Evaluation of Failure Probability Considering Seismic Correlation for Probabilistic Safety Assessment

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1. Introduction

In the nuclear power plant, two or more identical equipment with important function are installed to prevent from abnormal failure. If the failure probability of identical equipment is independent, this redundancy could increase the system safety remarkably. However, the failure of each component is highly correlated such as in an earthquake event, the expected redundancy effect will decrease. Therefore the seismic correlation of equipment should be evaluated quantitatively in seismic PSA. In this study, the computer code for calculating the failure probability considering seismic correlation effect was developed, and the implementation method is proposed.

2. Calculation of Seismic Correlation

2.1 SSMRP Methodology

The failure probability of equipment considering seismic correlation was developed by the SSMRP study [1]. A failure probability of a component is calculated from the distribution of a earthquake response and a seismic capacity. These distributions are usually defined as the lognormal distribution. When a number of components are exist in a cutset, and the response and capacity of components are defined as (X_1, X_2, … X_n) and (Y_1, Y_2, … Y_n), the failure probability is expressed as Equation (1).

$$P = P\left[Z_1 > 0, Z_2 > 0, \cdots, Z_n > 0\right] = \int_0^{\infty}\cdots\int_0^{\infty} f_z(z_1,\cdots,z_n)\,dz_1,\cdots,dz_1 \tag{1}$$

where, $Z=X-Y$, and f_z is the joint probability density function of Z. If X and Y are correlated, this integral becomes to Equation (2) [2].

$$P = \frac{1}{(2\pi)^{n/2}|C|^{1/2}}\int_0^{\infty}\cdots\int_0^{\infty}\exp\left\{-\frac{1}{2}(z-\mu_z)'C^{-1}(z-\mu_z)\right\}dz_1,\cdots,dz_1 \tag{2}$$

where, μ denotes mean values and $\mu_z=\mu_x-\mu_y$. C is covariance matrix of components. This equation cannot be solved analytically. Therefore numerical integration method such as Monte-Carlo simulation integration should be adjusted.

The covariance matrix is composed of the correlation coefficients between two components. It is represented as in Equation (3).

$$\rho_{ij} = \frac{\beta_{Ri}\beta_{Rj}}{\sqrt{\beta_{Ri}^2+\beta_{Si}^2}\sqrt{\beta_{Rj}^2+\beta_{Sj}^2}}\rho_{Ri,Rj} + \frac{\beta_{Si}\beta_{Sj}}{\sqrt{\beta_{Ri}^2+\beta_{Si}^2}\sqrt{\beta_{Rj}^2+\beta_{Sj}^2}}\rho_{Si,Sj} \tag{3}$$

where β_R, β_S are standard deviations of the response and capacity, and $\rho_{Ri,Rj}$, $\rho_{Si,Sj}$ are correlation coefficient of the response and capacity between two components

2.2 Correlated failure probability calculation

A computational code for calculating a failure probability of correlated components was developed. For each component, median values and standard deviations of the response and capacity are given and the correlation matrix is input in the program. Then the correlation matrix is composed and the correlated failure probability is estimated as shown in Fig 1.

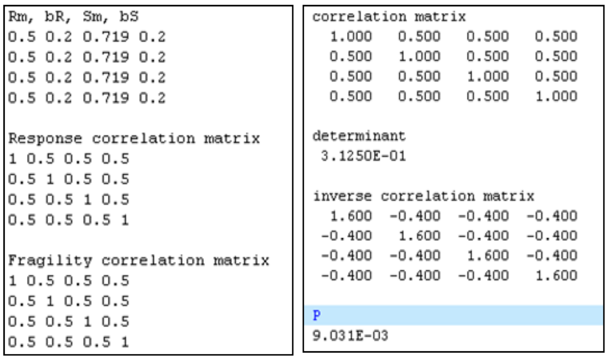

Fig. 1. Input and output of the code for calculating failure probability of correlated components

3. Seismic CCF Evaluation

3.1 Seismic CCF Estimation

If the identical equipment is installed to guarantee the redundancy, the correlated failure probability can be obtained by simplified method. Let the failure probability of single component is P. The failure probability of N number of components is P^N when they are uncorrelated, and it is P when fully correlated. Therefore the power adjusted to P will be between 1.0

and N. The power can be determined by the number of components, a failure probability of single component, and the correlation coefficient between two components. This relationship is plotted as in Fig 2.

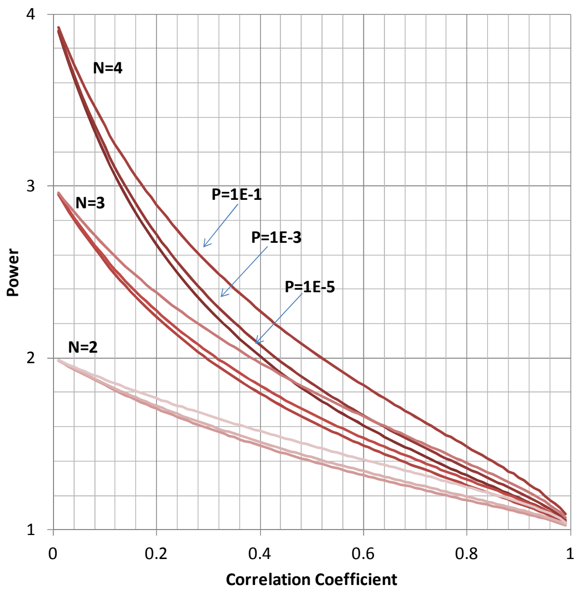

Fig. 2. Power in regard of correlation coefficient

3.2 Fragility Estimation of Correlated Component Set

The conditional probability of a failure of components is necessary for the seismic PSA. A component failure probability is easily obtained by fragility curve parameters, which are median capacity and variations of randomness and uncertainty. However the estimation of the failure probability of correlated component set needs much computational effort because the numerical integration should be performed in every seismic intensity increments. Therefore the pre-calculated data of power can be used for efficiency. To find the power value from the data table, interpolation in regard to the single failure probability and the correlation coefficient can be performed.

Another way is to define the relationship between a number of components, a correlation coefficient, single component failure probability and a power by regression equation. For simplification, the power value is normalized to be between zero and 1.0. And for the regression analysis, the equation formula was determined to fit the normalized power curve, as in Equation (4)

$$n_{normalized} = \left[\frac{1}{\rho^a + 1} (1-\rho)^b \right] (N-1) + 1 \qquad (4)$$

The normalized power and the curve obtained by regression analysis are shown in Fig 3. For example, the two cases with N=2, P=E-3 and N=4, P=E-1 depicted in this figure.

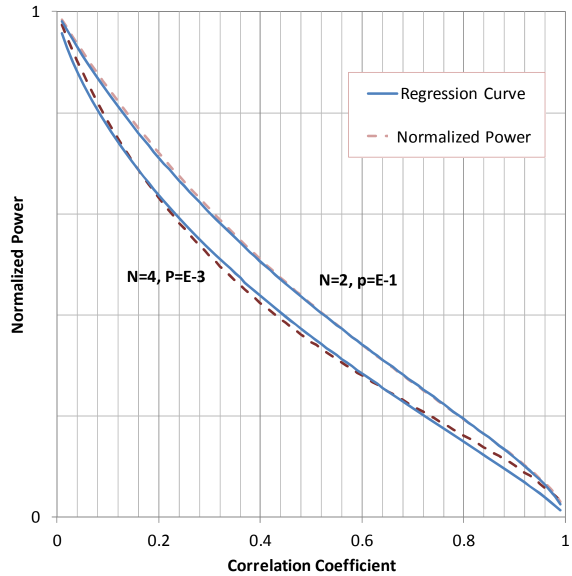

Fig. 3. Normalized power and its regression equation

4. Conclusions

In this study, the code to calculate the failure probability of correlated components was developed. The power value of the seismic CCF for various case was obtained by using the code. The data table or regression equation of a power can be used to evaluate the fragility curve of correlated component set. For advanced seismic PSA considering correlation effects, it need to be implemented in further study.

ACKNOWLEDGEMENT

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