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Seismic Fragility Analysis of Containment Buildings in Nuclear Power Plants Considering Concrete Voids and Material Degradation

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1. Introduction

Due to dense reinforcement bars in nuclear reactor containment buildings, concrete voids may exist, and the reinforcement bars within these voids will be exposed to the external environment so that they can be deteriorated easily. These voids and deterioration can reduce the seismic performance of the containment building. However, existing fragility assessment methods cannot adequately account for these factors. Therefore, seismic fragility assessment of the containment building that considers the effects of voids and deterioration is necessary. This study selected the most appropriate seismic fragility assessment method to account for voids and deterioration. Using this method, it calculated the seismic fragility for a containment building with a void ratio of 2.1% and 40 years of deterioration, and investigates these effects.

2. Selection of Seismic Fragility Assessment Methods

This study investigated SOV (Separation of Variables) [1] and IDA (Incremental Dynamic Analysis) [2] as representative seismic fragility assessment methods for nuclear power plants and general facilities. It also investigated ASMM (Approximate Second-Moment Method) [1] and LHS (Latin Hypercube Sampling) [1] as sampling methods for random variables. These methods were classified into three categories based on three classification criteria. The classification criteria were “whether probability variables are separated,” “sampling method,” and “method for considering nonlinearity.” The notation for the seismic fragility assessment methods based on these three criteria was SOV/COV, ASMM/LHS and L/NL as shown in Table 1.

The existing seismic fragility assessment methods for structures in nuclear power plants, SOV-ASMM-L, SOV-LHS-L, and COV-LHS-L, define the limit state of the containment building using the shear strength defined by Ogaki et al. [3]. Since this shear strength evaluates the overall shear resistance capacity of the containment building, it cannot reflect local behavior near voids. Therefore, the allowable shear strain (0.002) for low RC shear walls specified in JEAC 4601 is applied as the limit state to account for local behavior caused by voids [4].

Existing assessment methods based on linear analysis have been used, for computational efficiency in nuclear power plants, with the inelastic energy absorption factor to indirectly assess nonlinear behavior. This approach could not fully reflect nonlinear behavior caused by voids and degradation. Therefore, IDA (COV-LHS-NL method) was selected to directly evaluate this nonlinear behavior.

Table I: Classification of Seismic Fragility Assessment Methods

method	variable	sampling	analysis
SOV-ASMM-L	separation	ASMM	linear + inelastic energy absorption factor
SOV-LHS-L		LHS	
COV-LHS-L	combination		
COV-LHS-NL			nonlinear

3. Seismic Fragility of Containment Buildings with Voids and Degradation

The analysis model was developed to simulate the containment buildings of domestic nuclear power plants. Since IDA requires numerous nonlinear response history analyses, an efficient analysis model is necessary. Considering that in-plane shear behavior dominates the containment building's response to seismic loads, a multi-layered shell element [5] was used in the analysis model to reduce computational costs.

Probabilistic site response analysis was employed to generate input earthquakes considering ground condition variability. Natural ground motions for rock site condition were selected based on NUREG/CR-6728, and spectrum matching was performed against the Uljin uniform hazard spectrum reflecting domestic characteristics. Then, considering the soil's characteristic that shear stiffness decreases and the damping ratio increases as the shear strain rate increases, the shear stiffness and damping ratio were sampled to have a correlation coefficient of -0.5 to construct the soil profile. Finally, a probabilistic site response analysis was performed to generate 30 sets of input earthquakes for the three directions (x, y, z).

The void scenario was conservatively set based on the publicly released Nuclear Energy Commission report. The void locations were positioned to be vulnerable to seismic loads in the lower portion of the containment building (0.1~0.25H) and within the ±45° range from the center of voids in Figure 2. The void shape was defined as a square with a side length of 1 m, which is the same size as the element in the analysis model. The void ratio was assumed to be a maximum of 2.1% relative to the containment building wall volume. The voids were arranged diagonally as shown in Figure 2, where they are vulnerable to diagonal cracks due to seismic loads.

A deterioration scenario was configured to apply aging-induced degradation of the containment building to the structural analysis model. Changes in concrete compressive strength and elastic modulus, reductions in yield strength and cross-sectional area of rebars due to their corrosion, and decreases in prestressing force are specified as the deterioration scenario. The deterioration period was set to 40 years, considering expected service life of the operating nuclear power plant. Table II presents the properties of concrete, rebars, and tendons applied to the analysis model.

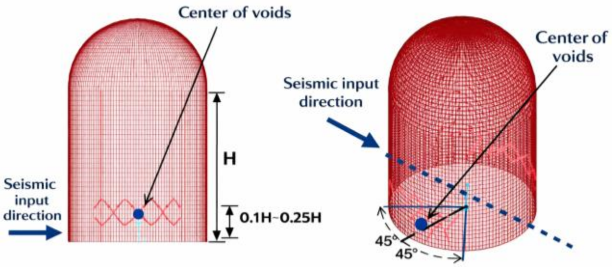

Fig. 1. The location of voids in the containment wall

Table II: Material property values over time applied to the analysis model

material property	degradation period [year]	
	0	40
concrete compressive strength [MPa]	41.4	67.0
concrete elastic modulus [GPa]	24.9	36.2
rebar yield strength [MPa]	420	386
reduction rate of rebar area [%]	0	-5.36
prestressing force [MPa]	1241	1098

4. Conclusions

Using COV-LHS-NL, the seismic fragility of containment buildings considering voids (2.1%) and degradation (40 years) was derived. Table III summarizes the median seismic performance and variability. The median seismic performance value was 4.074g without voids or deterioration, and increased slightly to 4.112g with 2.1% voids and 40 years of deterioration. This behavior could be attributed to the opposing effects of long-term concrete strength development and structural deterioration, including reinforcement corrosion, loss of prestressing force, and the presence of voids. While concrete strength gain enhanced seismic performance, reinforcement corrosion, prestressing force loss, and void-related deficiencies reduced it. Overall, the beneficial effect of concrete strength development appeared to be slightly more dominant. The combined variability was 0.407 when there were no voids or deterioration, and 0.393 when there were 2.1% voids and 40 years of deterioration, indicating only a small difference (3.44%) between the two cases. Since the randomness of the input earthquake had the greatest influence on variability compared to other analysis variables, the variability between the two cases above, which used the same input earthquake set, appeared to be similar.

Table III: Median and Variability of Seismic Performance Due to Voids and Degradation

case	A_m	β_c
w/o void & degradation	4.074g	0.407
w/ void & degradation	4.112g	0.393

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