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A Methodology for Assessing Seismic Risk in PSAs

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Abstract

This paper suggested a new framework for assessing seismic risk in PSAs. The framework used the concepts of requirement and achievement in the reliability physics. The quantified correlation which is a function of the requirement variable (hazard curve) and the achievement variable (fragility curve) results in a quantity, the unconditional frequency of exceeding a damage level. This framework can be applied to any other external safety assessment, such as Fire and Flood Risk in PSAs.

1. Introduction

The seismic Probabilistic Safety Assessments (PSAs), like any other external event PSAs, can be viewed as a problem in determining $f_k(z)$, which is the unconditional frequency of exceeding damage level z of consequence type k, resulting from potential reactor accident initiated by the seismic event. The quantity $f_k(z)$ can be expressed as

$$f_k(z) = \int \int \cdots \int_D \left\{ \sum_{j=1}^{J} f_{sj}(y) f_{klsj}(z) \right\} h(x) dx \tag{1}$$

where,

$h(x)$: Hazard density function,

x is the parameter representing harzard intensity, e.g .ground acceleration.

D denote the entire domain of x.

y is response at a component location, $y = G(x)$

$f_{sj}(y)$: Frequency of accident sequence j: joint frequency of failure of components $1,2,\cdots m_j$ in a single occurrence of the external event; it is a function of component fragility and response y (requirement parameter [1])

$f_{k|sj}(z)$: Conditional frequency of exceeding damage level z of consequence type k given the accident sequence, s_j (achievement parameter [1])

2. Seismic Hazard Curves

To get the hazard curve for a given site, the region around the site is divided into zones, each zone having a unique rate of earthquake occurrence, which is determined from the historical record. Then, for the region under consideration an attenuation law is determined which relates the ground acceleration at the site to the ground acceleration at the earthquake sources [2-3].

The seismic hazard curve (Fig. 1) is a family of complementary cumulative distribution function represents the annual frequency of earthquake exceeding a specific ground acceleration (g). The cumulative probability represents cumulative probabilities assigned to different curves.

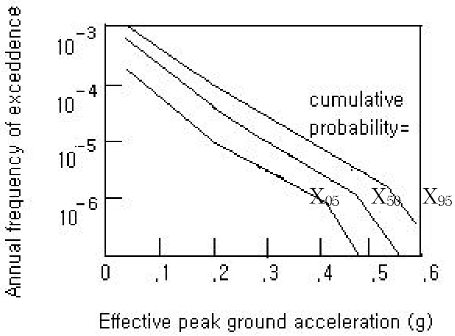

Fig. 1. Seismic hazard curves for a hypothetical site.

3. System and Structure Response Analysis

In order to calculate the failure frequencies of structures, equipment, and piping, it is necessary to obtain the seismic responses of these components to various levels of the ground motion parameter (e. g. peak ground acceleration). The output of response analysis is the frequency density function of peak response (e. g. moment, stress, and deformation) of each critical component responses.

4. Fragility Evaluation

The fragility of a components is defined as the conditional frequency of its failure given a value of the response parameter, such as stress, moment, and spectral acceleration. There are two approaches to assess the component fragility.

4.1. Seismic Capacity Method

The seismic capacity of a component is

$$C = F_C \cdot A_{SSE} \tag{2}$$

where, A_{SSE} is the fragility parameter specified for the reference earthquake (e.g. safe shutdown earthquake). F_C is the capacity factor of safety, which include the contribution of strength and inelastic energy absorption

$$F_C = F_S \cdot F_\mu \tag{3}$$

Kennedy et. al. developed a method [4]

$$C = \overline{C} \cdot \varepsilon_{C_R} \cdot \varepsilon_{C_U} \tag{4}$$

where ε_{C_R} is a random variable reflecting the inherent randomness in C and ε_{C_U} is a random variable reflecting the uncertainty in the calculation of $\overline{C}$.

$$\varepsilon_{C_R} \sim LN(0, \beta_{C_R}), \quad \varepsilon_{C_U} \sim LN(0, \beta_{C_U}) \tag{5}$$

β_{C_R} and β_{C_U} are related to the strength and inelastic properties of components. Once C, β_{C_R} and β_{C_U} are known, one can calculrate the conditional frequency of failure at any given spectral acceleration a as

$$P = P_r\{\overline{C} \cdot \varepsilon_{C_R} \cdot \varepsilon_{C_U} <= a\} \tag{6}$$

Fig. 2 is the family of fragility curves. The different Q represents uncertainty in the parameter $\overline{c}$, i.e. uncertainty represented by ε_{C_U}.

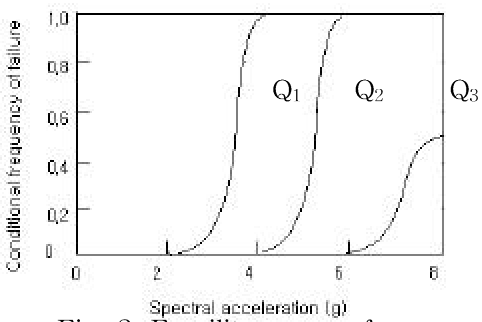

Fig. 2. Fragility curves for a component.

4.2. An Alternative Formulation of Component Fragility

In this formulation, the fragility of a component is expressed ad the conditional frequency for a given peak ground acceleration value. The ground acceleration capacity [4-5] is

$$A = \overline{A} \cdot \varepsilon_{AR} \cdot \varepsilon_{AU} \tag{7}$$

where, $\overline{A}$ is the median ground motion capacity

$$\varepsilon_{AR} \sim LN\,(0, \beta_R),\ \ \varepsilon_{AU} \sim LN\,(0, \beta_U) \tag{8}$$

$\overline{A}$, ε_{AR} and ε_{AU} are different for different components.

The fragility (i. e., the frequency of failure f′) at any nonexceedance probability level Q can be derived as

$$f' = \Phi\left[\frac{\ln\left(\frac{a}{\overline{A}}\right) - \beta_U \Phi^{-1}(Q)}{\beta_R}\right] \tag{9}$$

where, $Q = \Pr\{f < f' \mid a\}$ is the probability that the frequency f is less than f′ for a given peak ground acceleration a. Φ is unit normal and Φ^{-1} is inverse of Φ.

5. Plant System and Sequence Analysis

The major differences between the seismic and the internal events in the performance of plant systems and sequence analysis are

1) Identification of initiating events, e. g. inclusion of vessel rupture in assessing the seismic risk.

2) Increased likelihood of multiple failures of safety systems requiring a more detailed event tree development.

3) More pronounced dependencies between component responses and capacity.

6. Consequence Analysis

Consequence analysis for seismic events differs from that for internal events in that some parameters of the consequence analysis model may be influenced by the earthquake. A large earthquake may disrupt the communication network and damage the evacuation routes. It may also invalidate the assumption in internal event analysis that people will take advantage if structures in the neighbourhood of reactors in order to shelter from external irradiation by gamma rays. People may react differently in the presence of multiple hazards than if only a reactor accident is to be faced.

7. Treatment of Uncertainties

There are two major methods recommended in PRA Procedure Guide[2]. One is the method used in "Zion Probabilistic Risk Assessment"(ZPRA) [6]. The second method, developed in NRC funded research program at the Lawrence Livermore National Laboratory, is entitled the "Seismic Safety Margins Research Program"(SSMRP) [7]. These two methods differ in the level of detail in seismic response analysis. The ZPRA method relies heavily on the use of engineering judgement to supplement sparse data and limited analysis, whereas the SSMRP method emphasizes extensive components and system modeling, and detailed seismic response analysis.

Some major characteristics of both method are: ZPRA expressed the structural and equipment fragilities in terms of a ground motion parameter while SSMRP expressed fragilities in terms of local response parameters. Hence it models the plant more in detail.

The treatment of uncertainties is another major difference between the two methods. Discrete Probability Distribution (DPD) was used in ZPRA while Latin Hypercube Sampling (LHS) was used in SSMRP.

8. Final Results of a Seismic Safety Assessment

After all the previous steps, all information has been gathered and can be put into equation (1) to calculate $f_k(z)$, the frequency of exceeding damage level z of consequence type k. Both point estimate value and uncertainty analysis can be performed using eq. (1). The dependence on hazardous parameter (e. g. ground acceleration) can be integrated out after applying equation (1). An example of consequence result in terms of fatalities is shown in Fig. 3. In the figure P_i represents cumulative probabilities of each curve.

9. Conclusion

This paper suggested a framework for assessing seismic safety. The framework used the concepts of requirement and achievement in the reliability physics [1]. The quantified correlation which is a function of the requirement variable (hazard curve) and the achievement variable (fragility curve) results in a quantity, the unconditional frequency of exceeding a damage level. The development of seismic hazard curves and components fragility curves, as well as treatment of dependencies are important factors in seismic safty assessment. This framework can be applied to any external safety assessment of nuclear power plants. A good example is the NUREG-1150 seismic analysis[3] in which a method similar to SSMRP was used.

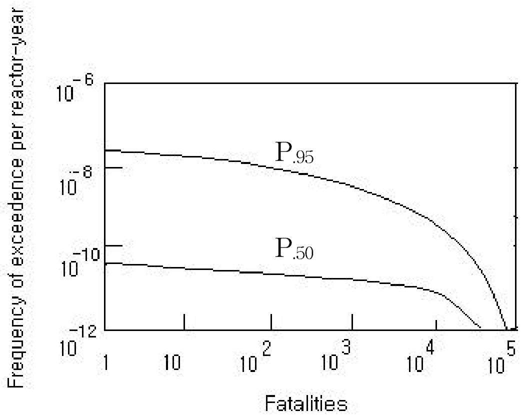

Fig. 3 Seismic risk curves.

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