

Risk-based Resilience Analysis of Nuclear Power Plants Subject to Earthquakes

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1. Introduction

The risk posed by external hazards such as earthquakes to nuclear power plants (NPPs) must be rigorously quantified. Seismic probabilistic safety assessment (PSA) provides a comprehensive framework for evaluating risk by the failure scenarios induced by earthquakes. However, the capability of NPPs to recover from undesirable states has not been systematically addressed. This study proposes a seismic resilience analysis framework for NPPs, where plant-level functionality is quantified by core damage frequency (CDF), derived from event tree (ET) and fault tree (FT) analyses.

2. Methodology

2.1 Seismic Risk of NPPs

The risk of earthquake events to NPPs is typically quantified by CDF in PSA. The CDF is obtained by summing the frequencies of all accident scenarios that result in core damage (CD). For this, the frequency of an initiating event can be evaluated as

$$\lambda = \int_a F(a) \left| \frac{dH(a)}{da} \right| da, \quad (1)$$

where a is an intensity measure of ground motions such as peak ground acceleration (PGA), $F(a)$ represents the seismic fragility function, and $H(\lambda)$ denotes a seismic hazard curve.

The scenario-level fragility is derived by combining the fragilities of structures, systems, and components (SSCs) through ET and FT analyses. The seismic fragility function for a component is formulated as

$$f(a) = \Phi \left(\frac{\ln a/A_m}{\sqrt{\beta_R^2 + \beta_U^2}} \right), \quad (2)$$

where A_m is the median capacity, and β_R and β_U are the logarithmic standard deviations for randomness and uncertainty, respectively.

2.2 CDF-based Resilience Analysis framework

In seismic resilience analysis, the post-earthquake functionality of SSCs is evaluated over the restoration period. For instance, Singhal et al. (2021) proposed a resilience assessment framework for civil structures, including nuclear power plants, quantifying overall functionality based on the expected loss of individual components. The restoration of initial losses is then modeled using recovery functions, such as linear, exponential, sinusoidal, or stepwise patterns. Moreover, specific scenarios and resilience indices for NPPs have been investigated (Demachi et al., 2016; Yan et al., 2023). Nevertheless, it remains imperative to incorporate practical risk measures to systematically assess the disaster resilience capability of NPPs.

This study proposes a resilience analysis framework for NPPs subject to earthquake events. The CDF is first adopted as a measure of plant-level functionality. Next, the variation in the CDF under failure assumptions of SSCs is investigated. To this end, the median capacity A_m of SSCs is modeled by recovery functions. For example, n components can generate $2^n - 1$ failure scenarios, corresponding to all non-empty subsets of the components. In each scenario, the median capacities of the failed components are described using recovery functions. Finally, CDF is evaluated over the restoration period. The restoration capability of NPPs is quantified using the resulting CDF histories.

3. Quantification of Seismic Resilience of NPPs

This section illustrates the proposed framework for typical Korean NPP. The detailed seismic PSA result of the NPP is provided in KHNP (2002). For describing the CD accident, six major initiating events are incorporated as follows (Kwag and Hahm, 2020): (1) loss of essential power (LEP), (2) loss of secondary heat removal (LHR), (3) loss of component cooling water/essential chilled water (LOCCW), (4) small loss of coolant accidents (SLOCA), (5) loss of offsite power (LOOP), and (6) general transient (GTRN).

Each initiating event is defined by FTs comprising 22 components. Among those, only 8 components that do not directly lead to CD are considered in the resilience

analysis. Consequently, 255 failure scenarios ($2^8 - 1$) are examined in terms of CDF. Figure 1 shows the evaluated CDF curves (divided by original CDF value) across these failure scenarios. In the figure, the red curve is the expected CDF curve for the failure scenarios at PGA of 0.1g.

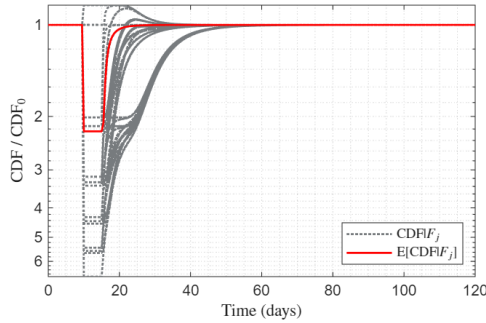


Figure 1. CDF curves for the failure scenarios

To quantify the restoration capability, two indices are investigated: the area of CDF increase and the time required to reach an allowable recovery level. The histograms of these indices across the failure scenarios are presented in Figures 2 and 3, where the red vertical lines indicate the outcomes corresponding to the expected CDF curve.

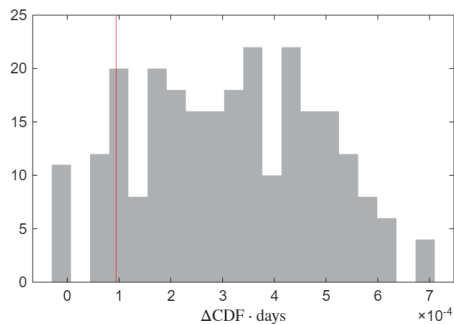


Figure 2. CDF increase integrated over the restoration period for the failure scenarios

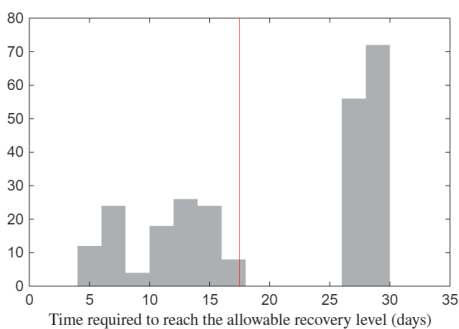


Figure 3. Time required to reach the allowable recovery level for the failure scenarios

4. Conclusions

This study presented a risk-based resilience analysis framework for NPPs. In the proposed framework, core damage frequency (CDF) was adopted as a measure of plant-level functionality, while median capacities of

basic components were modeled using recovery functions. The framework was demonstrated using a plant model of NPP in South Korea. In particular, two indices were evaluated across the failure scenarios to quantify the restoration capability of the NPP.

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