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A FRAMEWORK OF PERFORMANCE-GOAL BASED APPROACH FOR SEISMIC DESIGN OF NUCLEAR POWER PLANTS

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Abstract

Seismic probabilistic risk assessments have been widely performed for Japanese nuclear power plants (NPPs). In recent years, it has been pointed out that the utilization of risk information and a performance-goal based seismic design method are effective for improving the seismic safety of NPPs.

Kennedy has proposed a performance-goal based approach to establish a site-specific response spectrum of the safe shutdown earthquake. This approach provides the technical basis for the American Society of Civil Engineering Standard, ASCE/SEI 43-05, and was adopted as a part of the Regulatory Guide 1.208 of U.S. Nuclear Regulatory Commission. Gkimprixis et al. have summarized and reviewed similar performance-goal based approaches proposed by Kennedy and Short (1994) and Cornell (1996) to set the risk-targeted spectrum directly from the seismic hazard curves of each period. In their approaches, for the purpose of simplifying the calculations, seismic hazard curves were assumed to be linear when plotted on a log-log scale, and a coefficient of conservatism for significant inelastic deformation of structures, systems, and components (SSCs) was applied. When applying their approaches to Japanese NPPs, it is necessary to confirm the applicability of these assumptions.

This paper proposes a framework of performance-goal based seismic design method that does not incorporate the above assumptions. It was noted that the targeted risk of each SSC should be determined to keep the plant risk below the performance-goal of the NPP. In Consideration of the seismic hazard conditions at Japanese NPP sites, we have adopted a risk-diagram devised by Ohtori et al. The risk-diagram shows the relation between the required median capacity and the targeted value of the probability of failure. The risk-targeted spectrum is obtained from the risk-diagram corresponding to the targeted risk of the SSC and the uniform hazard spectrum of the NPP. This spectrum should be used for the target spectrum to generate the risk-targeted ground motion. As a risk-controllable method of the risk assessment, the seismic response of the SSC subjected to the risk-targeted ground motion is compared to the allowable seismic response based on the distribution data of the ultimate strength of the SSC. When the seismic response of the SSC subjected to the risk-targeted ground motion does not exceed the allowable seismic response, the mean annual probability of failure of the SSC definitely satisfies the targeted risk of the SSC. Furthermore, when the results of the risk assessments of all SSCs are acceptable, the performance-goal of the NPP is also achieved.

Keywords: performance-goal based, risk-targeted, seismic design method

1. Introduction

Seismic probabilistic risk assessments (PRAs) have been widely performed for Japanese nuclear power plants (NPPs). In recent years, it has been pointed out that the utilization of risk information and a performance-goal based seismic design method are effective for improving the seismic safety of NPPs [1, 2, 3].

Kennedy has proposed a performance-goal based approach to establish a site specific response spectrum of the safe shutdown earthquake [4]. This approach provides the technical basis for the American Society of Civil Engineering Standard, ASCE/SEI 43-05 [5], and was adopted as a part of the Regulatory Guide 1.208 of the U.S. Nuclear Regulatory Commission. Gkimprixis et al. have summarized and reviewed similar performance-goal based approaches proposed by Kennedy and Short (1994) and Cornell (1996) to set the risk-targeted spectrum directly from the seismic hazard curves of each period [6]. For applying these approaches to Japanese NPPs, the following issues of these approaches should be studied:

- For the purpose of simplifying the calculations, seismic hazard curves are assumed to be linear when plotted on a log-log scale.
- The coefficient of conservatism for significant inelastic deformation of structures, systems, and components (SSCs) is applied.

In this paper, we propose a framework for a performance-goal based seismic design method that does not require the above assumptions. Our framework includes the following:

- The targeted risk of a SSC is determined from the performance-goal of the NPP.
- The risk-targeted spectrum and the risk-targeted ground motion are defined by using a risk-diagram proposed by Ohtori et al (2010) [7, 8] corresponding to the targeted risk of the SSC and the uniform hazard spectrum (UHS) of the NPP.
- An allowable seismic response of a SSC is defined based on the distribution data of the ultimate strength of the SSC. Risk assessment of a SSC is performed by comparing seismic response subjected to the risk-targeted ground motion to the allowable seismic response.

2. Nomenclature

P_T	Targeted risk of a SSC
a	Peak ground acceleration (PGA) of UHS
A_X	PGA of UHS corresponding to failure probability X
A_{XT}	Required value of PGA of UHS corresponding to failure probability X for achieving the targeted risk P_T of a SSC
A_m	Median PGA of UHS of lognormal distribution of the capacity of a SSC
$\Phi^{-1}(X)$	Inverse of the standard normal cumulative distribution function for failure probability X
β	Logarithmic standard deviation of the capacity of a SSC
P_{ex}	Mean annual probability of exceedance of the limit state
$H(a)$	Mean annual probability of exceedance of peak ground acceleration a
$F(a\|A_X,\beta)$	Conditional probability of exceedance of the limit state under an earthquake with peak ground acceleration a
P_f	Probability of failure of seismic fragility
D_{Sm}	Median damage index of lognormal distribution of the ultimate strength of a SSC
D_{Rm}	Median damage index of lognormal distribution of the seismic response of a SSC

$D_{Rm,X}$	Median damage index of lognormal distribution of the seismic response corresponding to a failure probability X
β_D	Logarithmic standard deviation of the capacity of a SSC in damage index
β_{DR}	Logarithmic standard deviation of the seismic response of a SSC in damage index
β_{DS}	Logarithmic standard deviation of the ultimate strength of a SSC in damage index
D_{AL}	Allowable seismic response of a SSC
D_{PT}	Seismic response of a SSC subjected to the risk targeted ground motion

3. Framework of a performance-goal based approach for the seismic design of NPPs

The purpose of the seismic design of NPPs is to keep the plant risk below the acceptable level and to achieve the performance-goal of the NPP. Seismic PRA provides the mean annual probability of critical events and risk profile of the NPP. It is important to utilize the risk profile for the seismic safety improvement, however, the structural design and seismic response analyses are normally carried out for each SSC. This is why we focus on the process of the seismic design of each SSC. A flow diagram of the performance-goal based approach for the seismic design of a SSC of NPPs is shown in Fig.1. It consists of the following steps:

Step 1: Set up of the targeted risk (P_T) of a SSC from the performance-goal of the NPP.

Step 2: Calculate the risk-diagram from the seismic hazard curve at the NPP site; herein the logarithmic standard deviation of the capacity of the SSC is provided as the given value.

Step 3: Determine the risk-targeted spectrum from the risk-diagram corresponding to the targeted risk of the SSC and UHS of the NPP.

Step 4: Generate the risk-targeted ground motion that fits the risk-targeted spectrum as the ground motion for the risk assessment of the SSC.

Step 5: Define the allowable seismic response based on the damage index related to the ultimate strength of the SSC. Herein, the allowable seismic response is statistically calculated from the distribution data of the ultimate strength obtained by destructive testing or analysis.

Step 6: Perform seismic response analysis of the SSC subjected to the risk-targeted ground motion.

Step 7: Carry out the risk assessment by comparing the seismic response D_{PT} subjected to the risk-targeted ground motion with the allowable seismic response D_{AL}. If D_{PT} does not exceed D_{AL}, the mean annual probability of failure of the SSC is definitely less than the targeted risk of the SSC.

Step 8: If the result of the risk assessment is not acceptable, improvement of the plant system design or seismic design of the SSC is required. When the plant system design is improved, repeat Step1 to Step7 until the result of the risk assessment is acceptable. When the seismic design of the SSC is modified, repeat Step6 to Step7.

Step 9: Repeat Steps 1 to 8 for all SSCs.

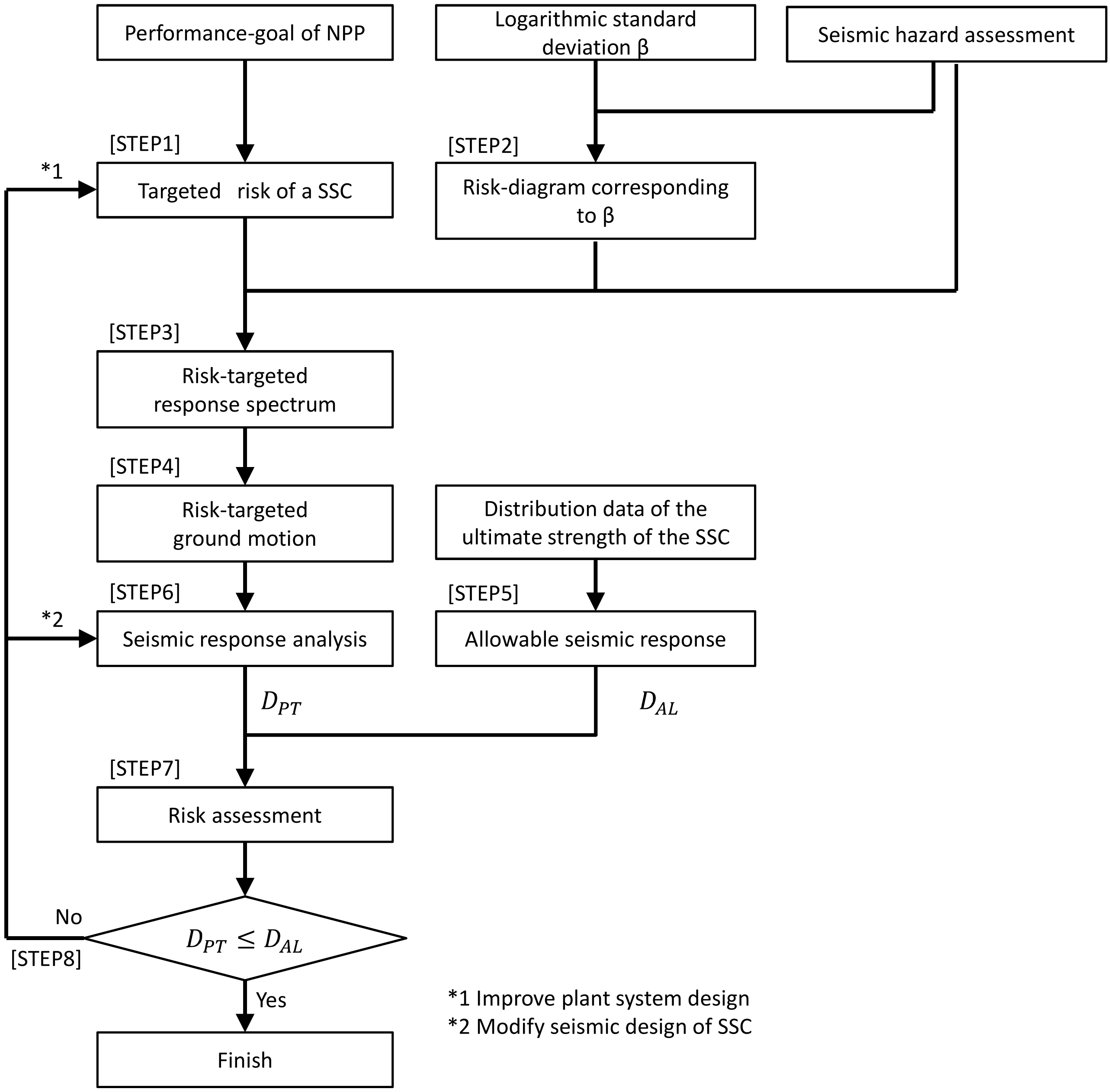

Fig. 1 – Framework of the performance-goal based approach for the seismic design of a SSC of NPPs

4. Detailed description of the method

In this chapter, the proposed framework of the performance-goal based approach for the seismic design of NPPs is described in steps.

4.1 Set the targeted risk value of SSCs

At the beginning of the process of the proposed seismic design of SSCs, it is necessary to set the targeted risk value of SSCs from the performance-goal of the NPP. The performance-goal of NPPs is determined based on social agreement, and it is generally defined as the mean annual probability of critical events such as core damage, containment failure, and large early release. The targeted risk P_T of a SSC can be expressed as the mean annual probability of exceedance of the limit state. Since the purpose of the seismic design of SSCs is to achieve the performance-goal of NPPs, the targeted risk of SSCs should be determined to keep the plant risk below the performance-goal of the NPP. The seismic PRA technique provides a realistic targeted risk value for a SSC that is calculated from the performance-goal of the NPP by an inverse procedure of event tree and fault tree analysis. More practically, the targeted risk of each SSC is set up by referring to previous seismic PRA results. The details of this procedure will be presented separately in the near future.

4.2 Creation of a risk diagram

The fragility curve gives the probability of failure as a function of the ground motion intensity such as peak ground acceleration (PGA). Under the assumption of a log-normally distributed capacity of SSCs, the fragility curve is expressed by two parameters: the median capacity and the logarithmic standard deviation of the capacity of the SCCs. The fragility curve can be expressed not only by the median PGA but also the PGA corresponding to a failure probability X. The PGA corresponding to a failure probability X can be expressed as follows:

$$A_X = A_m \cdot e^{\Phi^{-1}(X)\cdot\beta} \tag{1}$$

where A_X is the PGA corresponding to a failure probability X, A_m is the median PGA of UHS of the lognormal distribution of the capacity of the SSC, $\Phi^{-1}(X)$ is the inverse of the standard normal cumulative distribution function for the probability X, and β is the logarithmic standard deviation of the capacity of a SSC. By definition, $A_{0.5} = A_m$, obviously. The mean annual probability of exceedance of the limit state can be obtained as follows:

$$P_{ex} = \int_0^\infty H(a) \cdot \frac{dF(a|A_X,\beta)}{da} da \tag{2}$$

where P_{ex} is the mean annual probability of exceedance of the limit state, $H(a)$ is the mean annual probability of exceedance of the peak ground acceleration a , and $F(a|A_X,\beta)$ is the conditional probability of exceedance of the limit state in an earthquake with peak ground acceleration a. $H(a)$ represents the seismic hazard curve and $F(a|A_X,\beta)$ represents the fragility curve.

Figure 2 illustrates the relation between the mean annual probability P_{ex} of exceedance of the limit state and the PGA A_X corresponding to a failure probability X; this figure is referred as the “risk-diagram” proposed by Ohtori et al (2010) [7, 8]. The risk-diagram can be obtained by calculating P_{ex} under a parametrically changing A_X for a fixed β and plotting P_{ex} against A_X. Note that the calculation of the risk-diagram is performed without the linear-in-log–log-space approximation of the hazard curve. When this calculation of the probability of failure is conducted in advance, the risk-diagram represents targeted risk consistent PGA A_{XT}; in other words, when the targeted risk P_T is set, the PGA A_{XT} for the risk assessment required to satisfy the targeted risk is obtained directly from the risk-diagram by replacing P_{ex} with P_T. Thus, the risk-diagram shows the relation between the required capacity of the SSC and the targeted value of probability of failure.

4.3 Determination of the risk-targeted spectrum and the risk-targeted ground motion for the risk assessment of SSCs

Gkimprixis et al. reviewed the approaches proposed by Kennedy and Short (1994) and Cornell (1996) for setting the risk-targeted spectrum directly from the seismic hazard curves of each period [6]. These approaches need to assume that the seismic hazard curves are linear when plotted on a log-log scale, and SSCs are represented as single degree of freedom (SDOF) system. However, it is difficult to approximate the hazard curve in Japan to be linear in a log-log scale. In addition, complicated structures generally cannot be represented by SDOF system. This is why a more practical and general method of setting the risk-targeted spectrum should be proposed. Figure 3 shows the proposed method of setting a risk-targeted spectrum for the risk assessment of SSCs. The risk-targeted spectrum can be expressed as a UHS whose peak ground acceleration is equal to A_{XT}. This spectrum should be used as the target spectrum to generate a risk-targeted ground motion for the risk assessment of the SSC.

Since the value of the referenced failure probability X can influence the setting of the risk-targeted spectrum, it is necessary to study the appropriate value of X. Gkimprixis et al. summarized methods of developing risk-targeted seismic design maps and investigated the choice of X [6]. We recommend that the failure probability X be set in consideration of the seismic intensity dominating the risk of the NPP.

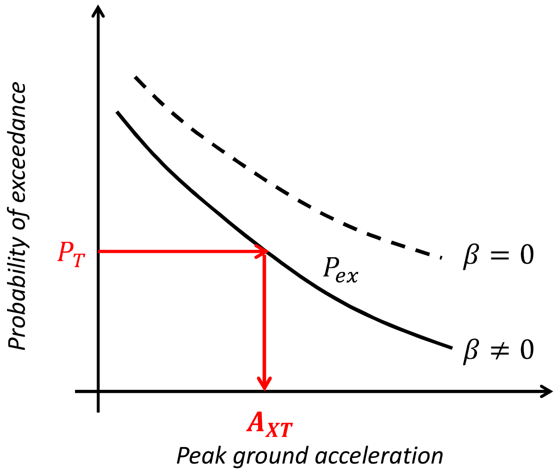

Fig. 2 – Risk-diagram

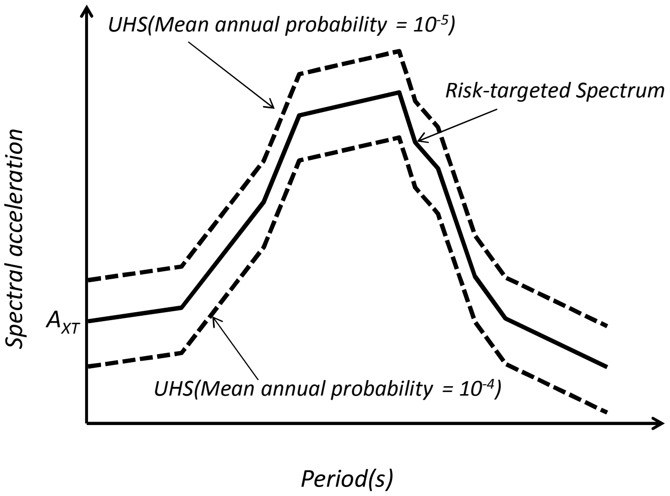

Fig. 3 – Risk-targeted spectrum

4.4 Allowable response related to the distribution of ultimate strength of SSCs

Figure 4 shows the method for setting an allowable seismic response based on the distribution data of the ultimate strength of the SSC. Under the assumption of a lognormal distribution of the response and the ultimate strength, the seismic fragility can be obtained as follows:

$$P_f = 1 - \Phi\left(\frac{\ln D_{Sm} - \ln D_{Rm}}{\beta_D}\right) \tag{3}$$

where P_f is the probability of failure of the seismic fragility curve, D_{Sm} is the median damage index of the lognormal distribution of the ultimate strength of the SSC, D_{Rm} is the median damage index of the lognormal distribution of the seismic response of the SSC, and β_D is the logarithmic standard deviation. Note that the ultimate strength and seismic response of SSCs are not defined based on the acceleration of ground motion or spectral acceleration, but rather on damage index of SSCs such as a ductility factor. If the value of D_{Sm} and the logarithmic standard deviation β_D are known, the median damage index of the lognormal distribution of the seismic response corresponding to a failure probability X can be expressed using Eqs. (3) as follows:

$$D_{Rm,X} = D_{Sm} \cdot e^{-\Phi^{-1}(X)\cdot\beta_D} \tag{4}$$

where $D_{Rm,X}$ is the median of the lognormal distribution of the seismic response corresponding to a failure probability X. The deviation β_D is defined as:

$$\beta_D = \sqrt{B_{DR}{}^2 + \beta_{DS}{}^2} \tag{5}$$

where β_{DR} is the logarithmic standard deviation of the seismic response, and β_{DS} is the logarithmic standard deviation of the ultimate strength of the SSC. Note that the deviation β_{DR} represents the deviation of the whole response analysis process including the ground motion, the response analysis of buildings and civil structures, and the response analysis of piping systems and components. The median ultimate strength D_{Sm} is statistically calculated from distribution data regarding the ultimate strength obtained by destructive testing or analysis. When D_{Sm} is given, the seismic response of the SSC should be limited to less than $D_{Rm,X}$ in order to keep the failure probability of the SSC less than X. That is, $D_{Rm,X}$ is provided as an allowable value of the seismic response of the SSC for satisfying the failure probability of the SSC less than X. Hereinafter, $D_{Rm,X}$ is defined as the allowable seismic response D_{AL}. The risk-targeted spectrum and the risk-targeted ground motion are determined considering the failure probability X of the SSC, therefore, the allowable seismic response is also defined by the median of the lognormal distribution of the seismic response corresponding to a failure probability X.

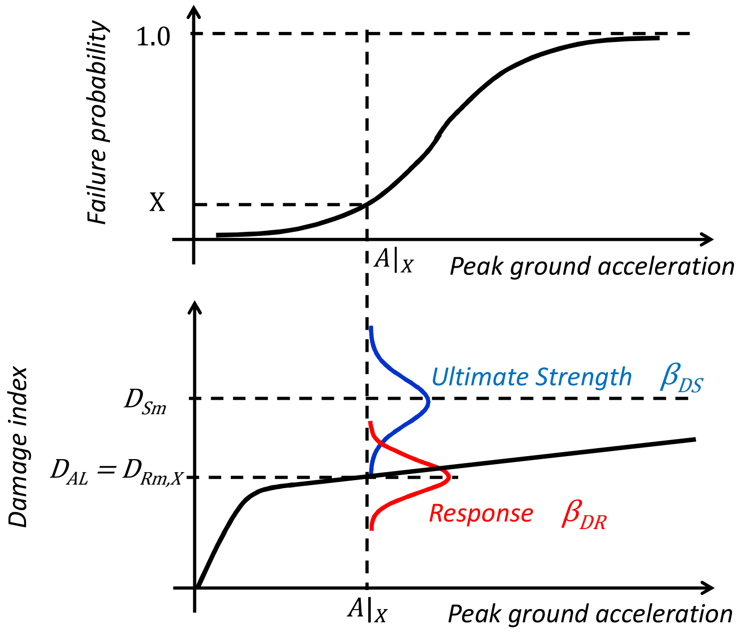

Fig. 4 – Allowable seismic response based on the distribution of ultimate strength of SSCs

4.5 Risk assessment

In this paper, risk assessment means to judge whether the failure probability of a SSC is acceptable or not. The risk-controllable method of risk assessment involves comparing the seismic response D_{PT} of SSCs excited by the risk-targeted ground motion with the allowable seismic response D_{AL}. D_{PT} is obtained by the seismic response analysis of the SSC. Since the allowable seismic response D_{AL} is defined by the median, D_{PT} is also defined by the median of the seismic response of the SSC. When D_{PT} does not exceed D_{AL}, the mean annual probability of failure of the SSC definitely satisfies the targeted risk of the SSC. By contrust, when the result of the risk assessment is not acceptable (D_{PT} exceeds D_{AL}), the plant system design or the seismic design of the SSC must be improved. The risk assessment should be conducted for all SSCs related to the safety of the NPP. When the results of the risk assessments of all SSCs are acceptable, the performance-goal of the NPP is also achieved.

5. Conclusion

In this paper, we propose a framework for a performance-goal based seismic design method for a SSC of NPPs that does not require the assumptions of a linear seismic hazard curve in log-log scale. It was noted that the targeted risk of each SSC should be determined to keep the plant risk below the performance-goal of the NPP. In Consideration of the seismic hazard conditions at Japanese NPP sites, we have adopted a risk-diagram devised by Ohtori et al. The risk-diagram shows the relation between the required capacity and the targeted value of the probability of failure for a fixed deviation β. When a fragility curve is defined as a cumulative distribution function of lognormal distribution, the probability of failure of a SSC can be calculated from a seismic hazard curve, the median capacity of the SSC, and the lognormal standard deviation of the SSC. Once this calculation of the probability of failure is conducted in advance by using the obtained seismic hazard curves, the median capacity for achieving the targeted probability of failure can be determined. The risk-targeted spectrum is obtained from the risk-diagram corresponding to the targeted risk of the SSC and the uniform hazard spectrum of the NPP. This spectrum is used as the target spectrum to generate the risk-targeted ground motion. In the risk assessment of a SSC, the seismic response of the SSC subjected to the risk-targeted ground motion is compared to the allowable seismic response based on the distribution data of the ultimate strength of the SSC. The allowable seismic response is calculated from the median damage index of the ultimate strength of the SSC for satisfying the targeted failure probability of the SSC. When the seismic response of the SSC subjected to the risk-targeted ground motion does not exceed the allowable seismic response, the mean annual probability of failure of the SSC definitely satisfies the targeted risk of the SSC. Furthermore, since the targeted risk of the SSC is defined to be related to the performance-goal of the NPP, when the results of the risk assessments of all SSCs are acceptable, the performance-goal of the NPP is also achieved.

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