SEISMIC RISK ANALYSIS APPLIED TO NUCLEAR POWER PLANTS

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SUMMARY

The basic elements of seismic risk analysis of nuclear power plant are 1) hazard analysis, 2) plant systems and structure response analysis, 3) evaluation of failure frequencies (fragilities) of structures, piping and equipment, 4) plant systems and sequence analysis, and 5) consequence analysis. The outputs are frequencies of radiological releases and frequencies of exceedence of different consequences (e.g., early fatalities and latent cancer deaths). This paper highlights the role of structural/mechanical analysts in performing the seismic risk analysis of nuclear power plants.

INTRODUCTION

Structures, systems and components of a nuclear power plant are conservatively designed to withstand the effects of a Safe Shutdown Earthquake (SSE) which is generally larger than the historical maximum earthquake for the plant region. The uncertainties in the seismic hazard prediction and in the different stages of design and construction can be quantified by performing a seismic risk analysis.

In the last four years, a number of electric utility-sponsored probabilistic risk assessment (PRA) studies on nuclear power plants have been conducted. These studies have underscored the need for detailed seismic risk analysis in view of the potentially important contribution of seismic events to the plant risk. The objectives of such a seismic risk analysis are to estimate the frequencies of occurrence of earthquake induced accidents that may lead to different levels of damage (e.g., early fatalities, latent cancer deaths, and property damage) and to identify the key risk contributors so that necessary risk reductions (e.g., changes in plant arrangement, equipment design, and plant design criteria) may be achieved.

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In the previous World Earthquake Engineering Conferences, several papers have been published under the general theme of seismic risk. In fact, these pertain to a particular aspect of risk, herein called the seismic hazard analysis, in which the frequencies of exceedence of different levels of earthquake ground motion are estimated taking into consideration the presence of active faults and seismotectonic provinces around the site. Seismic risk analysis as discussed in this paper is a major study involving close interaction between the seismic hazard analysts, structural/mechanical engineers, and system analysts aimed at providing guidance on plant safety decisions. It is also a major undertaking insofaras the practical application of probabilistic techniques to a complex system is concerned. The elements of a seismic risk analysis can be identified as analyses of 1) seismic hazard at the site, 2) responses of plant systems and structures, 3) component fragilities, 4) plant systems and accident sequences, and 5) consequences. Seismic hazard is represented by a family of hazard curves, each curve showing the frequencies of exceedence of different levels of earthquake ground motion. The uncertainties in the seismic hazard parameter values and in the mathematical model of the hazard are considered in assigning a probability value to each hazard curve. In the response analysis, the responses of plant systems and structures for a specified seismic input are calculated. The responses of interest could be spectral acceleration, moment, stress, and deflection at selected structural, piping, and equipment locations. In the evaluation of fragility, the conditional frequencies of component (i.e., structure, motor, pump, piping, valve, switchgear, etc.) failure for different values of the response parameter are estimated.

The plant systems and accident sequences analysis is performed by developing event trees and fault trees with a seismic event of a particular ground motion as the initiating event. The component fragilities are then used to compute the frequencies of failure for different safety systems. The frequency of core melt or of radionuclide release for a given release category is calculated using the event tree and fault tree logic and by integrating over the entire range of earthquake ground motion. The result of this analysis in the form of frequencies of release categories is input into a consequence analysis model to estimate the frequencies of exceedence of different levels of damage ("risk curves"). For more details on seismic risk analysis procedures, the interested reader is referred to the recently published PRA Procedures Guide (Ref. 1).

Structural and mechanical engineers play a key role in the seismic risk analysis by developing the fragility information which together with the hazard curves is used as input to the event tree and fault tree analysis.

SEISMIC FRAGILITY

Seismic fragility of a structure or equipment is defined as the conditional frequency of its failure for a given value of the seismic response parameter (e.g., stress, moment, and spectral acceleration). Seismic fragilities are needed in a PRA to estimate the frequencies of occurrence of initiating events (e.g., large loss of coolant accident, small loss of coolant accident, and reactor pressure vessel rupture) and the failure frequencies of different mitigating systems (e.g., safety injection system, residual heat removal system, and containment spray system). As described in the PRA Procedures Guide (Ref. 1), there are two approaches for evaluating the seismic fragilities: 1) the Zion Method (Ref. 2) wherein the fragility is expressed as a function of a global ground motion parameter (e.g., peak ground acceleration) and 2) the SSMRP Method (Ref. 3) which defines the fragility in terms of a local response parameter. Discussion in this paper is mostly concentrated on the Zion Method since it includes the major aspects of the SSMRP Method of fragility definition and has been used extensively in utility-sponsored PRA studies (Refs. 4 and 5).

The objective of fragility evaluation is to estimate the peak ground motion acceleration value for which the seismic response of a given component (i.e., structural element or equipment) located at a specified point in the structure exceeds the component capacity resulting in its failure. Estimation of this ground acceleration value, called the ground acceleration capacity of the component, is accomplished using information on plant design bases, responses calculated at the design analysis stage, and as-built dimensions and material properties. Because there are many sources of variability in the estimation of this ground acceleration capacity, the component fragility is described by means of a family of fragility curves; a probability value is assigned to each curve to reflect the uncertainty in the fragility estimation (Fig. 1). The entire family of fragility curves for a component can be expressed in terms of the median ground acceleration capacity $\breve{A}$ times the product of two random variables. Thus, the ground acceleration, A, corresponding to failure is given by (Ref. 6):

$$A = \breve{A}\ \varepsilon_R\ \varepsilon_U \qquad (1)$$

in which ε_R and ε_U are random variables with unit median. They represent, respectively, the inherent randomness (frequency) about the median and the uncertainty in the median value. It is assumed that both ε_R and ε_U are lognormally distributed and their variability is expressed by their logarithmic standard deviations, ε_R and ε_U, respectively. For computational convenience, we can write

$$A = F\ A_{SSE} \qquad (2)$$

where F = factor of safety on ground acceleration capacity above the SSE level specified for design and A_{SSE} = design ground acceleration of the SSE. For structures, the factor of safety can be modeled as the product of three random variables:

$$F = F_S \; F_\mu \; F_{RS} \tag{3}$$

The strength factor F_S, represents the ratio of ultimate strength (or strength at loss-of-function) to the stress calculated for A_{SSE}. The inelastic energy absorption (ductility) factor, F_μ, accounts for the fact that an earthquake represents a limited energy source and many structures or equipment are capable of absorbing substantial amounts of energy beyond yield without loss of function.

The structure response factor, F_{RS}, recognizes that in the design-analyses, the structural response was computed using specific (generally conservative) deterministic response parameters for the structure. Because many of these parameters are random (often with a wide variability), the actual response may differ substantially from the response calculated in the design analyses for a given peak ground acceleration level.

The structure response factor, F_{RS}, is modeled as a product of factors influencing the response variability

$$F_{RS} = F_{SA} \; F_\delta \; F_M \; F_{MC} \; F_{EC} \; F_{SD} \; F_{SS} \tag{4}$$

where

F_{SA} = spectral shape factor representing the variability in ground motion and the associated ground response spectra

F_δ = damping factor representing the variability in response due to difference in actual damping and design damping

F_M = modeling factor accounting for the uncertainty in response due to modeling assumptions

F_{MC} = mode combination factor accounting for the variability in response due to the method used in combining dynamic modes of response

F_{EC} = earthquake component combination factor acounting for the variability in response due to the method used in combining the earthquake components

F_{SE} factor to reflect the reduction of seismic input with depth

F_{SS} = factor to account for the effect of soil-structure interaction.

Assuming that the random variables included in Eqs. 3 and 4 are lognormally distributed, the median and logarithmic standard deviation of F are expressed as:

$$\check{F} = \check{F}_S \, \check{F}_\mu \, \check{F}_{SA} \, \check{F}_\delta \, \check{F}_M \, \check{F}_{MC} \, \check{F}_{EC} \, \check{F}_{SD} \, \check{F}_{SS} \tag{5}$$

and

$$\beta_F = \left(\beta_S^2 + \beta_\mu^2 + \beta_{SA}^2 + ---\right)^{1/2} \tag{6}$$

The logarithmic standard deviation β_F is further divided into random variability, β_R and uncertainty β_U. The median factor of safety, $\check{F}$, is multiplied by A_{SSE} to obtain the median ground acceleration capacity, $\check{A}$.

For equipment and other components, the factor of safety is made up of three parts consisting of a capacity factor, F_C, a structure response factor, F_{RS}, and an equipment response (relative to the structure) factor, F_{RE}. Thus,

$$F = F_C \, F_{RS} \, F_{RE} \tag{7}$$

The capacity factor F_C for the equipment is the ratio of the acceleration level at which the equipment ceases to perform its intended function to the design seismic level. This acceleration level could, for example, correspond to a breaker tripping on a motor control center, excessive deflection of the control rod drive tubes, or a support failure of the steam generator. The capacity factor of the equipment may be evaluated as the product of F_S and F_μ. For active components, however, operability limits are likely to govern so that the inelastic energy absorption capacity may be smaller than for structures. The structure response factor, F_{RS}, is based on the response characteristics of the structure at the location of component support. The equipment response factor, F_{RE}, depends upon the response characteristics of the equipment and is influeced by the same variables as those listed for structure response (Eq. 4).

In a typical seismic risk study, fragility evaluation is done for about six structures and over 100 items of equipment selected on the basis of the potential impact of their failure on the core melt or radiological release. For structures such as concrete shear walls, prestressed concrete containment, steel frames, masonry walls, field-erected tanks and buried structures, the fragility parameters are estimated using plant-specific information. For major passive equipment (e.g., reactor pressure vessel, steam generator, major vessels, heat exchangers, and major piping), it is preferable to develop plant-specific fragilities using design-analysis results. For other passive equipment (e.g., piping and supports, cable trays and supports, HVAC ducting and supports, conduit, and miscellaneous vessels and heat exchangers), it is necessary to use generic fragilities because of the large quantities of such equipment. For active equipment, use of a combination of generic and plant-specific information is needed to develop fragilities. Plant-specific fragilities are developed from design reports including test data on active devices in subsystems. Generic fragilities for active equipment are developed from Corps of Engineers shock test data, qualification tests, performance in past earthquakes, and expert opinion.

Table 1 shows the fragility parameters for structures and equipment in modern nuclear power plants.

ROLE OF SEISMIC EVENTS IN PRA

In the last two years, three major PRA studies on nuclear power plants (Refs. 2, 4, and 5) have been published. Although the public risks from these plants have been estimated to be acceptably low, the contributions from seismic events to these risk estimates are noted to be significant. The major reasons for these contributions are: 1) the unique ability of an earthquake to initiate an accident and simultaneously fail a number of otherwise redundant components required for mitigating the accident, and 2) the generally large uncertainties associated with the occurrence of large earthquakes and with fragilities of structural and mechanical components. The former reason may be overcome by careful planning at the time of plant design taking the seismic effects into account. Proper arrangement of structures and equipment within the plant and promoting seismic redundancy through diversity (procuring equipment from different vendors and introducing differences in support design) are some suggested approaches. It is also essential for the designers to look beyond the SSE level in order to assure that the structures and equipment are not excessively vulnerable to larger earthquakes.

The question of large uncertainties in seismic risk estimates needs to be further explored. Recognition and explicit treatment of uncertainty is a key feature of a seismic PRA. Uncertainties exist mainly in the seismic hazard prediction and the seismic fragility evaluation. These uncertainties are quantified using available information tempered with professional judgment based on expert opinion. Some of these uncertainties (e.g., seismic fragility) may be reduced only at exorbitant cost (e.g., nonlinar time history analysis, fragility testing). Sensitivity studies have indicated that the uncertainty in the seismic hazard dominates the uncertainty in the risk estimates. Seismic hazard uncertainty cannot be reduced unless major advances in the state-of-the-art take place. Hence, large uncertainty in seismic risk estimates is a fact of life. Also, the field of seismic risk analysis is still in its infancy. Any comparison of seismic risks with those of other much-studied internal events (e.g., random failure of equipment, and operator error) has to allow for these differences. As in any probabilistic study, such comparison should be over the entire uncertainty ranges and not be limited to point estimates (i.e., mean and median). In addition, numerical differences between the risk estimates of less than a factor of five (5) may not be considered significant.

A related topic is the adequacy of data for fragility evaluation and sensitivity of the fragility model. Static and dynamic tests on the load capacity of representative structural elements (e.g., shear walls, moment-frames, and beam-columns) have been performed and reported in the literature. Data exists on the performance of similar structures and equipment in past earthquakes. Limited fragility data on active equipment is available. It is ideal to have fragility test data on all the mechanical and electrical equipment in the plant. Since fragility testing is expensive, further studies are needed to identify the critical equipment and to plan the test program so that optimal data may be acquired. Sensitivity studies on the fragility model have shown that even large variations in median capacities, β_R and β_U have minimal influence on seismic risk estimates.

Despite the large uncertainties in seismic risk estimates, seismic risk analysis serves a very useful purpose in identifying the key risk contributors, discovering excessive conservatisms and/or weaknesses in current design procedures, and channeling future research effort.

REFERENCES

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3. P. D. Smith, et al., Seismic Safety Margins Research Program, Phase I Final Report, NUREG/CR-2015, 1981.

4. Power Authority of the State of New York, Indian Point Probabilistic Safety Study, 1982.

5. Philadelphia Electric Company, Severe Accident Risk Assessment, Limerick Generating Station, April, 1983.

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TABLE 1. REPRESENTATIVE FRAGILITY PARAMETERS FOR MODERN NUCLEAR POWER PLANTS

ITEM	MEDIAN FACTOR OF SAFETY $\check{F}$	RANDOM β_R	UNCERTAINTY β_U
STRUCTURES			
Capacity			
Ultimate Strength Versus Code Allowable, F_S	1.2 - 2.5	0.06 - 0.12	0.12 - 0.18
Inelastic Energy Absorption Capability, F_μ	1.8 - 4.0	0.08 - 0.14	0.18 - 0.26
TOTAL CAPACITY FACTOR, F_C	2.5 - 6.0	0.10 - 0.18	0.22 - 0.32
Response			
Design Response Spectra	1.2 - 1.4	0.16 - 0.22	0.08 - 0.11
Damping Effects	1.2 - 1.4	0.05 - 0.10	0.05 - 0.10
Modeling Effects	1.0	0	0.12 - 0.18
Modal and Component Combination	1.0	0.10 - 0.20	0
Soil-Structure Interaction	1.1 - 1.5	0.02 - 0.06	0.10 - 0.24
TOTAL RESPONSE FACTOR, F_{RS}	1.6 - 2.8	0.20 - 0.32	0.18 - 0.33
TOTAL STRUCTURE FACTOR, F	4 - 12	0.22 - 0.37	0.28 - 0.46
MECHANICAL EQUIPMENT			
Capacity Factor, F_C	1.5 - 8.0	0.10 - 0.18	0.22 - 0.32
Building Response Factor, F_{RS}	1.6 - 2.8	0.20 - 0.32	0.18 - 0.33
Equipment Response Factor, F_{RE}	1.4 - 1.6	0.18 - 0.25	0.18 - 0.25
TOTAL MECHANICAL EQUIPMENT FACTOR, F	3.5 - 20	0.29 - 0.44	0.34 - 0.52

FIGURE 1. FRAGILITY CURVES FOR A STRUCTURE