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Analysis of common cause failure effect on system reliability in seismic PSA

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ABSTRACT

In seismic PSA of nuclear power plant, the equipment failure probability is affected by two parts – response and fragility. In this paper causations of CCF in the above two parts is analyzed, the sensitivity of CCF factor is evaluated under different peak ground acceleration levels. When the peak ground acceleration is much lower than the component seismic resistance capacity, difference between the results of CCF factor $\beta = 0.05$ and $\beta = 1$ is about one magnitude, while the results of $\beta = 0.05$ and $\beta = 1$ are very similar when the peak ground acceleration is close to or even higher than the component seismic resistance capacity. Then a model for system reliability analysis based on Monte Carlo (MC) simulation is proposed: the effect of structure's response can be analyzed in the system reliability model, and the CCF methods used in internal event PSA are also suitable for CCF in response and fragility of the equipment in seismic PSA. The reliability of accumulator system in AP1000 is analyzed as an example under different seismic hazard curves, the system failure probability difference between uncertainties of structure's response $\beta_S = 0.1$ g and $\beta_S = 0.4$ g is about one magnitude, and the results of CCF factor of $\beta = 0.05$ and $\beta = 1$ are very similar since the component failure probability is close to 1 when peak ground acceleration is high.

1. Introduction

Redundant equipments are widely used in reactor design, especially in safety-related systems to enhance the nuclear power plant safety. However, common cause failure (CCF) can destroy the redundancy, which has been recognized as one of the dominant contributors to the system failure and core damage in probabilistic safety assessment (PSA) (Kang et al., 2011; He et al., 2007). Moreover, under seismic situation, the redundant equipments can be destroyed simultaneously more likely than under internal events since they bear the common ground shaking which occurs during an earthquake (Born et al., 1984). In recent years, more attention is paid to seismic probabilistic safety assessment (seismic PSA) (Shibata et al., 1993; Hakata, 2007; Nusbaumer, 2005), and how to evaluate the common cause failure (CCF) is one of the important factors affecting the result (Nusbaumer, 2005). CCF analysis in seismic PSA is recent drawing more interest, the response correlation of structures, systems and components depending on the characteristic of soil, soil-structure interface, architecture design and frequency spectral is considered, the generic rules for assigning response correlation is proposed in the Seismic Safety Margin Research Program (SSMA) (Born et al., 1984; Hakata, 2007; Born and Lambright, 1990).

The equipment failure probability induced by earthquake is affected by two aspects – the peak ground acceleration (PGA) and equipment seismic capacity, while the latter one is influenced by two parts – response of the equipment under earthquake and fragility of the equipment. For the peak ground acceleration, the structures and the equipments in the same area will share the same input value. And for the equipment seismic capacity, the common cause failure can be analyzed according with the above two parts: response and fragility (He et al., 2007; Watanabe et al., 2003). In this paper, the causations of the above two parts of CCF are analyzed, then the sensitivity of CCF factor of $\beta = 0.05$ and $\beta = 1$ is evaluated by FT method (Vesely et al., 1981) under different peak ground acceleration (PGA) levels. Simultaneity the equipment failure probability is the function of PGA and Monte Carlo (MC) simulation (Watanabe et al., 2003; Peng et al., 2011) is used in quantitative analysis of seismic PSA.

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Based on above analysis, a model is proposed for system reliability analysis in seismic PSA, in which the effect of structure's response is shared by all the equipments at the same place in the system failure probability model based on MC simulation (Zio, 2009; Yu et al., 2012) and the correlation of equipment's response and fragility can be expressed by the CCF models used in internal event PSA such as MGL model (Mosleh et al., 1998, 1988) since when PGA is much lower than the component seismic resistance capacity, the CCF in response and fragility of the equipment is more likely to be stochastic, and when PGA is close to or even higher than the component seismic resistance capacity, the effect of CCF is not important since the component failure probability is close to 1.

2. CCF analysis under earthquake

2.1. Equipment failure model analysis in seismic situation

The equipment failure probability under earthquake is a function of the peak ground acceleration and the seismic resistance capacity of the equipment which is usually characterized by the ground acceleration capacity *Am*. Here *Am* is the peak ground acceleration value at which the component would fail. And randomicity exists in the effect of the earthquake on the equipment failure, so parameter β_R is used to measure the randomness. Then the relationship between the peak ground acceleration and the equipment seismic resistance can be modeled as follow (Budnitz et al., 1985; Cover et al., 1985):

$$f = \varphi(\ln(a/Am)/\beta_R) \tag{1}$$

where, f is the conditional probability of equipment failure for a given PGA level, $\varphi(\cdot)$ is the standard Gaussian cumulative distribution function, a is the PGA level, *Am* is median ground acceleration capacity, β_R is randomness between earthquake and effects (Hakata, 2007):

$$\beta_R^2 = \beta_S^2 + \beta_F^2 \tag{2}$$

β_S is the uncertainty of response and β_F is the uncertainty of fragility.

2.2. CCF causation analysis

From the formula (1) and (2), it can be seen that the equipment failure probability is affected by two parts – the response of the equipment under earthquake and fragility of the equipment, so the CCF can be analyzed according with the above two parts. The correlation of the component failure during earthquake arises from (Born et al., 1984):

- Correlation between the responses the two components experience and
- Correlation between the fragilities of the two components

The following formula is proposed to express the correlation coefficient of the two components (Born et al., 1984):

$$\rho = \frac{\beta_{S1}\beta_{S2}}{\sqrt{\beta_{S1}^2+\beta_{F1}^2}\sqrt{\beta_{S2}^2+\beta_{F2}^2}}\rho_{S1S2} + \frac{\beta_{F1}\beta_{F2}}{\sqrt{\beta_{S1}^2+\beta_{F1}^2}\sqrt{\beta_{S2}^2+\beta_{F2}^2}}\rho_{F1F2} \tag{3}$$

here,

ρ = correlation coefficient between the failures of the components 1 and 2.
S1, S2 = response of components 1 and 2.
β_{S1}, β_{S2} = standard deviation of the logarithms of the responses R1 and R2.
β_{F1}, β_{F2} = standard deviation of the logarithms of the fragilities of components 1 and 2.
$\rho_{S1\ S2}$ = correlation coefficient between responses R1 and R2.
$\rho_{F1\ F2}$ = correlation coefficient between the fragilities of components 1 and 2.

Formula (3) describes the correlation between equipments under earthquake, which is induced by uncertainties in response and fragility. Formula (1) illustrates that equipment failure induced by earthquake is aroused from two aspects: the peak ground acceleration (a) and the ground acceleration capacity (*Am)*. So both the uncertainties in the two aspects will influence the equipment failure probability. The peak ground acceleration (a) is the earthquake motion parameter for all the equipments in the same area, its uncertainty will be shared by all the components and structures. The uncertainties in the ground acceleration capacity (*Am)* can be analyzed as response uncertainty and fragility uncertainty, and the response uncertainty are from uncertainties of structure's response and of component's response. Since the structure's response uncertainty will influence all the equipments, that is, the effect of structure's response arises from the common ground shaking which occurs during an earthquake (Born et al., 1984), and we consider all the components at the same location share the same input. In the model proposed in this paper, the response of the building is considered in parameter a in formula(1), that is, if the peak ground acceleration is a, the response of a certain location in the building (a') can be calculated by dynamics of structure methods, the probabilistic distribution of which is lognormal and β_S is the standard deviation. Then the component's ground acceleration capacity is modified to be *Am*', that is, the equipment failure will occur when the response of the structure at which the equipment locates exceeds *Am*'. The uncertainty of *Am*' is induced by uncertainties of component's response and fragility. The component's response uncertainty is only related to the characteristic of the component itself such as damping, support, etc, as well as the component's fragility uncertainty which is related to the component's strength, ductility, even the failure mode and so on. So we consider the correlation in response and fragility of the component only among the same kind of equipments, and the probabilistic distribution of *Am*' is also lognormal and β_F is the standard deviation.

From formula (1), it can be seen that the component failure probability is decided by a' and *Am*', based on the above analysis, the uncertainty of a' is shared by all the components at the same place, that is, the first item in formula (3) right side describing the correlation of response can be simulated in the structure's response. While uncertainty of *Am*' is only related to the component's characteristics, moreover, when *Am*' is close to a', the component failure probability is close to 1 and CCF is not important for system reliability, so the second item describing the correlation of fragility can be considered as random event, especially when *Am*' is much lower than a'.

2.3. CCF sensitivity analysis

2.3.1. System description

The accumulator system (Foret, 2003a) in AP1000 is passive system whose function is to provide water into the reactor coolant system (RCS) if the reactor coolant system pressure falls below the accumulator pressure, which is the subsystem of the passive core