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# DEVELOPING A LOGIC-TREE FOR UPDATING THE PROBABILISTIC SEISMIC HAZARD ASSESSMENT FOR THE ANGRA DOS REIS NUCLEAR POWER PLANT SITE IN BRAZIL

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## ABSTRACT

The seismic design loads for the existing reactors of the Angra dos Reis nuclear power plant in the state of Rio de Janeiro, SE Brazil, were defined using deterministic seismic hazard analysis. In the 1990s, work began to update the seismic hazard assessment for the site using a probabilistic approach, and characterizing the ground motions in terms of PGA. Following the accident at the Fukushima Daiichi power plant in March 2011, a project was initiated to re-evaluate the site hazard in accordance with modern practices. The new PSHA will characterize the ground motions in terms of response spectral ordinates rather than only PGA, so that uniform hazard spectra can be developed for the site. The most important development is that the hazard assessment is to be conducted within the SSHAC framework (as a Level 1 study) and will develop a logic-tree to capture the epistemic uncertainties in both the seismic source and ground-motion characterization models. In accordance with the SSHAC process, the first stage of the project is to update the geological and seismological databases for SE Brazil, with a particular focus on the earthquake catalog, for evaluation by a Technical Integrator team. The proposed procedure for the study is then to develop a relatively simple initial model that will allow extensive hazard sensitivity calculations to be performed in order to focus the efforts of the team on those elements contributing most strongly to the hazard and/or to the overall uncertainty.

## INTRODUCTION

The 'Almirante Álvaro Alberto' nuclear power plant (CNAAA, its Portuguese acronym) is located on Itaorna beach in the Ilha Grande bay near the town of Angra dos Reis, some 130 km west of the city of Rio de Janeiro close to the boundary between the states of Rio de Janeiro and São Paulo in southeast Brazil (Figure 1). The plant currently includes two operating pressurized water reactors, with a combined capacity of almost 1.9 GWe. The first unit was connected to the grid in 1985, the second in 2000. The plant currently contributes approximately 4% of Brazil's total electricity. A third unit is currently under construction.

Although the Brazilian territory lies within a tectonically stable region with relatively low levels of seismicity, earthquakes, some of which have caused moderate damage, have occurred in recent and historical times, and the geological record also shows evidence of earthquake activity (e.g., Riccomini & Assumpção, 1999; Saadi et al., 2002). For this reason, and in keeping with regulatory requirements for nuclear facilities globally, earthquake loading was considered in the design of the existing Angra units.

Following the Fukushima Daiichi accident in Japan provoked by the $M_w$ 9.0 Tohuku earthquake of March 2011, Eletrobrás Eletronuclear (ETN), the state-owned operator of the plants, initiated a re-evaluation of the seismic hazard at the Angra dos Reis site, as part of a general re-assessment of the seismic safety of the plant.

Figure 1. CNAAA plant at Angra dos Reis (*left*); location in SE Brazil (*right*) (Map source: Wikipedia)

## EVOLUTION OF SEISMIC HAZARD ASSESSMENTS FOR ANGRA DOS REIS

The original seismic design motions for the Angra I and Angra II units were based on deterministic seismic hazard analyses (DSHA) conducted in the 1970s and 1980s, as was common practice in the nuclear industry worldwide at that time. The scenario chosen based on the maximum intensity observed within a 320 km radius of the plants site, which was VI-VII MMI due to the 1967 $m_b$ 4.1 earthquake at Cunha in the state of São Paulo (Berrocal et al., 1984). This resulted in a value of peak ground acceleration (PGA) at the site of 0.07g, value that was used to select—following the guidance of the US Nuclear Regulatory Commission (NRC)—a horizontal design PGA of 0.10g. This value of PGA was used to anchor a standard design response spectrum, which was essentially that defined in Regulatory Guide 1.60 (USAEC, 1973)

In the 1990s, ETN initiated work to evaluate the seismic hazard using the probabilistic approach (PSHA), in response to requirements from the Brazilian regulatory body (CNEN) as well as to the global transition away from DSHA. The PSHA calculations were conducted using a single cruciform area source, approximately centered at the Angra dos Reis site, assuming uniform seismic activity and using a single ground-motion prediction equation (GMPE), namely the mid-continent model for Central and Eastern North America (CENA) of Toro et al. (1997). The hazard calculations were performed only in terms of PGA, using in-house software that treated all earthquakes as epicenters (point sources). This leads to a small underestimation of the hazard contributions from larger earthquakes when using a GMPE such as that of Toro et al. (1997) that is based on the Joyner-Boore distance metric, $R_{JB}$, measured relative to the extended fault rupture (Bommer and Akkar, 2012). No alternative models or parameter values were considered in either the seismic source characterization (SSC) or ground motion characterization (GMC) models, so no account was made for epistemic uncertainty.

The new PSHA project for the Angra dos Reis site will be conducted following the general guidelines of USNRC Regulatory Guide 1.208 (USNRC, 2007), calculating the hazard in terms of response spectral accelerations at a range of oscillator frequencies in order to develop uniform hazard response spectra (UHRS). Although the Angra I and Angra II units are very close to each other, the two reactors are founded on very different materials, for which reason the hazard will be calculated at the bedrock level in the first instance. The bedrock has a stiffness of approximately 20 $GN.m^{-2}$, which corresponds to a shear-wave velocity, $V_s$, of about 2,700 $m.s^{-1}$.

The most important development with regard to the earlier studies will be the construction of a logic-tree to represent the key elements of epistemic uncertainty in both the SSC and GMC models. Logic-trees were first introduced into PSHA by Kulkarni et al. (1984) and have become the standard tool for representing epistemic uncertainty and organizing its inclusion into hazard calculations, although they are not always used correctly (Bommer and Scherbaum, 2008). The logic-trees will be populated following a SSHAC Level 1 process (Budnitz et al., 1997), a claim that is rarely made because of widely-held misconceptions regarding what a SSHAC Level 1 study entails (Bommer and Coppersmith, 2013). To meet the requirements of a SSHAC Level 1 study, the PSHA must demonstrate earnest efforts to identify and capture epistemic uncertainty; in the current USNRC guidelines on implementing the SSHAC process in NUREG-2117 (USNRC, 2012b), this objective is stated as capturing the center, the body, and the range of technically-defensible interpretations, or the CBR of the TDI. To qualify as a SSHAC Level 1 study, it is also necessary to demonstrate that the study was subjected to independent peer review, and that closure was reached with the reviewers in terms of accepted responses to the comments, observations and suggestions.

The reason for not adopting a SSHAC Level 2 study for the current project is that the requirement to distinguish this study level from Level 1 is documented evidence for substantial interaction with experts who developed seismological or geological databases or models for the region under study in order to obtain greater insight. This would be difficult to achieve in this case since most of the key experts from the very small seismological communities in SE Brazil are already participating in the Technical Integration team for the PSHA. However, PSHA has not been widely implemented in Brazil and one of the purposes of this project is to strengthen local capacity in this area and in the application of the SSHAC approach. A boost to this effort was by a course delivered in São Paulo on February 2013 by Prof. Frank Scherbaum from the University of Potsdam together with the second and fifth authors of this paper.

## TECTONIC AND SEISMIC SETTING OF SOUTHEAST BRAZIL

In order to contextualize the new PSHA study for the Angra dos Reis site, it is useful to provide an overview of the tectonic and seismic setting of SE Brazil, as well as to briefly note the seismic hazard studies that have been conducted for this region.

### *Tectonics and Regional Geology*

The CNAAA site is located in the Mantiqueira province (a sequence of Neoproterozoic - Paleozoic fold belts), which was affected by the Atlantic rifting in the Mesozoic. The site is located in the foothills of the Serra do Mar coastal range, a relief originated from multiple Cenozoic tectonic reactivations of NE to E-W-oriented Neoproterozoic shear zones in a continental rift context in the passive continental margin of southeastern Brazil (Riccomini et al., 2004) (Figure 2). Thermal histories inferred from apatite fission-track (AFT) and (U-Th)/He analysis indicate important cooling events related to continental break-up in the Early Cretaceous, to Cretaceous alkaline magmatism and to Cenozoic tectonism (Hiruma et al., 2010; Cogné et al., 2011; Cogné et al., 2012).

The inversion of striae from Paleogene-Neogene faults indicated that the stress regimes in the region varied during the Cenozoic (Riccomini et al., 2004). Rifting processes, including faulting, sedimentation and magmatism in the continent occurred during the Eocene-Oligocene, firstly as a result of reactivation of NE to E-W-oriented shear zones as normal faults under NNW-SSE-oriented extension. After its installation the rift system was subjected to four phases of deformation, which has initiated in the early Miocene with left-lateral strike-slip and minor thrust reactivation of NE to E-W shear zones, under a general strike-slip regime with NW-SE extension and local NE-SW compression. The second phase of deformation, during the Late Pleistocene to Holocene, is recorded by right-lateral strike-slip and thrust reactivation of NE to E-W-oriented Neoproterozoic shear zones, resulting from a NW-SE compression and NE-SW extension. During the Holocene the region has experienced a rapid change of the stress regime, initially an E-W to WNW-ESE extension responsible for the development of N-S-oriented grabens, and finally an E-W compression, which affects colluvial and alluvial deposits younger than 3,410 yr BP (Riccomini and Assumpção, 1999; Modenesi-Gauttieri et al., 2002).

The different pulses of uplift and changes in the stress field played a major role in the development of the drainage network of this region. The major rivers in the Serra do Mar region are controlled by E-W to NE-SW-oriented basement structures, but the pulses of tectonic activity along NW-SE-oriented faults, mainly during Neogene and Quaternary, have promoted numerous river captures (Riccomini et al., 2010).


Figure 2 – Tectonic setting of the CNAAA: 1) Precambrian basement rocks; 2) Paleozoic sedimentary rocks of the Paraná Basin; 3) Early Cretaceous tholeiitic volcanic rocks of the Serra Geral Formation; 4) Mesozoic to Cenozoic alkaline rocks; 5) Cenozoic rift basins and 6) Precambrian shear zones, in part reactivated during the Mesozoic and Cenozoic. The Cenozoic rift basins are: 1- Itaboraí Basin, 2- Barra de São João Graben, 3- Macacu Basin, 4- Volta Redonda Basin, 5- Resende Basin, 6- Taubaté Basin, 7- São Paulo Basin, 8- Sete Barras Graben, 9- Pariqüera-Açu Formation, 10- Alexandra Formation and Guaraqueçaba Graben, 11- Curitiba Basin, and 12- Cananéia Graben). The red star indicates the site of the CNAAA. After Riccomini et al. (2004).

***Regional Seismicity***

Figure 3 shows the regional seismicity in SE Brazil where the maximum observed magnitude was a 6.1 $m_b$ in the continental shelf in 1955 (epicenter near $20^O$S in Figure 3). Earthquakes offshore tend to have reverse faulting mechanisms and occur mainly along the continental slope with magnitudes 5 and above once every 15-20 years on average (Assumpção et al., 2011). In the continent, the maximum known earthquake was a magnitude 5.1 $m_b$ in 1922 near the NE border of the Paraná basin. Closer to the site, magnitude 4 events are only known to have occurred in 1861, 1886 and 1967. Present tectonic stresses are not well known near the CNAAA site. Earthquakes near the southern border of the São Francisco craton indicate stresses characterized by E-W compression and N-S extension, suggesting a different seismic source zone compared to the offshore seismicity.

Near Angra dos Reis, notable seismic activity occurred as a seismic swarm between 1988 and 1989 in the vicinity of Monsuaba to the NE of the site (Berrocal et al., 1993). Although the earthquakes were all small—the largest was of magnitude $m_b$ 3.0—the epicenters clearly defined a small fault rupture plane located 24 km from the CNAAA site.

An interesting aspect of the seismicity in SE Brazil is its present low level in the Serra do Mar coastal ranges (as seen in Fig. 3) despite the presence of several neo-tectonic faults mapped in the area (Assumpção and Riccomini, 2010). The SSC model that is to be developed for the PSHA will need to take account of the fact that the earthquake catalog alone is unlikely to be a sufficient basis for defining the spatial distribution of future earthquakes. An important aspect of assessing epistemic uncertainty in the seismic source model will be degree to which the long-term earthquake potential in the Serra do Mar coastal ranges is consistent with the seismicity data.

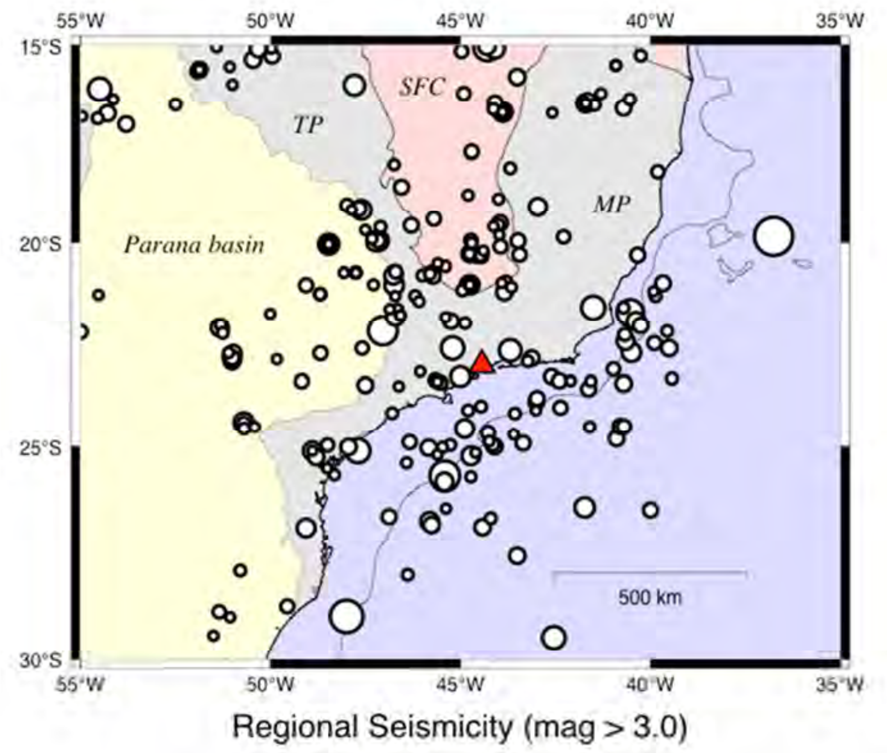


Figure 3. Regional seismicity in SE Brazil. White circles are epicenters from the Brazilian catalog (both historical and instrumental), magnitudes range from 3.0 to a maximum of 6.1. Red triangle is the ESAR seismographic station, close to the CNAAA. Pink area is the Archean São Francisco craton (SFC); gray areas are Brasiliano (~700-500 Ma) fold belt provinces (TP=Tocantins and MP=Mantiqueira Porvinces); yellow areas denote the intracratonic Paraná basin.

***Seismic Hazard***

As noted previously, relatively little attention has been given to the assessment of seismic hazard in Brazil. Within the GSHAP project (Giardini, 1999), a seismic hazard map in terms of PGA on firm ground for a 475-year return period was produced for South America, which indicated that in most of the Brazilian territory the peak ground acceleration is below 0.02*g* (Shedlock and Tanner, 1999). In the western and northwest regions of the country, higher hazard is encountered due to proximity to the Nazca-South American and Caribbean-South American high seismicity plate boundaries. The other exception is the Ceará/Rio Grande do Norte region of NE Brazil, where a localized source of seismic activity in this region results in hazard estimates of the order of 0.2*g*.

Santos and Lima (2008) report that up until 2006, Brazil was practically the only South American country without a general seismic design standard, and that this was remedied by the introduction of a standard called NBR 15421. The seismic zonation map for the country defines 5 zones, and is broadly consistent with the GSHAP map. The highest hazard zone, Zone 4, includes only the westernmost portions of the states of Amazonas and Acre. Zones 3, 2 and 1, are narrow zones that transition eastwards, and an additional region of Zone 1 exists in NE Brazil around the Ceará/Rio Grande do Norte seismicity. Most of Brazil is classified as Zone 0, where the 475-year accelerations are below 0.025g. The nominal design acceleration specified for the south-east region of Brazil, based on the 475-year return period PGA, based on the work of Almeida (2002), is specified as 0.025*g*. Work has recently begun on a project to develop a new seismic hazard map (and the course on PSHA mentioned previously was held within the framework of that endeavor).

## DEVELOPMENT OF DATABASES

As in any assessment of seismic hazard, the first stage of the project, which is now underway, is the compilation of databases that will subsequently be evaluated by the TI Team in order to inform the integration process in which the SSC and GMC logic-trees are constructed.

### *Earthquake Catalogue*

The regional earthquake catalog is being revised and updated. Large events from the Brazilian catalog (within 600 km from CNAAA) will be re-evaluated for location (epicenter and depth) and magnitudes. Small events recorded by the local station at Angra dos Reis (ESAR) will also be updated to help define possible limits of seismic source areas and the frequency-magnitude relation.

With the catalog expanded and updated, the key task will be to homogenize the measures of earthquake size in term of moment magnitude, $M_w$, especially since this is the scale employed in most current GMPEs. Magnitudes are currently assigned using the regional scale of Assumpção (1983), denoted $m_R$, which is based on P-wave amplitudes (frequency range 0.1 to 1 Hz) at stations in the 200-1500km distance range, and has been shown to be equivalent to the teleseismic body-wave magnitude, $m_b$. This was one of the key motivations behind the choice of the Toro et al. (1997) GMPE in the earlier PSHA for the site because that equation provides a version expressed as a function of the magnitude $m_{bLg}$, which is also equivalent to $m_b$, a scale not used in any other current GMPE.

Seismic moments using waveform inversion are only available for larger events in Brazil with magnitude around 4 and above. Moment magnitudes $M_w$ will be estimated from seismic moments for several additional events using the low-frequency Fourier displacement spectra. Using such data, an empirical relation between $m_b$ and $M_w$ will be established for Brazilian earthquakes and applied to transform the catalog into a consistent moment magnitude scale. The uncertainty associated with the magnitude conversions, and the even larger uncertainty associated with assigning magnitudes to historical earthquakes from analysis of intensity data, is known to influence the estimated activity rate in the recurrence relationship, although not the *b*-value (Musson, 2012). Methods for incorporating this uncertainty into the estimation of the activity rate, such as those used in the Central and Eastern US Seismic Source Characterization (CEUS-SSC) project (USNRC, 2012a) will be reviewed to select those most appropriate to application in this case.

### *Geological Database*

The CNAAA nuclear plant is close to the Serra do Mar coastal ranges where quaternary and even holocenic faults have been identified (Riccomini and Assumpção, 1999). A more detailed mapping of recent faults, within about 100 km from CNAA, will be carried out. The database will comprise mainly the compilation of available geological maps that will provide the basis for detailed field investigations of faults with record of Neogene and Quaternary displacements. The main purpose of the field survey is to determine the type and lengths of faults and also to estimate their depth, the latter assisted by making use of the available seismic reflection data. Another objective of the field study is to obtain ages of sedimentary deposits and paleosols affected by them. Trenching is not envisaged at this stage of the study, but as noted below sensitivity analyses will be run in order to identify those elements of the SSC and GMC models where efforts need to be focused to reduce major sources of uncertainty. The geological field investigations that will be conducted within the early phases of the project will provide information that would serve to guide more elaborate paleoseismological investigations that may be conducted subsequently.

***GMC Database***

No accelerograms are available yet in SE Brazil and our database consists of velocimetric data from broadband seismic stations. However, the high-frequency signal is generally well recorded as a result of the high sampling rate of the instruments. A database with available waveforms is being compiled and to date events with magnitudes between 2.5 and 5.2 are included. Larger events are recorded at larger distances but due to the high-quality of the stations even small events are recorded up to 500 km (see Figure 4).

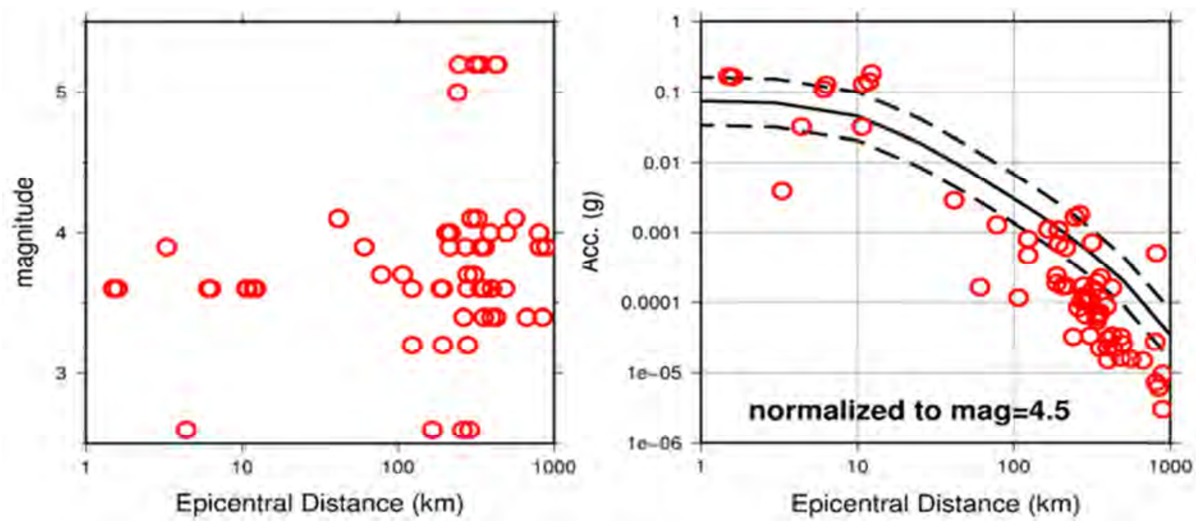


Figure 4. Data for PGA in the current database. *Left*: Distribution of magnitudes and epicentral distances. *Right*: PGA values normalized to magnitude 4.5 $m_b$ compare with the Toro et al. (1997) GMPE for Central and Eastern North America.

The database will be used to calculate seismic moments (from Fourier displacement spectra), and if possible to characterize attenuation properties of the region as well as site amplification. The long-term goal would be to produce a local ground-motion prediction model (GMPE) based on these data when their number will be sufficient. However, for application to PSHA, such a model would require extrapolation beyond the limits of the dataset that is likely to be available for this region, for which reason a logic-tree approach will be essential to capture the possible range of ground-motion amplitudes for larger magnitude earthquakes.

Second, the high frequency attenuation (known as *kappa* effect) will be evaluated from the Fourier spectra. There is an observed attenuation of the high frequencies related to local site conditions: the stiffer the site the lower the attenuation. This information will be useful to better characterize the recording sites in the comparison of our data with GMPEs from other areas, and will also be needed to adjust any imported GMPEs to the very hard rock reference site condition at Angra.

Finally, observed response spectra will be compared to GMPEs from other areas in order to try to select the most adequate models to build the logic-tree for the hazard calculation, and eventually to adjust these models in order to better reflect local properties. A preliminary comparison of PGA with the Toro et al. (1997) GMPE is shown in Figure 4. It should be noted that, although the scatter of the observed data is not too far from the model prediction, the Toro et al. model, which was derived using stochastic simulations, is nominally applicable magnitudes between 5 and 8 but seems to work well for the smaller earthquakes. Extrapolation of empirical GMPEs to lower magnitudes has been shown to generally result in overestimation of the ground motion (Bommer et al., 2007).

## MODEL BUILDING AND HAZARD SENSITIVITY ANALYSES

The approach that will be adopted for the study will be to build simple logic-trees in the first instance, to facilitate extensive sensitivity analyses in order to identify the components of the model where greatest attention should be focused. The seismicity will be initially represented by activity within a single circular source, which will only be sub-divided if the criteria established in the SSHAC Level 3 CEUS SSC project USNRC (2012a) are fulfilled, namely that spatially there are appreciable changes in recurrence rates, maximum magnitude estimates, or style-of-faulting. Initial studies suggest that a division between the continental and oceanic parts of the source is likely. Previous seismicity studies (Assumpção et al., 1998; Assumpção etal., 2011) indicate that earthquakes along the continental slope probably belong to a different seismic source zone than events in the continent.

For the mapped geological faults within 320 km of the site, the proposed approach is to assign to each of these the highest possible slip rates, which in many cases will be the maximum slip rate that could exist without clear detection. The potential contribution from each fault will then be assessed in terms of its relative impact compared to the hazard estimates due to the background seismicity.

Since the Brazilian territory is a stable region and the target site is a very hard rock condition, GMPEs from CENA are an obvious choice, but there are several limitations to current models, including poor near-source constraint and sigma values lacking a strong technical basis. For this reason, an alternative option being considered is the hybrid-empirical approach of Campbell (2003). Candidate empirical models could be selected using criteria such as those proposed by Bommer et al. (2010) and then, as a minimum, a site adjustment to the very hard rock conditions (e.g., van Houtte et al., 2011) would need to be applied. A simple way to populate a broad distribution of epistemic uncertainty and to enable large numbers of sensitivity analyses to be conducted simply, the so-called ‘backbone GMPE’ approach may be employed in which a single adjusted equation is scaled to create the alternative models that populate the branches of the logic-tree (e.g., Bommer, 2012).

## CONCLUDING REMARKS

A new PSHA study for the Angra dos Reis NPP site in Brazil is underway, initiated partly in response to the negative effects of the Fukushima Daiichi accident. This study represents the next phase in the ongoing evolution of the assessment of seismic hazard at this site, which is similar to that at many other nuclear power plant sites around the world. The initial design basis seismic motions were obtained from a deterministic seismic hazard analysis. The seismic design basis was subsequently re-evaluated using PSHA conducted in terms of PGA, used as the anchoring point for a standard design response spectrum. In the current study, the PSHA will be performed in terms of response spectral accelerations at a range of oscillator frequencies in order to enable the calculation of UHRS.

The most important development in the new study with respect to previous hazard assessments for the Angra dos Reis site is that it will be conducted within the framework of a SSHAC Level 1 process, with the explicit aim of capturing epistemic uncertainty in the SSC and GMC models. This is important both because the study is for a nuclear installation and also because moderate-magnitude earthquakes can occur in Brazil and there is evidence that several neo-tectonic faults could be seismogenic. The fact that seismic events in Brazil are not frequent means that the available data for their characterization are limited, and this inevitably leads to considerable epistemic uncertainty. In order to meet the SSHAC objective of representing the center, the body and the range of technically-defensible interpretations, a logic-tree will be developed for input to the PSHA calculations, and a multi-disciplinary team of geologists, seismologists and engineering seismologists has been assembled to conduct this work.

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