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Guidelines for improved probabilistic seismic hazard analysis

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ABSTRACT

Improved guidelines for probabilistic seismic hazard analysis (PSHA) resulting from a study of past PSHA practices were recently published [1]. The new guidelines concentrate on elicitation of expert opinions and on rigorous treatment of uncertainties - both areas of difficulty in the past. A significant advance in the expert elicitation process is the concept of the technical facilitator/ integrator (TFI). The TFI ensures full discussion of the issues and is responsible for results that represent current knowledge.

1) BACKGROUND

The Nuclear Regulatory Commission (NRC), in cooperation with the Department of Energy (DOE) and the Electric Power Research Institute (EPRI), assembled a panel of scientists for the purpose of analyzing PSHA methodologies and providing guidelines for an improved methodology that could be used for regulation of nuclear power plants and other critical facilities. The seven-member panel was named the Senior Seismic Hazard Analysis Committee (SSHAC); their report was completed in 1995 but published as a NUREG/CR report only this year [1], in order to include a review by the National Academy of Sciences/National Research Council (NAS/NRC) [2].

Originally, the idea leading to the SSHAC investigation was to "reconcile" the two methodologies used in nuclear plant regulation, namely the ones developed by Lawrence Livermore National Laboratory (LLNL) [3] and by EPRI [4]. Hazard results derived from these two methods were similar in that they gave a consistent relative ranking of U.S. nuclear plants. However, absolute hazard values at many sites differed by factors of 10 or more. The SSHAC gained valuable insights by analyzing these two methodologies but soon realized that it would be more suitable to consider general principles of PSHA and derive a new, state-of-the-art methodology instead of trying to combine the LLNL and EPRI methods.

The SSHAC found that, generally, the differences between existing PSHA methods were caused by procedural aspects, and particularly by flawed approaches to expert elicitation. They, therefore, concentrated on procedural guidance for PSHA and on rigorous treatment of uncertainties. Guidance related to earth science matters was only given where necessary and not in areas where there is general agreement. The SSHAC also attempted to formulate guidelines that would provide stable results when implemented by different investigators and to address the question of different levels of PSHA, ranging from a demanding application in the regulatory arena to less critical engineering applications.

2) OUTLINE OF THE SSHAC METHODOLOGY

a) General Principles

PSHA is used to estimate the likelihood for exceeding various levels of earthquake-induced ground motion at a given location in a future time period. The estimation is performed by assembling groups of earth scientists who provide their individual estimates of parameters related to seismic sources/seismicity, and ground motion attenuation. The experts also give their personal estimates of uncertainties in those parameters. Overall uncertainty is estimated in the PSHA process by combining the parameter estimates arrived at by the experts. PSHA thus calls for expertise not only in earth sciences, but also in expert elicitation/decision analysis and in statistics and uncertainty analysis. The study is led by a team or individual that performs the elicitations of earth science experts. The elicitations are grouped into ground motion and seismic source characterization. Inputs are then combined, or aggregated, and finally a hazard calculation is performed using a suitable computer program. In practice that is either the LLNL program using Monte Carlo simulation, or the EPRI program using event trees. It has been found that the programs produce identical results, given identical inputs. Therefore, no further remarks will be made about the programs themselves.

One of the significant advances made by the SSHAC is the concept of the technical facilitator/integrator (TFI). The concept is geared especially towards demanding, regulatory type PSHA applications, and it would not necessarily be used in less demanding situations. The TFI is the entity that conducts the PSHA and the needed expert elicitations, and the TFI has the intellectual responsibility for the overall results, whereas the experts have responsibility for their individual inputs. Usually the TFI consists of a group of a few people who collectively have the required expertise. Less complex investigations are led by a technical integrator (TI) who is often a single individual with a suitable range of experience. The special function of the TFI comes into play when the issue is complex enough to require panels of experts, and when *facilitation* is needed to avoid some of the most common pitfalls that were encountered in previous PSHA efforts.

The SSHAC insists on a rigorous treatment of uncertainties, because establishing an uncertainty level for the seismic hazards is one of the inherent advantages of the

probabilistic method of analysis. Two fundamental types of uncertainty are defined by SSHAC, namely aleatory and epistemic uncertainties. These names were chosen to eliminate ambiguities in terms, such as "uncertainty" for epistemic. Aleatory uncertainty is defined as the uncertainty inherent in a stochastic or random phenomenon. These uncertainties could also be considered part of a model of the world in that, even if "perfect information" is available, the aleatory uncertainties are still present for a given model. Epistemic uncertainty, on the other hand, is attributable to incomplete knowledge about a phenomenon that affects our ability to model it. Epistemic uncertainties, thus, may theoretically be reduced or eliminated with future advances in science. In practice, however, the two types of uncertainty are often difficult to separate; but the SSHAC maintains that a rigorous treatment is warranted to sharpen the thinking, as it were, and to arrive at as complete an error estimate as possible. Seismic hazard curves resulting from a PSHA are usually displayed as an annual probability of exceedance for a ground motion parameter, such as peak ground acceleration. As shown in Figure 1, epistemic uncertainty is indicated by displaying aleatory curves for percentiles of the probability density function. The 85th percentile, for instance, indicates that we assign a probability of 0.85 to the estimate that the "true" seismic hazard curve will be below this percentile curve.

b) The TFI Process

The TFI as an entity, although usually consisting of several individuals, leads the PSHA process through expert elicitation, aggregation of results, and derivation of the final hazard values. As mentioned above, the TFI carries the intellectual responsibility for the results, whereas the experts are responsible for the inputs they supply. The experts can be employed in different functions, and one expert can fill more than one of these functions in the course of the PSHA. The expert may be a proponent who advocates a particular hypothesis or technical position. A second function of an expert may be as an evaluator who judges the relative credibility of alternative hypotheses and provides 1. his own opinion and 2. his evaluation of what the opinion of the overall scientific community would be. Finally, the expert may function as a resource expert, that is as a technical expert with specialized knowledge of a certain data set or aspect of importance for the investigation.

The TFI process relies heavily on well-documented presentation of known facts; and on extensive interaction between the experts, and the experts and the TFI. The interaction must include sufficient feedback to discuss the meaning of opinions advanced by the experts. The panel of experts is viewed as a team, with the TFI as leader, with the goal of deriving a representation of the group's knowledge, and also a representation of the knowledge of the community at large. It is important to make the process as transparent as possible, leaving no expert "in the dark", which was one of the problems that occurred in previous PSHA implementations. The goal of the interactions between experts, and experts and the TFI is to build as much consensus as possible, based on facts presented, without forcing consensus or leaving an expert in an uncomfortable position. In this phase, the facilitator aspect of the TFI is of prime importance.

Although consensus is the general goal of the TFI process, it is recognized that this will not be reached in all cases. With consensus or reasonable agreement being achieved, it will be possible to use equal weighting for all the experts' opinions; and this is the preferred outcome. If, however, in a rare case true outlier opinions exist among the data, it is important for the TFI to reach a conclusion that best represents the composite judgment of the overall scientific community. In the past, both a priori mathematical schemes, usually equal weighting, and behavioral schemes have been used to aggregate expert opinions. Although mathematical schemes have certain advantages, such as being logically transparent and checkable, the SSHAC considers rigid adherence to such schemes a disadvantage. As has been observed in the past, incorporating outlier opinions on an equal basis without further evaluation can lead to severely skewed results, whereby one expert's opinion has in effect overruled the inputs of the other experts. For this reason, it may be advantageous to use behavioral aggregation by either downweighting the outlier opinion or weighing alternative models and reaching a balanced conclusion.

The process of elicitation advanced by the SSHAC is based on a seven-step process, which was adopted with slight modification from Keeney and von Winterfeldt [5]:

Step 1 Identification and selection of the technical questions
Step 2 Identification and selection of the experts
Step 3 Discussion and refinement of the technical issues
Step 4 Training for elicitation
Step 5 Group interaction and individual elicitation
Step 6 Analysis, aggregation, and resolution of disagreements
Step 7 Documentation and communication.

Additional principles underlying the SSHAC guidelines include adequate peer review and careful documentation of the process. Peer review can include both technical review and process review. Peer review can also be conducted in a participatory mode during the process, or as a late stage review after the project has been almost completed. Careful documentation of the whole process is essential for recording every step in the PSHA process, and for providing records in an accessible format for the technical community to review the inputs and decisions. This also makes it possible to later reanalyze and update a PSHA without redoing all of the work. The SSHAC gives detailed instructions on how to document all the steps in the process.

c) Ground Motion Elicitation

Ground motion models are among the more advanced technical subjects in PSHA. PSHA, as opposed to deterministic investigations, requires a continuous ground motion function as related to magnitude and distance. In accordance with SSHAC principles, it is also necessary to give aleatory and epistemic uncertainties. Although the SSHAC considers site effects to be one of the most important aspects of ground motion considerations, site effects have been omitted from consideration, and only motions on

rock sites are derived. This is because the scope of the study was limited, and sufficient funds to treat that subject were not available.

As general principles, the SSHAC recommends that response spectra be used as measures of ground motion rather than peak ground accelerations only. They also recommend that vertical motions, if they are needed, be derived independently from horizontal motions. In the elicitation, ground motion measures are best estimated by each expert for a selected set of specific points in the magnitude-distance space, rather than relying, for instance, on a and b values estimated in a general way. Workshops have shown this type of elicitation to be very effective. Also, the SSHAC strongly emphasizes that individual ground motion models should not be treated with equal weights. Again, the workshops have shown that the experts were able to reliably assign weights to different models, reaching a remarkable degree of agreement. A diagram of the ground motion elicitation process is shown in Figure 2.

d) Seismic Source Characterization

Seismic source characterization is used in PSHA for estimating the location, size, and frequency of future earthquakes. This activity involves various aspects of earth science, including geology and geophysics, in addition to seismology. The three main elements of this process are to determine seismic source locations and geometries, maximum earthquake magnitudes, and earthquake recurrence rates. The SSHAC points out that seismic sources are a construct used as a means of approximating the locations of earthquake occurrences. Although it is possible to permit some variation of seismicity parameters within a seismic source, the distribution of maximum earthquakes and the probability of activity are assumed to be uniform within a seismic source. Seismic sources can be broadly classified as faults or areal sources, although each category needs to be subdivided to arrive at more accurate results.

As in the ground motion elicitations, it is important for the TFI (if this process is used) to provide a complete and uniform database to the experts, and to foster interaction among the experts. In areas like the eastern United States, seismic source maps developed by different experts tend to be quite different, whereas in seismically more active areas the divergence is usually smaller. Because of the complexity of the task, it is especially important to provide substantial feedback to source models given by the experts, and to conduct sensitivity analyses to illuminate the relative importance of various inputs.

3) EXPERIENCES GAINED FROM IMPLEMENTATION OF THE GUIDELINES

During the SSHAC project, two workshops were held to test the process of ground motion elicitation, and to derive a composite ground motion model for the central and eastern U.S. The workshops were very successful and led to a remarkable degree of agreement between the experts after intensive feedback and discussion. In particular,the experts reached a consensus about the validity of various ground motion models, which

included intensity-based models, empirical models, stochastic or random-vibration models, and the empirical source-function method. The experts rejected intensity-based models and had a preference for the stochastic models. However, the treatment of uncertainties proved to be somewhat difficult, and substantial misunderstandings on aleatory and epistemic uncertainties were found during the second workshop.

At present, a project is underway at LLNL with the purpose of further testing and implementing the SSHAC guidelines. This project is concentrating heavily on seismic source characterization, although additional elicitations of ground motion values are also taking place with the aim of filling in areas that were missed during the SSHAC workshops, particularly with respect to lower magnitudes.

Once again, the workshops in seismic source characterization produced a remarkable degree of agreement among experts in a way that previously did not seem possible. Three source characterization workshops were held with the aim of obtaining a regional characterization for the southeastern U.S. with more specific consideration of two sites, namely the Vogtle and Watts Bar nuclear plants. The experts began with fairly different source zone maps in the first workshop. After discussion, feedback, and sensitivity studies, the experts were able to agree on a combined source zone map for the region. Some experts eliminated zones they did not consider to make a substantial difference, others slightly modified some source zones to agree with those of one or more other experts, and in other cases, the composite map includes one or more zones that were only advanced by one expert, but to which the others did not object. Near the specific sites, different zone interpretations were accommodated by incorporating, for instance different boundaries, to which varying levels of probability were later assigned. The resulting map has a variety of source zones, some with varied boundaries. However, it is one combined map, a result that contrasts very sharply with the innumerable and totally different source maps produced by different experts in the past.

This, again, can be considered a ringing endorsement of the advantages of a properly implemented TFI process. All of this was achieved with thorough discussion and feedback, without any expert feeling pressured or taken advantage of. In general, it is clear that experts will not agree to any forced solution, but instead will maintain their point of view in areas where they have a definite opinion.

As the NAS/NRC review panel pointed out, the principles contained in the SSHAC methodology lend themselves not only to seismic hazard analysis, but have more general implications that make them useful for other types of investigation as well. Indeed, the SSHAC guidelines have already been applied to a study of volcanic hazards at the proposed Yucca Mountain nuclear waste disposal site in Nevada.

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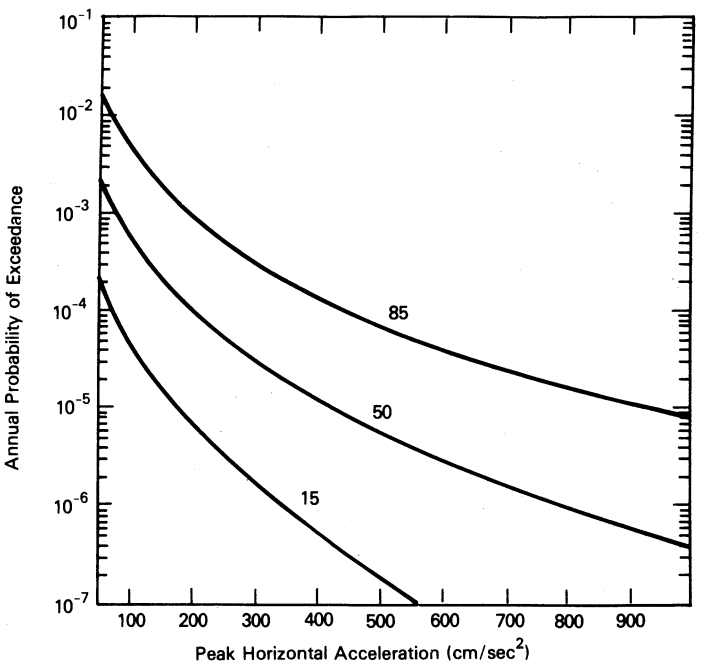

Figure 1. A typical family of seismic hazard curves showing 15th, 50th, and 85th percentiles.

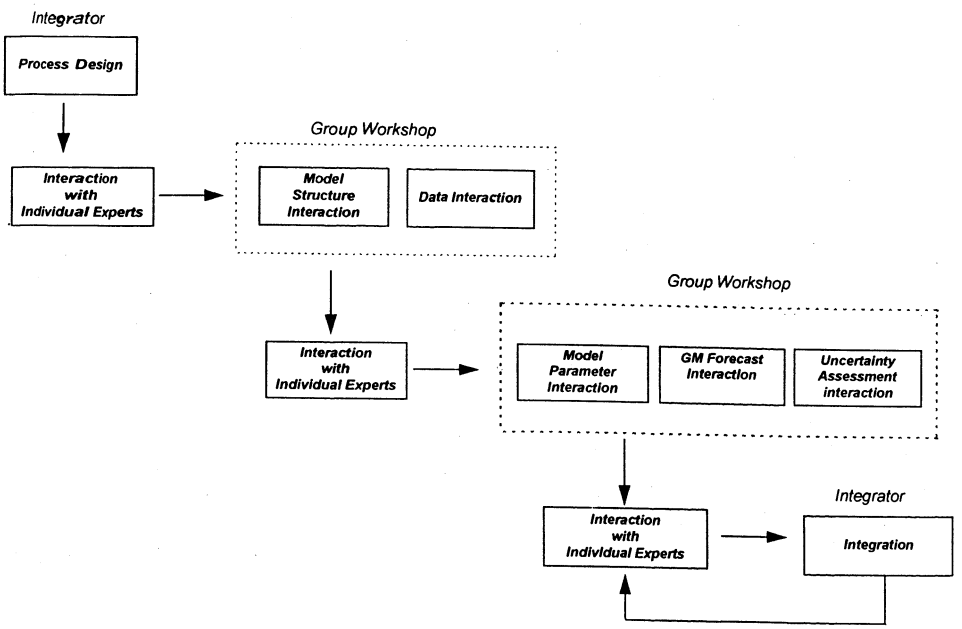

Figure 2. Roadmap of ground motion elicitation process.