Uncertainties in Probabilistic Seismic Hazard Analyses for Regions of Low-to-Moderate Seismic Potential: The Need for a Structured Approach

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ABSTRACT

The results of properly conducted probabilistic seismic hazard analyses (PSHA) in regions of low-to-moderate seismicity will exhibit significant uncertainties. While uncertainties also exist for regions of higher seismicity, the most important sources of uncertainty may differ between the two regions. The need to follow a structured process may be more important in regions of lower seismicity simply because of the lack of basic data available to constrain alternative conceptual models.

For higher seismic rate areas where the seismic sources can be identified with some degree of confidence, the uncertainty in seismic source characterization with respect to earthquake occurrence rate, recurrence model, and source geometry at depth usually has the greatest impact on hazard calculations. For ground motion prediction, defining the aleatory variability and the uncertainty associated with that estimate is very important. This is particularly true if regulatory requirements mandate the computation of hazard results for low probabilities.

The situation is somewhat different for areas with low-to-moderate rates of seismicity. First, the low rates of activity generally yield a small number of events of sufficient magnitude and/or ground motion amplitude to be of engineering or seismological interest. As a result, ground motion prediction equations (GMPEs) derived for these areas will have large uncertainties. It can be difficult to properly partition the epistemic and aleatory components of uncertainty in the GMPEs. Second, it can be much more difficult to confidently identify and characterize seismic sources. A seismotectonic framework model characterizes how and where crustal deformation is accommodated and if that deformation yields earthquakes. The development of these models is very important for the low seismicity case. However, the development of these models is inherently subjective and uncertain. To properly capture the range of plausible interpretations within the broader seismic hazard community, it is necessary to follow a structured process that provides a transparent, organized, and robust framework.

The failure to properly capture the epistemic uncertainty inherent in some of the inputs to the PSHA may result in a biased estimate of the mean hazard. Proper integration and evaluation is necessary to successfully identify and incorporate the uncertainties within any seismic hazard assessment. Key components of the structured approach must be technical and sponsor peer review throughout the process.

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1. Introduction

This paper assumes the primary objective of any seismic hazard analysis is to produce a defensible, unbiased estimate of the mean seismic hazard at a specified site. The mean seismic hazard is sensitive to uncertainties in the component pieces that together form the hazard model. As a result, the important sources of uncertainty must be explicitly included and evaluated as part of a comprehensive probabilistic seismic hazard analysis (PSHA). The paper examines some of the specific issues that arise when trying to satisfy that objective. Some of these issues become especially challenging in areas of low-to-moderate seismic activity. This discussion considers a few selected topics in seismic source characterization and in ground motion prediction that become problematic in low-seismicity-rate areas. The paper then concludes by discussing the need for a structured approach in hazard assessment for critical facilities.

2. Seismic source characterization

While the identification and characterization of seismic sources in areas of high seismic activity is still fraught with challenges, data are generally available with which to begin the process. The primary areas of discussion focus on the quality and relevance of the available data, and not on whether such data exist. In contrast, in regions of low-to-moderate seismic activity, the lack of relevant data provides a fundamental limitation to the identification and characterization process.

Figure 1 illustrates the recurrence interval for characteristic-magnitude earthquakes[2] on several faults in southern California, near the USA border with Mexico. These faults are in an area that is very seismically active and has received a significant amount of research interest. As a result, the recurrence interval for surface rupturing earthquakes on many of the faults is relatively well constrained based on extensive paleoseismic investigations.[3] Two aspects of Figure 1 are of interest to this discussion. First, the uncertainty in recurrence interval for each of these sources is generally less than a few hundred years. Second, as the best estimate of the recurrence interval (i.e., the location of the peak of the density function) decreases, the uncertainty about that estimate also decreases. This observation implies that the geomorphological evidence becomes better expressed and interpretation becomes less ambiguous as the activity rate increases.

The Yucca Mountain site located in southwestern Nevada, USA, is the proposed site of a high-level nuclear waste repository. The Yucca Mountain region has a much lower level of seismic activity than does the southwestern California area described above. The Yucca Mountain PSHA followed a formal structured process and included the experience and interpretations of a number of experts.[4] This was the first study to follow the guidelines outlined in the Senior Seismic Hazard Analysis Committee (SSHAC) Report and was conducted at the most rigorous level described in that document (i.e., Level 4).[5] The SSHAC Report is discussed in more detail below. The unparalleled level of detailed field and laboratory investigations conducted to support the study makes the Yucca

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[2] Schwartz, D.P., and K.J. Coppersmith, 1984. Fault behavior and characteristic earthquakes-examples from the Wasatch and San Andreas fault zones: *Journal of Geophysical Research*, **89**, pp. 5681–5698.

[3] Working Group on California Earthquake Probabilities, 1995. Seismic hazards in southern California: Probable earthquakes, 1994–2024: *Bulletin of the Seismological Society of America*, **85**, pp. 379–439.

[4] Stepp, J.C., et al., 2001. Probabilistic seismic hazard analyses for ground motions and fault displacement at Yucca Mountain, Nevada: *Earthquake Spectra*, **17**, pp. 113–152.

[5] NUREG/CR-6372, 1997. Senior Seismic Hazard Analysis Committee, "Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts," Lawrence Livermore National Laboratory, Livermore, California, USA.

Mountain PSHA unique. More than 50 paleoseismic trenches were excavated in the Yucca Mountain area. However, because of the low activity rates on the faults in the immediate vicinity of the site, interpretation of the results was not straightforward. Table 1 summarizes the interpretations across all six of the expert teams of maximum magnitude, recurrence interval, and slip rate from the Yucca Mountain PSHA for faults located near the proposed repository.[6] It is interesting to compare the recurrence intervals contained in Table 1 to those plotted in Figure 1 for the southern California faults. Notice that the recurrence intervals for the Yucca Mountain region are generally in the tens of thousands to hundreds of thousands of years with a very broad range assigned for each fault (usually at least an order of magnitude).

This large range in interpreted recurrence intervals manifests itself in the uncertainty in the computed hazard. Figures 2a and 2b illustrate the uncertainty in peak ground acceleration (PGA) hazard associated with source characterization only (i.e., no uncertainty in attenuation) for two of the Yucca Mountain expert teams.[7] Two features stand out in these plots—one is the large dispersion in the hazard curves (the range in hazard between the median (50th-percentile) and 16th- and 84th-percentile curves) and the other is increasing deviation between the median and mean curves at low-probability levels. The deviation between the median and mean is a result of an asymmetric distribution in the epistemic uncertainty in one or more elements of the seismic source characterization model. Figure 3 is a similar curve for PGA hazard at Yucca Mountain, but includes both the uncertainty in source characterization across all teams and the uncertainty in the ground motion prediction equations.[8] Comparison of Figures 2 and 3 clearly shows that uncertainty in source characterization alone does not explain the total uncertainty in hazard; the uncertainty in ground motion prediction also plays a major role. The uncertainty in ground motion estimation for the Yucca Mountain study is discussed in more detail below.

Table 1. Maximum Magnitudes, Slip Rates, and Recurrence Intervals for Local Faults Yucca Mountain Probabilistic Seismic Hazard Analysis

Fault	M_{MAX}	Slip Rate (mm/yr)	Recurrence (in 1000s of yrs)
Bare Mountain	5.8–7.5	.005–.025	20–200
Crater Flat—South	5.4–7.0	.002–.02	40–180
Crater Flat—North	5.5–7.0	.001–.005	120–160
Fatigue Wash	5.5–7.3	.002–.02	50–250
Paintbrush Canyon	5.9–7.4	.002–.03	20–270
Solitario Canyon	5.6–7.4	.002–.04	35–180
Stagecoach Road	5.3–7.1	.01–.07	5–75
Windy Wash	6.6–7.5	.01–.027	35–100

A seismotectonic framework model characterizes how and where crustal deformation is accommodated and whether that deformation yields earthquakes. The development of these models is an important component of any seismic hazard assessment, but is of particular importance in regions of low-to-moderate seismicity. Alternative tectonic interpretations can arise even among highly qualified and experienced practitioners in regions where seismic activity rates are moderate to low and

[6] Civilian Radioactive Waste Management System, Management and Operating Contractor, 1998. "Probabilistic Seismic Hazard Analysis for Fault Displacement and Vibratory Ground Motion at Yucca Mountain, Nevada" (I.G. Wong and J.C. Stepp, coordinators), report published for U.S. Geological Survey, in three volumes.
[7] G. Toro, pers. comm., 2008.
[8] Ibid.

data are difficult to obtain. Figure 4 illustrates the sensitivity to tectonic characterization of seismic sources near a site in north-central California.[9] That study used structured interactions among a group of experts generally consistent with the Level 2 evaluation described in the SSHAC Report. However, instead of using this technique for all elements of the PSHA, this study employed a detailed, structured, multi-expert approach only in a single portion of the PSHA, specifically that portion that was the most difficult to constrain, the most hazard significant, and potentially the most contentious.

The objective of this targeted interaction was to capture the informed technical community opinion on one element of the seismic hazard assessment that had particularly significant uncertainty associated with it, specifically the characterization of a 350-kilometer (km)-long, 50-km-wide northwest-striking zone of faults (the Foothills Fault System) within the Sierra Nevada Foothills. Initial studies of the Foothills Fault System considered it to be a zone of partially reactivated normal-slip faults. However, subsequent studies suggested that the system may have a significant dextral or oblique component of slip and slightly higher slip rates than previously estimated. Low slip rates combined with moderate erosion rates make preservation of the geomorphic evidence of faulting problematic, and development of a consensus seismic source model is very difficult in this case. The study incorporated alternative interpretations of the sense of slip, slip rate, and source geometry. Figure 4 shows that the range in hazard associated with the uncertainty in characterization of this zone of deformation is about a factor of 8 at a ground motion level of approximately 0.21 g (206 centimeter per second squared (cm/s^2)). This technique of applying the SSHAC framework in a targeted fashion or to key topics with significant uncertainty may be useful if resources available to undertake the PSHA are limited.

In areas of low seismicity, the earthquake catalog is often a mixed population of instrumentally recorded small and moderate magnitude events that have magnitudes and locations that have been assigned based on some historic intensity measure. In most cases, the magnitude range in the catalog for a source zone may be insufficient for the confident assessment of the maximum magnitude for the source zone. Figure 5 provides an example recurrence curve for a seismic source zone in a region of moderate seismicity. The recurrence data shown in Figure 5 allows for alternative maximum magnitude (M_{MAX}) estimates of 6 to 7. Figure 6 illustrates the implication of this uncertainty in M_{MAX} on the computed seismic hazard at a point in the center of this source zone. The results have been computed for PGA and 1-second (s) spectral acceleration (Sa) for each of the M_{MAX} values. The hazard is seen to increase with M_{MAX}, with the increase more pronounced for 1-s Sa. It is worth noting that for the 1-s Sa case, an increase in M_{MAX} results in a significant decrease in the slope of the hazard curve. This effect can be important if a performance-based approach to design that incorporates the ratio between ground motion amplitudes at specified hazard levels[10, 11] will be used.

This effect could also have an appreciable impact if a probabilistic risk analysis (PRA) is to be performed in which the hazard curve would be convolved with a fragility curve to produce estimates of annual frequency of damage. For situations in which the data do not provide a constraint on M_{MAX}, interpretations need to be developed and supported based on seismological and physical observations and theory. These interpretations will, necessarily, be somewhat subjective in nature, and alternative, equally scientifically valid hypotheses will be possible.

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[9] Anderson, L., and J. Ake, 2008. "Probabilistic Seismic Hazard Analysis for Folsom Dam and Mormon Island Auxiliary Dam, Central Valley Project, California," DRAFT Seismotectonic Report 2008-03, U.S. Bureau of Reclamation, Technical Service Center, Denver, Colorado, USA.

[10] U.S. Nuclear Regulatory Commission, 2007. Regulatory Guide 1.208, "A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion," Washington, DC.

[11] American Society of Civil Engineers, 2005. ASCE Standard 43-05, "Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities," Reston, Virginia, USA.

The above examples all show that alternative interpretations for parameters and models in seismic source characterization will arise in the conduct of a PSHA in low-seismicity regions. A disciplined and structured approach will be required to capture the breadth of scientifically valid potential interpretations of the informed community of experts. The failure to use a structured approach in characterizing the seismic sources may lead to a biased estimate of the hazard.

3. Ground motion prediction

Sites located in tectonically active areas are able to rely on ground motion prediction equations ("attenuation functions" or GMPEs) that have been developed using large datasets of empirical data. The existence of large datasets of relevant data allows for more confident development of equations for the prediction of median ground motion as well as estimates of the aleatory variability (σ_{LN}). The same situation holds if theoretical ground motion models are used, in that the existence of good datasets for use in the validation process significantly improves the confidence in the models for the tectonic region under investigation. The situation is quite different in regions of low-to-moderate seismic activity, such as stable continental regions, or in regions that have historically had limited seismic monitoring (such as regions of crustal extension and normal faulting). This lack of relevant data results in higher uncertainties in the prediction of ground motions.

Figure 7 illustrates some of the uncertainty in the estimation of the aleatory variability parameter (σ_{LN}) for various GMPEs. This figure contains estimates of σ_{LN} developed as part of the recent Next Generation of Attenuation Relationships (NGA) Project.[12] Those relationships were developed using data from, and applicable to, tectonically active regions (these are denoted WUS in the figure). Also plotted on Figure 7 are estimates for aleatory variability for the stable central and eastern United States (CEUS) that were developed over a timespan of more than 20 years. There are two factors to note in this figure. First, the aleatory variability estimates are generally lower in the data-rich active tectonic areas relative to the data-poor, tectonically stable CEUS. Second, the aleatory variability estimate in the CEUS steadily increases from 1989 to 2006.

The uncertainty in the aleatory variability certainly has an effect on the hazard that would be computed at a given site. Figure 8 illustrates the influence of sigma (σ_{LN}) on the computed PGA hazard for a simple area source zone. The hazard in this example was calculated for a site at the center of the source zone. For this simplified example, the hazard level for a ground motion level of approximately 0.4 g (390 cm/s^2) differs by a factor of nearly 3. As noted in the discussion on the effect of M_{MAX} on the calculated hazard above, the slope of the hazard curves is sensitive to the uncertainty in σ_{LN}. Hence, this may potentially impact the design ground motions and PRA results.

The Yucca Mountain PSHA explicitly considered the inclusion of uncertainty in the estimate of the median ground motion as well as the uncertainty in the aleatory variability by the ground motion experts.[13] Figure 9 illustrates the sensitivity of computed PGA hazard to the ground motion expert models. The range of predicted hazard levels between the experts is very large. Detailed analysis of these results has shown that the uncertainty in the aleatory variability assigned by the experts is a significant fraction of the total uncertainty in ground motion prediction.[14] The lack of an extensive dataset of ground motion recordings for normal faulting on rock was a primary issue in the

[12] Next Generation of Attenuation Relationships: http://peer.berkeley.edu/products/nga_project.html.

[13] Stepp, J.C., et al., 2001. Probabilistic seismic hazard analyses for ground motions and fault displacement at Yucca Mountain, Nevada: *Earthquake Spectra*, **17**, pp. 113–152.

[14] G. Toro, pers. comm., 2008.

Yucca Mountain PSHA and contributed to the large uncertainties estimated by the ground motion experts in that study.

As with the problem of source characterization, the development of GMPEs for regions of low-to-moderate seismic activity includes significant epistemic uncertainties that must be evaluated and incorporated in the final hazard model to produce an unbiased estimate of at-site hazard.

4. A structured process for probabilistic seismic hazard analysis

The seismic hazard (defined as the annual frequency of exceeding a specified ground motion level) is a derived product that contains significant uncertainty resulting from the uncertainties inherent in the data and models used. Major gaps exist in our understanding of the physics of earthquake generation and the resultant propagation of strong ground shaking to locations of interest on the earth's surface. Well-qualified experts can legitimately interpret the limited information differently. These differences in interpretation will result in differences in the numerical results of the PSHA. As discussed above, these issues may be particularly acute in regions of lower seismic activity.

As noted previously, the U.S. Nuclear Regulatory Commission (NRC), the U.S. Department of Energy, and the Electric Power Research Institute sponsored a project in the 1990s to evaluate, in part, the differences in PSHA results that can arise from alternative interpretations of the data and to develop guidance on the proper conduct of a PSHA.[15] The seven-member committee that performed the evaluation (i.e., SSHAC) produced a report summarizing the findings and recommendations. That report has been referred to in this discussion as "the SSHAC Report." The following are a few key findings of the report:

- The objectives of a modern, detailed PSHA are to (1) incorporate all relevant uncertainties, (2) include the range of diverse technical interpretations that are consistent with the available data, (3) consider any site-specific data and knowledge, (4) develop clear, complete documentation, and (5) conduct a detailed peer review process.

- Previous evaluations have shown that differences between PSHA studies are often not technical, but rather arise from differences in initial assumptions and in the information gathering and assessment processes. The integration of the diverse types of data and models used in a modern PSHA requires an interdisciplinary approach and a coherent project structure to ensure a defensible and traceable product. The SSHAC Report concluded that the way in which a PSHA is structured is at least as critical to its success as the technical details, and perhaps more so.

- The SSHAC Report discussed in detail the various roles played by experts in the PSHA process. Experts can be asked to play the roles of proponent, evaluator, and/or technical integrator in a significant PSHA study. In addition, the project sponsor needs to understand both the procedural/structural aspects of the process and at least some of the technical details to properly develop, oversee, and evaluate the PSHA process.

[15] NUREG/CR-6372, 1997. Senior Seismic Hazard Analysis Committee, "Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts," Lawrence Livermore National Laboratory, Livermore, California, USA.

- The SSHAC Report defined a hierarchy of complexity for studies based on the technical complexity and political sensitivity of the major issues. The most detailed studies (identified as Level 3 and Level 4) utilize an entity (either as an individual or as a group) termed the technical integrator (TI) or technical facilitor/integrator (TFI) to perform the integration and oversight in the study.

The NRC is currently conducting a focused research project to capture the lessons learned from the application of the SSHAC process to several major projects in the past decade and to augment the guidance contained in the original SSHAC document. In January 2008, the agency conducted the first in a series of three workshops to be held as part of this project. While the results of this project will not be final for some time, several points were raised in the workshop that had general consensus among the participants. The following summarizes some of these "working points of discussion":[16]

- Any new guidance should make a clear distinction between the SSHAC process of expert assessment (i.e., interaction and learning) and the classic expert elicitation process. This will help preclude applications of irrelevant procedures (e.g., expert scoring) to the SSHAC processes.

- As written in the SSHAC Report, the integrator role is "shared" by the TFI and the experts. There has been some discussion as to the feasibility of this approach. Perhaps the experts should just be evaluators who consider the views of the larger technical community in light of available data, and the TFI is the integrator who ensures that, in aggregate, the range of evaluator assessments is consistent with the community distribution. The attributes of a good evaluator should be identified and considered in the selection of experts. The most productive researchers do not necessarily make the best evaluators.

- Following a structure, such as that outlined in the SSHAC Report for Level 3 or 4 studies, the process properly quantifies sources of uncertainty and represents the broader community position. This results in a number of benefits such as regulatory stability, public defensibility, and longevity. It is also important to consider whether it is possible to reap some of those benefits with a more focused and less-resource intensive approach.

- A composite model that captures the essence of all significant uncertainties, but is computationally more manageable, is needed for many subsequent applications (such as sensitivity studies). However, it can only be meaningfully constructed after a full expert assessment has been completed, potentially adding to the total duration of the hazard analysis. Ownership of this composite model by the experts and TI/TFI is desired.

- Active, aggressive participatory peer reviews are an effective means of addressing difficult process and technical issues. The role of technical peer reviewers is especially important for Level 2 and 3 studies. The sponsors of a major hazard study need to have sufficient technical expertise to understand and clearly specify the desired products, to understand the process being followed, and to interpret the results when they become available. In this sense, they must become co-owners of the study, not just the underwriters.

- Additional guidance needs to be developed for updating major PSHA studies. A means for determining the need for an update should be defined.

[16] K. Coppersmith, T. Hanks, N. Abrahamson, pers. comm., 2008.

5. Conclusions

The goal of a modern, high-quality PSHA is to provide an unbiased representation of the informed scientific community's view of the important input components (both data and models) and ultimately the site-specific hazard. It must also appropriately separate and account for the various uncertainties that arise in the PSHA inputs and process. The SSHAC Report concluded that this can be best accomplished using a structured process.

The goal of a structured process, like that described in the SSHAC Report, is not to search for artificial consensus, but rather to search for a defensible representation of the range of technically supportable interpretations of the informed technical community and an assessment of the credibility of the differing hypotheses across that range. This constitutes technical integration. It is this explicit integration and facilitation role that defines the SSHAC process for technically complex issues. It is important to point out that the likelihood of achieving this goal and defending the results is improved by formally involving a large number of the members of the community in a major study (i.e., Level 3 or 4). However, it may well be that a study that only performs a rigorous multiexpert assessment of key or critical portions of the seismic hazard models and/or inputs, when coupled with strong peer review, can achieve a high-quality, defensible product. The example shown in Figure 4[17] employs this approach. Some tradeoff will occur between the effectiveness of a high-level study and the efficiency of a study of reduced scope. This is an area that will require additional investigation.

One of the key conclusions of the SSHAC Report relates to the need for participatory peer review by acknowledged experts. The need for participation and review by well-informed project sponsors is also a critically important factor that contributes to the overall success of a major project. By being actively involved, the project sponsors better understand the conduct of the study and minimize the likelihood of late-breaking "surprises" in the results. Such participation also enhances a sense of ownership in the process and product.

In regions of low-to-moderate seismic activity, the need for a disciplined and structured approach may be especially important as the lack of data will lead to fewer constraints on plausible interpretations. This range of interpretations represents an epistemic uncertainty that the final hazard estimates need to reflect. The components of the source characterization activity that contribute significantly to the epistemic uncertainty are development of a seismotectonic model (which defines how deformation is occurring and where earthquakes are likely to occur, as well as influences choices in the selection and/or weighting of ground motion prediction equations), the assignment of activity rate to the seismic sources, and the definition of the maximum magnitude for all sources. As part of the ground motion prediction activity, the hazard calculations will need to formally incorporate the epistemic uncertainty in predicting both the median ground motion (for a given magnitude, distance, fault type, and site type) as well as the aleatory variability. This has proven to be a difficult task in regions with limited relevant empirical datasets. The need to use theoretical ground motion simulation results to produce ground motion prediction equations for these regions leads to difficulties in properly assigning epistemic and aleatory uncertainties.

[17] Anderson, L., and J. Ake, 2008. "Probabilistic Seismic Hazard Analysis for Folsom Dam and Mormon Island Auxiliary Dam, Central Valley Project, California," DRAFT Seismotectonic Report 2008-03, U.S. Bureau of Reclamation, Technical Service Center, Denver, Colorado, USA.

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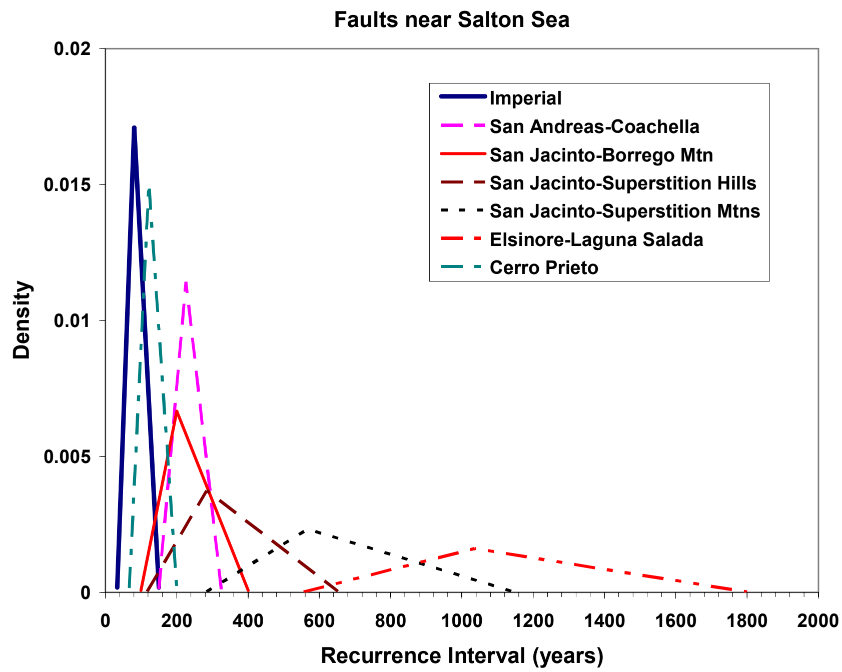

Figure 1. Density functions illustrating the uncertainty in recurrence interval for major faults in southern California near the Mexico-USA border.

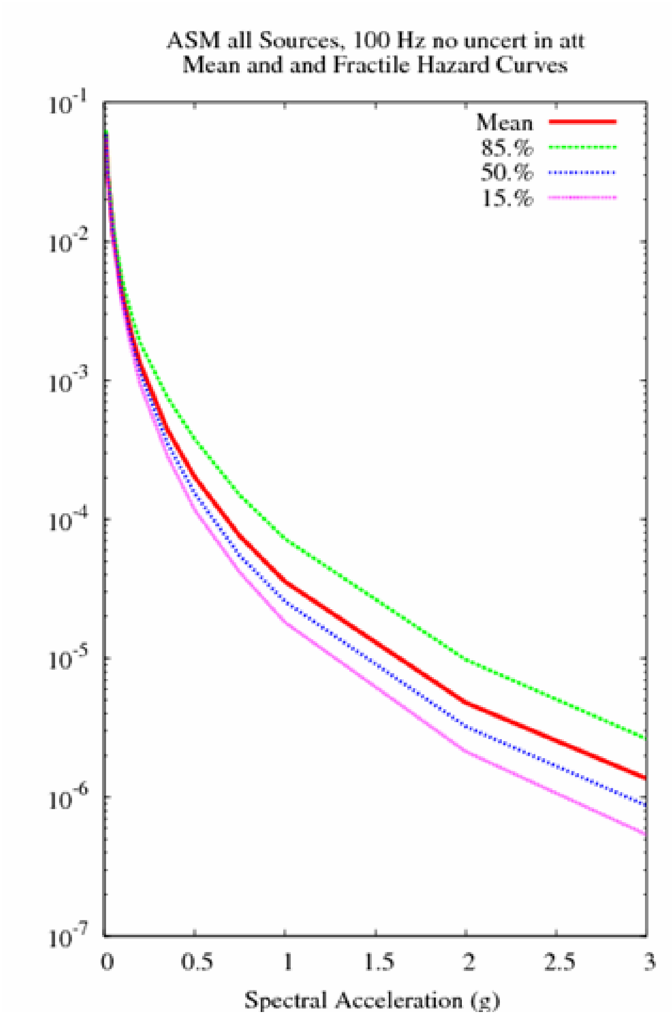

Figure 2a. Peak ground acceleration (PGA) hazard curve from Yucca Mountain PSHA showing effect of uncertainty in source characterization (i.e. no uncertainty in ground motion prediction model) for Team ASM.

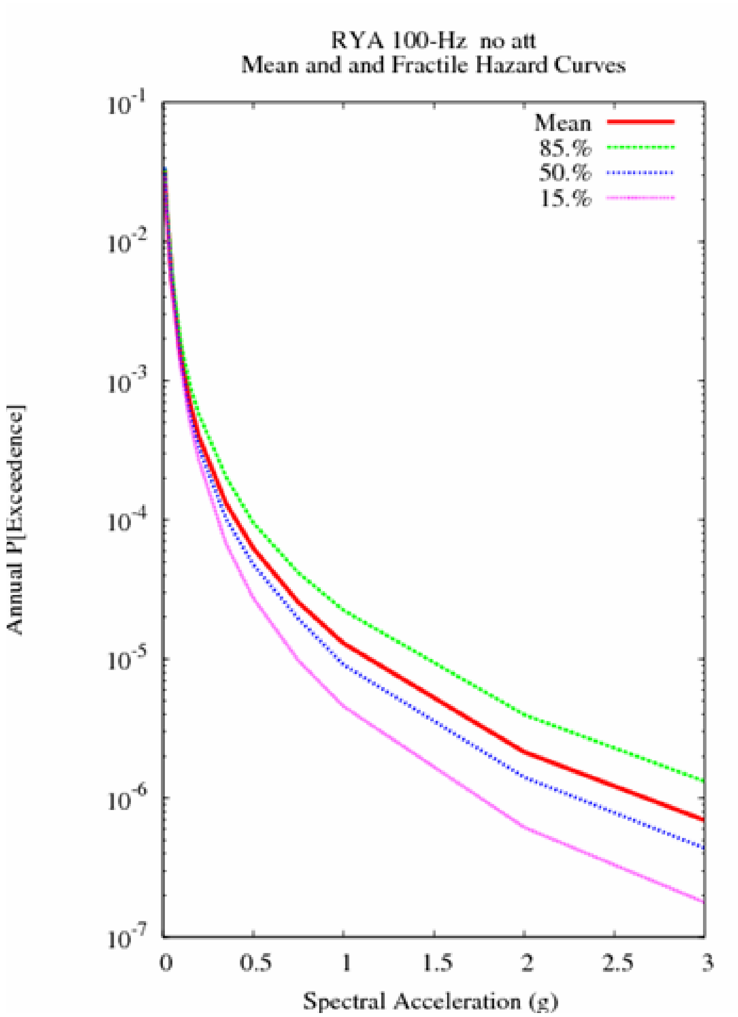

Figure 2b. PGA hazard curve from Yucca Mountain PSHA showing effect of uncertainty in source characterization (i.e. no uncertainty in ground motion prediction model) for Team RYA.

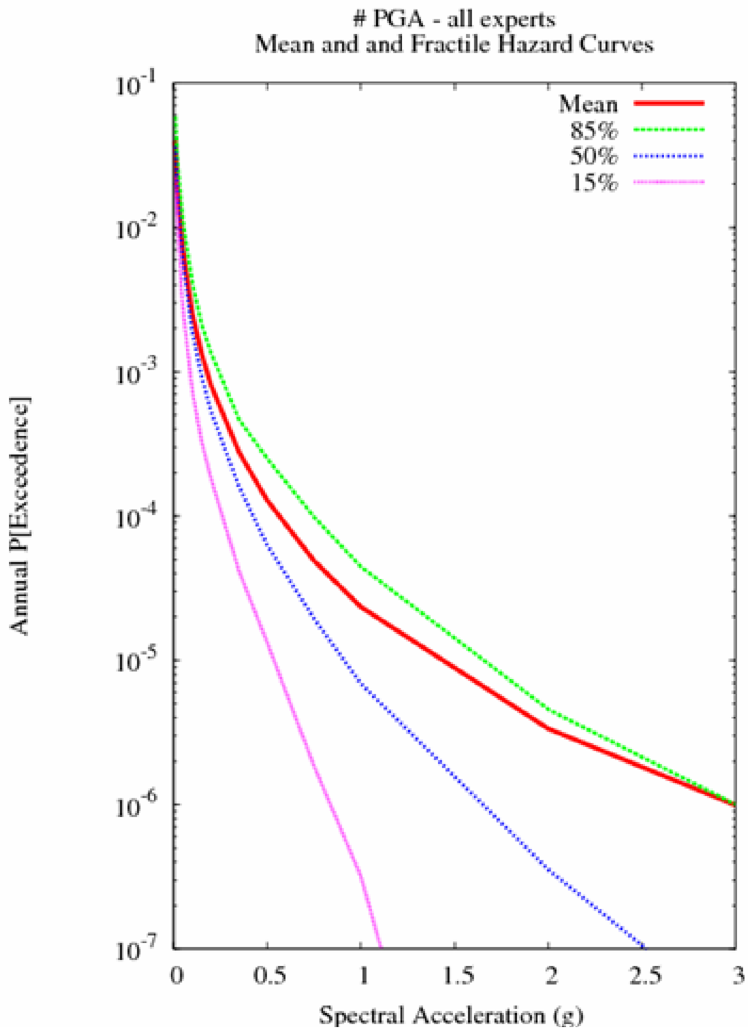

Figure 3. PGA hazard curve for Yucca Mountain site, Nevada USA. This curve contains uncertainty in both source characterization and ground motion prediction across all expert teams.

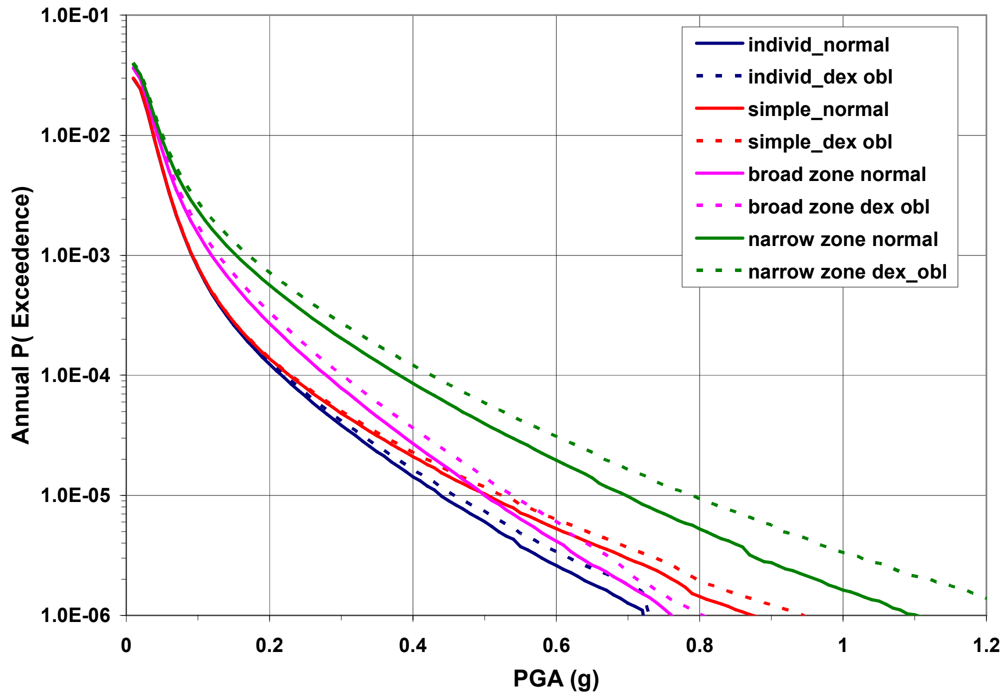

Figure 4. Comparison of mean PGA hazard curves for a site in north-central California illustrating the uncertainty due to source characterization. The different models in the caption refer to source geometry (discrete individual faults (indicated by "individ"), longer simplified representations of the faults ("simple"), either a broad or narrow zone of distributed deformation ("broad or narrow zone") and sense of slip on the faults ("normal" or "dextral-oblique").

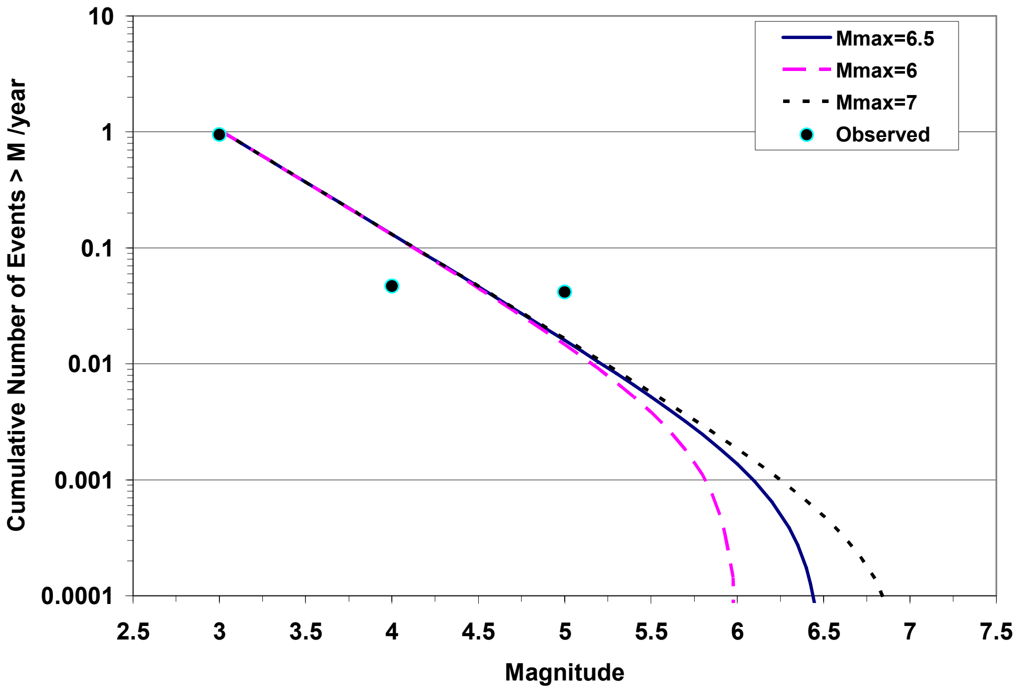

Figure 5. Cumulative recurrence data and curves for a source zone with moderate-to-low seismic activity rate. The observed data is plotted as circles in 1-magnitude unit bins. The recurrence curves were fit using the maximum likelihood method.

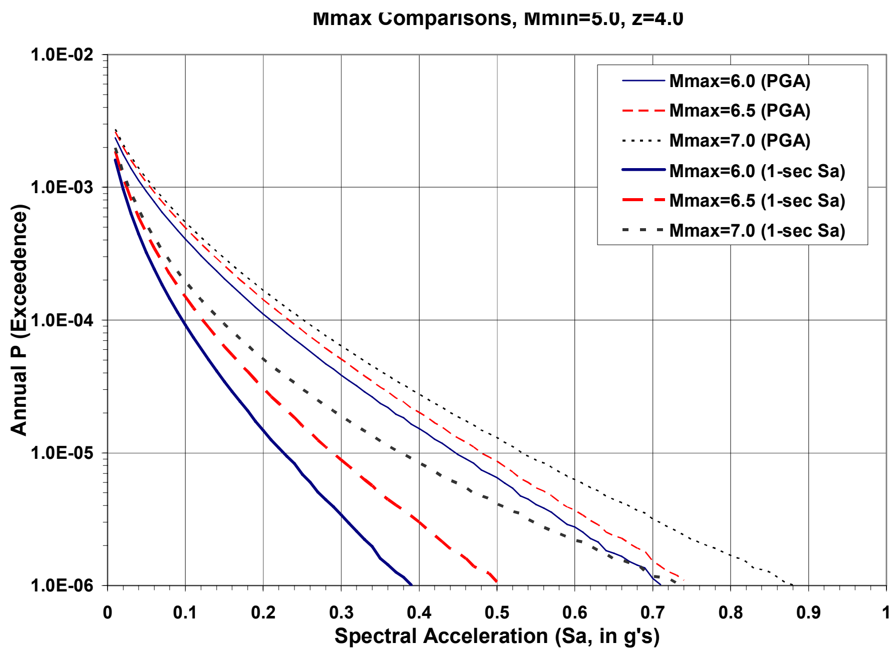

Figure 6. Comparison of mean hazard curves for alternative maximum magnitude scenarios shown in Figure 5. Results are shown for PGA and 1-s spectral acceleration (Sa). The site is located at the center of the source zone. A minimum magnitude of 5.0 and attenuation truncation of four standard deviations were used in the calculations.

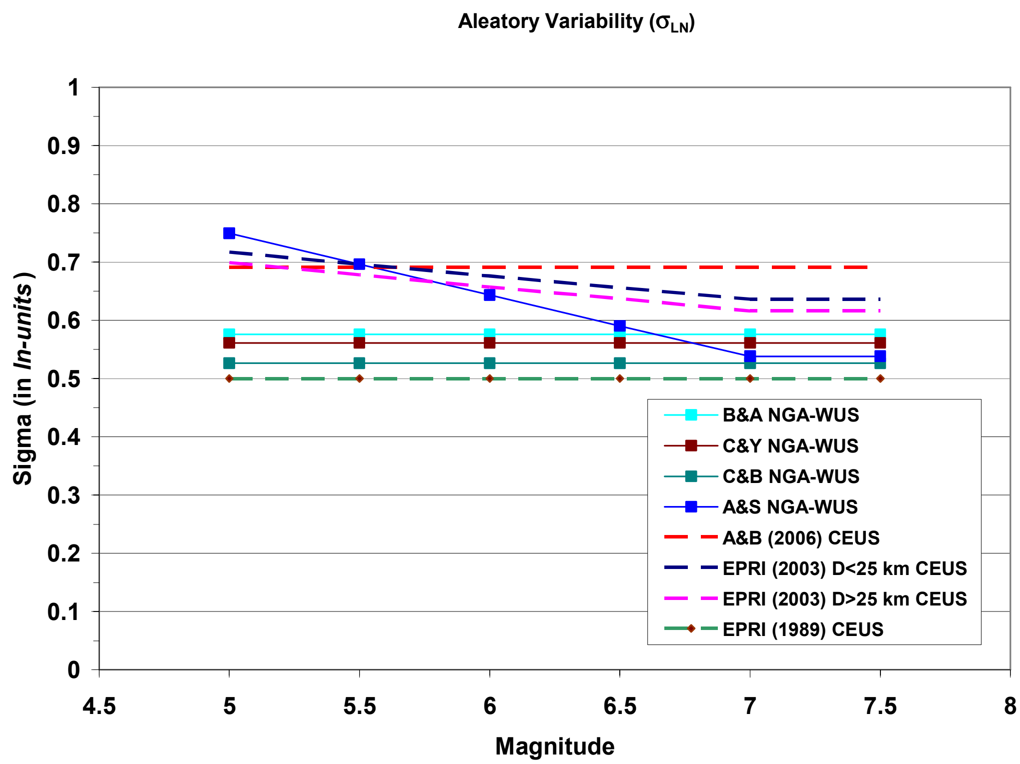

Figure 7. Comparison of estimates of the aleatory variability in selected ground motion prediction equations. The relationships denoted NGA-WUS are for the active tectonic portions of the western United States, those denoted CEUS are for the stable tectonic region of the central and eastern United States.

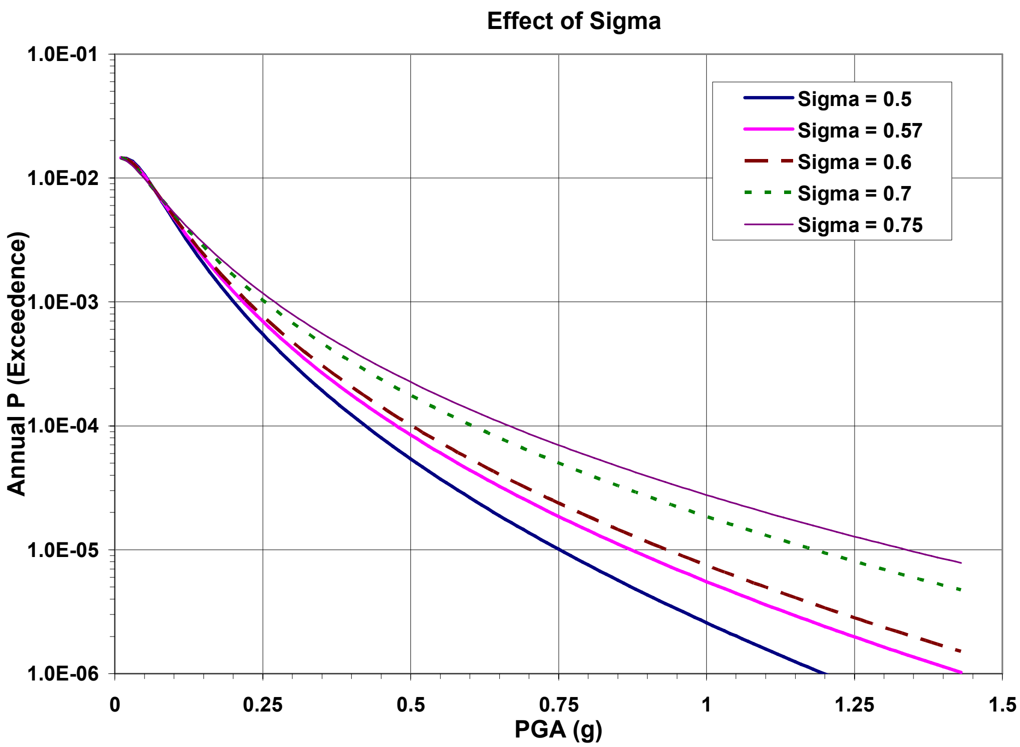

Figure 8. Comparison of mean PGA hazard for a simple area source zone illustrating the sensitivity to the aleatory variability (σ_{ln}). The hazard was calculated at the center the zone.

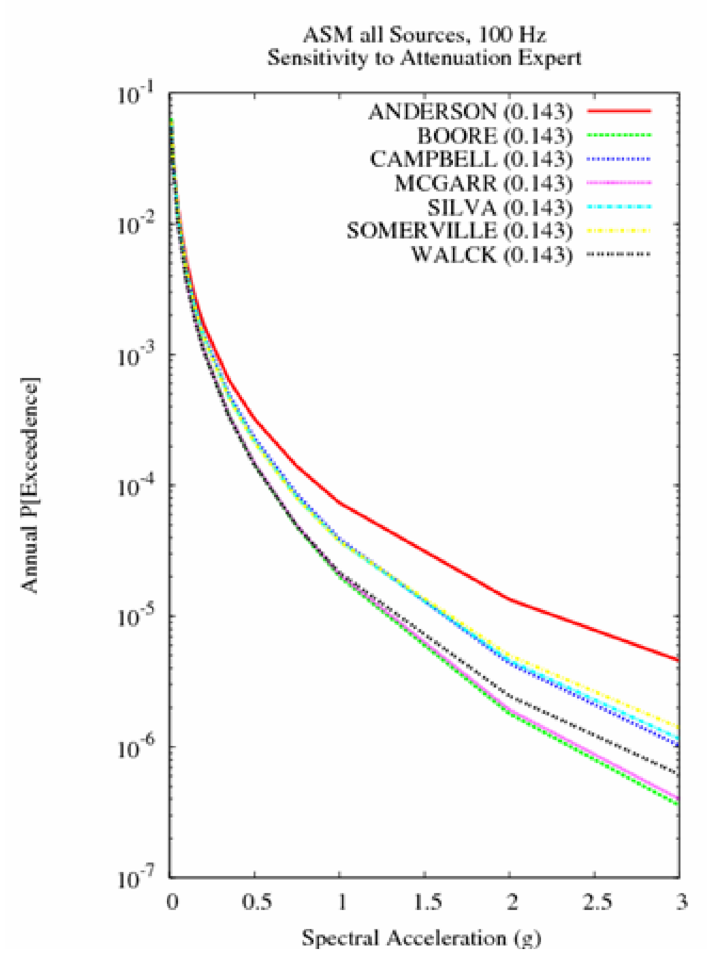

Figure 9. Comparison of mean PGA hazard for Yucca Mountain PSHA illustrating the sensitivity to ground motion expert models.