The Role of Uncertainty in Seismic Risk Analysis

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INTRODUCTION

A seismic probabilistic risk assessment (PRA) of a nuclear plant must incorporate uncertainties in the seismic hazard at the plant site, dominant accident sequences leading to core damage, and structure and equipment fragilities. Some of these uncertainties are inherent in nature, while others arise from modeling assumptions and limitations in the supporting technical data. These uncertainties lead to a frequency distribution in the estimate of probability of core damage which may span three orders of magnitude or more. This range affects the credibility and usefulness of insights that otherwise might be gained from the PRA (Ravindra, et al., 1985) and may impact the inferences and regulatory decisions that may result.

LIMERICK GENERATING STATION SYSTEM MODELS

The Limerick Generating Station (LGS) was selected for purposes of examining how uncertainties due to inherent randomness, modeling assumptions, incomplete data and errors affect estimates of seismic risk. The seismic PRA included in the LGS Severe Accident Risk Assessment (SARA, 1983) is well-documented and has been subjected to a published peer review (Azarm, et al., 1984). Six dominant accident sequences leading to severe core damage that might be initiated by a seismic event were identified. The sequence TsEsUX, described by the Boolean expression (SARA, 1983):

$$\mathrm{TsEsUX} = S1 * A \tag{1}$$

in which,

$$A = S11 + S12 + S13 + S14 + S15 + S16 + \mathrm{DGr} \tag{2}$$

accounts for approximately 60% of the total core damage probability and involves mainly electrical equipment failures. The core damage event, CM, is defined as the union of the six dominant accident sequences:

$$\mathrm{CM} = S4 + S6 + S1 *[A + (S3 + \mathrm{Cr})*(S10 + \mathrm{SLCr}) + (S17 + \mathrm{Wr})] \tag{3}$$

and includes both equipment and structural failures. In Eqns 1-3, events S1 through S17 denote seismic failures of equipment and structures, as described in Table 1. Events DGr, Wr, Cr and SLCr denote random (nonseismic) failures of diesel generators, containment heat removal, scram, and standby liquid control systems, respectively.

Table 1

Limerick Generating Station Fragility Parameters

No.	Component	Cause of failure	A_m	β_R	β_U
S1	Offsite power loss	Insulator breakage	0.20	0.20	0.25
S3	Reactor internals	Shroud support	0.67	0.28	0.32
S4	Reactor enclosure structure	Shear wall failure	1.05	0.31	0.25
S6	Reactor pressure vessel	Upper support	1.25	0.28	0.22
S10	SLC tank	Wall buckle	1.33	0.27	0.19
S11	440-V bus/SG	Power circuit	1.46	0.38	0.44
S12	440-v bus/breaker	Loss of function	1.49	0.36	0.43
S13	125/250-V DC bus	Loss of function	1.49	0.36	0.43
S14	4kV bus/SG	Breaker trip	1.49	0.36	0.43
S15	Diesel generator circuit	Loss of function	1.56	0.32	0.41
S16	Diesel generator heat and vent	Structural	1.56	0.32	0.41
S17	RHR heat exchangers	Lower support	1.09	0.32	0.34

FRAGILITY MODELING

The fragility of a component is defined as its probability of failure, given a value of peak ground acceleration. A common method for describing the fragility of a component is to use a lognormal distribution with three parameters: median capacity, A_m; and logarithmic standard deviations β_R and β_U denoting, respectively, inherent (irreducible) randomness and modeling uncertainty (Kennedy and Ravindra, 1984). The fragility thus is described by a family of lognormal distributions

$$F(a) = \Phi\left(\frac{\ln(a/A_m)}{\beta_R}\right) \tag{4}$$

The multiplicity of curves arises from the uncertainty in the median, A_m, which is assumed to be described by a lognormal distribution with parameter Table 1 summarizes the seismic fragility parameters for the components identified in Eqns 1-3 (LGS SARA, Appendix B, 1983).

The observation that the strength of many components can be described as the product of several random variables lends support to the selection of the lognormal distribution. However, other fragility models also may be appropriate. One alternate fragility model can be described by a family of Weibull distributions,

$$F(a) = 1 - \exp\left[- \left(\frac{a - a_o}{\sigma} \right)^{\gamma} \right]; \; a \geq a_o \qquad (5)$$

in which a_o, σ and γ are parameters of the distribution. With the median assumed to be a lognormal random variable, one obtains a family of curves that describes uncertainty in the component fragility.

In a seismic margin study, the plant logic and fragility modeling are uncoupled from the seismic hazard analysis (Budnitz, et al., 1985). Seismic margin studies compare a parameter denoting the HCLPF, or "high confidence, low probability of failure" value of fragility, to a review ground motion intensity. The HCLPF usually is selected as the lower 5% confidence interval estimate of the 5% exclusion limit of fragility. With a lognormal fragility model, e.g., the HCLPF can be estimated as,

$$HCLPF = A_m \exp\left[-1.645\ (\beta_R + \beta_U)\right] \qquad (6)$$

in which the constant 1.645 is the percent point function of a standard normal variate at its 5%ile value.

SEISMIC HAZARD

The seismic hazard at LGS is described by a relation between peak ground acceleration and annual probability of exceeding that acceleration at the plant site. The family of curves necessary to describe uncertainty in the basic seismic hazard at the plant site was developed from postulated seismotectonic provinces (LGS SARA, Appendix A, 1983). This family of hazard curves is illustrated in Figure 1.

ANALYSIS OF UNCERTAINTY

The uncertainties in the seismic hazard analysis and fragility modeling are propagated using a Latin Hypercube technique (Iman and Conover, 1981) to determine the frequency distributions of accident sequence and core damage probabilities. With sufficient repetition, a family of sequence or plant level fragilities can be generated which can be used to determine a plant level HCLPF, if desired. The plant level fragilities subsequently are (randomly) convolved with the seismic hazard curves, resulting in a series of accident sequence probability estimates. These accident sequence probabilities are rank ordered and plotted to describe the frequency distribution of core damage probability. The 5%ile, 50%ile, 95%ile, and mean sequence of core damage probability estimates are taken from this frequency distribution.

Base Case

The component fragilities are modeled by lognormal distributions and component failures are assumed to be statistically independent. Figure 2 illustrates the frequency distribution for the annual probability, P(TsEsUX). The results are summarized in Table 2 for sequences TsEsUX and CM. The accident sequence frequency distributions for all sequences are strongly positively skewed. The estimated mean core damage probability for TsEsUX corresponds approximately to the 75th percentile of the frequency distribution (see Figure 2) and, as indicated in Table 2, is nearly an order of magnitude above the median (50%ile) estimate. This range in the frequency distribution is a reflection of the uncertainties in the fragility modeling and in the seismic hazard analysis.

Fragility Modeling

The sensitivity of the analysis to the choice of a particular fragility model is evaluated by assuming that the fragility family is described by a family of two-parameter Weibull distributions (i.e., $a_o = 0$ in Equation 5). The Weibull parameters were determined assuming that the medians and logarithmic standard deviations are equal to those in Table 1. Table 2 compares the results obtained for sequences TsEsUX and CM using the Weibull and lognormal fragility models. The choice of fragility model has a pronounced effect on the 5-percentile value of risk (a factor of 20) but not on the 95-percentile value (a factor of about 2). When the Weibull model is used, the mean values of P(TsEsUX) and P(CM) increase by a factor of about 3 while the HCLPF decreases by a factor of one-third. This decrease carries with it some implications for the selection of fragility models for seismic margin studies (Budnitz, et al., 1985).

Table 2

Fragility Modeling Assumptions

Sequence	Model	HCLPF	5%	50%	95%	Mean
TsEsUX	LN	0.33g	1.8-8	5.0-7	2.0-5	3.4-6
	W	0.23g	3.6-7	6.1-6	3.9-5	1.1-5
CM	LN	0.32g	2.7-8	7.2-7	2.4-5	5.0-6
	W	0.21g	7.9-7	1.3-5	5.2-5	1.7-5

Dependent Failures

Dependence in component failures may be important when the initiating event, such as an earthquake, is external to the plant and may affect many systems simultaneously. To examine the potential significance of dependence, two cases were considered using sequence TsEsUX. In the first case, it was assumed that the fragilities of: (1) components S11, S12, S13 and S14, which are all located in the reactor enclosure, are perfectly correlated; (2) components S15 and S16, located in the diesel generator building are perfectly correlated; and (3) components in different buildings are statistically independent. In the second case, fragilities of all components in TsEsUX were assumed to be perfectly correlated irrespective of their location in the plant. The results of these analyses are compared to the base case in Table 3. The fractiles of P(TsEsUX) and the HCLPF are relatively unaffected by correlation in component capacities for the sequences considered herein.

Table 3

Effect of Correlation on P(TsEsUX)

Case	HCLPF	5%	50%	95%	Mean
Independent (base)	0.33g	1.8-8	5.0-7	2.0-5	3.4-6
Correlated (bldg)	0.34g	2.0-8	4.5-7	1.7-5	3.0-6
Correlated (plant)	0.32g	2.1-8	4.3-7	1.6-5	2.9-6

Seismic Hazard

The sensitivity of the core damage probabilities to the seismic hazard modeling was examined by collapsing the seismic hazard family in Figure 1 into the single curve defined by the "Decollement" model. The frequency distribution of core damage probability then reflects only uncertainty in the component fragility modeling. Table 4 summarizes the results of this analysis for core damage sequences TsEsUX and CM. As the uncertainty in the seismic hazard is collapsed into a single hazard curve, the spread in core damage probability is reduced from three (or more) to less than one order of magnitude.

Table 4

Role of Uncertainty in Basic Seismic Hazard

Sequence	Seismic	5%	50%	95%	Mean
TxEsUX	Base	1.8-8	5.0-7	2.0-5	3.4-6
	Dec.	4.7-6	1.1-5	2.6-5	1.3-5
CM	Base	2.7-8	7.2-7	2.4-5	5.0-6
	Dec.	7.5-6	1.9-5	2.8-5	1.8-5

CONCLUDING REMARKS

This examination of estimated earthquake-induced core damage probabilities for a typical plant in the Eastern United States shows that these probabilities, expressed in the form of a frequency distribution, are affected most significantly by how the basic seismic hazard at the plant site is modeled. Fragility modeling assumptions, in contrast, have less impact on risk. However, in a seismic margins study, where the fragility modeling and plant logic are uncoupled from the seismic hazard analysis, the fragility modeling may become relatively more important. Additional research in fragility modeling would be desirable for use in seismic margin reviews.

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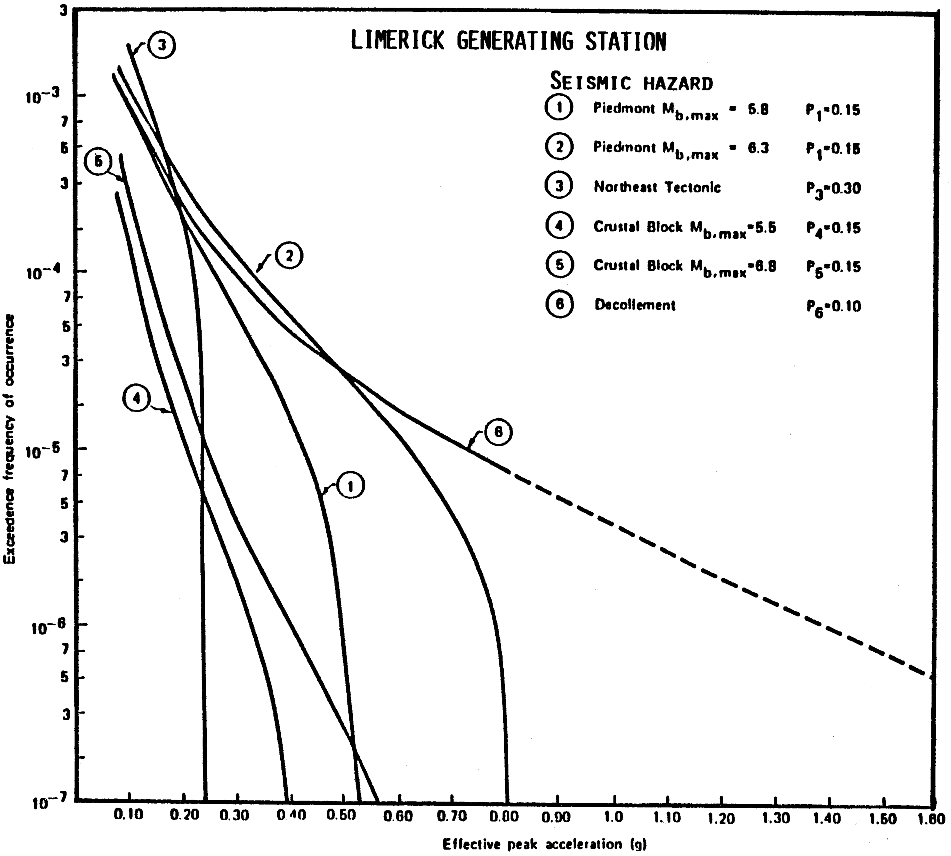

Figure 1. Seismic Hazard at Limerick Generating Station Site (from SARA, Appendix A, 1983)

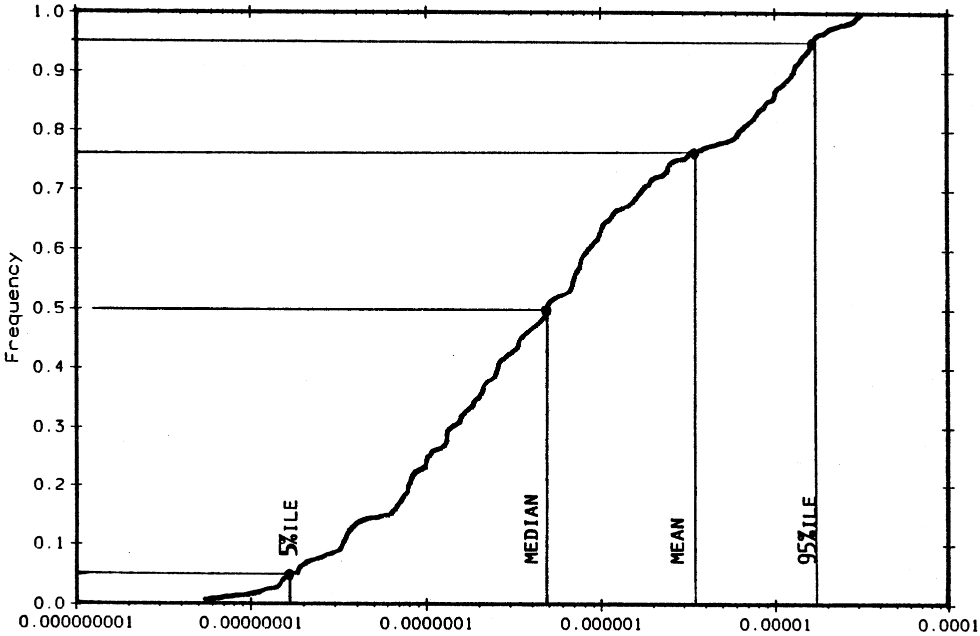

Figure 2. Core Damage Frequency Distribution for P(TsEsUX)