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Derivation of Seismic Fragility Curve of NPP Equipment by Numerical Approach

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1. Introduction

In the Republic of Korea, relatively large earthquakes occurred in consecutive years: Gyeongju in 2016 and Pohang in 2017. Notably, the frequency contents of the recorded seismic ground motions during these earthquakes were dominant at frequencies above 10 Hz. The natural frequency of nuclear power plant (NPP) equipment is mainly distributed between 10–30 Hz, and it can be vulnerable to earthquakes with such frequency characteristics. Therefore, it is necessary to secure the safety of the equipment by performing seismic fragility analysis for input ground motions with these characteristics.

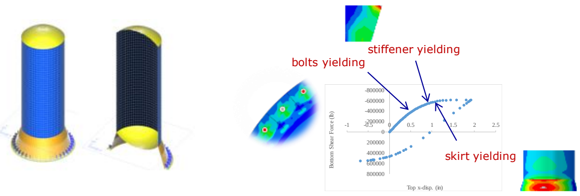
In this paper, the SGBD (steam generator blowdown) tank, a type of heavy equipment located in the auxiliary building, was selected for analysis, and seismic fragility curves of the SGBD tank were derived by a numerical method. A pushover analysis was performed to obtain three limit states of the SGBD tank. Then, a time history analysis of the SGBD tank was performed by inputting the floor response acceleration obtained from the auxiliary building. The probability of failure was calculated by evaluating the dynamic response of the SGBD tank for each limit state. As a result, fragility curves with parameters of the median acceleration capacity, A_m, and the logarithmic standard deviation, β, were derived using the MLE (maximum likelihood estimation) method.

2. Analysis of the SGBD tank

In this section, the probability of failure of the SGBD tank is obtained via numerical approach. First, a nonlinear pushover analysis is performed with a three-dimensional (3D) detail model, and then a nonlinear dynamic analysis is performed with a one degrees of freedom (DOF) lumped mass model to evaluate the probability of failure according to the dynamic behavior of the SGBD tank.

2.1 Pushover analysis

A nonlinear pushover analysis of the SGBD tank was performed with a 3D detail model. The SGBD tank was modeled by shell elements with the bottom 40 anchors modeled by beam elements. As a result of the pushover analysis, a nonlinear response curve with bottom shear force versus horizontal displacement at the top of the SGBD tank was obtained (Fig. 1).



(a) (b)

Fig. 1. (a) Finite element model of the SGBD tank and (b) three limit states from the pushover curve.

Three limit states of the SGBD tank were evaluated according to hysteresis behavior (Table I). Anchor bolts yielding occurs first, followed by stiffener yielding, and finally skirt yielding. If skirt yielding occurs, it may result in a collapse of the main body of the SGBD tank, and thus skirt yielding was considered as severe damage. In addition, the resulting response curve was used for the nonlinear plasticity behavior in the 1DOF simplified model representing the SGBD tank.

Table I: Limit states of the SGBD tank

Damage	Limit state	Displacement (in)
Anchor bolts yielding	Slight damage	0.139
Stiffener yielding	Moderate damage	0.508
Skirt yielding	Severe damage	0.851

The bolts used in the actual installation of the SGBD tank are manufactured of a material with a higher strength than the SGBD tank material, but in the current analysis, it is assumed that the bolt and tank material are the same. The result may therefore differ from actual behavior.

2.2 Time history analysis

In the time history analysis of the auxiliary building, 30 sets of ground motions and material models of concrete and rebar were used with the increase of peak ground acceleration (PGA) level (0.3, 0.6, 0.9, 1.2, and 1.5g). For seismic ground motions, the real earthquake records from PEER (Pacific Earthquake Engineering Research Center) were used. The real earthquake records were scaled to match with the target response spectrum based on the selection and scaling method (Fig. 2) [1].

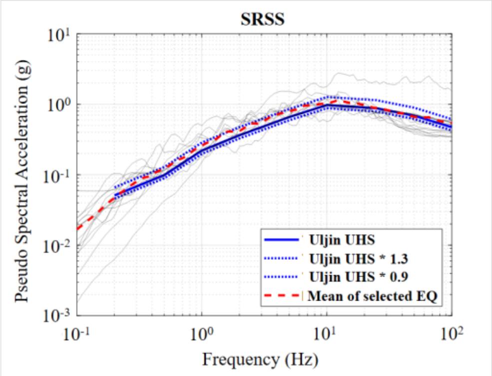


Fig. 2. Input ground motion selection from matching with target response spectrum.

Then, the floor acceleration at the location of the SGBD tank can be obtained from each the auxiliary building analysis and used as an input acceleration. The time history analysis of the SGBD tank was performed at empty and operating conditions according to the amount of water in the tank. The resulting dynamic behavior was evaluated by the limit states of the pushover analysis. The evaluation criterion for determining the failure of the SGBD tank was skirt yielding considered as severe damage. The calculated probabilities of failure are listed in Table II.

Table II: Probability of failure by ground motion and tank condition

PGA level (g)	Empty	Operating
0.3	0.0	0.11
0.6	0.44	0.59
0.9	0.70	1.00
1.2	0.88	1.00
1.5	1.00	1.00

3. Derivation of fragility curve

In the previous section, the probability of failure for each PGA level was calculated from the analysis of the SGBD tank. In this section, fragility curves are derived by estimating A_m and β for the obtained probabilities of failure.

3.1 Estimating the fragility parameters

When constructing seismic fragility curves using numerical simulations, the following considerations should be taken into account: methods to obtain dynamic responses and verify the limit states, and methods to derive fragility curves from the obtained data [2].

There are various procedures in dynamic structural analysis to obtain the failure probabilities to be used for deriving fragility curves, and among them, incremental dynamic analysis and multiple stripe analysis are representative analysis procedures [3]. In this paper, multiple stripe analysis was used to obtain the probability of failure at each increment of the input ground accelerations (Fig. 3).

Previous studies have confirmed that the MLE method estimates A_m and β more accurately than other methods [2, 4]. Therefore, A_m and β in the current analysis were estimated using the MLE method from the probabilities of failure obtained in the previous section. As a result, the fragility curves were derived from the estimated parameters (Fig. 3).

Table III: Estimated fragility parameters

Condition	A_m	β
Empty	0.69	0.40
Operating	0.50	0.35

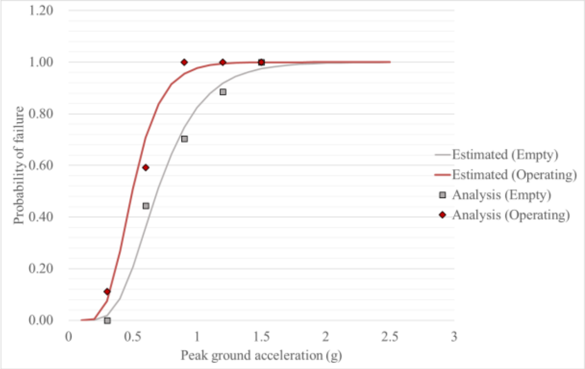


Fig. 3. Probabilities of failure from analysis and their derived fragility curves.

4. Conclusions

In this paper, fragility curves of the SGBD tank, a heavy piece of equipment in NPP auxiliary buildings, were derived by a numerical approach. The dynamic behavior of the SGBD tank was evaluated for PGA levels of 0.3, 0.6, 0.9, 1.2, and 1.5g. First, a pushover analysis of the SGBD tank was performed, and then a time history analysis of the SGBD tank was conducted. As a result of the pushover analysis, three limit states of the SGBD tank were obtained, with skirt yielding among them considered as severe damage. The severe damage limit state was used as a criterion for evaluating the hysteretic behavior obtained from the time history analysis of the SGBD tank, and the probability of failure for each PGA level was calculated. For the resulting failure probabilities, fragility parameters A_m and β were estimated using the MLE method, and fragility curves for two tank conditions were derived accordingly.

This study focused on constructing fragility curves by numerical analysis rather than evaluating actual SGBD tank behavior. As the actual material properties were not considered in the pushover analysis, it is necessary to revise the results of the SGBD tank according to the actual material properties once the fragility curve derivation process for NPP equipment is firmly established.

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