DEVELOPMENT OF IMPLEMENTATION GUIDANCE FOR SSHAC LEVEL 3 AND 4 ASSESSMENTS USED IN PROBABILISTIC SEISMIC HAZARD ANALYSES FOR NUCLEAR FACILITIES

A.M.Kammerer[1], J.J.Bommer[2], K.J.Coppersmith[3], J.P.Ake[1]
[1]US Nuclear Regulatory Commission, Washington D.C., USA
[2]Imperial College London, UK
[3]Coppersmith Consulting Inc., Walnut Creek, California, USA
Email of corresponding author: annie.kammerer@nrc.gov

ABSTRACT

Seismic risk analysis for nuclear facilities requires probabilistic characterization of both the earthquake loading and the fragility of structures, systems and components, including consideration of the important contributors to uncertainty. The seismic hazard is determined through a probabilistic seismic hazard analysis (PSHA), which requires demonstration that the analyses have identified, quantified and incorporated both aleatory and epistemic uncertainties. The explicit characterization of uncertainty contributes to regulatory assurance by reducing the likelihood of unforeseen circumstances that have not been considered in the safety evaluation. Aleatory (random) variability in both the degree and timing of future seismicity and the ground shaking generated by specific earthquakes is accounted for through an integration process within PSHA. However, the associated epistemic (modeling or interpretation) uncertainty requires expert judgment and the use of logic trees. For critical facilities such as nuclear power plants (NPPs), the judgments of multiple experts are required to capture the complete distribution of technically defensible interpretations of the available Earth science data. The guidelines developed by the Senior Seismic Hazard Analysis Committee (SSHAC) as described in NUREG/CR-6372 provide a structured framework for conducting multiple expert assessments. Following 15 years of experience in applying the SSHAC guidelines for hazard studies for critical facilities, the US Nuclear Regulatory Commission (NRC) conducted a study of the lessons learned from practice. These lessons have now been distilled into a new US NRC NUREG-series report that provides additional practical guidance on implementing the SSHAC assessment process. The NUREG focuses primarily on the higher levels of SSHAC process (Levels 3 and 4), which are the most complex but provide a higher degree of regulatory assurance. The new NUREG gives clear guidance on the requirements for such studies, particularly SSHAC Level 3, which received relatively little attention in the original SSHAC guidelines (where the emphasis was on Level 4 studies). This NUREG also corrects the misperception that the most significant increase in complexity and likelihood of regulatory assurance occurs between Levels 3 and 4. The actual increase occurs between Levels 2 and 3. Indeed, for new nuclear sites the NRC makes no distinction between Level 3 and 4 studies, both of which are viewed as appropriate processes for conducting new PSHA studies.

INTRODUCTION

Prior to issuance of a license to build and operate a nuclear power plant (NPP), adequate protection of the safety-critical systems, structures and components (SSCs) against internal and external hazards must be demonstrated. Advances in reactor design and the enhancement of regulations over recent decades have led to increasingly greater levels of safety in new and operating NPPs. However, because of the reduction in the relative contribution from internal hazards resulting from plant improvements and tightened operational control, “common cause” external hazards—and particularly earthquake loading—tends to be an important, and frequently dominant, contributor to calculations of core damage frequency. This observation has been found to hold even in regions of relatively low seismicity. A result of this evolution is that there is now increased focus on the assessment of seismic risk in NPPs, and consequently on the underlying assessment of the earthquake loading to which such facilities could be subjected. The focus of this paper is specifically on the method of assessment of seismic hazard for NPPs and new and existing NRC guidance describing the framework for conducting such studies within a regulatory environment.

Risk-informed design and assessment of critical facilities requires characterization of external loads, such as those related to earthquake-induced shaking, in a manner that captures both the rate of occurrence of earthquakes of different magnitudes and the natural randomness (often referred to now as aleatory variability) in earthquake location and ground motion amplitudes. This leads to the choice of probabilistic seismic hazard analysis (PSHA) as the preferred approach for determining ground motion inputs for seismic design and for risk analysis of critical structures [1]. PSHA was first introduced by C.A. Cornell in 1968 [2] and has undergone subsequent developments and refinement, a key focus of which has been ensuring inclusion of all aleatory variability [3,4]. For rock sites, the key inputs to a PSHA are a seismic source characterization (SSC) model and a ground motion characterization (GMC) model. The former defines the possible locations and rates of occurrence of earthquakes of different magnitudes, whereas the latter predicts the distribution of ground motion amplitudes at a particular location as a result of a specific earthquake. The basic steps of a PSHA to construct seismic hazard curves are illustrated in Figure 10.2 of the textbook by Reiter [5] and Figure 4.6 of the textbook by Kramer [6], as well as in Figure 1 of Fernandez Ares and Fatehi [7], for example. At soil sites, the change in ground motion properties due to response of geological materials at the site must also be addressed.

Epistemic Uncertainty, Logic Trees and Expert Judgment

The complexity of the processes that generate earthquakes and the consequent ground shaking, and the invariably limited data available for seismic source and ground motion characterization, result in a range of technically defensible interpretations of the complete set of Earth science data. This leads to many of the greatest challenges in SSC and GMC development. The fact that there is almost never a unique and unambiguous model for any component of the hazard input models reflects our generally imperfect knowledge of earthquake processes and of the factors influencing the shaking hazard at a specific location. This is referred to as epistemic uncertainty. In theory, epistemic uncertainty can be reduced through the acquisition of additional data and improved understanding of the physical processes involved in earthquake generation and seismic wave propagation. However, in practice a significant degree of epistemic uncertainty will always be associated with the SSC and GMC models developed for PSHA, and expert judgment is required to infer both the most defensible and the most likely technical interpretations and their associated epistemic uncertainties. The tool most commonly used to incorporate epistemic uncertainty in current PSHA practice is the logic tree [8,9], in which alternative parameter values are placed on different branches and assigned weights (summing to unity at each node). The weights reflect the relative merit of each alternative value in the view of the analyst. As described below, development of a complete PSHA model (in the form of a logic tree) that captures the center, body and range of technically defensible interpretations is the goal of the SSC and GMC development processes in NRC guidelines.

Seismic Hazard and Risk

The safety case for a NPP ultimately rests on demonstrating an acceptably low risk level, which will generally be specified in terms of an annual probability or frequency of core damage. The mean seismic core damage frequency (SCDF) is calculated from convolution of the mean hazard curve and the mean plant-level fragility [10], as illustrated in Fig. 1.

For both the hazard and the fragility, the mean is influenced by the range of uncertainty which requires that all contributions to uncertainty are identified, quantified and incorporated into the analyses. For a seismic margins approach, the required input is the median and 95-percentile fragility curves and the mean hazard curve, as embodied in ASCE 43-05 [11], for example. A full seismic probabilistic risk assessment (PRA) requires definition of the full suite of fractiles on both the hazard and fragility curves. This reinforces the need for the full range of epistemic uncertainty in the seismic hazard estimate to be adequately captured.

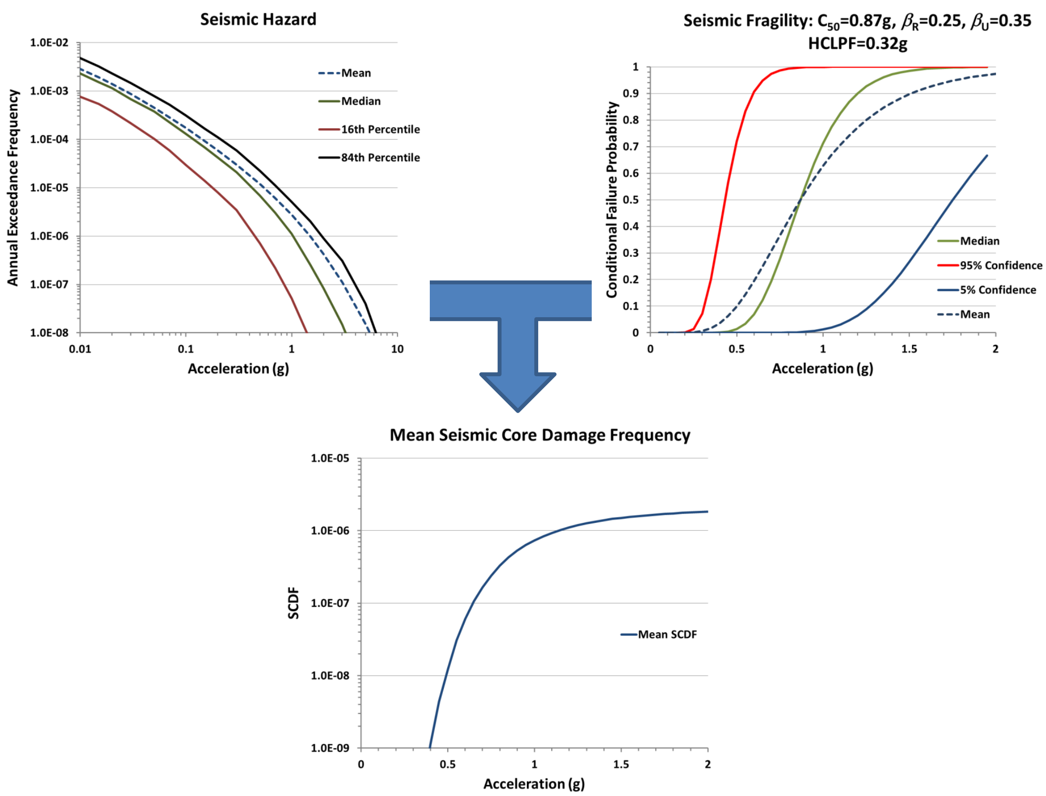

Fig.1: Illustration of the elements of a seismic risk analysis for a NPP in which the seismic hazard (*top left*) is convolved with the fragility (*top right*) to obtain the mean seismic core damage frequency (*bottom*)

SSHAC PROCESSES FOR SEISMIC HAZARD ANALYSES

This section outlines the motivation for the SSHAC Guidelines (more formally known as NUREG/CR-6372), the essential features of a SSHAC process and the lessons that have been learned from 15 years of practical experience in implementing the guidelines in practice. The section closes with a brief overview of the essential steps of a SSHAC Level 3 study, and a discussion of a new NUREG-series report that provides more detailed practical guidance on the execution of Level 3 and 4 studies.

Background to the SSHAC Guidelines

The motivation for the SSHAC guidelines lies in two major PSHA studies conducted in the 1980s for NPP sites in Central and Eastern United States (CEUS). The CEUS is a region of relatively low seismicity rates where significant earthquakes have occurred but where the tectonic associations of observed seismicity to tectonic features are tenuous and data on long term recurrence rates are very limited. Recognizing the degree of uncertainty that exists in the seismicity and ground motion models for this region, the seismic hazard studies undertaken for this region by the Electric Power Research Institute (EPRI) [12] and by Lawrence Livermore National Laboratory (LLNL) [13] included several experts—each developing their own hazard input models. The studies resulted in very different hazard estimates for many locations in the CEUS both between the projects and amongst the experts within each project. In both projects, the problem arose as to how to combine the various expert models into a single hazard assessment. This led to reflection on how the views of multiple experts can be reconciled and the degree of interaction that the experts should have during the process. Concerns about the issues and discrepancies that arose in the EPRI and LLNL studies eventually led the US Nuclear Regulatory Commission (USNRC), Electric Power Research Institute, and the US Department of Energy (DOE) to form the Senior Seismic Hazard Analysis Committee (SSHAC) to review the state-of-the-art in PSHA and to formulate guidelines for conducting such studies, with the goal of bringing more consistency and greater stability to the process. The initial finding of SSHAC was that the differences in the PSHA results from the LLNL and EPRI studies were mainly due to procedural—rather than technical—differences. As a result, the work of SSHAC was focused primarily on developing appropriate approaches to the organization and the methods used for gathering expert judgments rather than the technical aspects of probabilistic assessments.

The outcome of the work undertaken by SSHAC was a lengthy report published by the USNRC in 1997 [14] that in many ways defined a new benchmark for expert assessment and uncertainty treatment in seismic hazard analysis. This document, which came to be known as the "SSHAC guidelines", describes a formal process for structuring and conducting expert assessments in the development of PSHA models and studies. Recently, a new NRC NUREG (discussed below) has been developed to complement the original SSHAC guidelines by providing more detailed guidance for implementing the SSHAC assessment process.

The guidelines define four different levels at which PSHA studies can be conducted, increasing in sophistication and complexity from Level 1 to Level 4. The choice of study level in an instance will generally be consistent with the importance of the project for which the study is being conducted and with the resources and time made available for the study. As a result, for US NPPs only Level 3 and Level 4 studies can be used for new regional studies or site-specific studies where a regional study does not exist. Level 2 site-specific refinements to incorporate local sources should be undertaken for sites where a Level 3 or 4 regional study exists.

Key Components of a SSHAC Process

The fundamental objective of the SSHAC process is to develop PSHA SSC and GMC models that capture the center, the body and the range (CBR) of technically defensible interpretations (TDI) of the available data, models and methods. Any PSHA must begin with the compilation of databases, gathering all available information relevant to the assessment of seismic hazard at the site of interest, and possibly undertaking new data collection activities. This preliminary phase is very important to emphasize because expert judgment should never be an alternative for data or measurements that can reasonably be obtained. Uncertainty can be reduced by assuring that all available data have been compiled and analyzed. As noted, the first objective of a PSHA should be to identify the center, the body and the range of the TDI. The *center* describes the best models for characterizing the seismic sources and the ground motion predictions in the region. The *body* relates to the shape of the distribution around this best estimate and represents the associated uncertainty. Finally the *range* represents the limits of models or parameter values that are considered possible.

Essential to the SSHAC process is defining clear roles in a PSHA study and selecting individuals who have the required attributes, and who are willing to assume the responsibilities attendant to their assigned role. Each of these roles is briefly described in the following paragraphs.

The key role in the SSHAC process is that of an *evaluator expert*, which is an individual or a team that is tasked with objectively examining available data and diverse models, including challenging their technical bases and underlying assumptions. Where possible, the models should be tested against observations. The goal for the evaluator expert is to identify the full range of legitimate technical interpretations and to assign weights to each of these that reflect a relative degree of belief that the interpretation is the most appropriate representation of nature for the application in question. The evaluator expert is not obliged to include all models that have been put forward in the field, but the technical basis for excluding a model must be clearly documented bearing in mind the responsibility to capture the CBR of the TDI.

An equally important role in a SSHAC process is that of an *integrator.* The process of integration follows directly from the evaluation phase and is again performed by an individual or a team. In the integration phase, a model (essentially a logic tree for SSC or GMC inputs) is constructed that represents not only the evaluations of the experts but also those of the larger technical community. The evaluator experts and integrators are the same group in a Level 3 study, and are different groups in a Level 4 study.

In order to inform the assessments of evaluator experts, two other groups of experts are invited to participate in a SSHAC process. The first of these are *resource experts*, who possess (or acquire through extensive review conducted specifically for the study, in which case they are often designated as *Specialty Contractors*) knowledge of a particular dataset, model or method. The key characteristic of their participation is that the resource expert presents the data, methods or models impartially, highlighting assumptions, limitations and caveats. The evaluator experts will pose questions to resource experts in order to obtain insight into the nature and value of the data, models and methods. The other type of expert is the *proponent expert*, who presents a model or method from a partisan perspective. The proponent expert will propose that the method or model be adopted and will then defend that position in the face of technical challenge from the evaluator experts. The proponent role is a common role in the broader scientific community, whereby individual researchers develop hypotheses based on the available data and advocate those hypotheses to their peers through publication and professional interactions.

The core concept in all four levels of the SSHAC method is that of a Technical Integrator (TI), which may be an individual or a team. The TI takes on the task of defining the center, the body and the range of technically defensible interpretations. The TI role therefore combines the roles of evaluator and integrator. In a Level 1 study, the TI undertakes the assessment based only on the available published and unpublished data and models. The distinction of a Level 2 study is made when the TI (or TI team) interacts with resource and proponent experts – who are very often authors of the data reports or models that the TI is evaluating – in order to obtain additional insights and information. The majority of PSHA studies are carried out as Level 1 or 2 processes in the SSHAC framework.

When the degree of uncertainty or controversy regarding technical interpretations of seismicity in a given region is higher, there will be greater onus to engage more experts and hence adopt a higher SSHAC Level for the PSHA. However, the primary motivation for adopting a higher level of study will generally be the nature of the project or facility for which the PSHA is being conducted. For safety-critical installations such as NPPs, for example, it becomes particularly important to be able to provide assurance that the uncertainty has been fully captured in the hazard analysis. For this reason, in a nuclear regulatory environment, Level 1 and 2 studies will generally not be considered adequate for the initial development of hazard models, and it would be expected for PSHA studies to be conducted as Level 3 or Level 4 processes.

In a Level 3 process, the key entity is still the TI but this will generally be a larger TI Team of evaluator experts. In a Level 3, the TI Team will interact with resource and proponent experts through formal workshops (discussed below). The TI Team is ultimately responsible for the technical evaluations and the integration process.

The concept of Technical Facilitator-Integrator (TFI) was defined specifically for Level 4 studies, in which panels of evaluator experts are assembled. The panels interact in workshops, but also develop individual assessments. The TFI coordinates and facilitates the interactions within the workshops and also conducts one-to-one interviews with the evaluator experts regarding the development of their models. In essence, the integration is ultimately performed by the TFI supported by the evaluator experts. The SSHAC guidelines allow for the TFI to apply unequal weights to the members of the evaluator expert panels, but the more desirable approach is that the models from the individual evaluators (or evaluator teams) are assigned equal weights in the final logic tree.

Level 3 and 4 studies are significantly more intensive than Level 1 and 2 studies, requiring more time, effort and money, but they provide a much higher level of assurance within a regulatory environment. This is largely because greater numbers of experts are involved and their participation is clearly recorded through participation in workshops and the resulting documentation. Additional assurance comes from the fact that the experts' evaluations and decisions undergo extensive technical challenge, in the first instance from other experts and finally from the peer reviewers. Robust technical defenses must be provided.

Rigorous peer review is another feature of the SSHAC process that contributes towards higher levels of regulatory assurance. The SSHAC guidelines place great emphasis on the importance of peer review and strongly recommend that this be participatory and continual throughout the project, rather than late stage. This means that the reviewers are engaged from the beginning of the study and have interactions with the TI at regular intervals rather than simply receiving a draft final report to review. The advantage of on-going participatory review is that any required corrections can be made early in the study before the models are finalized and the hazard calculations executed.

Although participatory, or continual, peer review is recommended at all study levels, in SSHAC Level 3 and 4 processes, a formal Participatory Peer Review Panel (PPRP) is formed. The PPRP is compromised of individuals who collectively possess expertise in all of the key disciplines involved in the study, in addition to an understanding of the overall process of PSHA. The members of the PPRP should be familiar with the concepts of SSHAC and aware of the dangers of cognitive bias and anchoring, which can affect expert judgments. The PPRP has two roles to perform, the first being *technical* review, which means ensuring that the full range of technical views has been considered in the study and that the technical bases for all decisions and assessments is adequately presented to justify the final structure and weights on the logic tree. The PPRP is not charged with giving its own technical views, and this is to be discouraged in order to maintain a high degree of objectivity in reviewing the study. The second role of the PPRP is to review *process*, ensuring that the study has been conducted according to the principles set forth in the SSHAC guidelines, in particular with regards to the conduct of the workshops. The PPRP also plays a vital role in reviewing, for completeness and clarity, the final PSHA report in draft form and when it is finalized following feedback. At the very end of the project, it would normally be expected that the PPRP would issue a signed letter report stating that the PSHA is technically complete and has been conducted in accordance with the SSHAC guidelines. This letter report is then appended to the final project report. Thorough and clear documentation cannot guarantee regulatory acceptance of a seismic hazard assessment, but it can be expected to increase the likelihood of acceptance, and to minimize questions from the regulator, thereby potentially shortening review times for license applications.

Lessons Learned from Implementation

The SSHAC Level 4 process has been used for two PSHA studies, the first for the Yucca Mountain nuclear waste repository in Nevada [16] and the second for four NPP sites in Switzerland for the PEGASOS project [17]. Several SSHAC Level 3 studies have also been conducted, or are currently underway, and these are discussed subsequently. In order to gather and document the lessons learned from these higher level SSHAC studies, the US NRC launched a research program entitled "Practical Procedures for Implementation of the SSHAC Guidelines and for Updating PSHAs", which began with three workshops held jointly with the US Geological Survey in 2008. The findings from the workshops, which were attended by a total of 56 people with direct experience in SSHAC Level 3 and 4 studies, were summarized in a USGS Open File report [18].

One key conclusion from the review of practical experience in implementing SSHAC studies was that greater guidance was required for the conduct of SSHAC Level 3 studies. The detailed guidance on Level 4 studies—including the innovative concept of the TFI—was a major contribution of the original SSHAC guidelines, but very little attention was paid to Level 3 studies. This led to the widespread view that the most significant increment in terms of complexity, cost and subsequent regulatory assurance, came with the step from a Level 3 to a Level 4 study, whereas in reality the major change occurs as one moves from a Level 2 study to a Level 3 study. The NRC makes no distinction between Level 3 and 4 studies for conducting PSHA at nuclear sites. However, clear guidance on the requirements for a Level 3 study (which are not greatly different from that of a Level 4 study), was needed and this is one of the key purposes of the new NUREG that has been produced as part of the NRC research program mentioned above.

Essential Steps of a SSHAC Level 3 Process

A SSHAC Level 3 process involves assembling suitably qualified individuals to fill the roles described previously, including the PPRP and the TI Teams for SSC and GMC issues. Within the TI teams, it is helpful to assign a TI Lead.

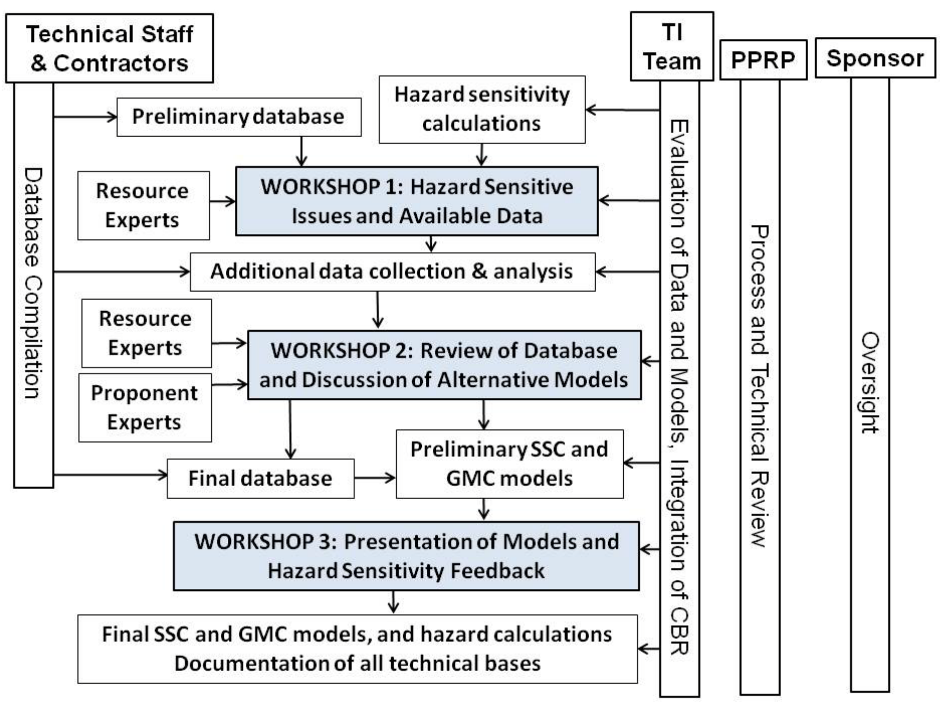

Fig.2: Overview of SSHAC Level 3 PSHA study (time is the vertical axis running from the top of the figure) [adapted from 19]

Moreover, it has been found that it is useful to also assign an individual to the role of Project Technical Integrator (PTI). The PTI acts as a single point of contact between the TI teams and with both the Project Manager and hazard calculation team. The PTI—who may also be one of the TI Leads—also has specific responsibility for ensuring that interface issues (between the SSC and GMC subprojects, and also between the hazard input models, the hazard calculations, and the engineering requirements downstream) are appropriately addressed. The project must include a minimum of three formal workshops, as illustrated in Fig. 2.

FUTURE PERSPECTIVES

The global nuclear renaissance, and increased public and regulatory concern regarding seismic safety of NPPs, is likely to lead to the more widespread application of higher level SSHAC processes. Because it offers advantages of flexibility and reduced time and costs, Level 3 processes will likely be used more often than Level 4 studies. At the time of writing, the first ever SSHAC Level 3 site-specific PSHA for a new nuclear site is underway in South Africa.

Site-Specific vs. Regional Hazard Assessments

For any country in which there will be NPPs built at multiple sites, it can become more cost-effective and efficient to conduct national or regional SSHAC Level 3 projects to develop SSC and GMC models, which can then be used as the basic input to site-specific PSHA conducted as Level 2 studies (Fig. 3). Although there may initially be additional time and costs in preparing the license application for the first site following such an approach, it can be easily shown that once three or more sites are under consideration, there can be considerable benefits both in terms of cost and schedule by conducting a single regional study [20]. There is a precedent for such an approach for nuclear facility sites in the Central and Eastern United States (CEUS) where USNRC, EPRI and DOE have funded a SSHAC Level 3 SSC project (to be completed in 2011), and a parallel GMC project (NGA-East) that is scheduled for completion in 2014. In the case of the US, site-specific Level 2 updates to the CEUS SSC regional model should be conducted in order to bring in local sources.

SSHAC Processes for Other Geo-hazards

Although the SSHAC Guidelines were originally written specifically for PSHA in terms of ground shaking, the Yucca Mountain project applied Level 4 processes to the probabilistic assessment of fault rupture hazard [16] and volcanic hazard. As probabilistic approaches to the analysis of other geo-hazards (e.g., tsunamis, liquefaction and seismically-induced slope instability) grows, the SSHAC Level 3 and Level 4 assessment frameworks could easily be adapted to the assessment of these hazards. There is also no reason why the SSHAC Level 3 and 4 processes could not be adapted to capturing the center, body and range of interpretations in developing fragility models for nuclear facilities.

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