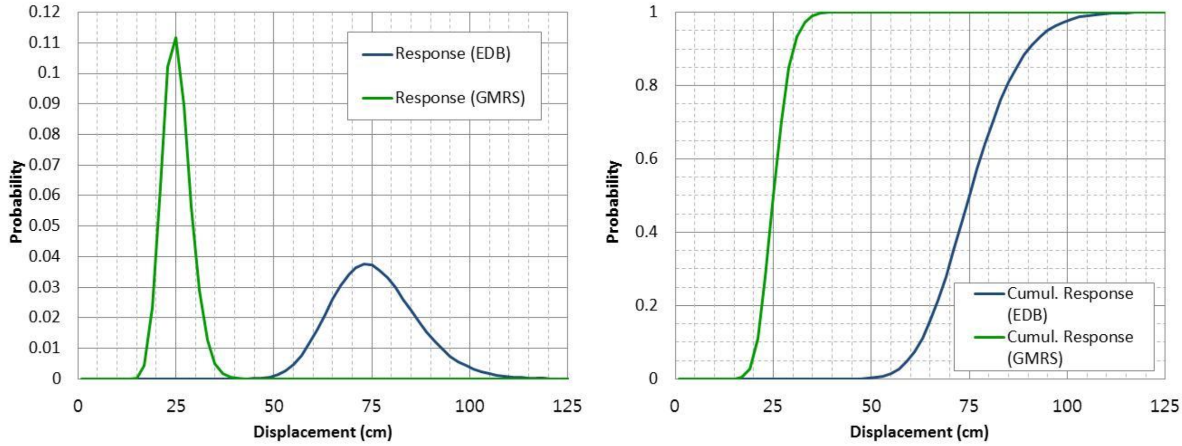
- All equipment on the seismic isolated NPP were safe
- Only the failure of seismic isolators and moat wall were considered
- A seismic hazard for a risk analysis was assumed as GMRS (10e-4 return period) of 0.5 g and EDB GMRS (10e-5 return period) of 1.0 g with the RG 1.60 design spectrum shape
- The displacement of a seismic isolator according to 0.5 g and 1.0 g are simply assumed to be 25 cm and 75 cm, respectively.
- The CHS is assumed to be 90 cm, which is the 90th percentile of EDB GMRS displacement.
- The uncertainty value of β_R be 0.143.

Based on an assumption of the risk assessment, seismic hazard relations and displacement according to the acceleration are shown in Figure 2. The failure probabilistic distribution and cumulated failure probability distributions according to the input design level are shown in Figure 3.



(a) Seismic Hazard for Risk Assessment (b) Acceleration and displacement relation

Figure 2: Assumed Seismic Hazard



(a) Failure Probability (b) Cumulative Failure Probability

Figure 3: Failure Probability according to Seismic Ground Motions

A seismic risk assessment can be categorized, as shown in table 1, according to the considered hard stop and uncertainty of the capacity. As shown in Table 1, a hard stop is not considered in cases (1) and (2). This means that it assumed that there are no hard stops in the nuclear power plant. In case (1), it assumed that there is no uncertainty in the capacity of a seismic isolator. The meaning of the no uncertainties in the capacity of a seismic isolator is that the seismic isolator fails abruptly when a displacement reaches the ultimate capacity. In cases (3) and (4), a hard stop will be considered, but it assumed that there are no uncertainties in a seismic isolator. In case (3), the mean capacity of the seismic isolator (Cm) is greater than CHS. Because there are no uncertainties in the seismic isolator capacity, if the capacity of the seismic isolator is larger than CHS, the failure probability is zero. In addition, case (4) is same as case (1) because the ultimate capacity of the seismic isolator is less than CHS. In cases (5) and (6), a meaningful conclusion can be made. Through case (5), the required capacity of the seismic isolator can be defined. However, case (6) is the worst case because the capacity of the seismic isolator is smaller than CHS. Through this calculation, we can estimate the ultimate capacity of the seismic isolator to prevent the failure of seismic isolated NPP structures.

Table 1: Risk Assessment Cases

Index	HS	βc	Cm vs CHS	Pf	Remark
(1)	w/o HS	0	-	P(R>C)	
(2)	w/o HS	βc	-	P(R>C)	
(3)	w/ HS	0	Cm>CHS	P(R>C .and. C<CHS) = 0	
(4)	w/ HS	0	Cm<CHS	P(R>C .and. C<CHS)	N/A
(5)	w/ HS	βc	Cm>CHS	P(R>C .and. C<CHS)	
(6)	w/ HS	βc	Cm<CHS	P(R>C .and. C<CHS)	N/A

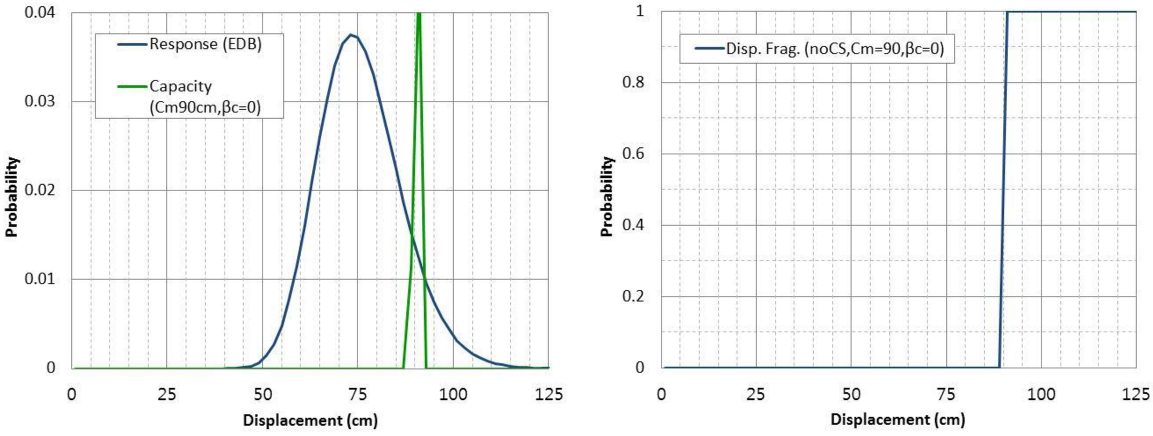
where R = response, C = capacity,
Rm, βr, Cm, βc = median and standard deviation of R and C,
w/ HS, w/o HS = with/without hard stop, and
CHS = clearance to the hard stop.

5. RISK ASSESSMENT OF SEISMIC ISOLATION SYSTEM

In this study, a seismic risk assessment for seismic isolated NPPs only considering the clearance hard stop (CHS) was performed. CHS is one of the most important concepts for seismically isolated NPPs. CHS should prevent the excessive displacement of seismic isolation devices and the clearance to the hard stop should be enough for the movement of isolated structures. As shown in the previous chapter, a seismic risk assessment was performed for six cases considering the hard stop and uncertainties of response and capacity of isolators. This chapter shows all six cases of the seismic risk assessment procedures and results.

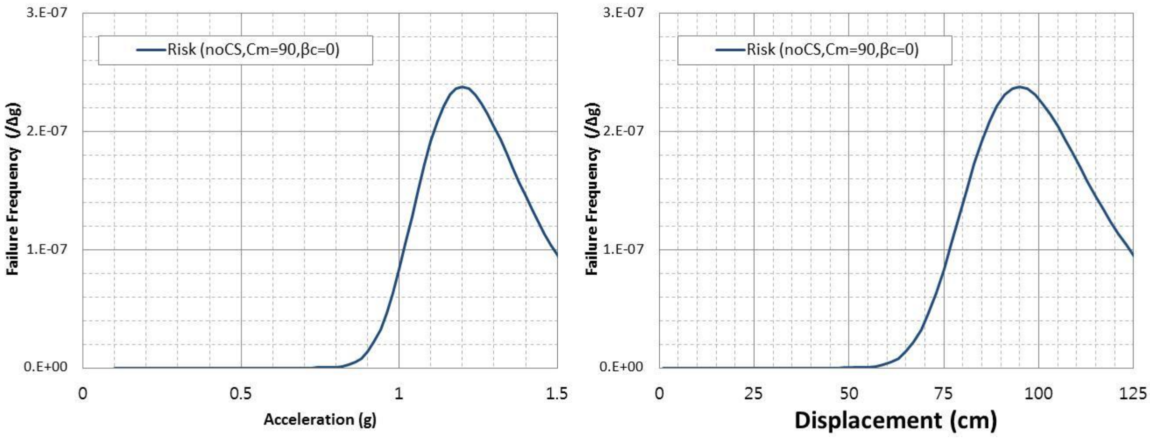
5.1. Without considering a hard stop

The seismic risk calculations were performed without considering a hard stop. These cases are indexes (1) and (2) of table 1, and were performed by considering the uncertainty of the capacity of the isolators. When not considering the uncertainty, βc=0, the capacity and response can be as shown in Figure 4. In addition, the failure probability of the seismic isolators can be as shown in Figure 5. As shown in Figure 4, because the median capacity of the seismic isolator was assumed to be 90 with no uncertainties, the failure probability of the seismic isolator has a step function.



(a) Failure Probability (b) Seismic Fragility

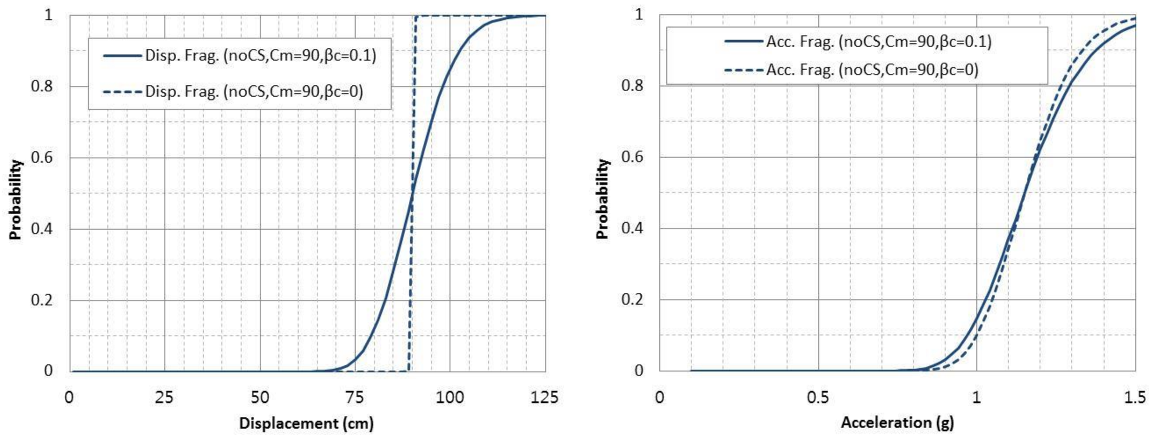
Figure 4: Displacement Fragility (no CHS, Cm=90cm, βc=0)



(a) Seismic Risk according to Acceleration (b) Seismic Risk according to displacement

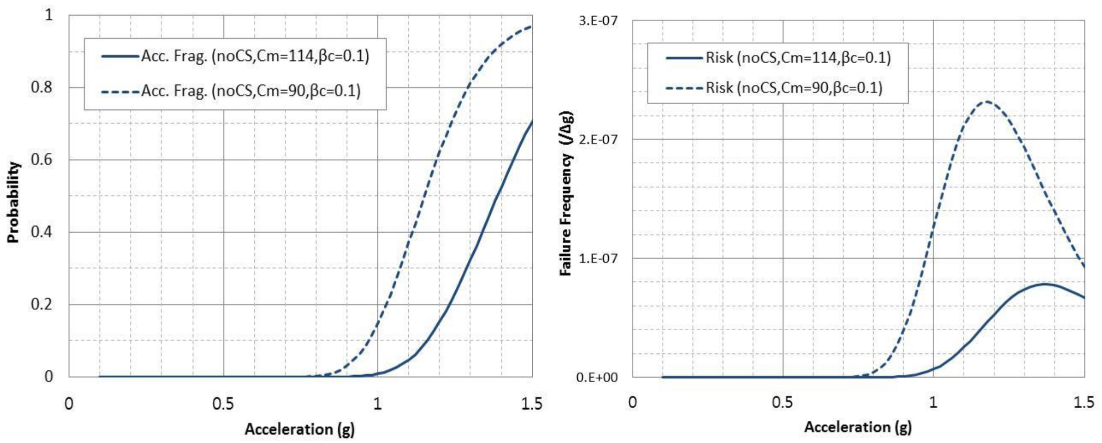
Figure 5: Seismic Risk (no CHS, Cm=90cm, βc=0)

When considering the uncertainty of the isolator's capacity, the seismic fragility can be calculated as shown in Figure 6. As shown in Figure 6, seismic fragilities are shown according to the displacement and acceleration. According to the NUREG draft, the probability of the isolated superstructure striking the hard stop or moat wall is less than or equal to 1% for the GMRS+ shaking. To satisfy the NUREG guideline, a 90 cm median capacity is insufficient. The median capacity should be 114 cm to satisfy the NUREG guideline. The seismic fragilities and risk according to the median capacities are as shown in Figure 7.



(a) Displacement Fragility (b) Acceleration Fragility

Figure 6: Seismic Fragility Results (no HS, Cm=90cm, βc=0.1)

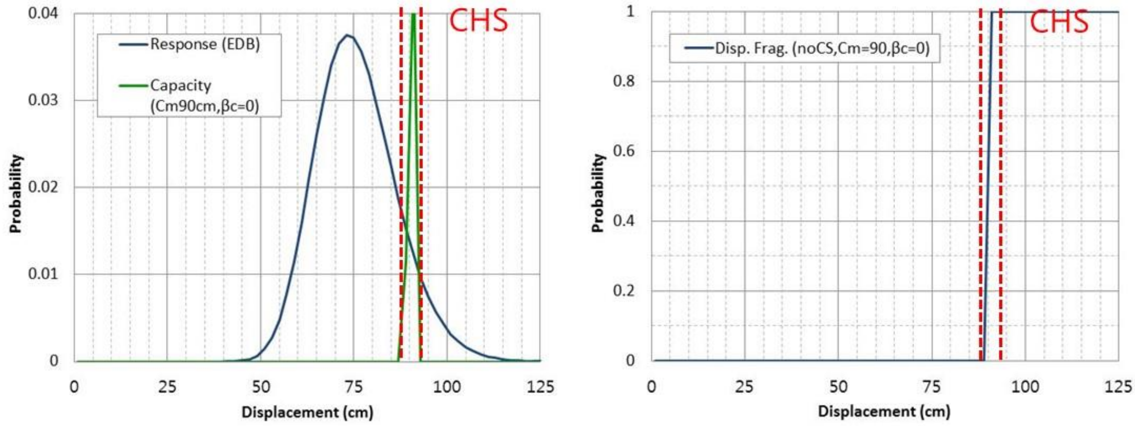


(a) Seismic Fragility (b) Seismic Risk

Figure 7: Seismic Fragility and Risk according to the median capacity of seismic isolator

5.2. Considering the Hard Stop and not Considering the Uncertainty of Capacity

If there is a hard stop in an isolated nuclear power plant, the hard stop can resist the excessive behavior of the seismic isolators. If the shear capacity of a seismic isolator is larger than the CHS, isolation system will not fail, but if lower than CHS, the seismic isolation system can be failed and it can lead to an unacceptable initiating event of NPP system. The response and capacity of the seismic isolators are as shown in Figure 9(a), and the failure probabilities of seismic isolators are as shown in Figure 9(b). However, because a failure in the capacity of a seismic isolator has a number of uncertainties, this assumption is not realistic. Based on this assumption, however, the limit value of risk can be calculated.

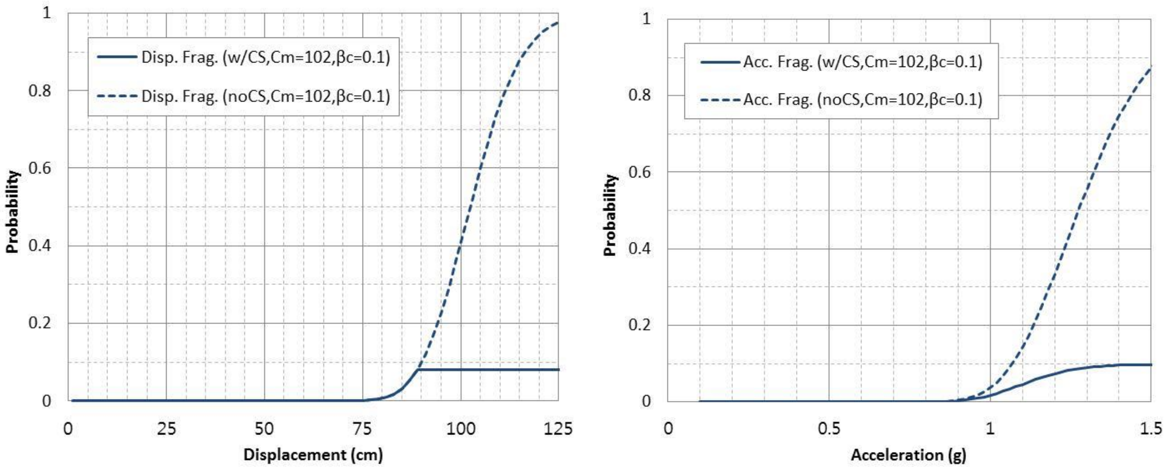


(a) Response and capacity of seismic isolator (b) Failure probabilities of seismic isolator

Figure 9: Failure probabilities of when considering the hard stop and not considering the uncertainty of the capacity

5.3. Considering the Hard Stop and Uncertainty of Capacity (Cm>CHS)

Seismic risk considering the hard stop and uncertainty of the seismic isolator was calculated. In particular, a case in which the mean capacity of a seismic isolator is larger than the CHS was considered. The mean capacity of a seismic isolator is assumed as 102 cm, and the uncertainty of the capacity is 0.1. The failure fragility of seismic isolators is shown in Figure 10 according to the displacement and acceleration. In the case of displacement failure probability, a failure probability of over 90 cm in displacement does not increase according to the displacement because the CHS is assumed as 90 cm. In addition, the final seismic risk is shown in Figure 11. As shown in Figure 11, the seismic risk can be reduced dramatically by applying a hard stop.



(a) Seismic Hazard for Risk Assessment (b) Acceleration and displacement relation

Figure 10: Seismic Fragility Results (w/ HS, Cm=102cm, βc=0.1)

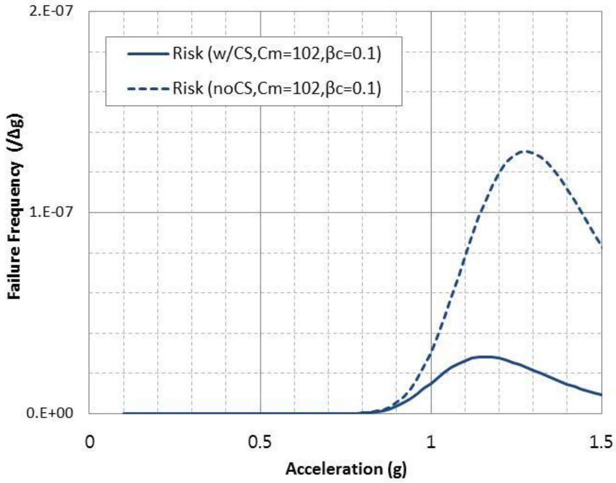
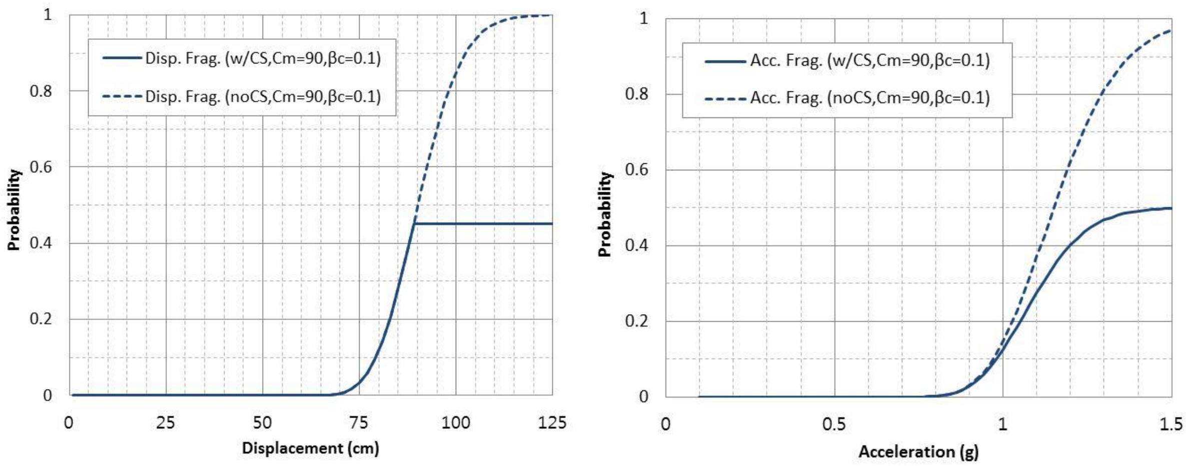


Figure 11: Seismic risk results considering the hard stop and uncertainty of capacity (Cm>CHS)

5.4. Considering the Hard Stop and Uncertainty of Capacity (Cm<CHS)

When considering the hard stop and uncertainty of the capacity, if the median capacity is smaller than the CHS, the failure probability of the seismic isolator is increased compared to the previous case. The seismic fragility can be as shown in Figure 12.



(a) Displacement fragility (b) Acceleration Fragility

Figure 12: Seismic Fragility Results (w/ HS, Cm=90cm, βc=0.1)

5.5. Seismic Risk Results

The seismic risk calculation results are summarized in Table 2. As shown in Table 2, the best cases are an ultimate capacity of a seismic isolator of 114 cm, and an assumed uncertainty of 0.1. In actual cases, the uncertainties of a seismic isolator's failure probability can be larger than 0.1, and even if the median capacity of the seismic isolator is 114 cm, the risk may lower.

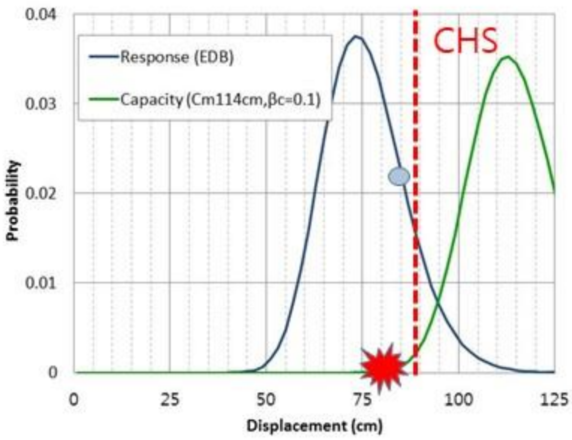
Table 2: Risk Assessment Results

HS	βc	Cm vs CHS	Pf	Remark	Risk
w/o HS	0	-	P(R>C)	Cm=90cm, βc=0.0	5.59E-06
w/o HS	βc	-	P(R>C)	Cm=102cm, βc=0.1	3.50E-06
w/ HS	0	Cm>CHS	P(R>C .and. C<CHS)		0
w/ HS	0	Cm<CHS	P(R>C .and. C<CHS)		5.59E-06
w/ HS	βc	Cm>CHS	P(R>C .and. C<CHS)	Cm=114cm, βc=0.1	6.22E-08
w/ HS	βc	Cm<CHS	P(R>C .and. C<CHS)	Cm=90cm, βc=0.1	3.85E-06

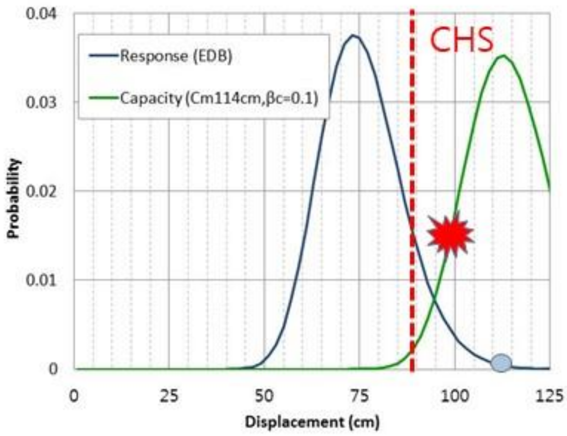
6. DISCUSSION OF RESULTS

6.1. Failure Mode

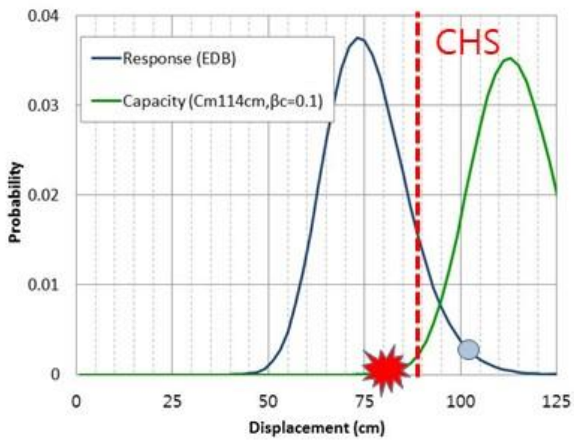
The failure mode of seismic isolated NPP structures can be categorized according to the hard stop. The first failure mode is an existing hard stop, and an impact does not occur, but the seismic isolators fail (P(C<R<CHS)). This case is shown in Figure 13(a). The second failure mode is, if the hard stop exist, this failure will not be occurred (P(CHS<C<R)). The second failure mode can be explained through Figure 13(b). The last failure mode is a failure that occurs even though an impact also occurs (P(R>CHS) x P(C<CHS). The last failure mode is shown in Figure 13(c). The seismic fragility considering all previous failure modes is shown in Figure 14.



(a) P(C<R<CHS)



(b) P(CHS<C<R)



(c) P(R>CHS) x P(C<CHS)

Figure 13: Seismic Hazard and Displacement

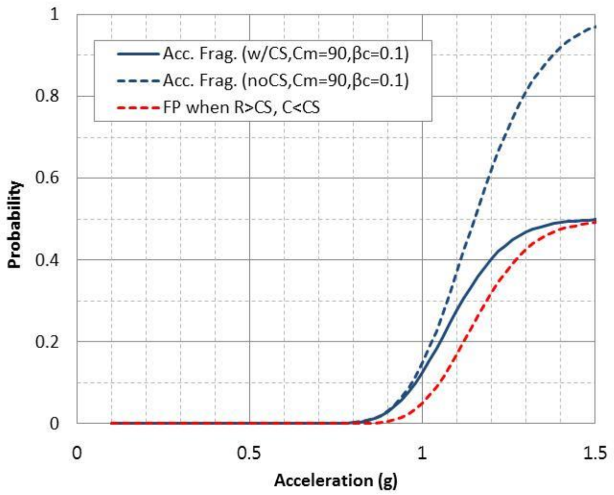


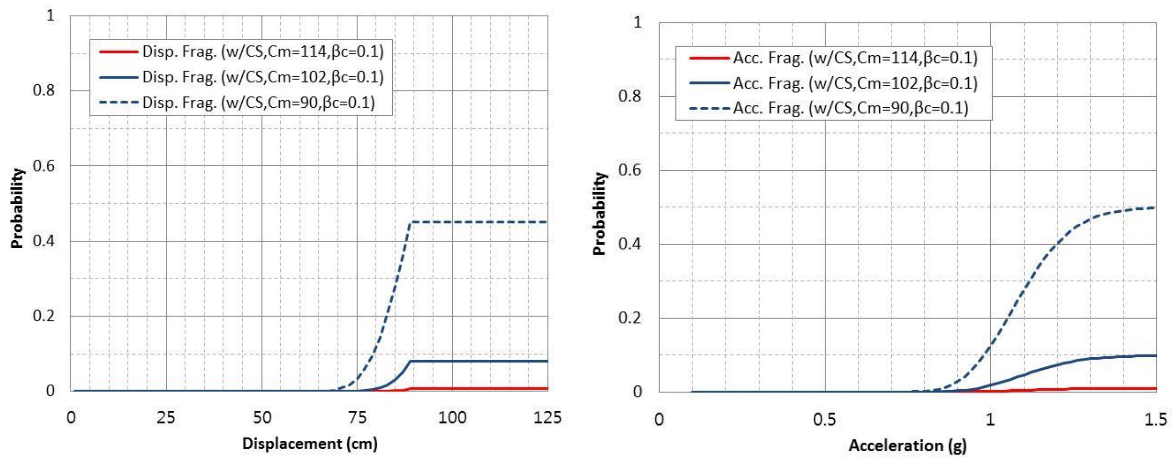
Figure 14: Seismic Hazard and Displacement

6.2. Risk Variation according to the Capacity of Seismic Isolator

The failure probabilities according to the confidence at a CHS are shown in Table 3 and Figure 16. As shown in Table 3, a larger confidence requires larger median capacity and it creates less failure probability. Using this relation, a designer can determine the required median capacity and uncertainties of a seismic isolation system.

Table 3: Seismic Fragility according to confidence at CHS

Confidence at CHS	Median Capacity	Failure Frequency(/yr)
99% confidence	113.7cm	6.22E-08
90% confidence	102.4cm	6.65E-07
50% confidence	90.0cm	3.85E-06



(a) Displacement Fragility (b) Acceleration Fragility

Figure 16: Seismic Fragilities of the Seismic Isolation Device according to the median capacity

7. CONCLUSION

Through this study, a seismic risk assessment for seismic isolated NPP structures can be achieved.

- Major risks of seismic isolated NPPs
  - A seismic isolation system risk caused by the failure of a seismic isolator
  - A cooling system risk caused by a failure of interface piping system
  - An equipment risk caused by a seismic isolation (vertical vibration, impact to the hard stop)
- Seismic isolation system risk
  - Because there is no redundancy in a seismic isolation system, the seismic isolation system failure should be screened out
  - To prevent a seismic isolation failure, the hard stop should be considered, and CHS should be determined according to the probabilistic approach
  - To reduce the seismic risk of seismic isolated NPP structures, the failure capacity of a seismic isolator should have a sufficient margin against CHS
- General
  - A seismic isolation system for NPP structures has a number of benefits for a design; however, to perform a risk assessment, a detailed investigation is needed because all nuclear power plants should satisfy a particular safety goal.

Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (NRF-2017M2A8A4039749) and the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20171510102020).

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