Framework for Modeling Ground Motion Variability at a Nuclear Power Plant Site for Use in a Seismic Multi-Unit Probabilistic Risk Assessment

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Abstract: The March 2011 Fukushima Daiichi accident highlighted the importance of considering multi-unit accidents at a nuclear power plant (NPP) site as part of a probabilistic risk assessment (PRA). In order to properly understand the risk at a multi-unit NPP site, one must account for the dependencies among the reactor units [1]. This paper describes research to develop a framework for modeling ground motion variability that could be used in a multi-unit seismic PRA. Existing ground-motion correlation models (e.g., [2], [3]) define the correlation model for the spatially distributed intra-event variabilities (errors) as a function of the separation distance between structures. These existing models generally focus on modeling ground motion correlation for structures that are located at distances of 1km or more apart. However, the subject application involves modeling correlations at NPP units that are located in close proximity. If the aforementioned correlation model were to be used for the multiple units at an NPP site, the correlation would be close to 1.0 because of the short separation distance between units (i.e., less than 1 km). This result may lead to the unrealistic assumption that the ground motion intensities experienced by the multiple units at the site are the same (i.e., perfectly correlated or zero variability). However, at the NPP site scale, there is spatial variability in the ground motion due to various factors (e.g., site-response effects) and it can be characterized using the variation of response spectral values from dense accelerograph arrays [4]. The research described in this paper builds upon existing work by developing a framework for addressing these factors to realistically model dependencies among the units; for example, addressing the variability in ground motion amplitude and local soil profiles.

Keywords: probabilistic risk assessment, seismic PRA, multi-unit PRA, spatial variability of ground motions.

1. Introduction

Throughout the world, nuclear power plant (NPP) sites typically contain multiple reactor units. Historically, probabilistic risk assessments (PRAs) have been performed on a unit-by-unit basis and neglected the possibility that other units at the site may experience concurrent adverse conditions. However, the Fukushima Daiichi accident demonstrated the importance of accidents involving multiple units and highlighted the need for considering multi-unit accidents as part of a PRA. In order to properly understand the risks at a multi-unit NPP site, it is necessary to account for the dependencies among the reactor units [1]. Schroer and Modarres [1] proposed a classification schema for these dependencies to facilitate consideration of multi-unit accidents in a comprehensive manner. In Schroer and Modarres [1], the dependencies are classified as initiating events, shared connections, identical components, proximity dependencies, human dependencies, and organizational dependencies. Within this classification schema [1], earthquakes are classified in the initiating event dependency category because earthquakes are events that have the capacity to affect multiple units at an NPP site. Further, earthquakes are classified as "definite" events because, when they occur, they will always affect multiple units.

Typically, when extending the single-unit PRA structure to a multi-unit seismic PRA, the analyst assumes that the same ground motion intensity is experienced by all the units at the NPP site (i.e., perfect correlation or zero variability) [5]. At the NPP site scale, there is expected to be spatial variability in the ground motion at different locations around the site for a given earthquake due to various factors (e.g., site-response effects). Thus, the perfect correlation (zero variability) assumption may not be realistic. Lack of realism in a multi-unit PRA (e.g., through the use of over- or under-conservative assumptions) may lead to distorted risk insights and can adversely affect risk-informed decision-making.

The issue of spatial variability of ground motion at an NPP site was identified during the November 2014 workshop on multi-unit PRA (MUPRA) [6]. Specifically (per Table 2 of [6]), in the technical area of accident sequence quantification and site-based risk metrics, the workshop participants identified the following technical issue and challenge: “Need to address variations in site response to the same earthquake and correlation among component fragilities in the [MUPRA] context.”

The paper describes recent research efforts being carried out with an overall objective of developing a method that allows the inclusion of the spatial variability of ground motions at an NPP site for use in a seismic MUPRA. This will be achieved by characterizing the spatial variability of ground motions, integrating models of ground motion variability with the results of a probabilistic seismic hazard analysis, and developing a method that allows the spatial ground motion variability to be addressed in the seismic MUPRA.

2. Ground Motion

Earthquakes originate on various types of sources (e.g., faults) and the energy released from the earthquake dissipates as seismic waves. The seismic waves travel from the earthquake source to a location of interest on the ground surface (i.e., a particular site). When the seismic waves reach the ground surface, they produce ground shaking (or ground motion). The travel of the seismic waves overwhelmingly occurs through rock. However, the final portion of the travel of the seismic waves is often through soil and the characteristics of the soil can greatly influence the nature of the ground motion [7]. Figure 1 illustrates this concept. Since soil conditions often vary dramatically over short distances, levels of ground motion can vary significantly within a small area [7].

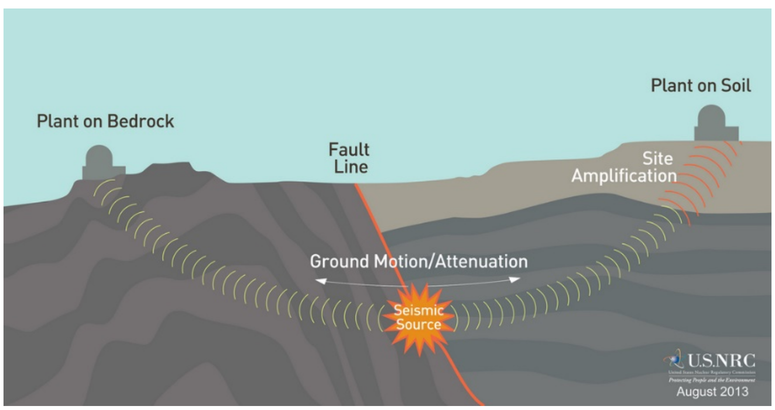

Figure 1. Illustration of the seismic wave travel from earthquake source to a site [8]

Engineers are interested in strong ground motions, that is, ground motions that can affect people and their environment.[1] Ground motions are measured by accelerographs in three orthogonal (i.e., perpendicular) directions: north-south, east-west, and vertical. The north-south and east-west directions are the horizontal components of the ground motion. The measurements by the accelerographs are expressed in the form of accelerograms, which are essentially acceleration time histories. Three characteristics of ground motions are typically of interest to engineers and these are: (1) the amplitude, (2) frequency content, and (3) duration of the motion. Engineers quantitatively describe the ground motion characteristics using ground motion parameters. Usually more than one ground motion parameter is needed to adequately characterize the ground motion [7].

The nuclear industry typically uses ground motion parameters for the amplitude and frequency content. An example of an amplitude ground motion parameter is the peak ground acceleration (PGA), which is the largest, absolute value of acceleration in the acceleration time history. “The frequency content

[1] From hereafter, the terms “strong ground motion” and “ground motion” are intended to have the same meaning.

describes how the amplitude of a ground motion is distributed among different frequencies" [7]. An extensively used way to describe the frequency content of ground motion is with the response spectrum. A response spectrum describes the maximum response (i.e., displacement, velocity, or acceleration) of a single degree of freedom (SDOF) system to a particular input motion (in our case an earthquake) as a function of the natural vibration period T_n (or natural vibration frequency ω_n or f_n [9]) and damping ratio ζ. These maximum response values are the spectral displacement, spectral velocity, and spectral acceleration (SA)[2], respectively [7]. At a particular damping ratio (usually $\zeta = 0.05$), the response spectrum is expressed as a plot of the maximum response quantity versus the natural vibration period (or natural vibration frequency) of the SDOF system.

Ground motion models (GMMs) provide estimates of the response spectrum ordinate (i.e., the y-axis). A particular response spectrum ordinate of interest is the pseudo-spectral acceleration.[3] Examples of GMMs that estimate the pseudo-spectral acceleration are those developed for the Next Generation Attenuation (NGA) for Western North America (NGA-West2) (e.g., [10], [11]) and Central and Eastern North America (NGA-East) [12], [13] projects. The NGA-West2 and NGA-East GMMs were developed from ground motion databases that include response spectrum ordinates for periods ranging from 0.01 to 20 sec [14] and 0.01 to 10 sec [15], respectively, at 5% damping. The use of GMMs in seismic PRA is discussed below.

For the purposes of a seismic PRA, ground motions and their respective annual exceedance frequencies at a particular site are estimated using the probabilistic seismic hazard analysis (PSHA) process. To be brief, PSHA is composed of the following steps [16]:

1. Identify all earthquake sources capable of producing damaging ground motions.
2. Characterize the probability distribution of earthquake magnitudes (the rates at which earthquakes of various magnitudes are expected to occur) based on a magnitude recurrence relationship, such as the Gutenberg-Richter recurrence relationship, which includes the rate of earthquakes with magnitudes greater than m.
3. Characterize the probability distribution of source-to-site distances associated with potential earthquakes.
4. Predict the resulting conditional probability distribution of the amplitude ground motion parameter (e.g., PGA or SA) as a function of earthquake magnitude, source-to-site distance, and other relevant parameters. This distribution is usually assumed to follow the lognormal distribution. The parameters of the distribution are obtained from a GMM, which generally has the following form:

$$ln\left(SA_{ij}\right) = g\left(M_i, R_{ij}\right) + \eta_i + \varepsilon_{ij} \tag{1}$$

where $ln\left(SA_{ij}\right)$ is the natural logarithm of the ground motion parameter at the j^{th} location from the i^{th} earthquake; $g\left(M_i, R_{ij}\right)$ is the GMM, which is a function of earthquake magnitude M_i and source-to-site distance R_{ij} in this case, but can be a function of other explanatory variables as well (e.g., style of faulting) and can have complicated mathematical forms; η_i is the inter-event variability, which is assumed to be normally distributed with a mean equal to zero and standard deviation of σ_η; and ε_{ij} is the intra-event variability, which is also assumed to be normally

[2] The correct way to express spectral acceleration is $SA(f, \zeta)$, but for simplicity we will use SA or $SA(f)$.
[3] The term "pseudo" is added because it is not the "true" maximum value of the acceleration. However, the pseudo-spectral acceleration is a very close approximation of SA and, in practice, they are assumed to be equal [7].

distributed with a mean equal to zero and standard deviation of σ_ε. The inter- and intra-event variabilities are usually assumed to be independent of each other.

5. Combine uncertainties in earthquake size, location, and ground motion intensity through application of the total probability theorem.

In nuclear applications, the PSHA results are typically provided for a "control point" elevation at the site (e.g., at the reactor building foundation, at bedrock) [17]. For a rock site, the PSHA steps described above are sufficient to determine the rock seismic hazard curve. For a soil site, an amplification factor $AF(f)$ (where f is the oscillator frequency in Hz) is used. The amplification factor is defined as the ratio of ground motion at the soil ($SA^s(f)$) to the ground motion at bedrock ($SA^r(f)$) as follows [18], [19]:

$$AF(f) = \frac{SA^s(f)}{SA^r(f)} \tag{2}$$

The amplification factor $AF(f)$ is determined by modeling the characteristics of the soil profile under the site as explained by Bazzurro and Cornell [18]. Then, the conditional distribution of $AF(f)$ given $SA^r(f)$ is incorporated into the total probability theorem calculation to determine the soil seismic hazard curve [19]. It should be noted that the above approach to obtain the soil seismic hazard curve is known as "Approach 3B" in NUREG/CR-6728 [20].

3. Spatial Variability of Ground Motions

It is prudent to start this discussion by defining the phrase "spatial variability of ground motions." Various authors have provided definitions of this phrase. Specifically, Zerva [21] states: "[t]he term 'spatial variation of seismic ground motions' denotes the differences in the amplitude and phase of seismic ground motions recorded over extended areas." Similarly, Schneider, et al. [22] state: "[t]he spatial variation of ground motion has two parts: variation in waveform (phase) and variation in amplitude." Schneider, et al. [22] further state: "[t]he spatial coherency describes variation in waveform and the amplitude variation describes variation in scaling [of the ground motion]".

Existing work related to spatial variability of ground motion has focused mostly on the variation of the seismic waveform (phase) (i.e., coherency). The amplitude variability of ground motion has received less attention [21]. The work in the nuclear industry with respect to coherency has focused on distances on the scale of the foundation size of an NPP (i.e., up to about 150 m) and has primarily focused on applications related to soil-structure interaction [23]. In general, the correlation (variability) of the ground motions decreases (increases) as the frequency increases and the separation distance between the earthquake recording stations increases [21].

Ground motions vary spatially on local as well as regional scales [7]. Vanmarcke [24] refers to a "local field" (or local scale) as "surface areas that are small enough that the internal variation of motion amplitudes with distance from the earthquake source, as expressed by attenuation laws [i.e., GMMs] is negligible." Vanmarcke [24] further states: "specifically, within the confines of a 'local field,' peak accelerations estimated in [sic] function of magnitude and distance differ negligibly [when] compared to measurements of peak accelerations by (actual or hypothetical) closely-spaced accelerographs; these may differ by factors of 2 or more, even over distances of the order of meters." The case of an NPP site can be considered as a local scale (or site scale) because, as confirmed by a review of several updated final safety analysis reports (UFSAR) from U.S. multi-unit NPP sites (e.g., [25]–[28]), the separation distance between units is on the order of tens to hundreds of meters (see Figure 2).

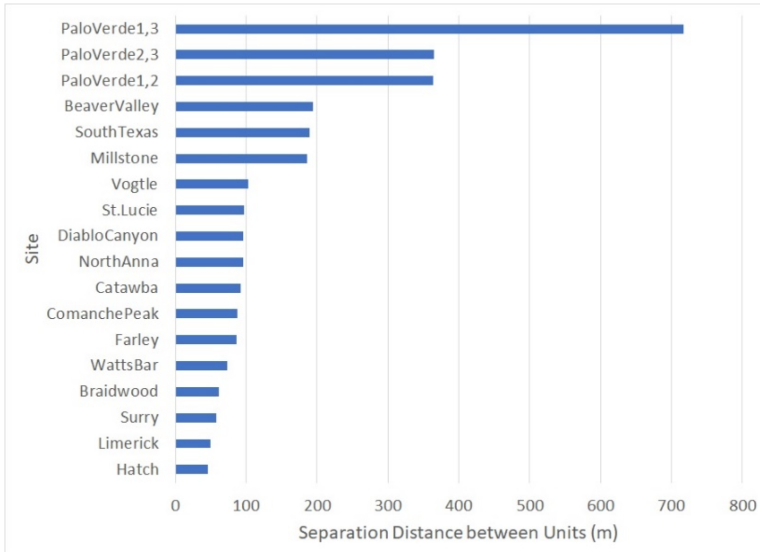

Figure 2. Separation Distance between Units in Several U.S. NPP Sites

Our proposed framework for modeling ground variability for use in an NPP seismic risk assessment is based on the idea of ground motion varying at structure (i.e., up to about 150m), local (i.e., 150m up to about 1 km), and regional (i.e., above 1 km) scales. Specifically, the structure, local, and regional scales can be viewed as relevant to a single-unit seismic PRA, multi-unit seismic PRA, and multi-site seismic PRA, respectively. Figure 3 illustrates the different scales and their relation to PRA. It should be noted that the selection of 150 m as the boundary between the structure and local scales is consistent with the distances shown in Figure 2 and due to the work already performed in the nuclear industry with respect to coherency. It is expected that the variability of ground motion in the structure and local scales can be modeled using the same methods and techniques (i.e., amplitude variability and phase variability) while the correlation at the regional scale requires alternate conceptual formulations (e.g., [2], [3]).

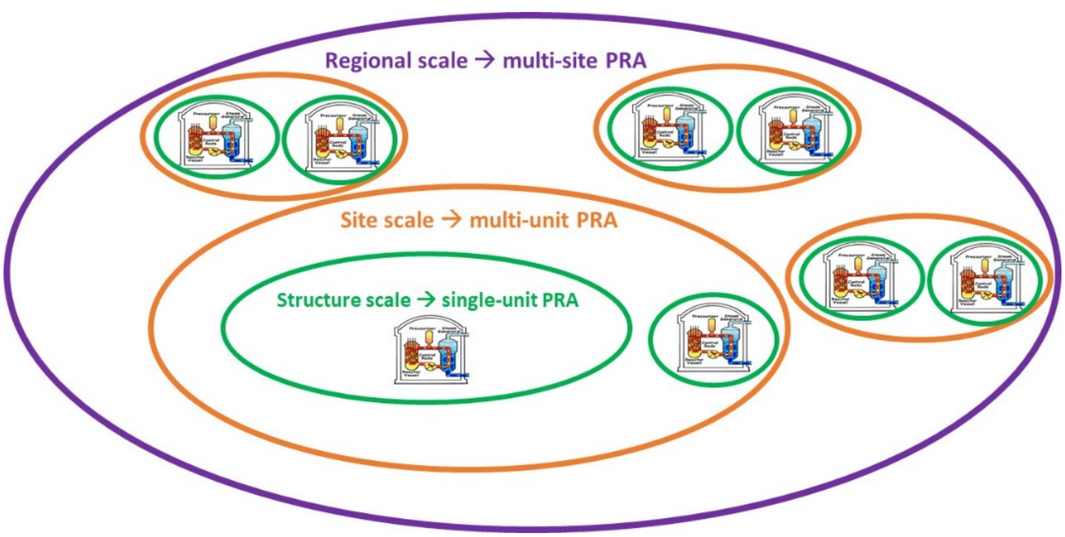

Figure 3. Illustration of the Structure, Local/Site, and Regional Scales[4]

[4] The use of the same reactor in this figure is for illustration only and does not imply that the units have to be identical within the proposed framework.

3.1. Factors Affecting the Spatial Variability of Ground Motions

Der Kiureghian [29] explains that "[f]our distinct phenomena give rise to the spatial variability of earthquake-induced ground motions" and these are:

1. Incoherence effect – refers to the loss of coherency of seismic waves due to scattering in the heterogenous medium of the ground, as well as due to the differential super-positioning of waves arriving at each station from an extended source.[5]
2. Wave-passage effect – refers to the difference in arrival times of waves at separate stations.
3. Attenuation effect – refers to the gradual decay of wave amplitudes with distance due to geometric spreading and energy dissipation in the ground medium.
4. Site-response effect – refers to the spatially varying local soil profiles and the manner in which they influence the amplitude and frequency content of the bedrock motion underneath each station as it propagates upward.

Figure 4 illustrates the incoherence (i.e., scattering and extended source), wave-passage, and attenuation effects. In Figure 4(a), the seismic waves propagating away from the source encounter a heterogeneity in the ground that modify their waveform and direction of propagation causing differences in the ground motion at the various locations. In Figure 4(b), as the rupture propagates along an extended fault, it transmits energy that arrives delayed on the ground surface resulting in variability of the shape of the waveforms at the various locations. In Figure 4(c), the inclination of the wave front causes time delays in the arrival of the waveforms at the various locations in the ground surface. Finally, in Figure 4(d), as the seismic waves propagate away from the source their amplitude decreases as the distance from the source increases. However, Der Kiureghian [29] and Zerva [21] note that the attenuation effect is insignificant for the typical size of most man-made structures, which is consistent with Vanmarcke's remarks about the local field/scale [24].

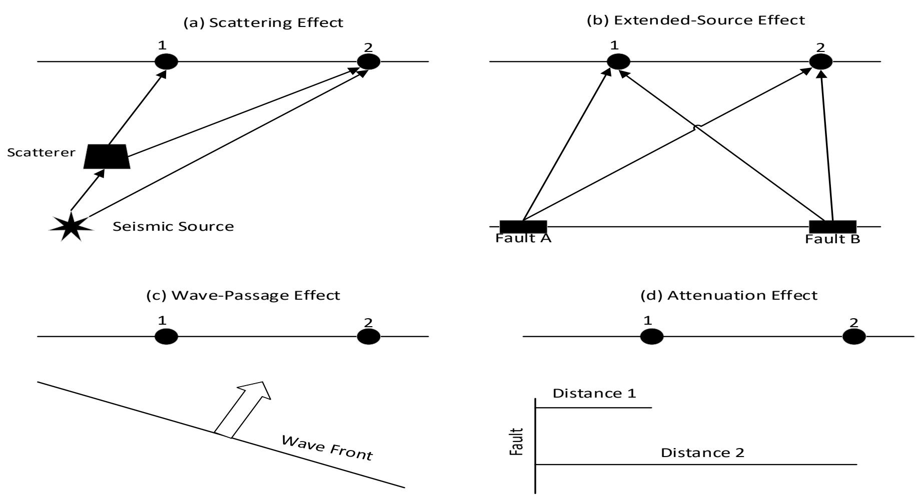

Figure 4. Illustration of the Causes of Spatial Variation of Ground Motions (adapted from [21], [30])

3.2. Existing Work to Model Correlation (Variability) of Spatially Distributed Ground Motions

In the literature, the work related to spatial variability of ground motions is addressed in several ways. These ways include the spatial correlation of intra-event variability, variability of the seismic waveform, and variability of the seismic amplitude. The majority of the work related to the variability of seismic waveform (i.e., coherency [23]) and amplitude [22] has been derived using Fourier amplitude spectra, which is not directly applicable for our application because available GMMs provide estimates in terms of SA (and other response spectrum ordinates). There is a limited number of works related to the amplitude

[5] In the work by Abrahamson [30], these two causes are referred as the scattering effect and extended-source effect, respectively.

variability using SA (e.g., [4]). The spatial correlation of intra-event variabilities and the spectral amplitude variability are described below.

Spatial Correlation of Intra-Event Variabilities

Existing ground motion correlation models (e.g., [2], [3]) generally focus on modeling spatial ground motion correlation for structures that are located at distances of 1 km or more apart. Within the framework described in the last paragraph of Section 3, this distance can be considered as a *regional scale*. These works define the correlation model for spatially distributed intra-event variabilities (i.e., ε_{ij} in Equation 1) as a function of separation distance between structures or other locations of interest. For example, Goda and Hong [3] proposed the following functional form:

$$\rho_{\varepsilon}(\xi, T_n) = exp\left(-\alpha\xi^{\beta}\right) \tag{3}$$

where $\rho_{\varepsilon}(\xi, T_n)$ is the correlation between the intra-event variabilities ε_{ij} and ε_{ik} at locations j and k during earthquake i, ξ is the separation distance between the locations, T_n is the natural vibration period, and α and β are the model parameters. Even though T_n is not shown explicitly in the model, it is included in recognition that the spatial correlation of ground motion can vary as a function of T_n. Using an exponential form allows $\rho_{\varepsilon}(\xi, T_n)$ to tend to one as ξ tends to zero and $\rho_{\varepsilon}(\xi, T_n)$ to tend to zero as ξ tends to infinity. In other words, the correlation increases (decreases) as the separation distance decreases (increases). If the aforementioned ground motion correlation models were to be used to model ground motion variability in a seismic MUPRA, the correlation would be close to 1.0, because of the short separation distance between units (i.e., less than 1 km). It should be noted that the aforementioned the ground motion correlation models were developed using regional ground motion databases such as the NGA-West2 database.

Spectral Amplitude Variability

Abrahamson and Sykora [4] analyzed the variability of SA over short distances (< 100 m) using empirical recordings of seismic ground motion at dense arrays. Some of the analyzed dense accelerograph arrays include the Electric Power Research Institute (EPRI) Lotung Large Scale Seismic Test (LSST) array in Taiwan and the EPRI Parkfield array in California. They estimated the variability of SA as follows: Let $SA_{ij}(f)$ be the average horizontal component of the acceleration response spectrum for the *j*th station and the *i*th earthquake and let $\Delta SA_{ijk}(f)$ be the difference between the log values of SA at the *j*th and *k*th stations (which are separated by a distance ξ) from the *i*th earthquake. That is,

$$\Delta \mathrm{SA}_{ijk}(f) = ln\left[\mathrm{SA}_{ij}(f)\right] - ln[\mathrm{SA}_{ik}(f)] \tag{4}$$

The mean of $\Delta\mathrm{SA}_{ijk}(f)$ is assumed to be zero (similar to how the inter- and intra-event variabilities in a GMM are zero mean). According to Abrahamson and Sykora [4], the standard deviation of $\Delta\mathrm{SA}_{ijk}(f)$ ($\sigma_{\Delta\mathrm{SA}_{ijk}(f)}$) is independent of the event and it is used to quantify the variability in ground response. The model developed for $\sigma_{\Delta\mathrm{SA}_{ijk}(f)}$ is [4]:

$$\sigma_{\Delta\mathrm{SA}_{ijk}}(M, \xi, f) = c_1(f, M)(1 - exp\{-\xi\ c_2(f)\}) \tag{5}$$

where ξ is the separation distance between stations j and k in meters, f is the oscillator frequency in Hz, M is the magnitude, and $c_1(f, M)$ and $c_2(f)$ are coefficients estimated by regression using a maximum likelihood approach. These coefficients were estimated using data from nine dense arrays with five arrays classified as "rock" and four arrays classified as "soil" and are provided by Abrahamson and Sykora [4] (see their Table 3 for $c_1(f, M)$, which depends on whether the site is classified as rock or soil, and their Equation 3 for $c_2(f)$).

Abrahamson and Sykora [4] found that the variation in $\Delta \mathrm{SA}_{ijk}(f)$ (i.e., $\sigma_{\Delta \mathrm{SA}_{ijk}}(M, \xi, f)$) is strongly dependent on earthquake magnitude with larger magnitudes having less variation. They also found that the variability at rock sites is larger than or equal to the variability at soil sites. Abrahamson and Sykora [4] state that "one possible source for [the] difference in variation on soil and rock is that a slight shift in resonance across a site can easily generate large variations in amplitude at a given frequency." They continue, "[i]n this regard, small changes in layer thickness would produce more predominant shifts in resonance for shallow layers; thus, shallow soil sites and rock sites with complex geology would tend to experience the largest amplitude variations." Due to the rock site variability generally being larger than the soil site variability, Abrahamson and Sykora [4] conclude that it is not appropriate to simply combine the variability of rock motions with the variability of soil site response to estimate the total variability of ground motion at soil sites.

Overall, $\Delta \mathrm{SA}_{ijk}(f)$ is normally distributed with zero mean and standard deviation $\sigma_{\Delta \mathrm{Sa}_{ijk}}(M, \xi, f)$, which is given by Equation 5.

4. Proposed Framework to Model Ground Motion Variability for Use in a Seismic MUPRA

The intended result of this research is to develop a framework for defining the conditional relationship between the ground motion at the individual units at an NPP site as a function of the ground motion at the site control point. This allows consideration of the ground motion correlation (variability) across the site using the ground motion at the site control point (i.e., the location where the ground motion hazard has been characterized using a PSHA) as an "anchor."

The proposed framework for modeling spatial variability in ground motion is shown in Figure 5 using a probabilistic graphical model (PGM) and illustrations of most of the variables. The PGM in Figure 5 is a general case for a two-unit site assuming that information about the locally varying soil profiles underneath each unit is known. In some instances, the control point may coincide with one of the units at the site. If this is the case, the framework would have less variables to model. Each node (oval) in Figure 5 represents a random variable (RV). The RVs are defined below and the arrows (links) represent a probabilistic dependence between the connected nodes. The model has two sources of variability in ground motion among the units: amplitude variability and local soil profile variability. The amplitude variability model shown as Equation 5 may be used, but its applicability is limited because it was developed for separation distances up to 100 m and, as shown in Figure 2, the distance between units can be greater than 100 m. For this reason, a new amplitude variability model may be needed that takes into consideration the site conditions and larger separation distances. Since the amplitude variability model depends on the earthquake magnitude [4], the process of disaggregation of the PSHA results is expected to be used. The local soil profile variability would be incorporated by using different amplification factors.

Implicit in Figure 5 is that most variables (except $Source$, M, Loc, R, and ξ) are a function of the oscillator frequency f. Each of the nodes in Figure 5 is defined as follows:

- $Source$ represents the earthquake source;
- M is the earthquake magnitude and it is taken as the moment magnitude;
- Loc represents the earthquake's location;
- R is the distance from the earthquake source to the site;
- $\ln\left(\overline{SA_{CP}^{r}}\right)$ is the ground motion predicted at bedrock using a GMM;
- η and ε represent the inter-event and intra-event variabilities, respectively;
- $\ln(SA_{CP}^{r})$ is the ground motion at bedrock at the control point after incorporating the inter- and intra-event variabilities, as shown in Equation 1;

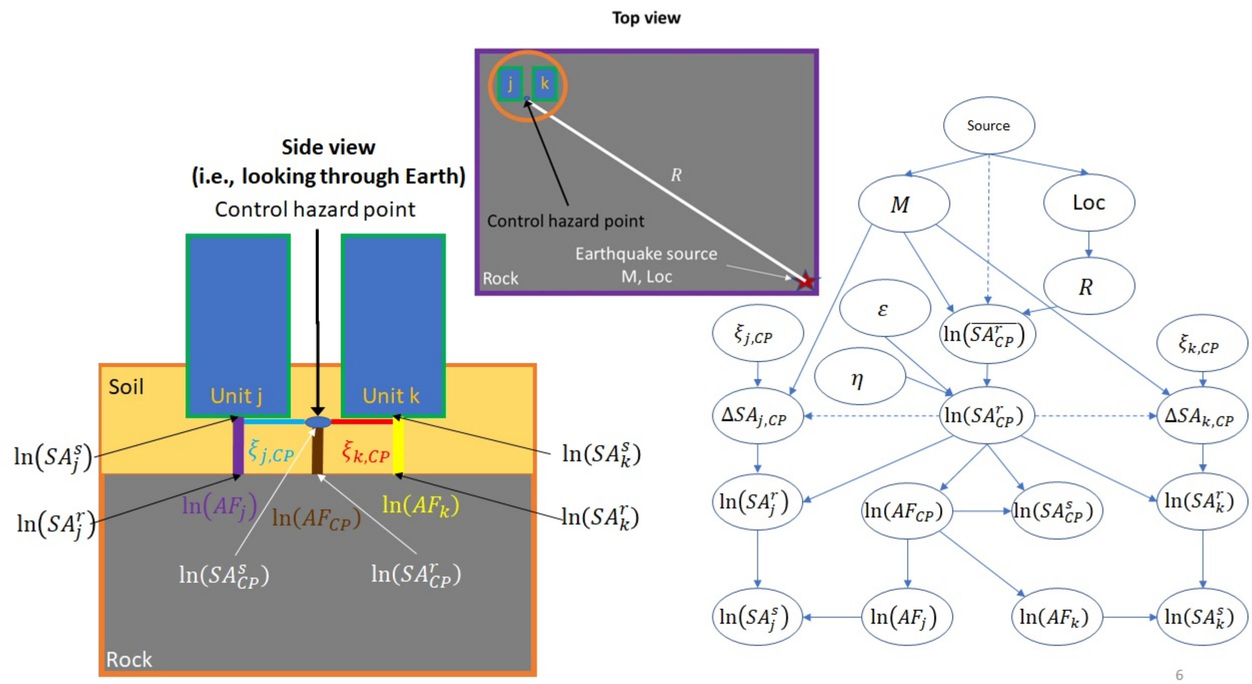

Figure 5. Amplitude and Local Soil Profile Variability PGM for a Single Site with Two Units

- $\xi_{j,CP}$ and $\xi_{k,CP}$ are the separation distances (in meters) between unit j and the control point, and unit k and the control point, respectively;
- $\Delta SA_{j,CP}$ and $\Delta SA_{k,CP}$ represent the amplitude variability model for units j and k each with respect to the site control point (see Equations 4 and 5), respectively
- $\ln(SA_j^r)$ and $\ln(SA_k^r)$ represent the natural logarithms of the ground motion at bedrock underneath units j and k, respectively, after considering the amplitude variability model;
- $\ln(AF_{CP})$, $\ln(AF_j)$, and $\ln(AF_k)$ are the natural logarithms of the amplification factor for the control point, unit j, and unit k, respectively;
- $\ln(SA_{CP}^s)$ represents the natural logarithm of the ground motion at soil at the site control point, it is equal to $\ln(SA_{CP}^r) + \ln(AF_{CP})$ (this obtained by applying natural logarithms to both sides of Equation 2 and after some algebra); and
- $\ln(SA_j^s)$ and $\ln(SA_k^s)$ represent the natural logarithms of the ground motion at soil for units j and k, respectively, and they are equal to $\ln(SA_j^r) + \ln(AF_j)$ and $\ln(SA_k^r) + \ln(AF_k)$, respectively.

Using Figure 5, we can determine the ground motion at a specific unit given the ground motion at the control point. The characterization of the ground motion hazard at the control point and the respective disaggregation results are obtained from an already performed PSHA at the site. To better understand how the model in Figure 5 can be used in a seismic MUPRA, assume that the control point coincides with unit k (alternatively, unit k is the location where the ground motion hazard has been characterized using a PSHA). In other words, unit k is the reference unit. This would lead to the PGM shown in Figure 6, [6] which in general terms represents the seismic MUPRA model. Specifically, the conditional probability distribution for the ground motion at all the units is combined with a conditional risk metric for each unit

[6] For simplicity, the natural logarithms from Figure 5 have been dropped and in the case of a rock site, SA_j^r and SA_k^r would be used instead of SA_j^s and SA_k^s.

(in Figure 6, the metric conditional core damage probability (CCDP) is used as an example) to obtain the appropriate multi-unit risk metrics (MURM).

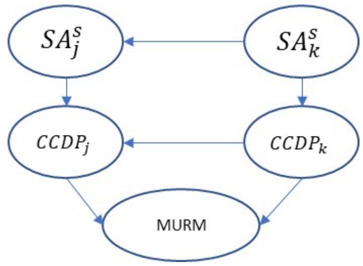

Figure 6. PGM for the MUPRA Risk Metrics

Using PGM quantification techniques, the distribution of the MURM can be determined as follows:

$$p_{MURM}(murm) = \sum_{sa_k^s}\sum_{sa_j^s}\sum_{ccdp_k}\sum_{ccdp_j} p_{SA_k^s}(sa_k^s)\, p_{SA_j^s|SA_k^s}(sa_j^s|sa_k^s)\, p_{CCDP_k|SA_k^s}(ccdp_k|sa_k^s)\, p_{CCDP_j|SA_j^s,CCDP_k}(ccdp_j|sa_j^s, ccdp_k)\, p_{MURM|CCDP_j,CCDP_k}(murm|ccdp_j, ccdp_k) \quad (6)$$

where $p_{SA_k^s}(sa_k^s)$ is obtained from the PSHA; $p_{SA_j^s|SA_k^s}\left(sa_j^s|sa_k^s\right)$ is obtained from a ground motion variability model as the one shown in Figure 5; and $p_{CCDP_k|SA_k^s}(ccdp_k|sa_k^s)$, $p_{CCDP_j|SA_j^s,CCDP_k}\left(ccdp_j|sa_j^s, ccdp_k\right)$, and $p_{MURM|CCDP_j,CCDP_k}\left(murm|ccdp_j, ccdp_k\right)$ come from a MUPRA model.

Risk metrics for an NPP site is an active area of research. Examples of research in multi-unit risk metrics include the work by Modarres [31] and the International Atomic Energy Agency (IAEA) [32]. It should be noted that even though the presentation here focused on two units at an NPP site, this concept could be used for more than two units having the ground motion at the site control point or at a reference unit as an "anchor." In the case of more than two units, more nodes would be needed in Figure 5 and Figure 6 to represent the additional units.

5. Conclusion

We have proposed a framework to model ground motion variability for use in a seismic MUPRA. Additional research is needed to develop the ground motion amplitude variability and local soil profile variability models and refine the approaches for addressing the magnitude dependence through disaggregation. Lastly, a method to consider the ground motion dependencies across the units needs to be developed, as recognized by Zhou et al. [33]. Equation 6 is a first step in that direction.

6. References

[1] S. Schroer and M. Modarres, "An event classification schema for evaluating site risk in a multi-unit nuclear power plant probabilistic risk assessment," *Reliab. Eng. Syst. Saf.*, vol. 117, no. Supplement C, pp. 40–51, Sep. 2013.

[2] N. Jayaram and J. W. Baker, "Correlation model for spatially distributed ground-motion intensities," *Earthq. Eng. Struct. Dyn.*, vol. 38, no. 15, pp. 1687–1708, Dec. 2009.

[3] K. Goda and H. P. Hong, "Spatial Correlation of Peak Ground Motions and Response Spectra Spatial Correlation of Peak Ground Motions and Response Spectra," *Bull. Seismol. Soc. Am.*, vol. 98, no. 1, pp. 354–365, Feb. 2008.

[4] N. Abrahamson and D. Sykora, "Variation of Ground Motions Across Individual Sites," in *Proc. of the Fourth U.S. Department of Energy Natural Phenomena Hazards Mitigation Conference, LLNL CONF-9310102*, 1993, pp. 192–198.

[5] IAEA Division of Nuclear Installation Safety, "Methodology for Multi-Unit Probabilistic Safety Assessment." International Atomic Energy Agency, Nov-2017.

[6] K. Fleming, “Summary Report of the International Workshop on Multi-Unit Probabilistic Safety Assessment. Ottawa, Ontario, Canada, November 17-20, 2014.” Canadian Nuclear Safety Commission, E-docs reference #4704298, 2014.
[7] S. Kramer, *Geotechnical Earthquake Engineering*. Pearson, 1996.
[8] U.S. Nuclear Regulatory Commission, *NRC Analyzes Seismic Hazards at Nuclear Power Plants https://www.flickr.com/photos/nrcgov/10461149524/in/photolist-cN4Bho-gWq8hY-dUMo5N-cXiB8Y*. 2013.
[9] A. K. Chopra, *Dynamics of Structures: Theory and Applications to Earthquake Engineering*, 4th ed. Prentice Hall, 2012.
[10] N. A. Abrahamson, W. J. Silva, and R. Kamai, “Update of the AS08 Ground-Motion Prediction Equations Based on the NGA-West2 Data Set,” Pacific Earthquake Engineering Research Center, PEER 2013/04, May 2013.
[11] D. M. Boore, J. P. Stewart, E. Seyhan, and G. M. Atkinson, “NGA-West2 Equations for Predicting Response Spectral Accelerations for Shallow Crustal Earthquakes,” Pacific Earthquake Engineering Research Center, PEER 2013/05, May 2013.
[12] “NGA-East: Median Ground-Motion Models for the Central and Eastern North America Region,” Pacific Earthquake Engineering Research Center, PEER 2015/04, Apr. 2015.
[13] “NGA-East: Adjustments to Median Ground-Motion Models for Central and Eastern North America,” Pacific Earthquake Engineering Research Center, PEER 2015/08, Aug. 2015.
[14] T. D. Ancheta *et al.*, “PEER NGA-West2 Database,” Pacific Earthquake Engineering Research Center, PEER 2013/03, May 2013.
[15] C. A. Goulet *et al.*, “PEER NGA-East Database,” Pacific Earthquake Engineering Research Center, PEER 2014/17, Oct. 2014.
[16] J. W. Baker, “An Introduction to Probabilistic Seismic Hazard Analysis (PSHA).” 2008.
[17] EPRI 3002000709, “Seismic Probabilistic Risk Assessment Implementation Guide.” Electric Power Research Institute, 2013.
[18] P. Bazzurro and C. A. Cornell, “Ground-Motion Amplification in Nonlinear Soil Sites with Uncertain Properties,” *Bull. Seismol. Soc. Am.*, vol. 94, no. 6, pp. 2090–2109, Dec. 2004.
[19] P. Bazzurro* and C. A. Cornell, “Nonlinear Soil-Site Effects in Probabilistic Seismic-Hazard Analysis,” *Bull. Seismol. Soc. Am.*, vol. 94, no. 6, pp. 2110–2123, Dec. 2004.
[20] NUREG/CR-6728, “Technical Basis for Revision of Regulatory Guidance on Design Ground Motions: Hazard- and Risk-Consistent Ground Motion Spectra Guidelines,” U.S. Nuclear Regulatory Commission, Washington, D.C., Oct. 2001.
[21] A. Zerva, *Spatial Variation of Seismic Ground Motions: Modeling and Engineering Applications*. CRC Press, 2009.
[22] J. F. Schneider, J. C. Stepp, and N. A. Abrahamson, “The Spatial Variation of Earthquake Ground Motion and Effects of Local Site Conditions,” in *Proc. of the Tenth World Conference on Earthquake Engineering*, Madrid, Spain, 1992.
[23] EPRI 1015110, “Program on Technology Innovation: Effects of Spatial Incoherence on Seismic Ground Motions.” Electric Power Research Institute, 2007.
[24] E. Vanmarcke, “Local spatial variation of earthquake ground motion,” presented at the Tenth World Conference on Earthquake Engineering, 1994, pp. 6615–6621.
[25] “Limerick Generating Station, UFSAR, Chapter 2, Site Characteristics. Available at: https://adamswebsearch2.nrc.gov/webSearch2/main.jsp?AccessionNumber=ML16357A122.”
[26] “Comanche Peak Nuclear Power Plant, UFSAR, Chapter 2, Site Characteristics. Available at: https://adamswebsearch2.nrc.gov/webSearch2/main.jsp?AccessionNumber=ML16180A431.”
[27] “South Texas Project Electric Generating Station, UFSAR, Chapter 2, Site Characteristics. Available at: https://adamswebsearch2.nrc.gov/webSearch2/main.jsp?AccessionNumber=ML16207A536.”
[28] “Palo Verde Nuclear Generating Station, UFSAR, Chapter 2, Site Characteristics. Available at: https://adamswebsearch2.nrc.gov/webSearch2/main.jsp?AccessionNumber=ML17193A048.”

[29] A. Der Kiureghian, “A Coherency Model for Spatially Varying Ground Motions,” *Earthq. Eng. Struct. Dyn.*, vol. 25, no. 1, pp. 99–111, Jan. 1996.
[30] N. Abrahamson, “Spatial Variation of Multiple Support Inputs,” in *Proc. of the First U.S. Seminar on Seismic Evaluation and Retrofit of Steel Bridges*, San Francisco, CA, USA, 1993.
[31] M. Modarres, “Multi-Unit Nuclear Plant Risks and Implications of the Quantitative Health Objectives,” presented at the PSA 2015, 2015 International Topical Meeting on Probabilistic Safety Assessment and Analysis, Sun Valley, ID, USA, 2015.
[32] IAEA International Seismic Safety Centre, “Technical Approach to Multi-Unit Probabilistic Safety Assessment.” International Atomic Energy Agency, 2014.
[33] T. Zhou, M. Modarres, and E. L. Droguett, “An improved multi-unit nuclear plant seismic probabilistic risk assessment approach,” *Reliab. Eng. Syst. Saf.*, vol. 171, no. Supplement C, pp. 34–47, Mar. 2018.