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SUMMARY

The Seismic Safety Margins Research Program (SSMRP) is a NRC-funded, multi-year program conducted by Lawrence Livermore National Laboratory (LLNL). One of the goals of the program is to develop a complete, fully coupled analysis procedure (including methods and computer codes) for estimating the risk of an earthquake-caused radioactive release from a commercial nuclear power plant. The analysis procedure is based upon a state-of-the-art evaluation of the current seismic analysis and design process and explicitly includes the uncertainties inherent in such a process. The results will be used to improve seismic licensing requirements for nuclear power plants.

In Phase I, we successfully developed and demonstrated a probabilistic computational procedure for the seismic safety assessment. In Phase II, we ran sensitivity studies, improved our codes and models, and completed our analysis of the Zion plant. We also constructed confidence bounds for the probabilities of radioactive release at Zion.

The local site amplification was found to have a significant effect on structural response as well as being a major source of modeling uncertainty. A study of local site effect on structural response at Zion was performed using the time histories tailored for that site and comparing with responses based on non-site-specific time histories.

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In order to put confidence bounds on the final radioactive risk probabilities, it is necessary to separate the uncertainty of the input parameters into components due to random (irreducible) and modeling (reducible by further testing) uncertainty, and then propagate these uncertainties separately through the analysis. To propagate them from input to responses (which are then used for the final risk calculations) we used sampling and repeated calculations. This approach is described, and comparisons are made with earlier approaches.

In a study of sensitivity of responses to the input parameters, we used regression analysis to develop a response surface approximation to the full dynamic calculation. The logarithm of response (acceleration or piping moment) was modeled as a linear function of the logarithms of the input parameters, with one term quadratic in the logarithm of piping frequency. Results and quality of approximation are described. From the response surface model we computed (1) response sensitivities to inputs and (2) how the response uncertainty arises from the input uncertainties. This in effect explains for the greater part how the input parameter uncertainties propagate through the response calculation model.

1. Introduction

The Seismic Safety Margins Research Program (SSMRP) is an US NRC-funded, multi-year program conducted by Lawrence Livermore National Laboratory (LLNL). One of the goals of the program is to develop a complete, fully coupled analysis procedure for estimating the risk of an earthquake-caused radioactive release from a commercial nuclear power plant. In Phase I (completed January 1981), we successfully developed and demonstrated a probabilistic computational procedure for seismic safety assessment--the demonstration calculations were performed for the Zion nuclear power plant. In Phase II (presently completed), improvements were made to the methodology and models and a final seismic risk analysis was performed on the Zion nuclear power plant. One major improvement of the methodology was the calculation of confidence intervals on the results--Ref. 1 details these. Other changes in seismic response entail improvements in modeling [2,3] and completion of subsystem and piping models for the auxiliary feedwater system.

Seismic risk analysis can be considered in five steps: seismic hazard characterization (seismic hazard curve, frequency characteristics of the motion); seismic response of structures and components; structure and component failure descriptions; plant logic models (fault trees and event trees); and probabilistic failure and release calculations. The present paper deal principally with the seismic response of structures and components and, in particular, (1) separate treatment of random and modeling uncertainties in the inputs and in the responses; and (2) the effect of one modeling uncertainty issue (the local site effects).

2. SSMRP Seismic Response Calculations

In the SSMRP, seismic responses are calculated by the computer program SMACS [4] which links together seismic input, SSI, major structure response, and subsystem response. Time history analysis is performed which is intended to be as realistic as possible. In addition, uncertainties are treated explicitly in the response calculations. In the seismic input, uncertainties are introduced through ensembles of time histories; in SSI, the mechanism to include uncertainty is variability in soil shear modulus and material damping in the soil; in the major structures and subsystems, variations in frequencies and modal damping properties are the mechanisms. Hence, a limited number of input parameters are used to incorporate uncertainty (of both random and modeling types) into the calculations.

An additional point is that the seismic response and systems analyses are performed for discretized intervals of the seismic hazard curve and the hazard curve is then convolved with these conditional results as a final step in the process. In all SSMRP Zion analyses, the seismic hazard curve was discretized into six increments of peak ground acceleration. The majority of these analyses included site response calculations for the Zion site; hence, the six increments were 0.06-0.10g, 0.10-0.20g, 0.20-0.32g, 0.32-0.42g, 0.42-0.53g, and 0.53-0.69g as measured on a hypothetical rock outcrop.

3. Calculation of Confidence Intervals

In seismic risk analyses, it is helpful to distinguish between two types of uncertainty--random uncertainty and modeling uncertainty--and propagate each through the analysis separately. The first, random uncertainty, is fundamental to the phenomenon being represented. It is also irreducible given present state-of-the-art understanding and modeling of the phenomenon. The second type, modeling uncertainty, reflects incomplete knowledge of the model itself. Modeling uncertainty, in many cases, can be reduced within present limits of the state-of-the-art by improved analytical models, tests, etc. Although general agreement exists that separating and identifying the two types of uncertainty is essential to a practical seismic risk analysis, judgment plays a paramount role in the process. Also, future improvements in the state-of-the-art of representing a phenomenon may reduce uncertainty and/or may shift a component of uncertainty from being categorized as random to being categorized as modeling. The combination of random and modeling uncertainty yields total uncertainty.

The importance of separating random and modeling uncertainty in a seismic risk analysis relates to their effect on the result--random uncertainty leads to a point estimate of the end item of interest (e.g., core melt frequency); whereas treating modeling uncertainty leads to a probability distribution on this end item from which confidence intervals may be established. When random and modeling uncertainty are combined a priori and the seismic risk analysis performed based on this total uncertainty, a higher point estimate is obtained. In the SSMRP analysis, uncertainty in the seismic hazard characterization, seismic response of structures and components, and structure and component failure descriptions was separated into random and modeling uncertainty; their combination reflects total uncertainty. Three sets of analyses were performed:

- o Random variability only which may be denoted best estimate analysis.
- o Total variability which may be interpreted as a bound.
- o Random/modeling uncertainty propagated separately which yields confidence intervals on end items of interest.

Selected results from the first two sets of analyses are presented here. The computational procedure to treat random and modeling uncertainty in the seismic response of structures and components is also described. Additional discussion of the combination of response results with the seismic hazard characterization and fragility descriptions is contained in Ref. 1. Results in the form of probability distributions on frequency of core melt and release category probabilities are included in Ref. 1.

Two aspects of treating random and modeling uncertainty are discussed here: the computational procedure which permits each type of uncertainty to be propagated separately; and the separation of random and modeling uncertainty for the seismic response calculations.

Computational procedure. The computational procedure to isolate and propagate random and modeling uncertainties separately is a two loop process--the outer loop treats modeling uncertainty and the inner loop treats random uncertainty. We restrict our discussion to the seismic response of structures and components, however, the two loop process is used in the systems analysis also, where uncertainty in the seismic hazard characterization and the fragility descriptions is included. [1] The procedure involves the following steps:

- o Identify input parameters which model uncertainty. Section 2 itemized the parameters for the seismic response calculations.
- o Assign uncertainty to these input parameters. Random uncertainty is represented by a probability distribution on the parameter value. Modeling uncertainty is represented by a probability distribution on the mean value in the parameter's distribution.

- o Construct two experimental designs--one for the inner loop which used 20 earthquake simulations for each discretized acceleration range and one for the outer loop which used 14 simulations. Latin hypercube experimental designs were used in each instance.
- o Perform seismic response analyses and transmit results to systems analysis.

For the cases of random uncertainty only and total uncertainty no outer loop exists and the inner loop contains 30 earthquake simulations for each interval of the seismic hazard curve.

Random and modeling uncertainty. Table I tabulates the separation of total uncertainty into random and modeing components for the input parameters of the seismic response calculations. The values representing total uncertainty are identical to those of SSMRP Phase I. Lognormal distributions were assumed for the input parameters; coefficients of variation (COV) are shown in Table I. The variations in Table I apply to each of the six acceleration ranges of the discretized seismic hazard curve. The median values of excitation-sensitive parameters, such as soil shear modulus and damping, and subsystem and structural damping, change with each acceleration range. The separation of random and modeling uncertainty was accomplished by examining in detail uncertainty attributed to random sources. A two-fold approach was taken:

- o Examine recorded data of the input parameters themselves (soil shear modulus and damping, structure and subsystem frequency and damping) and assign COVs accounting for the range of excitations and the phenomenon represented by the parameter. An example is soil shear modulus. Ref. 5 recommends a range of COV values of 0.5-1.0 for soil "stress-strain behavior." Ref. 6 contains a series of data recorded for a variety of sites and soil conditions with COVs in the range of 0.5 and above. Undoubtedly the former estimate contains random and modeling uncertinaty whereas modeling uncertainty in the latter estimate should be less. A COV of 0.4 for soil shear modulus was used in the analysis to represent random uncertainty. Similar estimates were made for the remaining input parameters.

o Perform preliminary response calculations for the selected variations and compare the calculated response distributions with recorded data. One of the only sources of recorded response data for multiple earthquakes on a structure and on equipment and piping supported on the structure is reported by Shibata [7] for the Chiba Field Station. Table II tabulates results taken from Ref. 7. Note this data is normalized--horizontal response is normalized by peak ground acceleration in the horizontal direction and vertical response by peak ground acceleration in the vertical direction. The range of COVs for response is approximately 0.3 to 0.7. These values can be interpreted as due to random sources of uncertainty in the seismic input, SSI, structure, and subsystem characteristics. Figure 1 shows a summary of response variability for two of the six levels of peak acceleration for which our seismic risk analysis was performed. These results are for random variability only and the responses have been normalized by their input peak horizontal ground acceleration to be compatible with the Shibata data. Variability is characterized by "beta", the standard deviation of the logarithms of the data. Beta values are approximately equal to COVs for values less than 0.5 with increasing deviations above 0.5. For our purposes, they may be considered comparable. Each plot summarized response information sorted by type--responses 1-4 free-field accelerations (peak and spectral), responses 29-60 structure acceleration (peak and spectral), responses 71-218 subsystem peak accelerations, and responses 229-373 subsystem moments. Subsystem response beta values range from approximately 0.2 to 0.7 in general for the six ranges of acceleration, which is comparable to those of Shibata's data. Note that the Chiba Field Station structure and subsystems are relatively simple in comparison with the Zion structures and piping systems and some variation would be expected. Also, beta values obviously vary substantially relative to location, subsystem characteristics, etc.

One example is the very low values of betas for responses 122-129 which are accelerations on a piping system in the Zion crib house whose excitation is not amplified through its supporting structure.

To assess the effect of input parameter variability on seismic response variability and to provide seismic responses for the systems analysis, SMACS analyses for the total uncertainty condition were performed. Figure 2 shows the effect on the response uncertainty descriptor beta, plotted as a ratio of the response beta for total uncertainty to response beta for random only. The effect of increasing the variability of the input parameters as shown in Table I is to increase the betas of response by 1.2-2 times.

4. Local Site Amplification

One major source of modeling uncertainty which we did not treat with our inner/outer loop computatonal procedure was the phenomenon of local site amplification for the Zion site. Amplification of free-field ground motion by a shallow soil site such as Zion (110 ft. of soil over bedrock) can have a profound effect on the seismic hazard curve and on the free-field acceleration time histories. Modeling of site amplification is discussed in some detail in Ref. 3. For the Zion analysis, local site amplification was modeled explicitly in generation of the seismic hazard curve and in the seismic response calculations. This represented our best estimate of the effects of local site amplification; however, we recognize the large uncertainty in all such models for the present state-of-the-art. The procedure was to define the free-field ground motion and associated seismic hazard curve on a hypothetical rock outcrop. This seismic hazard curve was developed from a ground motion model with that uncertainty removed which was thought to be due to differences in site conditions at which ground motion data was recorded. The time histories were then propagated through a linear viscoelastic soil model of the Zion site with soil properties consistent with those of the SSI model in the experimental design. The resulting soil free-field time histories were used in the SMACS analyses.

To assess the effect of local site amplification on seismic responses and seismic risk, a second analysis was performed with free-field acceleration time histories uncorrected for local site effects and for a seismic hazard curve developed for a generic site condition, i.e., developed from all data recorded on rock and soil. Two comparisons are presented here. The first is seismic responses. Fig. 3 shows the ratios of median responses for two intervals of the seismic hazard curves. Note the basis for comparable intervals here is equal probability of occurrence of the earthquakes. For the two differing seismic hazard curves, intervals of equal probability of occurrence lead to earthquake with different peak accelerations. Figure 3a shows a comparison of median responses for acceleration level 2--peak surface accelerations of 0.17-0.48g with local site effects and 0.11-0.22g without local site effects. In this case, median values of free-field, foundation, structure, and subsystem accelerations are 40% higher with local site effects for the same probability of occurrence and subsystem moments are 10% higher. Figure 3b shows similar results for acceleration level 4--peak surface acceleration of 0.49-1.1g with local site effects and 0.53-0.69g without. For this case, median responses are similar and the case with local site effects exceeds without by approximately 5%. Hence, at high probabilities of occurrence, large differences in response are observed whereas for rarer events the differences are less pronounced. One method of assimilating this information is examining the probability of core melt frequency for the two modeling approaches. The results of such a comparison includes differences in the seismic hazard curves and in the seismic responses. The core melt frequency with local site effects was 7.6×10^{-6} per year and without local site effects was 2.2×10^{-6} per year. [1] Hence, modeling uncertainty associated with local site amplification leads to an uncertainty in core melt frequency of 5.4×10^{-6} per year.

5. References

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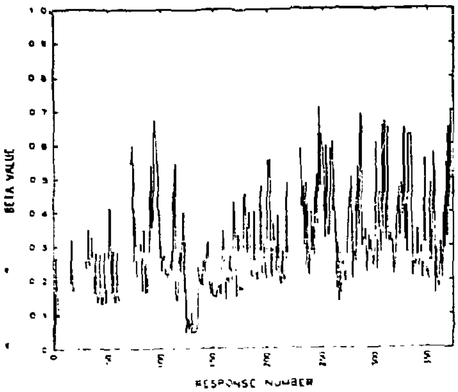
Table 1. Uncertainty in the normalized input parameters. Values of the coefficients of variation (COV) ar given.

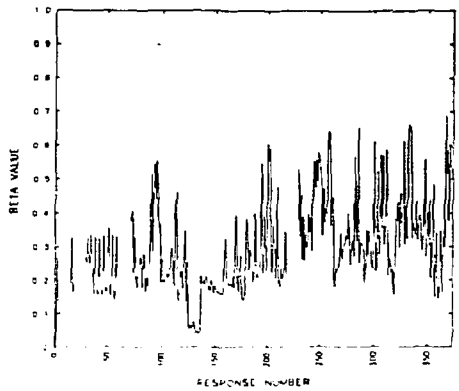
Parameters	Total Uncertainty COV	Random Uncertainty COV	Modeling Uncertainty COV
Soil shear modulus	0.7	0.4	0.57
Soil damping	1.0	0.5	0.866
Structure frequency	0.5	0.25	0.43
Structure damping	0.7	0.35	0.606
Subsystem frequency	0.5	0.25	0.43
Subsystem damping	0.7	0.35	0.606

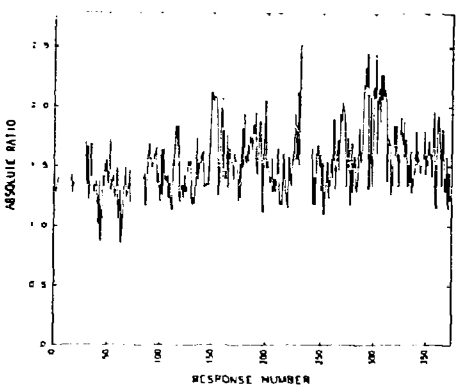
Table 2. Summary of Shibata's data (Ref. 7) on coefficient of variation of normalized response structure/piping/equipment at the Chiba Field Station due to natural earthquakes. North-south data was normalized by peak acceleration in north-south direction. Vertical data was normalized by vertical peak ground acceleration.

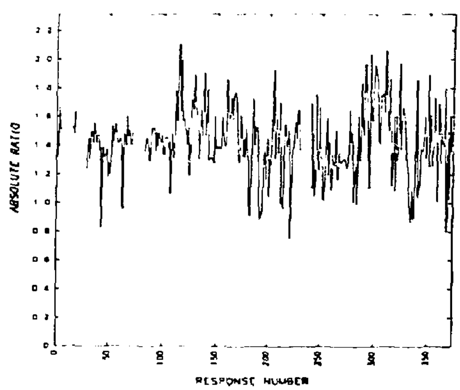
Location	Number of Earthquakes	Coefficient of Variation Cov[5]
North-South		
Hanged tank[1]	77	0.492 (0.262)
Piping[1]	57	0.345
Saddle tank[1]	58	0.538
Self-standing tank[1]	58	0.248
Frame structure[2]	21	0.30
Horizontal tank[2]	21	0.33
Vertical		
Foundation[3]	12	0.136
Hanged tank[3]	16	0.39
Piping[3]	17	0.35
Horizontal tank[3]	9	0.70
Frame structure[4]	15	0.45

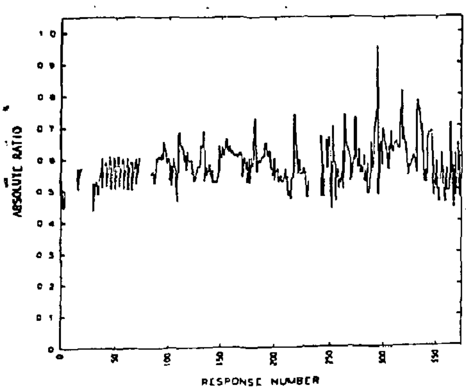
Notes:
1. From Table 3(a) of Ref. 7
2. Estimated from Fig. 6 of Ref. 7
3. From Table 3(b) of Ref. 7
4. Estimated from Fig. 7 of Ref. 7
() Abnormal data omitted











RATIO OF MEDIANS, W/OLSE VS W/LSE, LEVEL 4

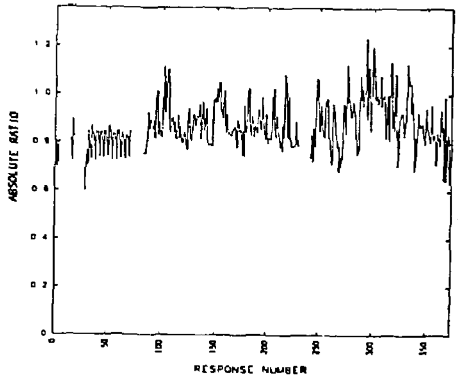


Figure Captions

1 Summary of response beta for random only: a) for earthquake level 1, peak ground accelerations ranging from 0.06 to 0.1g on the rock outcrop; b) for earthquake level 5, accelerations ranging from 0.42g to 0.53g.

2 Ratio of the response beta for total uncertainty to response beta for random only: a) for earthquake level 2; b) for earthquake level 5.

3 The effect of local site conditions: ratio of median response without local site effect to median response with local site effect: a) for earthquake level 2; b) for earthquake level 4.