Development of the Seismic Input for Use in the Seismic Safety Margins Research Program

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SUMMARY

To evaluate the conservatism in present reactor seismic design techniques, a probabilistic based systems model is being constructed. This model will be used to estimate the probability of a seismically induced radioactive release. The systems model requires as input a probabilistic definition of the seismic hazard in suitable form for a site located in the eastern part of the United States. Establishment of the seismic hazard at a site is made in terms of the annual probability of exceeding a given ground motion parameter. Difficulties arise in the probabilistic assessment of seismic input parameters because of the significant uncertainties associated with the earthquake occurrence model and the ground motion model including attenuation relationships. We describe an overview of our approach to deal with these uncertainties and evaluate the seismic hazard at a site located in the eastern United States. In particular, we discuss our experience in the use of expert opinion to supplement inadequate data sets to arrive at reliable estimates of exceeding various levels of ground motion. Some examples are provided to illustrate our approach.

[1]This work was supported by the United States Nuclear Regulatory Commission under a Memorandum of Understanding with the United States Department of Energy.

1. Introduction

The Seismic Safety Margins Research Program [1] is a multiyear program being carried out at the Lawrence Livermore National Laboratory, and funded by the U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research. The major objectives are to develop an improved deterministic seismic safety design methodology and to develop a procedure to perform seismic risk assessments for nuclear facilities. The approach to achieve these objectives is to develop probabilistic methodology that more realistically estimates the behavior of nuclear power plants during an earthquake. In the first phase of this program, this methodology has been developed for a specific nuclear power plant, Zion I, located a little north of Chicago, Illinois. The developed model is being used to perform sensitivity studies to gain engineering insights into seismic safety requirements. The failure probability of structures, systems, and components and the probability of radioactive releases over a range of earthquake levels will be used to help determine priorities for the future research.

The overall probabilistic based system model used in the SSMRP contains various methodologies. They are seismic input, site response, soil-structure interaction (SSI), structure and subsystem response, combination of seismic and nonseismic loads, failure assessment, event/fault tree and system analysis.

One of the unique features of the overall program is the manner in which the seismic hazard is incorporated into the overall systems model. Time histories are developed and input directly into the SSI model. These time histories will be characterized by peak acceleration and a spectral shape parameter; however, for Phase I they have been characterized only by peak acceleration. Statistics of structural response have been developed from these time histories conditional on the occurrence of a given peak acceleration. The probability of occurrence of a given peak acceleration and the statistics of structural response are input into the overall systems model along with component fragilities and event/fault trees to compute the probability of release of radioactive matter. The approach used for the overall systems model is described in Ref. [2].

It is important that the uncertainty in the definition of the seismic hazard be reduced to a minimum because all system failures are conditional on the probability of a given peak acceleration and spectral shape parameter pair. Clearly it will not be simple to reduce the uncertainty in our estimates of the seismic hazard. One of the main goals of Phase I of our program is to attempt to bound the uncertainty associated with the key parameter of the hazard model. We then will determine which parameters have the most influence on the risk. This will set the necessary research goals for Phase II of the program.

In this paper we deal with the probabilistic development of the seismic input and the uncertainty associated with our estimates of the seismic ground motion at the Zion site. We also outline our approach to bounding and assessing the uncertainty in the various parameters which govern the seismic hazard.

2. Overall Approach

Probabilistic estimation of seismic load parameters has received much attention recently. Once source release, transmission patterns, and site effects can be defined,

estimates of the probability of exceeding different levels of any ground motion parameter can be generated. Various procedures are available for evaluating seismic exposure Ref. [3]. Typically, these procedures consist of three parts:

- A source seismicity model.
- A ground motion generation model.
- An exposure evaluation model.

The difference between the procedures lies in the assumptions used in developing the model and in the methodology for applying the model. The assumptions and methodology used for some procedures may not adequately model the physical processes of earthquake occurrences and attenuation and, consequently, exposure estimates may differ significantly.

The key elements that must be included in the source seismicity model are:

- Earthquake source regions. This defines where the earthquakes occur relative to the site. For the eastern U.S., because it is a region of low seismicity, it is not possible to correlate earthquakes with faults, hence, the earthquakes are assumed to occur randomly over large regions.

- Earthquake occurrence model. This defines the distribution of earthquakes in time and size (magnitude or intensity) for each source region.

The key elements that must be included in the ground motion model are:

- Relation between the earthquake size parameter and its potential to generate ground shaking.

- Attenuation of the ground motion from the earthquake's location to the site.

- Effect of the site's local geology on the ground motion.

- Spatial variation of the ground motion over the site and with depth.

These key parameters can be divided into two groups: 1) parameters for which no conceptual models or little direct data are available, e.g., source zones, largest earthquake in a source zone; 2) parameters for which conceptual models and/or sufficient data are available; e.g., parameters of the occurrence model, earthquake source models, attenuation of seismic energy. To bound/assess the uncertainty associated with the first group we must resort to using expert opinion and sensitivity studies. To bound/assess the uncertainty from the second group we are using computer simulation, a variety of statistical approaches and expert opinion.

Typical exposure evaluation models have the major limitation that estimates for only one ground motion parameter at a time can be made. This is a significant limitation for our purposes as we need time histories. For this reason we used a Monte Carlo approach.

To overcome the difficulty of needing a large number of trials we have modified the Monte Carlo approach. These modifications are discussed in a later section of this paper.

As pointed out above, certain key elements of source seismicity model can only be obtained by expert opinion. For other aspects there is some data and/or theory which can also be used, however, as discussed in Ref. [4 and 5], it is still very useful to incorporate expert opinion into all facets of our model. Considerable care must be taken when using expert opinion so that opinion, data and theory are properly weighted, and to insure that one is not lulled into the feeling our true state of knowledge is more certain than it in fact is. Although we are still in the process of exploring the best ways to make use of expert opinion in our analysis, we have made considerable progress. Some of the key features of our approach to obtain and use expert opinion are:

- Appropriate panels of experts have been formed.
- Detailed written questionnaires were used requiring several days to complete.
- Experts were generally being paid.
- Follow-up meetings/questionnaires were held.
- The input from each expert was used in a separate hazard analysis to gain insight into the uncertainty in the analysis as well as guidance to the best way to obtain a synthesis of the major results.

At this time three panels have been formed. The members of one panel are ten well known geoscientists knowledgeable about the eastern U.S. Each panel member was sent a questionnaire which dealt with the overall regional characteristics of the eastern U.S. Five areas were covered: 1) geometry and probability of existence of the earthquake source regions; 2) largest earthquake that could occur in each region; 3) earthquake occurrence model and parameters of model; 4) earthquake source models and attenuation; and 5) self ranking. See Ref. [4] for the highlights of our questionnaire. The experts responses were then encoded along with other data and studies. The seismic hazard was then developed for a number of eastern sites including the Zion site. A number of sites were examined to insure that the Zion site is reasonably generic. See Ref. [5] for complete details.

The second panel that we have formed was a review panel which had four members--two geoscientists and two engineering statisticians. The purpose of the review panel was to provide a detailed peer review of our first questionnaire; our initial encoding and incorporation of these results to make up our source seismicity models; and hazard evaluation. The panel provided us with suggestions for improvements which we incorporated into our final model.

The third panel was formed to evaluate various ground motion models and their attenuation, Ref. [5]. This panel consisting of two noted seismologists and three experienced geotechnical engineers, looked into the problem of correcting the strong ground motion data base for the lower attenuation in the eastern U.S. and attempted to reduce the uncertainty in the relation between earthquake magnitude, distance, and ground motion parameters of interest.

4. Data Analysis and Modeling

As noted above, sufficient data and/or theoretical models exist to help assess some of the key elements which are included in the analysis. Thus, in addition to our effort in obtaining and incorporting expert opinion, a number of specific studies have been undertaken to supplement/improve our current understanding in several areas. These include: (i) a strong earthquake ground motion data gathering/verification task; (ii) a task using the computer to simulate the earthquake rupture and (iii) several data analysis tasks.

In the space available we can only discuss a few key items. See Ref. [1] for details about all of the ongoing tasks. Here we want to discuss our computer simulation study which will allow us to model the significant differences in the earth's structure and Q between eastern and western U.S., and such earthquake parameters as: (i) stress drop (both dynamic and static); (ii) length and width of the rupture zone; (iii) rupture velocity and focusing and (iv) depth of energy release. The intent of this study is to assess the relative effect each of these parameters have on the ground motion at the Zion site for a range of the parameters and epicentral distances. Some parameters (Q), e.g., are known to be significantly different in the eastern U.S. as compared to the western U.S. For other parameters there is some potential that they are systematically different than for the set of earthquakes which make up the strong motion data set. We can use the computed relative difference in the ground motion between western and eastern U.S. and expert opinion to develop appropriate bounds for the ground motion from earthquakes in the eastern U.S.

Another importnt aspect of the earthquake simulation study will be to compute the spatial variation of the earthquake ground motion over the site. This variation can play an important role in the soil structure interaction analysis that was performed, Ref. [6]. Very little data exists from earthquakes which can be used to determine the variation of ground motion over the area the size of the foundation mat of a large nuclear power plant. This variation is a function of the earth's structure between the site and earthquake fault, the depth of the earthquake and mechanism of the earthquake. For Phase I, our analysis shows that the spatial variation of the ground motion over the Zion site is not an important consideration as the site has a very high apparant wave velocity.

We are exploring the use of ARMA models to develop time series for the earthquakes in our exposure evaluation model for input into the SSI analysis. Our first study, Ref. [7], indicates that the use of ARMA modeling is potentially very useful. Continued effort is ongoing in this area.

5. Exposure Evaluation Model

The exposure evaluation model we are going to use is a second generation improvement on the model discussed in Ref. [3]. A number of significant improvements have been incorporated and discussed in detail in Ref. [5]. First, the uncertainty of the seismic source regions are included by having a number of different models (one from each expert) and allowing some of the seismicity to be random over a larger background region. The number of earthquakes allowed to migrate is related to the probability of existence of each expert the various source regions. Secondly, we have incorporated not only the

uncertainty in the earthquake occurrence model; but, also the uncertainty of the largest earthquake that can occur in each source region to generate time histories. The third major improvement is the introduction of a Monte Carlo simulation [8]. First, on the basis of the characteristics of the various seismic zones and the information developed for the occurrence model, each ring Z_i at a distance R_i from the site was described by an earthquake occurrence frequency λ_{ij} for each magnitude range $M_j \pm \Delta M_j/2$. Secondly, for each magnitude-distance pair, we next introduced a Monte Carlo simulation of N_{ij} trials, where N_{ij} is proportional to λ_{ij}. Each trial produced a peak spectral acceleration and spectral shape, selected from lognormal distributions corresponding to R_i and M_j. The distributions were based on our ground motion model. From the many such spectra generated, we randomly selected 30 in each of six peak acceleration ranges (0.15-0.30g, 0.30-0.45g, 0.45-0.60g, 0.60-0.75g, 0.75-0.98g, and >0.98g). Finally, time histories were generated for each response spectrum using the program SIMQ.

6. Initial Results and Summary

We have completed initial studies and our results indicate the use of expert opinion to supplement the lack of data is a viable approach. Although very significant differences of opinion exists about most of the parameters of the model, the overall net effect on the estimate of the seismic hazard is much less. This is illustrated by Fig. 1, which shows one part of our preliminary estimates of the seismic hazard at the Zion site. Shown in Fig. 1 is the 1000 year return period for the uniform hazard relative velocity spectrum for 5% damping. It is seen, for the shorter period range of interest for nuclear power plant seismic analysis, that there is only about a factor of two variation between all experts.

Some of our results include: 1) there are significant differences among experts as to the seismic zonation of the eastern U.S.; 2) the significance of the uncertainty in seismic zonation is regionally dependent and causes the peak ground acceleration to vary 15 to 25%; 3) different ground motion models lead to large variations in the peak ground acceleration and the spectral shape, and the uncertainty associated with each ground motion model is also an important parameter; and 4) there is significant variation among the experts with regard to the largest earthquake that can occur in each seismic zone, and this variation was on the order of 2 to 3 in magnitude units, leading to significant variations in the seismic hazard at the site in question. Additionaly, we found the uncertainty due to the different earthquake occurrence models increases with decreasing probability of exceedance, and this is illustrated in Fig. 2.

In summary, the unique features of our approach are: 1) our methodology to develop the seismic hazard makes extensive use of expert opinion, available data and modeling studies; 2) we model the uncertainties in the boundaries of the source regions, earthquake occurrence model, largest earthquake for each source region, and attenuation of seismic energy; 3) the seismic hazard for use in the overall systems model will be given by two parameters which define the spectral level and shape and 4) the structural response statistics are developed from appropriate sets of time histories. The same sets are used to develop the seismic hazard curve.

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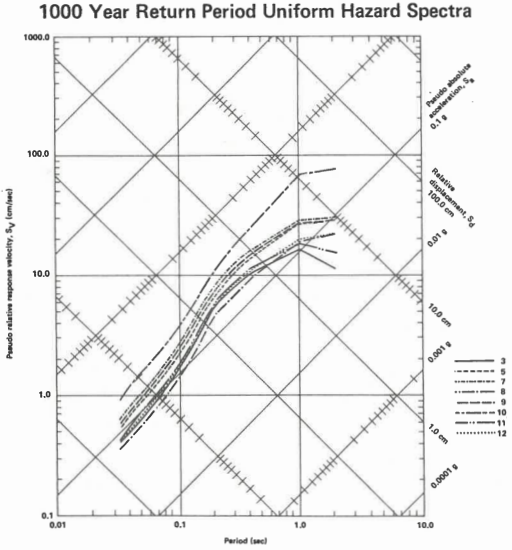

Figure 1. Probabilistic estimate of the 1000 year return period for the 5% damed uniform seismic hazard relative velocity spectra for each expert's model. Note that the different earthquake models provided by the experts introduce a significant but not unmanageable uncertainty.

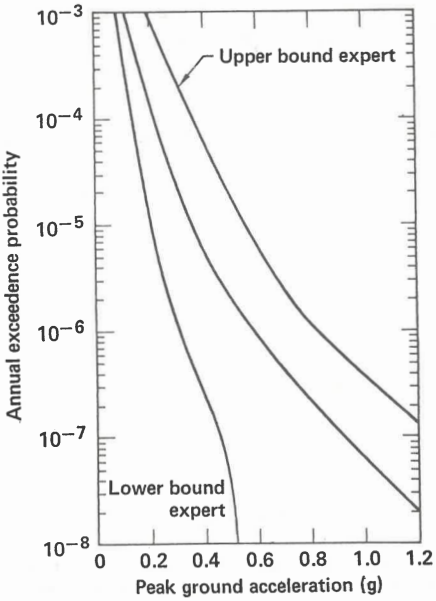

Figure 2. Computed annual exceedence probability as a function of peak ground acceleration (in g) for different earthquake occurrence models. Note that the uncertainty due to the different earthquake occurrence models increases with decreasing probability of exceedence.