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Using expert opinion for assessing seismic hazard in low-seismicity areas

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Abstract

The uncertainty in seismic hazard is especially important in regions of low seismicity where empirical observations alone do not constrain the locations and characteristics of future seismicity. In these regions, subjective judgment, properly defined and documented, must be used to quantify the uncertainty in earthquake occurrences and ground motion. A project to use expert opinion to quantify uncertainties has been conducted in the eastern United States, revealing several important rules that such studies must follow. These are that the judgments and documentation must be firmly based and justified on a scientific plane, that diversity among experts must be resolved if it is caused by misunderstanding or miscommunications, and that the earth scientists themselves must be involved in the development of the procedures to quantify and document expert opinion.

Introduction

The chance of occurrence of earthquake-induced ground motion is uncertain in all parts of the world, because we do not have a full understanding in any region of the exact causes of physical processes associated with fault rupture, seismic energy release, and seismic wave transmission. As a result, decisions regarding earthquake risk mitigation can be made in an informed way only if existing uncertainties are evaluated and documented in a rational way. The issue of uncertainty in seismic hazard is especially important and challenging in regions of low seismicity, where empirical observations of earthquake occurrences and the associated ground motions allow multiple interpretations of the physical mechanism governing earthquake occurrence and seismic wave generation and transmission in the earth. In these regions, it is especially important to develop a mechanism to quantify the seismic hazard and its uncertainty.

The purpose of this paper is to relate some experience that comes from a major effort to quantification of seismic hazard in the eastern United States. The objective of the study was to evaluate the possibility of moderate to large earthquakes such as the 1886 Charleston, South Carolina, event ($M \approx 7$) to occur in the future in locations where they have not been observed historically. In order to make decisions on seismic re-evaluations and retrofits on a site-specific basis, the seismic hazard was cast in terms of ground motion occurrences at the sites of nuclear power plants. The study was funded by the Seismic Owners Group of nuclear utilities and by the Electric Power Research Institute (EPRI), and was conducted during the 1980s (EPRI 1988). Comparisons with another similar study by the Lawrence Livermore National Laboratory (Bernreuter et al. 1989), sponsored by the US Nuclear Regulatory Commission, have taken place in the last four years and are ongoing.

This paper represents the views of the author gained from this responsibility for the development and application of the original EPRI methodology, and gained from subsequent comparisons. These views are not presented as the *only method* for quantifying seismic hazard, but as a *recommended method* that has worked well in this application. Other methods that have worked well in other applications include Burton (1990) and Mayer-Rosa et al. (1993). Ultimately, the best method for a particular application will depend on the level of effort available, the use of the results (the decisions that will be made), and the people involved.

Seismic hazard and its uncertainty

Seismic hazard herein is defined as the probability of occurrence of certain ground motion levels at a site. The calculation of seismic hazard requires models of earthquake occurrence, of the characteristics of energy release, of seismic wave transmission through the earth, and of the effects of near-surface geology on seismic waves. Uncertainty in the appropriate models leads to uncertainty in the estimated seismic hazard.

In order to quantify seismic hazard and its uncertainty, it is first useful to define the relevant sources of variability. We segregate variability in the problem into two categories:

- *Randomness*, or aleatory variability, derives from the chance occurrence of phenomena. Even if we could develop the 'correct' models of earthquake occurrences and effects, there would still be randomness in the magnitude, location, and ground motions of future earthquakes. In other words, even with the correct models we would not be able to predict the exact characteristics of earthquake ground motions at the site in the future.
- *Uncertainty*, or epistemic variability, derives from our lack of knowledge of the physical processes governing earthquake occurrences and effects. In concept, uncertainties can be reduced with the collection of additional data or the development and acceptance of better theory.

In real applications the distinction between randomness and uncertainty is not unique. With time, parts of the seismic hazard model may evolve so that what is considered randomness at one time may be treated as uncertainty at a later time. The important point is to develop a logical, consistent, and accepted set of definitions for a given analysis, and to maintain them.

In seismic hazard analysis, the calculations integrate over *randomness* to generate results, often in the form of a seismic hazard curve. The important step in state-of-the-art seismic hazard studies is to quantify, in addition, the *uncertainty* caused by lack of knowledge of the correct models of earthquake occurrences, characteristics, and ground motions.

The reasons for being so careful to quantify the uncertainty in seismic hazard are several. First, even if the hazards are uncertain, we wish to make *correct and appropriate decisions* about mitigating earthquake risks. We wish to expend the correct amount of resources in reducing future earthquake costs, neither leaving ourselves vulnerable because of lack of preparation nor wasting investment to guard against very improbable events. Second, in the environment of regulations for critical engineering facilities, we desire *stability* in the estimates of seismic hazard (and their uncertainty) over time, so that decisions made today are not likely to be reversed in the near future, causing the expenditure of resources even when no additional knowledge or data have been gained. Third, progress in quantifying seismic hazards can be made in an informed manner only if we understand our current lack of knowledge and how that lack of knowledge influences current evaluations. An informed assessment of current uncertainties is necessary for informed decisions on the knowledge necessary to reduce that uncertainty.

Finally, assessments of seismic hazard are not static. They change with time, as we gain more knowledge of the earthquake phenomenon. However, we are faced with earthquake mitigation decisions today, even though we know that the estimate of hazard will change in the future. Taking account of the possibility of future changes in today's decisions is an important part of the decision process (McGuire 1987). Therefore, in contrast to classical decision analysis we cannot consider randomness and uncertainty the same, and cannot integrate over both sources of variability to derive an overall mean hazard for decision making.

Figure 1 illustrates the historical earthquakes in the eastern part of the United States, which was the study region for the EPRI (1988) study. Seismicity is diffuse, with multiple faults and tectonic structures in the region being candidates for the sources of earthquakes. Within this context the EPRI project developed and applied a methodology for quantifying the uncertainty in seismic hazard for any site in the region.

Table 1. Probability of activity of tectonic features with different characteristics, as assessed by Bechtel team (EPRI 1988)

	ASSOCIATION WITH HISTORICAL SEISMICITY					
	MODERATE-TO-LARGE EARTHQUAKES		SMALL EARTHQUAKES ONLY		NO SEISMICITY	
DEEP CRUSTAL ASSOCIATION	GEOMETRY RELATIVE TO STRESS AND SENSE OF SLIP					
	Favorable	Unfavorable	Favorable	Unfavorable	Favorable	Unfavorable
YES	0.80	0.40	0.30	0.10	0.060	0.012
NO	0.64	0.20	0.15	0.05	0.024	0.004

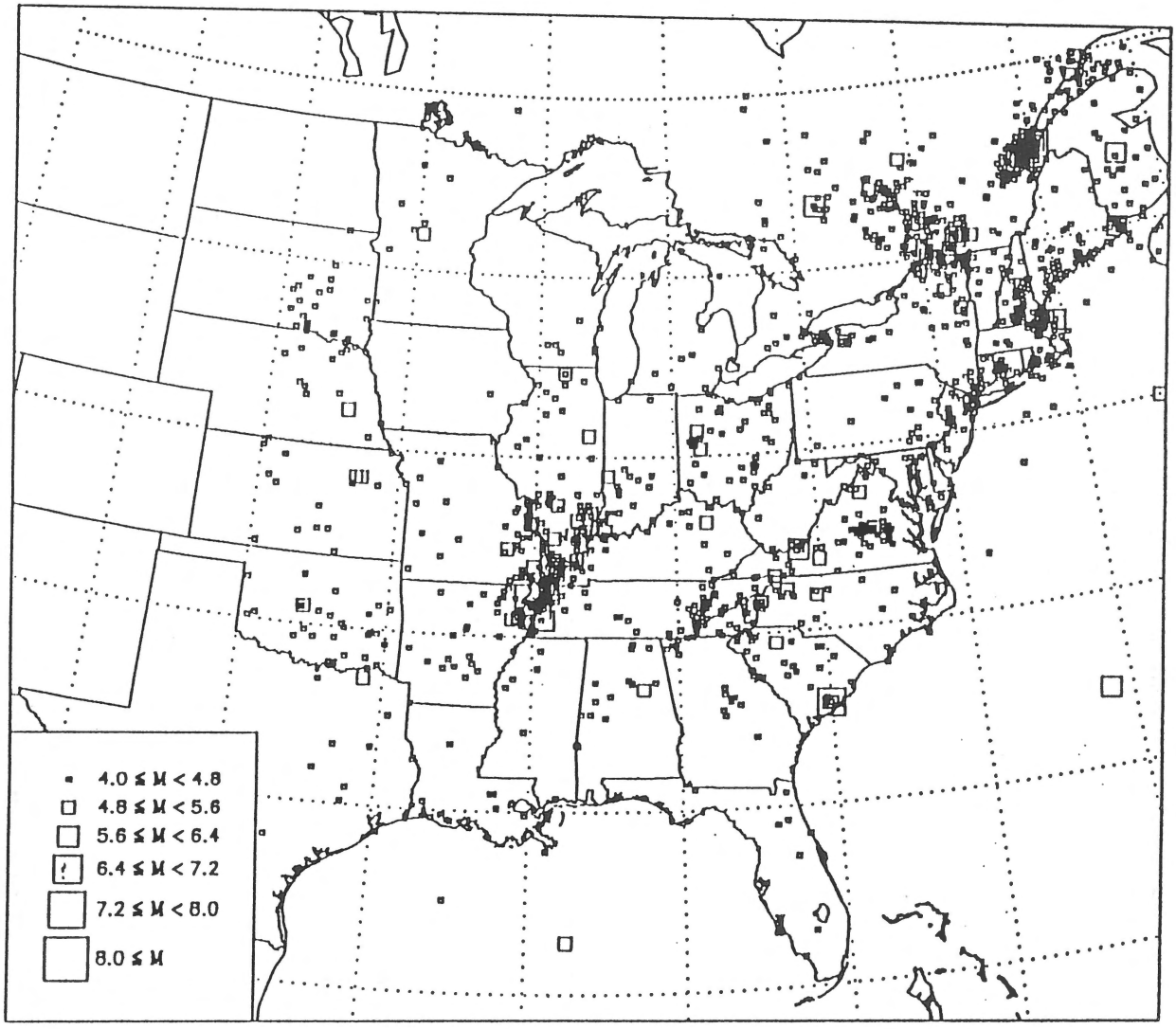

Fig. 1. Historical seismicity ($M \geq 4$) in the eastern United States (from McGuire et al. 1989).

Quantification of seismic hazard uncertainty

Seismicity inputs to the EPRI seismic hazard calculations required the following steps:

1. Definitions. Substantial effort was made to ensure that all participants (some 50 earth scientists and earthquake engineers) in the study understood and used the same definitions for critical concepts. This included terms such as:
   - *Tectonic Feature:* a fault, basin, intrusion, or other inhomogeneity in the earth's crust, either observed or inferred from geophysical measurements, that might cause a stress concentration or strain release resulting in earthquakes.
   - *Tectonic Framework:* a representation of the tectonic features and their characteristics (location, geometry, sense of slip, slip rate, probability of being active, etc.) that might cause tectonic earthquakes in the future.
   - *Seismic Source:* a tectonic feature that is potentially active, or an area covering numerous features or a part of the earth's crust with similar tectonic features, within which the potential seismicity is similar (but not necessarily spatially homogenous).
   - *Seismically Active:* having the potential to cause earthquakes of any magnitude.

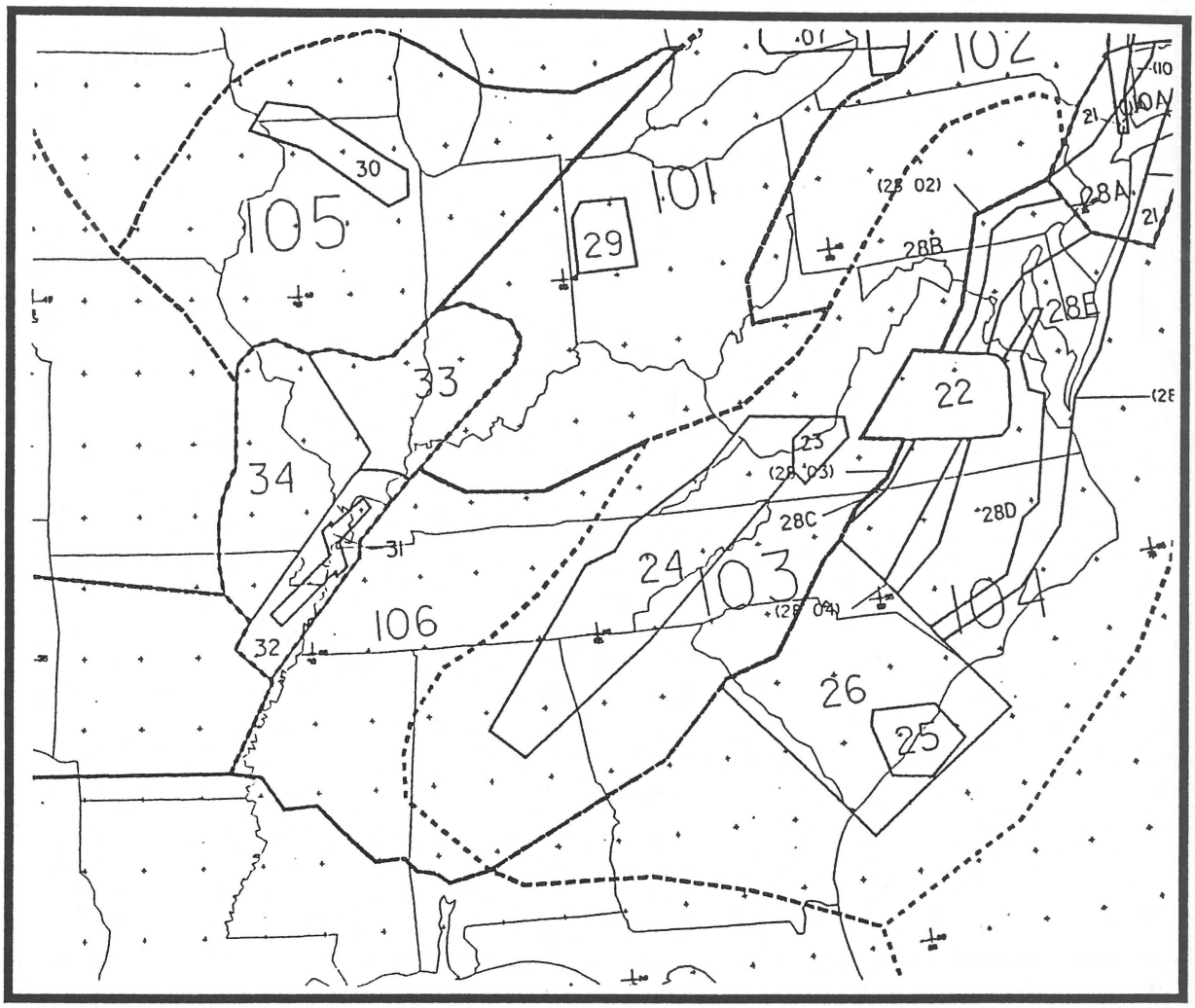

Fig. 2. Areas defined as seismic sources in the eastern US, derived by the Weston team (from EPRI 1988).

Efforts to use consistent definitions were important in avoiding miscommunications among participants.

2. Crustal stress field. The crustal stresses in eastern North America were evaluated by examining and comparing available borehole stress measurements, earthquake focal mechanisms, and other data. It was concluded that crustal stresses are predominantly NE–SW compression, caused by ridge-push of the North American plate.

3. Causative structures. Tectonic features that might be the source of crustal strain release were identified. There was much diversity among the participants on what structures were appropriate to identify, and how to synthesize these structures into seismic sources for calculation of hazard.

4. Probability assessment. The candidate causative structures were quantitatively evaluated to assess the probability that each, in fact, was seismically active and could generate earthquakes in the future.

5. Seismicity parameters. The parameters describing potential seismicity on each structure were evaluated (rate of activity, magnitude distribution, maximum magnitude, depth of seismicity). This evaluation included uncertainty estimates on the parameters.

Additional, similar work was done to evaluate potential seismic ground motions; that work is not described here.

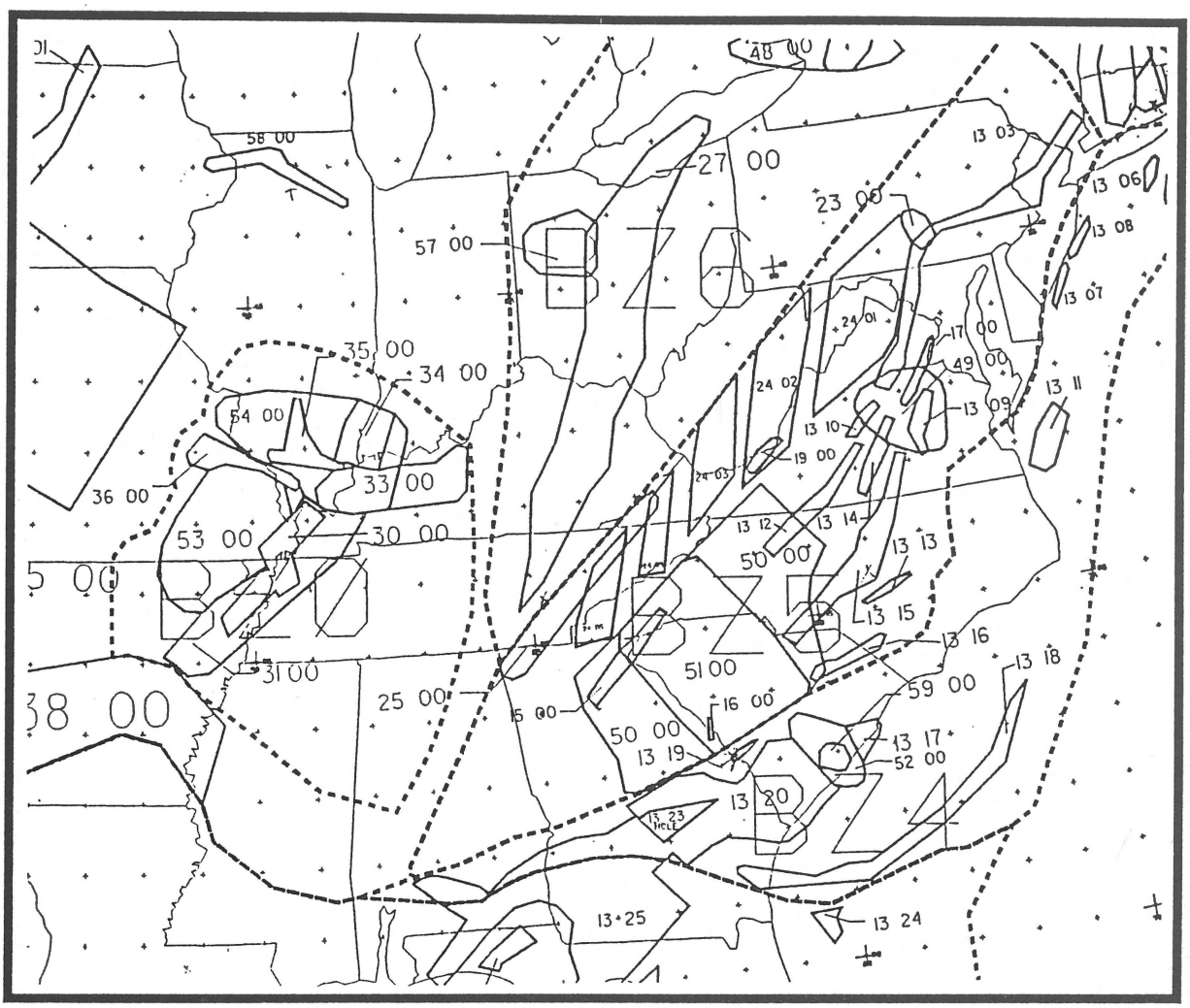

Fig. 3. Areas defined as seismic sources in the eastern US, derived by the Bechtel team (from EPRI 1988).

Several aspects of the seismicity evaluation were critical. First, the evaluations were founded in basic earth science principles. In particular, steps 1 through 3 above were normal evaluations that the participating earth scientists felt comfortable with. Only after the deterministic evaluations were set did the assessment of probabilities occur (step 4). A similar process was used in the evaluations of parameters (step 5). This reliance on fundamental earth science meant that participants were comfortable defending the conclusions of the study.

Second, the participants were divided into 'Earth Science Teams' whose charge was to derive a single set of interpretations representing the team's views. Each team had at least one seismologist, one geologist, and one geophysicist, to promote interaction and diversity of opinion. With this range of opinions, each team's interpretations had to be broad enough to encompass the views of its members.

Third, interaction and communication among teams was recognized as an important factor. Seven workshops of two days each were held to develop a common data base and to promote communications. This ensured that each team was aware of the other teams' interpretations and could consider those in developing its own. The interaction was also an important part of the scientific process, wherein hypotheses are developed and compared to data, draft conclusions are drawn and defended in front of peers, and revisions to conclusions are made based on that feedback. This

Table 2. Probability of activity of tectonic features with different characteristics, as assessed by Rondout team (EPRI 1988)

		ASSOCIATION WITH HISTORICAL SEISMICITY					
		MODERATE-TO-LARGE EARTHQUAKES		SMALL EARTHQUAKES ONLY		NO ASSOCIATION WITH SEISMICITY	
DEEP CRUSTAL EXPRESSION	SEISMICITY LEVEL	GEOMETRY RELATIVE TO STRESS					
		FAVORABLE GEOMETRY	UNFAVOR. GEOMETRY	FAVORABLE GEOMETRY	UNFAVOR. GEOMETRY	FAVORABLE GEOMETRY	UNFAVOR. GEOMETRY
DEEP CRUSTAL EXPRESSION NEAR INTERSECTIONS	HIGH	1.0	0.95	0.8	0.65	0.5	0.3
	LOW	0.99	0.9	0.7	0.5	0.3	0.1
DEEP CRUSTAL EXPRESSION NOT NEAR INTERSECTIONS	HIGH	0.95	0.9	0.7	0.55	0.4	0.2
	LOW	0.93	0.85	0.6	0.4	0.1	.05
NO DEEP CRUSTAL EXPRESSION	HIGH	0.85	0.8	0.55	0.4	0.2	.05
	LOW	0.83	0.75	0.4	0.2	.05	.005

process was an important factor in the defendability of the results.

Even with this substantial interaction and feedback there was a large diversity in interpretations among the teams. Figures 2 and 3 show the seismic sources derived in the southeastern United States by two of the teams. One team (Fig. 2) indicates a relatively simple interpretation using broad sources in the region, whereas the other team (Fig. 3) shows multiple, alternative sources including some very detailed interpretations. Tables 1 and 2 show the matrices used to quantify the probability that a given tectonic feature, with observed characteristics, is active and capable of generating a tectonic earthquake, for two teams. In one case (Table 1), three characteristics are used: association with historical seismicity, geometry, and extent of deep crustal expression. In this example, 'association with historical seismicity' meant whether moderate-to-large ($M > 5$), small ($M < 5$), or no earthquakes had occurred in the vicinity of the feature (within several kms). 'Favorable geometry' meant that the features were oriented favorably for slip to occur, given the understanding of the crustal stress regime. 'Deep crustal association' meant that the feature extended more than several kilometers into the earth's crust. In the second case (Table 2), the level of historical seismicity was also thought to be an important diagnostic in assessing feature activity.

These matrices were applied by assessing each feature's characteristics, then estimating its probability of activity from the matrix given that set of characteristics. In practice, many of the characteristics were uncertain, so weights were assigned based on degree of belief and a weighted probability of activity was calculated. The teams always had the opportunity to revise the final probability of activity based on judgment, as long as that judgment was documented.

The explicit expression of probabilities of activity, such as illustrated in Tables 1 and 2, was to document scientific judgment, not to replace or subvert it. This was made clear during the evaluation process. With this understanding, the interpretations of each team were clear and open for review.

The results of the EPRI study are illustrated in Fig. 4, which shows fractile and mean seismic hazard curves for one nuclear power plant site located in Georgia. For typical seismic design levels for these facilities (150 to 250 cm/sec^2 acceleration), the difference between the 15th and 85th percentile annual probability is one order of magnitude. This illustrates the effect of the diversity in interpretations among the earth science interpretations in the study (as well as in the estimates of ground motion, which are not discussed here). The specific contributions to this uncertainty were investigated by comparative analyses showing the uncertainty resulting from seismic sources, teams, seismicity interpretations, and ground motion attenuation equations. Sensitivity analyses also could indicate how important each input is to the total uncertainty.

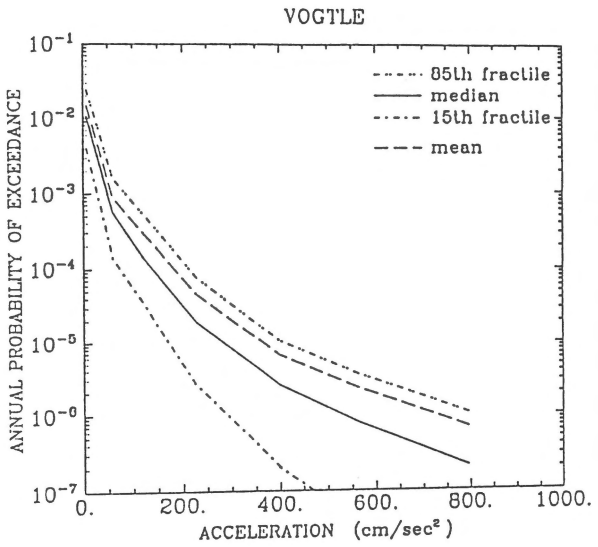

Fig. 4. Seismic hazard for peak ground acceleration at a site in Georgia, showing mean and fractile seismic hazard curves (from McGuire et al. 1989).

Experience with uncertainty quantification

This application of seismic hazard analysis has shown that a structured approach to the quantification of hazard and its uncertainty can lead to a defendable quantification of seismic hazard. The defendability of the methodology and results was an important criterion in the application. This defendability resulted because a wide range of earth science expertise was used in the interpretations (multiple disciplines), the fundamental data were available for review, the basis for the interpretations was documented (in the form of maps and tables, as illustrated in Figs 2 and 3 and Tables 1 and 2), the individual assessments were clear enough that they could be reproduced by a second party, if necessary, and reviewers of the methodology were involved in the design and application of the methodology, as observers. The process was an open one, in which active efforts were made to subject the methodology to review and critique as it was being derived and applied.

Important lessons were learned from this application. As stated in the introduction, these are not *necessary* conditions for a successful methodology, but they have proven to be *sufficient* conditions. These lessons are:

1. Multi-discipline teams should be used, not individual experts, and consensus should be required within each team. This approach fosters cross-fertilization, commitment, and critical evaluation of conjecture by peers.
2. The process should use a structured, step-wise approach that reaches consensus and approval at intermediate stages. This means that deliberate progress is made toward the overall interpretations, and hard decisions are not left until the final stage of the project.
3. The procedures must be based on, and compliant with, fundamental earth science principles. If earth scientists are to defend their interpretations, the deterministic evaluations of tectonics and structures must come first, with probability assessment added, not the reverse.
4. The overall scheme should be strictly defined, but each team should be allowed separate applications. It did not prove feasible, for example, to require all teams to agree on a master seismic source map, or to require identical probability matrices (Tables 1 and 2).
5. The quantitative probability estimates should be represented as a documentation of subjective earth science judgment, not as a substitute for it. This leads to a clearer concept of the use of these estimates, and allows the participants to defend these evaluations based on their training and experience.
6. Enough time must be allowed for definitions, differences of opinions, and objections to be resolved on a scientific level. Otherwise the final results will be undermined by qualifications and criticisms by the participants.
7. Data bases must be provided uniformly to all teams and participants. Then the participants know that they are all working from the same knowledge base on the data available.
8. Justification of interpretations against relevant data should be required. This is the standard scientific process. This is not to say that all interpretations must be empirically based; rather that comparisons to relevant data must be made and deviations explained and justified if appropriate. For example, the predicted rate of seismicity in a region may be larger than that observed historically, and may be justified based on a non-stationary model of seismicity.
9. Communications among teams should be promoted to eliminate lack of information and to give interim feedback on draft results. This is part of the scientific process, and leads to a stronger commitment to the final interpretations by the participants.

10. Earth scientists and earthquake engineers must be in the lead roles in developing and applying the methodology, not subjective probability analysts. This helps to ensure that the scientific interpretations are most important, not the subjective probability assessments. As a result the earth scientists will more readily and easily defend their interpretations; they are most familiar with the earth science, not with subjective probability interpretation.

These conditions help to ensure that the seismic hazard results are both valid and defendable. Again, there is no single process that is right; ultimately the methodology must be acceptable and comfortable to the participants, while still providing the required input for the seismic hazard analysis.

Conclusions

Uncertainty in seismic hazard for regions of low seismicity can be assessed through a structured process that relies on fundamental earth science interpretations, with the uncertainty in those interpretations documented. With the use of multiple experts acting in teams, miscommunication and misunderstanding can be minimized, so that invalid interpretations are eliminated. This process still leaves substantial uncertainties in seismic hazards for regions of low seismicity such as the eastern United States. However, the methodology and its application can be defended in front of reviewers and regulators as a reasonable assessment of earthquake hazard given current knowledge of earthquake processes and effects.

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