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CHAPTER 1 INTRODUCTION

1.1 Background and History

The Central and Eastern United States Seismic Source Characterization for Nuclear Facilities (CEUS SSC) Project was conducted over the period from April 2008 to December 2011 to provide a regional seismic source model for use in probabilistic seismic hazard analyses (PSHAs) for nuclear facilities. As such, the CEUS SSC model replaces regional seismic source models for this region that are currently accepted by the Nuclear Regulatory Commission (NRC) for assessing seismic design bases and their associated uncertainties satisfying the requirements of the seismic regulation, 10 CFR Part 100.23. The models being replaced are the Electric Power Research Institute–Seismicity Owners Group (EPRI-SOG) SSC model (EPRI, 1988) and the Lawrence Livermore National Laboratory (LLNL) SSC model (Bernreuter et al., 1989) sponsored by the NRC.

Unlike the pioneering EPRI and LLNL projects, which were conducted independently, the CEUS SSC Project had multiple stakeholders who joined to sponsor it. They include the EPRI Advanced Nuclear Technology Program, the U.S. Department of Energy (DOE) Office of Nuclear Energy and Office of the Chief of Nuclear Safety, and the NRC Office of Nuclear Regulatory Research. Importantly, in the time since these early regional seismic source models were developed, the methodology for developing PSHA models has benefited from extensive application and regulatory review. As will be described in Section 1.1.2, following review of the EPRI and LLNL SSC models, which were developed using somewhat different process methodologies to evaluate and quantify uncertainties, the NRC, DOE, and EPRI jointly sponsored development of a standard methodology called the SSHAC methodology. This project used a SSHAC Level 3 assessment process in order to adequately ensure compliance with the requirement of the seismic regulations to properly quantify uncertainties in seismic design basis for nuclear facilities.

The regional SSC model developed by this project can be used for site-specific PSHAs with appropriate site-specific refinements as required by current regulatory guidance. For example, NRC Regulatory Guide 1.208 requires the development of an up-to-date, site-specific earth science database to support every nuclear facility license application. In the course of developing the database, local refinements to the CEUS SSC model may be necessary to accommodate local information.

The SSC model has incorporated earthquake source parameters in order to be compatible with current and anticipated ground-motion characterization (GMC) models. The current accepted ground-motion models for use at nuclear facilities are those developed by EPRI (2004, 2006), The ongoing Next Generation Attenuation–East Project will provide ground motion models that are appropriate for use with the CEUS SSC model; these models are expected to be adopted as part of the seismic safety regulatory guidance, replacing the EPRI (2004, 2006) models.

The remainder of this chapter provides a summary of the historical context for the CEUS SSC Project and a description of how the project meets the needs of the seismic hazard community.

1.1.1 EPRI-SOG and LLNL Projects

The CEUS SSC Project replaces the SSC components of the landmark seismic hazard projects conducted in the 1980s by EPRI-SOG (EPRI, 1988) and LLNL (Bernreuter et al., 1989). Both of these projects developed PSHA models for application in the broad region of the United States to the east of the Rocky Mountains. Recent licensing applications for nuclear facilities submitted to the NRC have followed regulatory guidance by using the EPRI-SOG SSC model as a starting point, with updates as appropriate on a site-specific basis for site-specific PSHAs. However, while the regional SSC model has been updated for specific sites, it has not been systematically updated to account for the significant new data in the CEUS. The CEUS SSC Project takes full advantage of the following historical and new sources: data used to develop the two previous CEUS models; new data and information developed over the past 20 years, including that developed for the U.S. Geological Survey (USGS) seismic hazard mapping program (Petersen et al., 2008); and other information and hazard analyses that were developed as part of licensing actions for proposed and existing nuclear power facilities. In addition to the new data, updated methods for evaluating the data and quantifying uncertainties have been implemented in the CEUS SSC Project.

1.1.2 Development of the SSHAC Process

Methodological guidance on how to perform a PSHA properly representing uncertainty was developed by the Senior Seismic Hazard Analysis Committee (SSHAC) in 1997 in a study jointly sponsored by the NRC, DOE, and EPRI (Budnitz et al., 1997). Both technical and procedural guidance was developed by SSHAC based on its evaluations of past PSHAs, which included the EPRI-SOG and LLNL models. Although both of those large projects relied on evaluations and assessments by multiple experts, there were significant technical and procedural differences between the two. There were also significant differences between the hazard results obtained at many of the same sites. The formation of SSHAC was motivated by the need to (1) understand these differences and (2) develop guidelines for evaluating and quantifying uncertainty in seismic hazard models—specifically, guidelines that would ensure that future PSHAs would satisfy the requirements for seismic safety regulation of nuclear facilities. The final guidelines resulting from the study were published in 1997 in NUREG/CR-6372 (Budnitz et al., 1997) and, following review by a committee of the National Academy of Sciences, were incorporated into the NRC's seismic regulatory procedures guidance.

The SSHAC guidelines provide a structured procedure for systematically compiling applicable data sets, evaluating those data relative to their application for SSC, assembling representatives of alternative hypotheses and interpretations within the technical community for discussion of their hypotheses and associated uncertainties, and performing integration of a SSC model that represents the center, body, and range of technically defensible interpretations in light of the views of the larger technical community. The formalism imposed by the SSHAC process was not available at the time the EPRI-SOG and LLNL projects were conducted two decades ago, so it is timely that a new SSC model was developed that takes advantage of the technical and procedural knowledge gained since those studies were carried out. As will be discussed in Section 2.1, the CEUS SSC Project is only the latest in a number of PSHA model development projects conducted using the SSHAC guidelines since the time of their issuance.

Under NRC sponsorship, the USGS completed an assessment of the lessons learned from the application of the SSHAC process in various projects since the SSHAC guidelines were issued. The results of that evaluation are given in Hanks et al. (2009). In light of the experience gained in actual SSHAC projects, the NRC (2011) has developed a NUREG document that provides detailed implementation guidance for conducting SSHAC Level 3 and 4 projects. That document will be issued later this year.

1.1.3 Implementation of the SSHAC Methodology

SSHAC concluded that *how* a seismic hazard project is carried out can be just as important as *what* is being assessed technically. This emphasizes that process methodology is important, and experience implementing the methodology is equally important. The project team assembled for the CEUS SSC Project is composed of distinguished experts from industry, government, and academia. These experts have extensive experience in developing PSHAs for sites both throughout the United States and worldwide. In addition, most of these experts have developed key data sets used for SSC in the CEUS and have participated in important studies that form the basis for conducting PSHAs. Most of the participants have considerable experience with implementing SSHAC processes as either expert evaluators or peer reviewers. The roles and responsibilities of participants in the CEUS SSC Project were explicitly defined, following SSHAC guidelines, for a successful Level 3 assessment project (see Section 2.2), and were diligently followed. Because many of the project participants have significant experience on recent and ongoing SSHAC projects, they knew these roles and appreciated their importance from the outset. All participants were reminded of their roles throughout the project. This experience makes the project team exceptionally qualified to develop the CEUS SSC model.

1.1.4 Regional SSC Model for Nuclear Facilities

The CEUS SSC Project is a user-community–based project for developing a regional SSC model in that it has the sponsorship of multiple user stakeholders. Site-specific seismic hazard assessments will be required as part of licensing proposed sites for next-generation nuclear power plants in the CEUS. Likewise, sites in the DOE nuclear facility complex require updated seismic hazard assessments. Conducting these assessments and updates independently is a time-consuming, overlapping, and costly process; therefore, developing a regional seismic source model that can be applied to all sites in the CEUS is highly stabilizing and cost-beneficial. Furthermore, developing the CEUS SSC model using the SSHAC Level 3 process, which has been developed and endorsed by nuclear utilities, the NRC, and the DOE, provides a stable basis for future site-specific PSHAs for any nuclear facility. Standardization at a regional level will provide a consistent basis for computing seismic hazard, which will assist regulators such as the NRC and the Defense Nuclear Facilities Safety Board (DNFSB) in their safety review and oversight of nuclear facilities.

The CEUS SSC model was developed by a comprehensive implementation of a transparent, and traceable process, as described in this report. The model will be used by the following groups:

- Utilities that have submitted or will submit an Early Site Permit (ESP) application or a Combined Construction and Operating License (COL) application for NRC review.
- The NRC, DNFSB, and other regulatory and review groups that are responsible for ensuring the seismic safety of existing and new nuclear facilities.
- The DOE, which is responsible for conducting seismic design studies and seismic safety evaluations of new and existing nuclear facilities.
- The NRC and utilities that must respond to generic seismic safety issues for existing plants.

1.1.5 Differences from USGS National Seismic Hazard Mapping Project

In 2008, as part of the USGS National Seismic Hazard Mapping Project, national seismic hazard maps were released (Petersen et al., 2008) that are updates of previous seismic hazard maps developed by the USGS (e.g., Frankel et al., 1996, 2002). The national seismic hazard maps display the ground-motion hazard component of the seismic provisions of national building codes and support earthquake insurance rate structures and public policy decisions related to the national infrastructure. Earthquake strong ground motions for varying probability levels across the United States are displayed on these maps consistent with the seismic design basis requirements of national building codes. The maps are not intended to serve as seismic design bases for nuclear power plants, however.

Although many of the same types of data underpin the development of both the USGS seismic hazard mapping project and the CEUS SSC model, the products have different uses and different demands. For example, the CEUS SSC model is used to obtain seismic hazard at lower annual frequencies of exceedance (AFEs) than those required for the USGS seismic hazard maps. This is because the CEUS SSC Project is focused on the needs of nuclear facilities, whose seismic design requirements are more stringent than those of conventional infrastructure facilities, and whose safety analyses depend on occurrence of rare ground motions because of the critical safety requirements of these facilities. Thus, while the national seismic hazard maps are focused on AFEs in the range of 10^{-2} to 4×10^{-4}, the CEUS SSC model must support PSHAs focusing on AFEs in the range of 10^{-3} to 10^{-7} for design and safety evaluations for nuclear facilities. The properly complete representation of uncertainty at very low AFEs that must meet the requirements of the seismic regulations for nuclear facilities demands a focused effort to assess and represent low-probability hypotheses and parameter values, and also careful evaluation and characterization of large, rare earthquakes, such as those interpreted from the paleoseismic record, and maximum earthquake magnitudes for all seismic sources.

As part of the effort to ensure that these critical demands have been satisfied, the evaluation processes of the CEUS SSC Project involved the active participation of scientists who have contributed to the development of the national seismic hazard maps. Their participation was a major factor in ensuring that the CEUS SSC model properly represents the center, body, and range of current technical community knowledge.

1.2 Purpose of the CEUS SSC Project

The objective of this project is to develop a regional SSC model for the CEUS that can be used to obtain site-specific PSHAs for nuclear facilities and that includes the following:

- A comprehensive project database as the basis for the evaluation and integration processes underpinning the development of the CEUS SSC model.
- Assessment and incorporation of uncertainties in data and in the range of technical interpretations of earthquake processes that constitute current scientific community knowledge.
- Detailed and traceable documentation of the evaluation and integration processes that support the SSC model.
- A comprehensive participatory peer review of both the technical and process aspects of the project.

The achievement of this objective provides reasonable assurance of stability and longevity for the SSC model.

Experience has shown that stability and longevity are achieved through comprehensive characterization of current scientific knowledge and associated uncertainties. Assurance that this has been achieved is enhanced by the participatory involvement of the technical community, regulators, and oversight groups. The process guidance developed by SSHAC sets the goal of *all* probabilistic hazard analyses, namely, to "represent the center, the body, and the range of the technical interpretations that the larger informed technical community would have if they were to conduct the study" (Budnitz et al., 1997). As documented in Section 2.1, there is assurance that the SSHAC goal has been met by the CEUS SSC Project's implementation of the SSHAC Level 3 process.

In using the CEUS SSC model for site-specific PSHAs in accordance with current regulations and regulatory guidance (e.g., NRC Regulatory Guide 1.208), site-specific studies will be required to identify any potential refinements needed for the regional seismic sources and any potential capable seismic sources within the site region and vicinity. The findings of these site-specific studies could indicate possible local sources of seismicity (e.g., local faults with evidence of Quaternary activity, or nearby tectonic features with a significant probability of being seismogenic).

1.2.1 Implementation of SSHAC Level 3 Process

SSHAC defines four "study levels" representing increasing process implementation complexity that can be used to evaluate and assess the knowledge and uncertainties in the important components of a PSHA. While the SSHAC labeled these "study levels," they are described as levels of increasing complexity of process implementation. The SSHAC guidance emphasizes that independent of the process implementation complexity, the goal is to represent the center, body, and range of technically defensible interpretations in light of an evaluation of the available data, models, and methods in the larger technical community.

According to the current SSHAC guidance (NRC, 2011), the two higher levels of process implementation complexity (Levels 3 and 4) should be used to develop regional PSHA models for sites requiring high levels of regulatory assurance—including nuclear facilities—to remain stable over an extended period of time, and for regions of complex seismotectonics where there are contentious alternative scientific interpretations. Lower SSHAC levels are recommended for non-nuclear facilities or for sites that have existing and viable Level 3 or 4 assessments. The higher assessment levels provide the degree of assurance required by the regulators for seismic safety decision-making.

Both SSHAC Levels 3 and 4 implementation processes formalize interactions with the technical community through a series of workshops in which the peer reviewers fully participate and sponsors and other oversight groups may attend and offer observations. The key difference between Level 3 and Level 4 is that the former entails evaluations and integration of the SSC model by a Technical Integration (TI) team of evaluators, while the latter uses individual (or small teams) of evaluators. For both levels, the expert evaluators are charged with evaluating the current scientific community knowledge and performing as integrators in their characterization and assessment of current knowledge and uncertainty in the SSC model. These broad interactions lead to higher assurance that alternative interpretations of complex scientific/technical issues representing the range of knowledge of the scientific community have been completely evaluated and properly characterized and that the associated uncertainties are understood and properly assessed.

Selection of a SSHAC level depends primarily on the amount and nature of uncertainty, controversy, and complexity involved, but also on regulatory concerns and public perceptions. The time and resources that the sponsor can commit to a proposed project may also be determinants of the level. As the SSHAC level increases, project costs and the number of participants involved increase; the broad acceptance of the final product, however, is also expected to increase. The lessons learned from conducting PSHAs at SSHAC Levels 3 and 4 were compiled and evaluated in a joint USGS and NRC study that began in 2007 and was reported in USGS Open-File Report 2009-1093 (Hanks et al., 2009). These lessons learned were then used to develop more specific recommendations for the selection of SSHAC levels given in NRC (2011).

From a review of Level 4 projects completed since the SSHAC guidance was written, the three or four years required to complete these projects and the high associated costs were cited as posing significant barriers for project sponsors (Hanks et al., 2009, p. 44). The additional time and costs associated with Level 4 projects can be attributed to the need to train the experts in the evaluation process, conduct individual working meetings with each expert, and prepare individual documentation of the evaluations and assessments made by each expert. In contrast, the TI team on a Level 3 project is trained as a team in the evaluation process, works together in workshops and working meetings, and develops a single comprehensive report of its evaluation of the state of scientific knowledge and integration to characterize and represent the center, body, and range of technically defensible interpretations. Now that the SSHAC methodology has been in use for a number of years, a Level 3 process has been established as suitable for developing regionally applicable seismic hazard models intended for computing PSHAs at multiple sites over an extended time.

The use of a Level 3 process is also consistent with the needs of the sponsors, who are responsible for safe design and operation of nuclear facilities. The CEUS SSC Project was conducted during a period when it could take full advantage of the experience gained from recent and ongoing SSHAC Level 3 projects, the lessons learned from a systematic review of past SSHAC projects (Hanks et al., 2009), and the NRC's detailed implementation guidance for Level 3 and 4 projects (NRC, 2011).

The selection of the SSHAC Level 3 methodology for the CEUS SSC Project was made during the planning stages and is summarized in the Project Plan. The decision was made by the Project Manager in consultation with the Project Sponsors and the TI Lead. The detailed recommendations for the selection of SSHAC levels given in Chapter 6 of more recent guidance (NRC, 2011) were not available at that time, but the decision criteria given in the original SSHAC guidelines (Table 3-1 in Budnitz, 1997) were used. The SSHAC guidelines do not define an explicit "prescription" for the appropriate SSHAC study level for a given set of conditions, but they indicate that the decision should be based on a consideration of the "issue degree" and various "decision factors."

The issue degree includes consideration of whether the technical issue of interest (seismic source characterization in the CEUS, in this case) is uncertain, controversial, subject to diverse interpretations, complex, and significant to hazard. Clearly, all of these factors apply. The decision factors include regulatory concern, available resources, and public perception. Given the significant issue degree and in light of the decision factors, it was decided that the project should be conducted at a high SSHAC level (i.e., Level 3 or 4). A SSHAC Level 3 methodology was selected over a Level 4 because of the advantages in maintaining a reasonable cost and schedule for completion of the study.

Comparison of the decision to use the SSHAC Level 3 methodology with the recommendations given in the current regulatory guidance (NRC, 2011, Ch. 6) supports the decision. For example, Chapter 6 in that document describes the decision criteria to be used in the selection of the SSHAC level as a function of the "viability" of the preexisting hazard study. The position taken in the guidance is that there is no significant difference in the degree of regulatory assurance provided by the SSHAC Level 3 or Level 4 methodology. As discussed in Section 6.3 and Table 6.1 of the NRC guidance (2011), SSHAC Level 3 or 4 methodologies are appropriate for nuclear facilities when the previous hazard study was either not conducted using the SSHAC methodology or was conducted using a Level 2 or lower SSHAC level, or where the existing study is not viable. Viable is defined as (1) based on a consideration of data, models, and methods in the larger technical community; and (2) representative of the center, body, and range of technically defensible interpretations.

Given these criteria, the existing regional seismic hazard studies in the CEUS would not be considered viable and, given the explicit application of the CEUS SSC Project for nuclear facilities, a SSHAC Level 3 or 4 would be consistent with the current regulatory guidance. Because of the equivalent levels of regulatory assurance for Level 3 and 4 studies, coupled with the cost and schedule advantages of Level 3, the selection of a Level 3 methodology for the CEUS SSC Project is reasonable and defensible.

1.2.2 Goals: Stability and Longevity

Stability and longevity are important goals of the SSHAC assessment methodology, and these goals are highly important to the CEUS SSC Project. Stability means that the integrated assessments that result from a SSHAC assessment process should generally not be subject to significant change without new hazard-critical scientific findings. This is because the knowledge of the affected scientific community has been systematically compiled and evaluated throughout the project, and uncertainties in the community knowledge have been appropriately characterized and represented in the CEUS SSC model.

Longevity means that the model will last for a number of years before requiring a significant revision or update. New scientific findings will continue to be promulgated after the project is completed, along with new models and methods for interpreting data. Although evaluations of evolving scientific knowledge may potentially lead to the need to update elements of the model during site-specific use, it is likely that the regional model will remain viable, avoiding the need for an extensive revision for a number of years. Experience shows that community knowledge will not change in a systematic and significant way in a short time. The process of gathering scientific data, developing interpretations and hypotheses regarding those data, and vetting those hypotheses within the technical community takes time. With periodic updates, as necessary to reflect advances in the field as well as new data sources, the CEUS SSC model is expected to last several years before a significant revision is needed.

1.2.3 Interface with Ground Motion Models

After the EPRI-SOG project was completed, EPRI performed a major CEUS ground-motion project targeted on developing an understanding of ground motion variability. The project resulted in the EPRI ground-motion model for the CEUS (EPRI, 1993), which included an assessment of epistemic uncertainty in the median motions and an assessment of aleatory variability. The project involved nearly all of the then-active ground-motion modeling experts. Consequently, it stimulated follow-on research by a number of the participants who produced an equal number of ground motion models in the years following. The EPRI (1993) model, together with models developed by individual researchers, formed the body of knowledge for development of the EPRI (2004) GMC model for the CEUS, which updated the assessment of epistemic uncertainty in the median models and aleatory variability.

The EPRI (2004) ground-motion project was the first avowed application of a SSHAC Level 3 process. The development of a composite understanding of ground motion attenuation is a contentious, complex issue, and uncertainty in ground motion contributes significantly to the uncertainty in PSHA. A SSHAC-defined Level 3 process was implemented, in which a TI team was responsible for conducting workshops involving the community of ground-motion-modeling scientists to compile and evaluate current knowledge. The TI team was additionally responsible for integrating the knowledge base and characterizing the range of knowledge and assessing the composite distribution of ground motion based on evaluations of available information, including interactions with ground motion experts.

The TI team for the EPRI (2004) ground motion project brought together, in a series of three workshops, a panel of ground motion experts comprising proponents of the range of available models. The workshops were structured to gain a common understanding of the uncertainties in the modeling approaches and to develop the evaluation and assessment process for representing the uncertainty distribution of the technical community. The final product of the project was a ground-motion attenuation model defined by a set of equations and coefficients for estimating ground motion measures and their aleatory variability (standard deviation) as a function of earthquake magnitude and source-to-site distance. The model includes the epistemic uncertainty in the median estimate of ground motions and in the aleatory variability. The model is applicable to two general regions in the CEUS: the Midcontinent (CEUS excluding the Gulf Coast) and the Gulf Coast. The model is applicable to three classes of seismic sources: general conditions involving area sources; distant, large-magnitude sources; and nearby large-magnitude seismic sources.

Shortly after completion of the EPRI (2004) project, another project (EPRI, 2006) was conducted at a SSHAC Level 2 to further examine the value of the standard deviation for the ground motion variability for the CEUS. The value of the standard deviation in the models developed in the EPRI (2004) ground-motion project was much larger than recent studies of large data sets of ground motions applicable to the Western United States (WUS) had shown. An evaluation of differences in the standard deviation in the CEUS and WUS, based on the variability of the source, path, and site terms, indicated that the WUS intra-event standard deviations are generally applicable to the CEUS, with some epistemic uncertainty about the effect of focal depth at short distances. The evaluation also indicated that the inter-event standard deviations may be larger in the CEUS than in the WUS, based on larger variability in the stress drops. Alternative models for the total standard deviation (combined intra-event and inter-event) were developed that can be applied to the CEUS. Overall, these new models show a significant reduction in the total standard deviation, particularly at short distances. Compared to the EPRI (2004) models, this lower value of the standard deviation tends to reduce the computed hazard.

The EPRI (2004) GMC model and an updated assessment of aleatory variability (EPRI, 2006) together are the most current and applicable ground-motion model for the CEUS and are currently in use in ground motion analyses for COL applications. The ongoing Next Generation Attenuation–East project is aimed at replacing the GMC model developed by EPRI (2004, 2006). That effort has just begun and is not scheduled for completion until 2014. In anticipation of the types of ground motion models that will result from that project, the CEUS SSC Project provides outputs that are judged to be compatible with the needs of future ground-motion models. For example, seismic sources are each characterized according to the characteristics of future earthquakes (see Section 5.4), such as the style of faulting, seismogenic crustal thickness, depth distributions, and orientation of ruptures.

1.3 Study Region

The project study region (Figure 1.3-1) is the region within which the CEUS SSC model has been developed. The SSC model is applicable to all sites within the project study region; however, for application at particular sites, such as those near the study region boundaries, additional seismic sources may need to be defined depending on the applicable regulations or guidance. The western boundary is located approximately along the foothills of the Rocky Mountains at longitude 105° W. On the north, the study region extends a minimum of 322 km (200 mi.) from the U.S.-Canadian border. On the south and east, the study region includes the offshore area a minimum of 322 km (200 mi.) from the coastline. Only seismic sources that lie within continental crust are included. The earthquake catalog developed for the CEUS SSC Project includes coverage of the entire area within the study region boundaries.

Seismic sources that are *not* considered in this project are those in areas outside the study region boundaries; this applies to sources in the WUS, Mexico, Canada, and the Caribbean Plate boundary area.

1.4 Products of Project

The CEUS SSC Project resulted in a series of products that document the bases for the technical assessments made and that provide the inputs to probabilistic seismic hazard analyses at locations in the CEUS. These products are discussed below.

1.4.1 Seismic Source Model for Study Region

A seismic source model has been developed for the CEUS that contains descriptions of parameters that define the frequency of occurrence, spatial distribution, and rupture characteristics of potential future earthquakes. A conceptual SSC model was developed for use on the project, which is hazard-informed and takes advantage of knowledge gained from SSC projects conducted over the past several years. The framework includes a hierarchical approach to the identification and characterization of seismic sources that considers the importance of seismic source characteristics to the hazard results. The hierarchy calls for identifying seismic sources—and quantifying their characteristics—according to their importance to earthquake recurrence, maximum magnitudes, future earthquake rupture characteristics, and the activity of tectonic features. Following directly from this framework, sources of repeated large-magnitude earthquakes (RLMEs; magnitude [**M**] greater than 6.5) are identified where recurrence is defined primarily from the paleoseismic record.

The choice of **M** 6.5 is simply because this is a magnitude earthquake that can usually be confidently identified within the paleoseismic record. Two alternative approaches to defining the spatial distribution of earthquakes outside of the RLME sources were (1) to define source boundaries only on the basis of maximum magnitude differences, and (2) to define zones by their different seismotectonic characteristics. (Note that for simplicity in this section and later in the report, the term *RLME* is used to refer to the actual past earthquakes and the forecast of future occurrences; the term *RLME source* is used to refer to the seismic source used to model the spatial and temporal distribution of the RLMEs.)

The spatial distribution of future earthquakes is defined by the geometry of the RLME sources, the maximum-earthquake source zones, and the seismotectonic zones. In all cases, uncertainties in these boundaries are captured by alternatives in the logic tree. In addition, the spatial distribution of the recurrence rate within the zones is defined using a spatial smoothing process that allows for spatial variation in *a*- and *b*-values. The temporal distribution of earthquakes that occur within RLME sources is defined by alternative temporal models that provide for the occurrence of temporally clustered behavior and, if the data suggest it, a temporal renewal process. The CEUS SSC model placed heavy emphasis on the compilation and analysis of paleoseismic data, reflecting the focus on these types of data by the larger technical community in recent years.

The upper truncation of the earthquake recurrence relationships occurs at the maximum magnitude (Mmax), and these are estimated for all seismic sources. The assessment of Mmax for sources in stable continental regions (SCRs) such as the CEUS is subject to considerable uncertainty. The CEUS SSC Project employed two methods for assessing Mmax: a Bayesian methodology using an updated SCR database of earthquake magnitudes and related information, and a well-founded mathematical procedure that estimates Mmax based on seismic data (where sufficient) only for the source being considered. Many of the Mmax distributions are quite broad and reflect the uncertainties that currently attend the conceptual models and parameter uncertainties regarding constraints on Mmax.

The identification and quantification of uncertainties associated with seismic source characteristics is an important component of a PSHA. As recognized by SSHAC (Budnitz et al., 1997), a PSHA incorporates both aleatory variability and epistemic uncertainty. Aleatory variability is the natural randomness in a process that is known and understood. Examples of aleatory variabilities include an assessment of the size and location of the next earthquake, and the relative frequency of earthquakes having different rupture orientations. Epistemic uncertainty is the scientific uncertainty in a process that is due to limited data and knowledge. Examples include alternative recurrence models to describe future earthquakes, and the probability distribution describing the maximum magnitude of a particular seismic source. Epistemic uncertainties in the CEUS SSC model are captured in the master logic tree and the logic trees for each seismic source.

Epistemic uncertainty is the result of limited data (often, very limited). In seismic hazard analyses, evaluating alternative models involves considering alternative simplified physical models, data from analogous regions, and empirical observations. These are subjective. In some cases, uncertainties are developed from formal statistical assessment of fitting models to data (e.g., recurrence rate and *b*-value parameters obtained from fitting the truncated exponential recurrence model to recorded seismicity).

The CEUS SSC model was developed in four stages. After the second workshop, a "sensitivity SSC model" was developed that was designed to incorporate all potentially important source characteristics. This model was used in hazard calculations and sensitivity analyses discussed at the third workshop as feedback. With that feedback, a "preliminary SSC model" was developed that focused more specifically on the quantification of uncertainties. After review of another round of hazard calculations and sensitivity analyses, a "Draft SSC model" was developed, which was described in the Draft Project Report. The TI Team and the PPRP reviewed the associated hazard calculations and sensitivity analyses for that model and made refinements that are now part of the "Final SSC model" described in this report. These refinements included additional work in the magnitude conversions for the CEUS SSC Project earthquake catalog and the inclusion of a range of smoothing parameters to express the epistemic uncertainty in the spatial variation of recurrence parameters.

1.4.2 Hazard Input Document

A hazard input document (HID; see Appendix H) was prepared to provide the documentation necessary for users to implement the CEUS SSC model in PSHA calculations for future applications. The HID contains all of the information required for a future user to exercise the model within a PSHA, but it does not include the technical basis or justification for the elements of the model. Included are the logic tree structure, all branches and weights, and tabulations of the outputs from all calculations conducted within the context of the source characterization effort. Such outputs include the Mmax distributions for all sources, recurrence calculations using paleoseismic data for the RLME sources, and spatially defined *a*- and *b*-values resulting from the smoothing algorithm. The purpose of the HID is to ensure that the expert assessments made by the TI Team are captured faithfully and accurately and delivered for use by the hazard analyst for a PSHA at a specific site. For the CEUS SSC Project, the final HID was used by the hazard analyst to carry out hazard calculations at seven demonstration sites (Figure 1.3-1), as summarized in Chapter 8.

1.4.3 Documentation of Technical Bases for All Assessments

The results of a PSHA serve a range of users with different needs, from earth scientists to engineers and regulators. The SSHAC process requires complete documentation of every step of the methodology used and the results obtained, thereby allowing all users to understand the technical justification for all parts of the assessment. This report documents the process and methodology followed for the project and the technical bases for the models, parameter values, and weights included in the source model. For example, Section 5.2 provides a detailed description of the methodology that was used to develop assessments of maximum magnitude (Mmax) for individual seismic sources, including the epistemic uncertainties that result from alternative conceptual models and from the range of parameter uncertainties. The Mmax methodology is then applied to each seismic source using the source-specific information related to the largest observed earthquakes within the zone, the numbers of earthquakes of various magnitudes, and the tectonic characteristics of the zone. The source-specific characteristics and resulting Mmax distributions are provided in the applicable sections of Chapters 6 and 7.

The documentation for the CEUS SSC Project describes the process used to compile and evaluate the data, models, and methods, and to integrate current knowledge and uncertainties in a logic tree format depicting alternatives that represent the center, body, and range of technically defensible interpretation. The goal of the project documentation is to provide an adequate basis for future users of the project to fully understand the process that was implemented, data that were used, evaluations that were performed, and the technical bases for the characterization and uncertainty assessments represented in the models.

1.4.4 Other Key Products

In addition to the key products identified above, which have direct application to future seismic hazard studies, the CEUS SSC Project also resulted in a number of other products that have value for future users. These products are described below.

1.4.4.1 Data Evaluation and Data Summary Tables

The CEUS SSC model development entailed the consideration of an extensive amount of data. Part of the responsibility of the TI team is to document the data that were used in the assessment. To supplement this documentation, the TI Team developed a series of tables that specifically identify all of the data that were considered by the team (Data Summary tables) and that indicate the team's views of the quality of the data and the degree of reliance placed on any given data set (Data Evaluation tables). These tables provide a clear picture to future users of the data that were available at the time the project was conducted and how those data were used. The data tables are discussed in Section 4.1.2 and are given in Appendices C and D.

1.4.4.2 Database of Geologic, Geophysical, and Seismological Data

Because more than two decades have passed since the large regional seismic hazard studies (EPRI-SOG and LLNL) were conducted, the CEUS SSC Project entailed the compilation of a large amount of potentially applicable data. While no new data were gathered for the CEUS SSC Project (e.g., geologic mapping, paleoseismic investigations), a new regional database was developed for the project for use in SSC. The comprehensive database was formatted in a manner that allowed for dissemination of the data to all TI Team members during the course of the project. Where applicable, GIS data layers were developed that included new geophysical data compilations developed specifically for the project. A list of the available data sets included in the project database is provided in Appendix A. The project database, which includes an extensive bibliography of literature compiled for the project, was designed to be publically available following the completion of the project. In addition, a project website was developed for public use and can be found at www.ceus-ssc.com .

1.4.4.3 Earthquake Catalog with Uniform Moment Magnitudes

The CEUS SSC Project devoted a major effort to developing a comprehensive and uniform earthquake catalog for use on the project. Starting with the USGS national catalog and a number of regional catalogs, the various catalogs were updated to include all earthquakes through 2008. For modern PSHAs, moment magnitude is required for ground-motion prediction equations and must be assessed for all earthquakes in the catalog. Accordingly, magnitude conversions between various instrumental magnitudes and moment magnitude were reassessed. Likewise, existing special studies of a number of historical earthquakes were reviewed in order to develop reliable moment magnitudes for these shocks. Uncertainties in the magnitude of all instrumental and historical earthquakes are included in the catalog. The CEUS SSC Project earthquake catalog is discussed in Chapter 3 and was used in defining and characterizing seismic sources as well as characterizing recurrence and Mmax parameters in the SSC model.

1.4.4.4 Updated Paleoseismicity Data and Guidance

Because of the significance of paleoliquefaction data in the CEUS, part of the scope of the project was to compile that data and develop written guidance for representing uncertainty in evaluations and interpretations of that data to estimate the locations, occurrence times, and magnitudes of causative earthquakes. The purpose of this study is to provide a basis for seismic source characterizers in the future to evaluate paleoseismic data relative to their quality and associated uncertainties. The results of the paleoseismicity study are given in Appendix E.

1.4.4.5 Recommendations for Future Applications of SSC Model

The CEUS SSC Project provides one of two models that are needed for PSHA calculations. Still, during the course of the project, hazard calculations were conducted for purposes of evaluating the significance of various SSC issues and providing that information as feedback to the TI Team. These calculations were carried out using the EPRI (2004, 2006) ground-motion models at seven demonstration sites for purposes of illustration. The area covered by this model is shown on Figure 1.3-1, along with the locations of the test sites used for hazard sensitivity calculations. In addition, as documented in this report, hazard was calculated for purposes of comparison with other hazard studies.

This report contains an evaluation of the "precision" of the hazard estimates for use in evaluating whether changes to the seismic hazard are significant. This provides a basis for evaluating the significance of new findings and associated hazard changes in the future. And finally, the report includes a discussion of how the results of this project should be applied in the future. This discussion is given in Chapter 9.

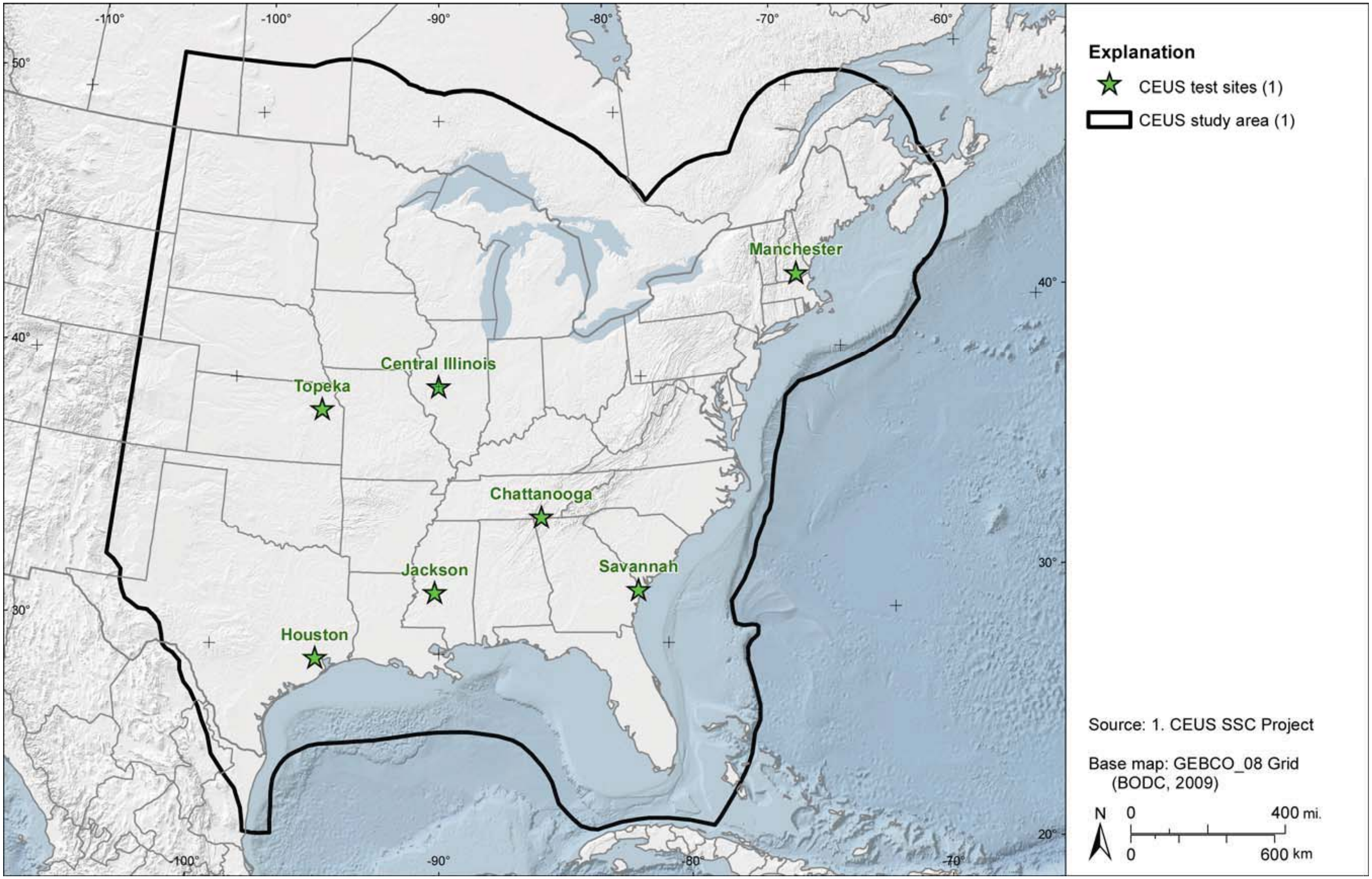

Figure 1.3-1
Map showing the study area and test sites for the CEUS SSC Project