Seismic Source Issues in Siting New Nuclear Power Plants in the Central and Eastern United States

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Abstract

The U.S. Nuclear Regulatory Commission (NRC) is currently reviewing several new reactor applications and is expected to receive more applications in the near future. Most of the proposed new reactor sites are located in the central and eastern United States (CEUS). In contrast to the western United States (WUS), the CEUS is less active in earthquake activity and can be considered as a low to moderate seismic area. Lack of surface expression of active faults and strong seismic recordings in the CEUS make seismic siting more difficult. Probabilistic seismic hazard analysis (PSHA) provides a tool to estimate seismic hazard for the CEUS because it is capable of incorporating uncertainties. The NRC endorsed the PSHA method and some PSHA models in Regulatory Guide 1.165, "Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion," issued March 1997. A popular practice for new applications is to use one of the recommended PSHA seismic source models as a starting point and update those source areas where new paleoseismic evidence have emerged since the models were published. However, most applications usually do not update other areas where there is no new paleoseismic evidence. The challenges are then that (1) these source models are almost 20 years old and, as indicated in Regulatory Guide 1.165, they need to be updated every 10 years, and (2) some other competing source models use very different theories and mechanisms to characterize the CEUS seismic sources in their PSHA methods. A subsequent question involves whether there is a need to completely update these source models to address the issues. Recently, the nuclear industry agreed to update the Electric Power Research Institute seismic source model published about 20 years ago and has a 2-year plan to reassess seismic sources in the CEUS. This paper presents some basic information about the seismic background in the CEUS and some key differences among the existing CEUS PSHA models for the discussion. In addition, the paper discusses the industry's plan to update the EPRI source model and potential challenges for the new update.

1. Introduction

The U.S. nuclear industry has announced that it will build as many as 30 new nuclear reactors in coming years, and most of these new reactor sites will be scattered in the central and eastern United States (CEUS). The application process started in 2003; to date, the U.S. Nuclear Regulatory Commission (NRC) has granted three early site permits (ESPs) and has docketed several combined license (COL) applications. During the review processes, the staff followed the regulations in Title 10, Section 100.23, "Geologic and Seismic Siting Criteria," of the *Code of Federal Regulations*

(10 CFR 100.23), which recommends probabilistic seismic hazard analysis (PSHA) method for siting nuclear power plants. Some applications used the existing Regulatory Guide (RG) 1.165, "Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion," issued March 1997[1], the first guide endorsing PSHA. In addition, the NRC published RG 1.208, "A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion," in March 2007[2] to incorporate the latest advances in seismic siting. The guide summarizes the staff's positions in using PSHA method for seismic siting and also incorporates the performance-based approach to determine a site-specific ground motion response spectrum. With the publication of RG 1.208 and the update of Section 2.5.2 of NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants,"[3] applicants can better prepare their applications to comply with the regulations. To streamline the licensing process, the staff frequently engaged the industry on many of the latest seismic issues. However, even with combined efforts from both the staff and the industry through many interactions, some new issues have emerged during the review processes. This paper will discuss those issues related to seismic source characterization.

2. CEUS seismic background

It is common in seismic hazard study to conceptually divide the conterminous United States into two geographical regions—the CEUS and the WUS. The boundary is along the longitude of about 104–105° W, approximately along the Rocky Mountain Front. The CEUS has the following general seismic characteristics—(1) it is less seismically active than the WUS, (2) the dominant motion is the vertical motion caused by ice-mass unloading from the last glaciations[4], (3) it has relative older crustal rocks and seismic waves attenuate less quickly than in the WUS, (4) there are very few exposed seismic faults, and (5) strong earthquakes occur with relatively longer recurrence intervals, usually 500 years and longer.

Overall, characterizing seismic sources in the CEUS is more difficult than in active plate-margin regions such as California and other parts of the WUS, mainly because seismic faults are rarely exposed at the surface and strong earthquakes occur less frequently. The earthquake history is relatively shorter compared to other parts of the world, such as Japan. There is no clear understanding on the causative faults for scattering seismicity inside the vast areas of the CEUS. Even in some of the well-known seismic zones where strong historical earthquakes have occurred, such as the New Madrid seismic zone (NMSZ) and the Charleston seismic zone (CSZ), there is not unambiguous insight regarding the corresponding seismic faults (e.g., their source geometry). The determination of key seismic parameters for these sources, including maximum magnitudes and recurrence intervals, were somehow relied on paleoseismic studies. Although paleoliquefaction data can be used to expand earthquake history into several thousands of years, large uncertainties exist because of the limitation in identifying and in constraining the ages of old liquefaction features. Because of the lack of strong motion recordings, some attenuation relationships for the CEUS were derived based on the data from small events, and others were modified from WUS ground motion attenuation relationships or based

1 Regulatory Guide 1.165, "Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion," U.S. Nuclear Regulatory Commission, March 1997.

2 Regulatory Guide 1.208, "A Performance-Based Approach to Define Site-Specific Earthquake Ground Motion," U.S. Nuclear Regulatory Commission, March 2007.

3 NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants," Section 2.5.2, "Vibratory Ground Motion," Revision 4, U.S. Nuclear Regulatory Commission, March 2007.

4 Stein, S., "Approaches to Continental Intraplate Earthquake Issues," The Geological Society of America Special Paper 425, 2007.

on theoretical simulations. Therefore, large uncertainties exist in defining seismic source and wave attenuation relationships in the CEUS. The ideal method to characterize seismic hazard is using PSHA, which enables COL or ESP applicants to incorporate uncertainties in seismic sources and seismic wave attenuations as well as other seismic modeling parameters. In general, it is relatively less controversial to define those special seismic source areas such as the NMSZ and CSZ because of their recent seismic history and expanded earthquake chronology based on paleoseismic studies. However, outside of these special source zones, for the other areas inside the CEUS, large model input parameter discrepancies exist among different modeling groups. Because new nuclear power plants are most likely to be located inside these kinds of areas, those seismic source model discrepancies from different modeling groups usually create significant differences in seismic hazard for individual sites.

3. Seismic source characterization history in the CEUS

In the late 1980s and early 1990s, the Electric Power Research Institute (EPRI) and the Lawrence Livermore National Laboratory (LLNL) implemented comprehensive PSHA studies for nuclear power plants in the CEUS. Both EPRI and LLNL used a procedure similar to that recommended by the Senior Seismic Hazard Analysis Committee (SSHAC)[5]. Using the procedure, EPRI gathered six expert teams to work on source characterization for the CEUS. Each of these teams followed the same guidelines in translating earth science interpretations into seismic source models and associated parameters and reflecting a current understanding of earthquake tectonics. Each team also developed its own interpretations regarding current earthquake tectonic theories and practices. Relying on experts from these earth science teams, the CEUS was divided into numerous seismic sources with their associated parameters and probability of activities. These sources were used in calculating mean and median seismic hazard curves for nuclear power plant sites. LLNL also implemented a similar modeling process covering the same area, however; it used individual experts rather than teams to establish seismic source models.

Another important PSHA study covering the CEUS is the U.S. Geological Survey (USGS) seismic hazard mapping project; its product, the often updated USGS seismic hazard map, actually covers the entire country. Since the publication of the new generation probabilistic seismic hazard map in 1996, USGS has already updated the hazard map twice (2002 and 2007), and the map targets seismic hazards with return periods of 1000 years and less (annual probability of exceedance $1x10^{-3}$ and larger). As a result, civilian building design makes extensive use of the map. USGS adopted a different approach from EPRI and LLNL to estimate the CEUS seismic hazard. It used four different models to characterize seismic hazards, including a combination of regularly spatially smoothed seismicity for several magnitude ranges, large background sources, and characteristic earthquake sources.

The ESP and COL application processes made extensive use of the EPRI seismic source modeling in 1980s. The NRC endorsed both the LLNL and EPRI source models for the seismic siting of nuclear power plants in RG 1.165, with applicants updating these models as necessary. Applicants usually used the EPRI source model as a starting model for their site-specific seismic siting. If any new paleoseismic evidence provided additional information for a particular existing source or a new source, the applicant would revise the affected EPRI sources by either modifying source parameters for the existing source configurations or by adding new sources into the EPRI seismic source model. Some significant seismic zones in the CEUS, such as the NMSZ and CSZ, were all updated; the

5 NUREG/CR-6372, “Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts,” Senior Seismic Hazard Analysis Committee for the U.S. Nuclear Regulatory Commission, 1997.

modeling process also incorporated other potential new seismic sources, such as the Saline River and Wabash Valley source zones, where new paleoliquefaction evidence emerged. Two common approaches to add a new source are either to overlap the newly added Saline River source zone in the Grand Gulf ESP[6] or to replace the corresponding part with the newly characterized seismic sources from the EPRI source model, such as the CSZ in the Vogtle ESP[7]. After the modification, the new sources are used in calculating seismic hazard at the site.

However, EPRI released its source model almost 20 years ago. Although each applicant updated site-specific seismic sources individually, many other sources date to the original model. Both the industry documents (EPRI, 1986) and RG 1.165 state that an update is needed every 10 years. Moreover, after the completion of the EPRI and LLNL modeling, other models have been implemented with different mechanisms and ideas, especially for the areas without much seismic activity. For example, the USGS hazard map used a large background source with uniform magnitudes, and other parameters to cover the possibility of having a large earthquake in areas with little seismic activity. On the other hand, some of the EPRI teams defined large area sources where they assigned a low probability of activity because those teams believed that earthquakes had to occur along a fault. According to them, if no clear evidence indicates the existence of a seismic fault, the probability of activity for the corresponding sources can be very low and even close to zero. Because there is still no definitive understanding regarding earthquake-forming mechanisms and poor correlation between earthquakes and tectonics, the best strategy is to reconcile different theories with a scientific consensus while reserving sufficient conservatism in the process.

4. Discussion

In general, there are probably two typical potential earthquake sources in the CEUS (a simplified view for the sake of discussion) in lieu of seismic activity and data availability—(1) where large historic earthquakes occurred and modern seismic activity continues, and where paleoseismic data are abundant, such as the NMSZ and CSZ, and (2) the areas with either little or moderate seismic activity but without any paleoseismic data,.

Three strong earthquakes with magnitudes of about 7–8 occurred in the NMSZ in 1811–1812, and small earthquakes (magnitude less than 5) still continuously strike the area. Paleoseismic studies demonstrated that strong earthquakes also occurred in the area earlier than 1811–1812, with an average recurrence interval about 500 years. In the CSZ, a strong earthquake with a magnitude about 7.3 occurred in 1886 and paleoseismic studies also indicated that similar size of earthquakes occurred before 1886, with an average recurrence interval of about 550 years. Almost all the existing PSHA models treated the NMSZ and CSZ similarly in terms of maximum magnitude and recurrence interval, but they differ from one another on the source geometry. These two zones have dominating influence on regional seismic hazard in the CEUS. This especially pertains to the NMSZ, which contributes seismic hazard to almost every ESP and COL site in the CEUS, even to some sites located more than 200 miles away, the largest recommended radius for carrying out a site investigation for a new reactor. It is common to model seismicity in this kind of area with a characteristic earthquake model.

6 NUREG-1840, "Safety Evaluation Report for an Early Site Permit (ESP) at the Grand Gulf Site," U.S. Nuclear Regulatory Commission, 2006.

7 "Early Site Permit Applications for Vogtle Electric Generating Plant Units 3 and 4, Final Safety Analysis Report," Southern Nuclear Operating Company, 2006.

Outside of the aforementioned seismic zones, seismic source characterization in the CEUS is more challenging because each seismic modeling group can define those source areas different source parameters based on different hypotheses. Those areas can be further separated into two different sub areas. The first sub area has quite significant earthquake activities but without large historical earthquakes, such as the Eastern Tennessee Seismic Zone (ETSZ). The ETSZ is the representative seismic source of this type of area. It is claimed as one of the most active seismic zones in the CEUS, but the largest historical event that occurred in the zone was 4.6 (Moment Magnitude). No paleosiesmic proof or other evidence so far indicates that any larger historical events have occurred in the area. The USGS Quaternary Database defined some faults in the area as Category C faults, meaning that they "have little or no published geologic evidence of Quaternary tectonic faulting that could indicate the likely occurrence of earthquakes larger than those observed historically." Different seismic models characterize this zone quite differently. Some defined it with an individual area source but others defined the seismic distribution with secondary structures. Some researchers used global analogies as a basis to estimate that the zone is capable of having an earthquake as large as magnitude 7.5[8]; however, others assigned much smaller magnitudes for the maximum earthquake that would occur in this area, citing historical earthquakes and lack of other supporting data. The second subarea consists of areas without much of seismic activity and that lack paleoseismic evidence. EPRI used different earth science teams to characterize these types of sources. Some of the teams believed that many of these source areas simply do not have the capability to produce large earthquakes. As a result, they assigned very low probabilities of activity to them. USGS used spatially smoothed seismicity to cover those areas. It also included some large background sources with uniform maximum magnitudes to reflect global analogous study of stable continental region seismic activities.

For these source areas which have little or only moderate seismic activity and have no any supporting paleoseismic evidence, scientific consensus must be built to reflect various understandings and different opinions on seismotectonics. With consideration of the merits from different seismic PSHA models, it might be beneficial to develop a model to integrate spatial smoothed seismicity with relatively small background sources to characterize seismicity in these areas. These background sources should be more seismictectonic specific and configured based on deep structures where earthquakes frequent, instead of on surface structures.

5. Comments on the recent industry plan to update on the CEUS seismic source model

Recently, the U.S. nuclear industry accepted a proposal to update the original EPRI source model published in the 1980s. The proposal includes a 2-year plan to make a new assessment to render the future model suitable as a generic basis for computing a site-specific PSHA for any geographic location in the region[9]. The project will also involve obtaining NRC reviews of the updated PSHA model and acceptance as a generic model to determine site-specific seismic hazard for new reactor sites.

To update the model, the industry proposed the following three key steps:

(1) Establish appropriate project participants.
(2) Update the geological, geophysical, and seismological database for the CEUS.

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8 Frankel, A., et al., "Documentation of national Seismic Hazard Maps ," US Geological Survey Open –File Report 02-420, 2002.

9 Salomone, L.A., Washington Savannah River Company, "Expediting the Licensing of Next Generation Nuclear Power Plants," 2007.

(3) Develop updated assessments of CEUS seismic sources and seismic source characterizations.

The proposal suggested using a SSHAC Level II study for the updates. However, according to SSHAC, the Level II study would only use a technical integrator to interact with proponents and resource experts to identify issues, synthesize interpretations, and estimate community distribution. A Level III study would have a technical facilitator/integrator bring proponents and resource experts together for both debate and interaction. The technical facilitator/integrator would focus debates, evaluate alternative interpretations, and estimate community distribution. With such a large-scale update and an ambitious scope to integrate into the PSHA different methods and the latest developments in earth science, the SSHAC Level II study is probably not sufficient to provide a forum for various groups with different opinions. Without a SSHAC Level III study, it will be difficult to handle contentious and controversial opinions regarding nuclear power plant seismic siting. Historically, the older EPRI and LLNL 1980s PSHA modeling was similar to a SSHAC Level III–IV study with a panel of technical facilitators/integrators involved. Level II studies were often used to resolve site-specific seismic issues for updating individual seismic sources, such as the CSZ.

The update should heed lessons from the past PSHA practices, including not just domestic but also international experience. A long lasting and scientific consensus based seismic source model will provide the support to regulatory stability and avoid potential generic safety concerns. The new seismic source model needs to have the following,

- Provide a conservative and realistic assessment of seismic hazard with the state-of-the-art understanding about seismotectonics.
- Foresee near –term potential changes, including methodology, mechanism, and emerging new seismic and paleoseismic information, so that the model will not need to be updated in a short time frame.
- Incorporate new technology and new data into the modeling process, such as using GPS data to constrain seismic moment.
- Can be updated relatively easily so that it only needs site-specific local update even with future new data, instead of complete overhauls.

For those new reactor applications that potentially affected by the seismic source updating issue, the applicant proposed to perform sensitivity tests to review the difference among competing models covering these sites. A basic approach is to replace key parameters used in the existing EPRI model with relevant parameters from other models to estimate seismic hazard for those sites.

DISCLAIMER

The Views expressed in this paper are those of the authors and should not be construed to reflect the official U.S. NRC position