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ON THE USE OF SITE-SPECIFIC PROBABILISTIC SEISMIC HAZARD ANALYSIS AND THE ATTENUATION PARAMETER κ IN HAZARD ASSESSMENTS OF CRITICAL FACILITIES

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ABSTRACT

Probabilistic seismic hazard analysis (PSHA) is the preferred approach to evaluate potential earthquake motions at the sites of critical facilities, such as nuclear power plants. Aleatory variability in ground motion prediction models (GMPEs) used in PSHA is represented by a logarithmic standard deviation known as sigma, σ. This standard deviation has proven to exert a strong influence on hazard estimates, especially at low annual exceedance frequencies typically considered for critical infrastructure. Traditional PSHA applies the standard deviations corresponding to GMPEs based on global datasets, at a single site. This results from the ergodic assumption. However, partial or fully non-ergodic PSHA can be conducted if the systematic contributions of the site to the ground motion are known or can be estimated. In addition to capturing the effects of shallow sedimentary deposits, the site term must account for the deep shear-wave velocity structure and site attenuation parameter. The high-frequency spectral decay parameter κ is a low-pass filter, which captures damping in the upper geologic structure at the site of interest. This work presents the various instances where estimations of the site parameter κ_0 can be integrated into the hazard assessment of critical facilities, from the definition of consistent energy in the high-frequency range of ground motions, improving attenuation or damping models for shallower sedimentary deposits, to the development of host-to-target adjustment factors.

INTRODUCTION

The Probabilistic seismic hazard analysis (PSHA) framework identifies, quantifies and combines uncertainties associated with the size, location and resulting ground shaking intensity of future seismic events in a rational way. This is the preferred approach to evaluate the seismic demand of critical facilities such as nuclear power plants (Rodriguez-Marek et al., 2014). Aleatory variability (i.e., inherent randomness) in ground motion prediction models (GMPEs) used in PSHA is represented by a logarithmic standard deviation known as sigma, σ. This standard deviation has proven to exert a strong influence on hazard estimates, especially at low annual exceedance frequencies (Al Atik et al., 2010; Rodriguez-Marek et al., 2014) typically considered for critical infrastructure. Defensible reductions in sigma are desirable not only because of their ultimate effect on the results from PSHA at long return periods (Figure 1); they also result from a clear separation of aleatory variability and epistemic uncertainty (Rodriguez-Marek et al., 2014). Aleatory variability is theoretically irreducible, while epistemic uncertainty can be reduced with the collection of new data. Traditional PSHA applies the standard deviations corresponding to GMPEs based on global datasets, at a single site. Such practice implicitly assumes the variability at a single site to be the same as the variability observed in many different sites (Al Atik et al., 2010). However, the variability in ground motions recorded at individual sites is generally lower than the variability resulting from GMPEs (Atkinson 2006).

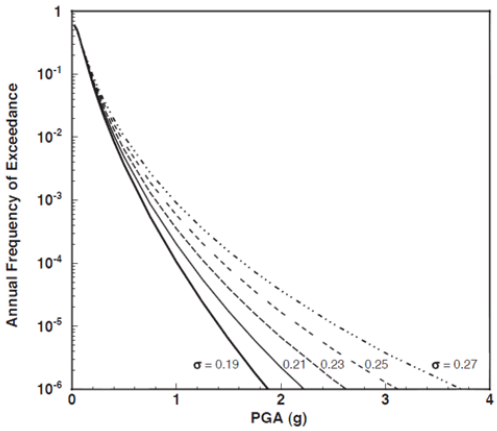

Figure 1. Effects of reductions in sigma on seismic hazard estimates (after Bommer and Abrahamson 2006).

The systematic contributions of the site of interest to the ground motion can be estimated if multiple recordings exist at such location, or if the site effects can be accurately modeled. Knowledge of these repeatable contributions allows to adjust the median ground motion prediction, and the sigma value can be reduced by an amount that represents the actual variability at the site (Rodriguez-Marek et al., 2014). Figure 2 summarizes the process involved in the translation of the seismic hazard from a reference depth (typically bedrock) to the ground surface at the site of interest. The resulting value of sigma corresponds to the standard deviation for site-specific PSHA. If sufficient recorded motions are not available at the site, site response effects can be incorporated into seismic hazard calculations by estimating amplification functions (AFs), which are then coupled with the estimated hazard at the corresponding rock site. Amplification functions define the trend of computed amplifications from site response analyses (SRA) with input motion amplitude (Stewart et al. 2014). They result from a regression fit, either a linear or a nonlinear relationship, of the amplification as a function of the spectral acceleration of the rock at the same oscillator period (e.g. Abrahamson and Silva, 1997; Goulet et al. 2007, Stewart et al. 2014). The amplification at a given site is typically obtained as the ratio of spectral acceleration at the surface and the assumed reference depth at a given oscillator period. Accurately constraining SRA results and their associated uncertainty is necessary to invoke the partially non-ergodic PSHA concept. Details concerning the convolution approach of the hazard curves for the reference rock with the AFs and the corresponding variabilities to provide surface (or any other target horizon) hazard curves can be found in Bazzurro and Cornell (2004).

In addition to capturing the effects of shallow deposits, the site term must account for the deep shear-wave velocity (V_s) structure and the site attenuation parameter (κ_0) (Ktenidou et al., 2016). These effects can be captured by V_s-κ_0 corrections to the GMPE from host to target regions (Rodriguez-Marek et al., 2014). The host is typically a seismically active region, such as the Western US, whereas the target could be a low-to-moderate seismicity region, such as Central and Eastern US (CEUS). For instance, the associated V_s and κ_0 values for the reference rock at typical sites in CEUS were found to be 3000 m/s +/- 300 m/s and 0.006 sec, respectively (Hashash et al. 2014). However, it is virtually impossible to find ground motions recorded at such hard rock conditions (Cabas and Rodriguez-Marek, 2017).

This work presents the various instances where estimations of the site parameter κ_0 can be integrated into the hazard assessments of critical facilities, from the definition of consistent energy in the high-frequency range of ground motions, improving attenuation or damping models for shallower sedimentary deposits, to the development of host-to-target adjustment factors. These areas are highlighted within the non-ergodic PSHA framework shown in Figure 2.

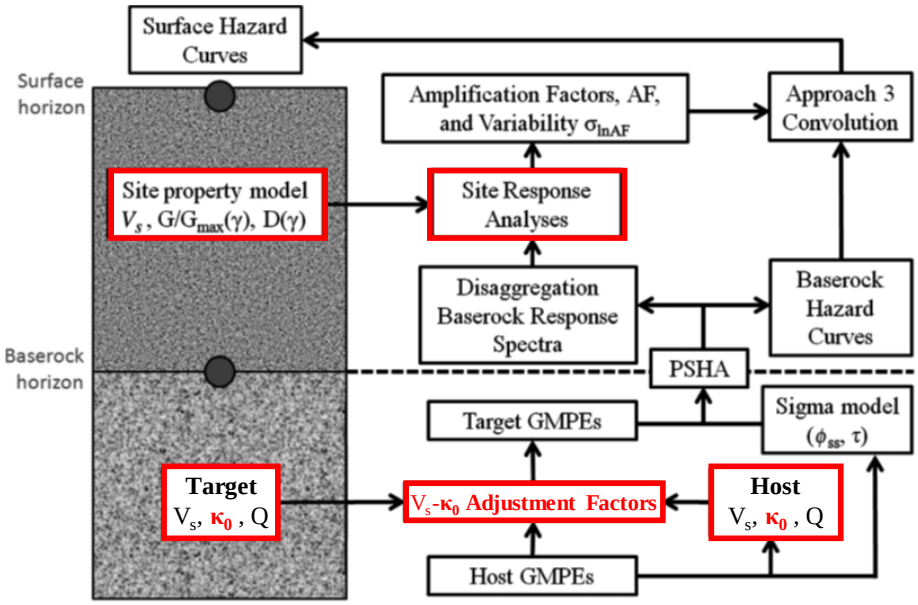

Figure 2. Schematic diagram of the modifications to the host ground-motion prediction equation to obtain site- specific hazard curves (modified from Rodriguez-Marek et al., 2014).

Uncertainty in the estimation of κ is large (Ktenidou et al., 2014), and may have important implications for seismic risk in practice; especially at rock sites, where the estimation of the attenuation or damping in the profile is vital to assessing appropriate levels of high-frequency (> ~5 Hz) design motions. Site attenuation controls the scaling from soft to hard rock at high frequencies (Cotton et al., 2006). Consequently, adjusting the GMPEs to hard-rock conditions is sensitive to κ_0 (Ktenidou et al., 2016). For instance, the Pegasos Refinement Project (Biro and Renault 2012) demonstrated how κ_0 corrections from soft-rock to hard-rock conditions can lead to differences up to a factor of 3 in the high-frequency part of the response spectrum (Figure 3). As a direct corollary, large uncertainties in the probabilistic risk at nuclear facilities with safety-related equipment that is sensitive to ground shaking at frequencies above 20 Hz can be expected (Ktenidou et al., 2016).

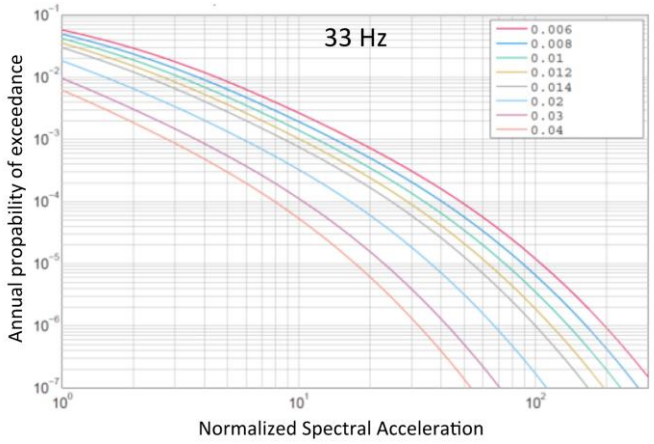

Figure 3. Hazard sensitivity to different target κ_0 values for 33 Hz at an example site in Switzerland. The host κ_0 is fixed as 0.04 sec with V_{s30}=800 m/sec. The target conditions are V_{s30}=2000 m/sec with different κ_0 values ranging from 0.006 sec to 0.04 sec (from Ktenidou et al., 2016).

KAPPA

The concept of κ was originally introduced by Anderson and Hough (1984) as a site and distance dependent low-pass filter. It was based on the observation that in log-linear space, the acceleration Fourier amplitude spectrum (FAS) can be assumed to decay linearly for high frequencies above a certain value (Figure 4b). The zero-distance intercept of κ is known as site-specific κ or κ_0 (Figure 4a), and it has been found to be dependent on the site rather than the source (e.g., Ktenidou et al., 2014; Edwards et al., 2015). It captures the attenuation of seismic waves as they travel vertically through the subsurface geological structure underneath the site (Anderson and Hough, 1984). Individual values of κ can be measured directly from ground motions recorded in the field. They increase with epicentral distance as shown in Figure 4(a), where κ_R represents the regional attenuation term (assuming a unique ray path and unique value of the seismic quality factor, Q).

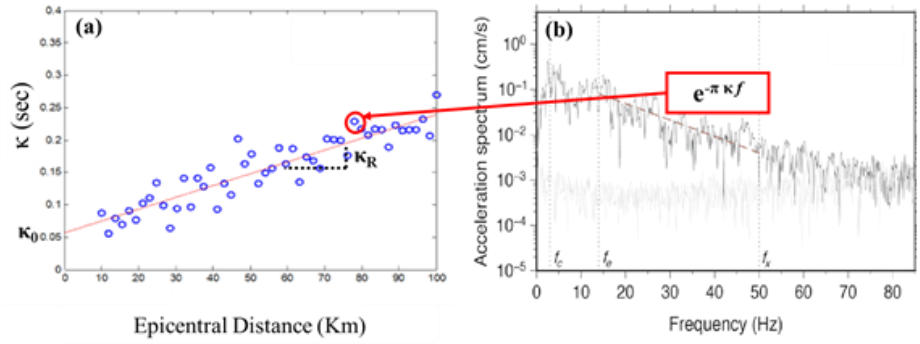

Figure 4. (a) Linear regression of individual measurements of κ (blue circles) with epicentral distance, and (b) Individual measure of κ (modified after Ktenidou et al., 2013).

In recent years, the interest in κ_0 has increased because of its advantages when adjusting GMPEs from host to target regions, and its applications in site-specific PSHA. Values of κ_0 can also be used to constrain high frequencies for synthetic or simulated ground motions (e.g., Boore 2003, Cabas et al., 2015; Cabas and Rodriguez-Marek 2017). It has been shown that the seismic motion on rock and stiff-soil sites does not only depend on the shear wave velocity of near-surface materials, but also on κ_0 (Laurendeau et al., 2013). Additional applications include the use of κ for development of site-specific amplification factors for Ground Motion Response Spectra screening at facilities with limited site characterization data (e.g., EPRI 2013). A comprehensive description of the various methodologies to compute individual values of κ can be found in Ktenidou et al., (2014). Likewise, a description of the relationship between κ and other attenuation descriptors such as the seismic quality factor, Q (Knopoff 1964) is provided by Campbell (2009) and Ktenidou et al., (2015).

Approaches to estimate kappa

Different methodologies to compute κ values or to estimate them based on empirical correlations with other site parameters such as the time-averaged shear wave velocity in the top 30 m of the profile, V_{s30}, have populated the literature recently (e.g., Silva and Darragh, 1995; Chandler et al. 2006; Drouet et al., 2010; Van Houtte et al., 2011). However, the scatter in κ_0-V_{s30} relationships is rather large. When it comes to site-specific PSHA, one of the main challenges is the lack of data (particularly events with magnitudes larger than 3), and usable bandwidth (Perron et al., 2017) in low-to-moderate seismicity regions (i.e., target regions). The Anderson and Hough (1984) approach (Figure 4b) is often implemented in host regions, which are not affected by the scarcity of records. However, the aforementioned limitations prevent the use

of the acceleration spectrum methodology (i.e., the Anderson and Hough, 1984 method) to compute individual values of κ in regions such as the CEUS.

To ensure consistency between κ values associated with host and target regions, it is important to understand the differences among the resulting κ_0 values from the wide variety of methods available in the literature. Ktenidou et al., (2016) explored four approaches (two band-limited and two broadband) for estimating the site κ_0 for rock sites in the NGA-East database (a ground motion database corresponding to stable continental regions): the acceleration slope (AS) above the corner frequency, the displacement slope (DS) below the corner frequency, the broadband (BB) fit of the spectrum, and the response spectral shape (RESP) template. These authors found discrepancies among the various methods, and only the broadband methods provided a good agreement with the value provided in the literature for the region (i.e., 6±2 ms after Campbell et al., 2013). Other recent efforts also included the DS, and AS methods to estimate and compare values of κ_0 in mainland France (i.e., Perron et al., 2017). However, "given the simplistic and empirical nature of κ, it is difficult to choose the more correct κ model. Instead, it is important to retain consistency between derivation process of κ and any forward application, such as stochastic simulations or site response analysis" (Edwards et al., 2015).

The *Displacement Spectrum method* (Biasi and Smith, 2001) is a promising approach as it was derived for low-magnitude events and, as indicated by Perron et al., (2017) because "the flatness of the displacement source spectrum below the corner frequency is better understood than the ω^{-2} fall-off above the corner frequency", which is the basis for the AS method. The DS method is based on estimating κ from the low-frequency portion of small earthquake displacement spectra. It was introduced by Biasi and Smith (2001), and data from approximately 263 earthquakes with a median magnitude of M_L=0.3 were evaluated. One of the largest sources of uncertainties of this method is the estimation of corner frequencies for the selected events, as they are a function of moment magnitude and stress drop. The stress drop may not be well constrained for low-to-moderate seismicity regions (Ktenidou et al., 2016).

The *Transfer Function method* (Drouet et al., 2010) provides a site-specific (independent of distance) κ_0 value directly on the high frequency portion (i.e., frequencies higher than 10 Hz) of a site's transfer function (TF). Source-path-site inversions using weak to moderate earthquakes recorded by the French Accelerometric Network were used to estimate the TF at 76 stations. Kappa values derived from this methodology are called κ_{0_TF} (Ktenidou et al., 2013).

The *Inverse Random Vibration Theory Method* (Al Atik et al., 2014) allows the computation of κ-scaling factors for GMPEs so that high-frequency spectral content can be more robustly characterized. The method is based on inverse random vibration theory as implemented in the computer program Strata (Kottke and Rathje, 2008a,b). A Fourier amplitude spectrum (FAS) is derived such that it is consistent with the response spectrum from the selected GMPE (Al Atik et al., 2014). Then, estimated FAS is scaled from in accordance with the assumed κ values for host and target regions. Finally, Random vibration theory (Cartwright and Longuet-Higgins, 1956) is used to convert the κ-adjusted FAS to response spectrum. This method also provides κ-scaling factors computed as the ratio of the κ-scaled response spectra to the GMPE response spectra (Al ATik et al., 2014).

More recently, Mayor et al. (2018) suggested that multiple-scattered coda waves can be used for determining κ_0 for reference rock conditions, which would be relevant for site response analyses in the site-specific PSHA framework as shown in Figure 2. Pilz and Cotton (2019) proposed a new methodology, which offers an opportunity to capture κ_0 values representative of reference rock (in a regional scale) by correlating individual values of κ and the properties of *multiple-scattered coda waves*. As the frequency increases, energy transport by body waves becomes more and more efficient and enhances the sensitivity of the coda to deeper crustal structures (Aki and Chouet 1975). The high frequency decay of coda waves,

κ_0^{CODA}, was further proven to be insensitive to soil type, but to have significant regional variations (Mayor et al., 2018; Pilz and Cotton, 2019).

APPLICATIONS OF KAPPA IN SEISMIC HAZARD ASSESSMENT OF CRITICAL INFRASTRUCTURE

Figure 5a provides the geographical distribution of US operating commercial nuclear power reactors, while Figure 5b depicts the 2018 National Seismic Hazard Maps for 0.2 s spectral acceleration, 2% probability of exceedance, and National Earthquake Hazard Reduction Program (NEHRP) site class B/C (i.e., V_{s30}=760 m/s). As seen in Figure 5, the majority of nuclear power reactors are located in CEUS, where the seismic hazard cannot be considered trivial. Current estimates of κ_0 for CEUS have been based on a comprehensive literature review (Hashash et al., 2014), where an average value of 6 ± 2 ms was selected as representative for the region. Campbell et al., (2013) provides more details on the determination of such value. Improving our understanding of κ and its estimation in low-to-moderate seismicity regions is a key step toward advancing site-specific seismic hazard assessments of critical infrastructure in the US.

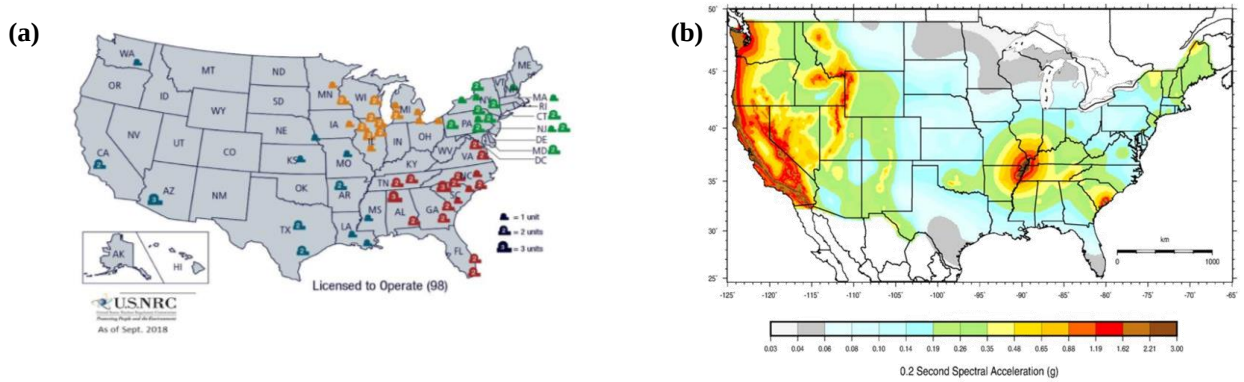

Figure 5. (a) Geographical distribution of US operating commercial nuclear power reactors (US NRC, 2018), and (b) the 2018 National Seismic Hazard Maps for 0.2 s spectral acceleration, 2% probability of exceedance, and a NEHRP site class B/C (i.e., V_{s30}=760 m/s) (USGS).

The following subsections provide examples of some applications of κ in seismic hazard assessments of critical facilities, such as nuclear power reactors. These applications include: the definition of hazard-consistent high-frequency motions, the improvement of damping models of near-surface materials, and the development of host-to-target adjustments.

Definition of Hazard-consistent High-frequency Motions

Appropriate characterizations of the seismic attenuation at a site of interest are relevant when recordings from active tectonic regions, which are generally located at sites with high attenuation, are used as input motions in site response analysis in regions where the surface geology is mostly composed of hard, unweathered rocks and very stiff soils (e.g., CEUS). As seen in Figure 2, seismic site response analysis constitutes a key step in the translation of the seismic hazard from a reference rock condition to the ground surface. Civil infrastructure sensitive to high-frequency excitation might be designed non-conservatively when overlooking the effects of near-surface attenuation on input ground motion selection (Cabas and Rodriguez-Marek, 2017).

Ground motions with a significant content of high-frequency energy are common in CEUS, where the V_s for bedrock is estimated to be 3000 m/s (Hashash et al. 2014). The 2011 M_w 5.8 Mineral, Virginia earthquake provided an opportunity to study ground motion characteristics in this region. The mainshock

occurred as the result of a reverse faulting on a northeast-striking plane within a previously recognized seismic zone known as the Central Virginia Seismic Zone. The epicenter was located near to Mineral, Virginia, at approximately 61 km from Richmond, VA and 135 km from Washington, DC. The moment magnitude of the event was 5.8 and ground motions were recorded at 14 stations (including records at North Anna Power Plant) located at distances that ranged from 53.5 km to 787.9 km from the epicenter. Figure 6 shows the values of peak ground acceleration (PGA) obtained from a selected group of GMPEs applicable to stable continental regions, including Toro, Abrahamson and Schneider (1997), TAS97; Campbell (2003), C03; Silva, Gregor and Darragh (2003) and Silva, Gregor and Lee (2004), SGD03&SGL04; Atkinson and Boore (2006), AB06; and Atkinson (2008), A08. Also, the recorded values of PGA at each station are provided for comparison purposes. Some stations, such as Corbin, VA and Reston, VA experienced higher PGAs than predicted by the GMPEs used in this study. Stations in Corbin, VA and Reston, VA also recorded motions with an unusual content of high-frequency spectral energy when compared with spectral values from GMPEs (at short periods) for stable tectonic regions.

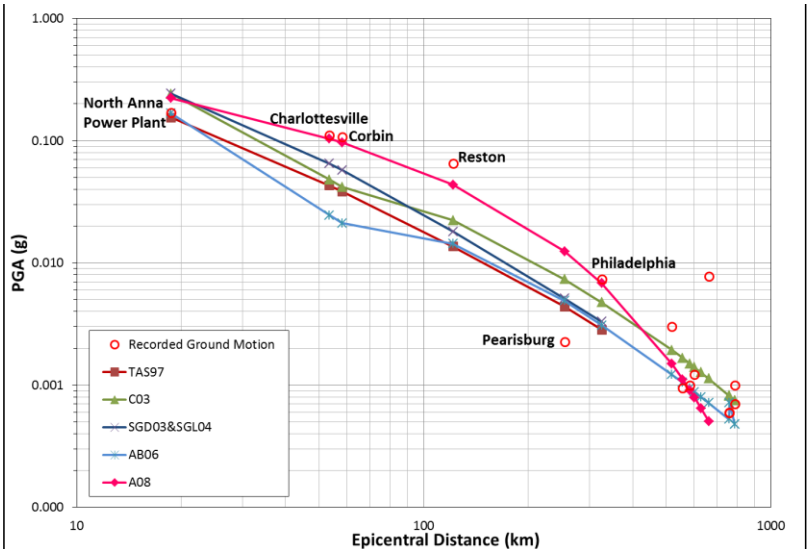

Figure 6. Comparison between recorded observed peak ground acceleration values after the 2011 M 5.8 Mineral, VA earthquake and predictions from selected GMPEs for stable continental regions.

Adjustments to ground motions used as input in site response analysis have been proposed to render them compatible with the assumed properties of the reference depth at the site (Cabas and Rodriguez-Marek 2017). Estimates of κ_0 values can be used to adjust the high-frequency content of motions recorded at the ground surface, so that they are compatible with bedrock conditions (i.e., reference horizon for site response analyses).

Improvement of Damping Models of Shallow Sedimentary Columns

Site response effects can be incorporated into hazard calculations by estimating amplification functions which are then coupled with the estimated hazard at the corresponding rock site. Accurately constraining SRA results and their associated uncertainty is necessary to invoke the partially nonergodic PSHA concept. The variability and uncertainty in SRA results are typically attributed to the uncertainties in soils' dynamic properties (e.g., damping), the input motion selection process, and modeling assumptions. Here, the focus is on the role of κ in the pursuit of more representative values of near-surface attenuation in sedimentary deposits.

Recent research efforts have focused on investigating the influence of damping in site response analysis. The consideration of larger values of damping than those obtained from geotechnical laboratory-based models, led to a noticeable improvement in the accuracy of the predictions (e.g., Rathje and Zalachoris, 2015; Cabas et al., 2017; Cabas and Rodriguez-Marek, 2018). Only anelastic attenuation can be captured in small-scale testing in the laboratory, while other mechanisms of attenuation are overlooked (e.g., scattering). The integration of attenuation parameters estimated from recorded ground motions, such as κ, can improve traditional geotechnical damping models by considering the multiple sources of energy dissipation in porous media.

Development of Host-to-Target Adjustments

Downhole arrays are not the norm when it comes to instrumented seismic data around the world, and in general, there is a lack of hard rock recordings in global datasets. As seen in Figure 7 for three global databases, the likelihood of GMPEs being representative of hard-rock sites is low because surface accelerometric stations are rarely installed on hard-rock sites (Perron et al., 2017). Hence, efforts towards more efficient, representative, and accurate host-to-target adjustments are not only relevant, but also necessary to move the state-of-the-art and practice in seismic hazard assessment forward.

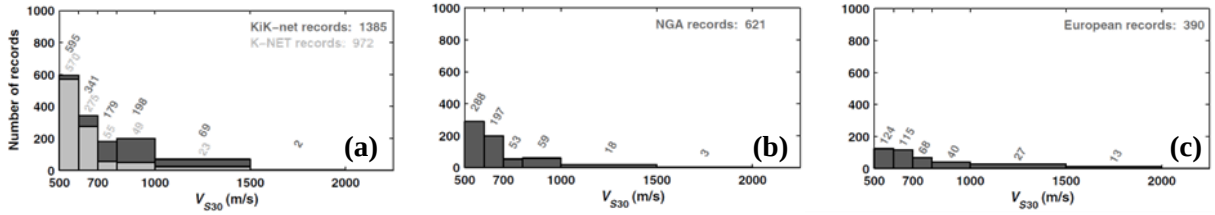

Figure 7. Distribution of ground motions recorded at different site conditions (modified after Laurendeau et al., 2013) for three global databases: a) Kik-net, b) NGA, c) European database.

Examples of host-to-target adjustments include Campbell (2003) who introduced host-to-target correction factors used to adjust GMPEs from a region where strong motion recordings are abundant to a region where the data are sparse. Cadet et al. (2011) proposed simple corrections to modify site amplification factors, whereas Al Atik et al. (2014) developed a κ scaling approach for GMPEs. Al Atik et al. (2014) emphasized the importance of capturing the differences in the attenuation of the shallow-crust when estimating seismic hazards, especially for critical facilities that might be sensitive to motions with significant high-frequency spectral content.

CONCLUSION

Characterizing site-specific attenuation at depth would be extremely valuable for site-specific analysis that require design ground motions at a reference rock level. The lack of recordings at hard-rock sites limits our options in terms of methods of characterization, predictive model development, and collection of relevant data to define earthquake demands on critical civil infrastructure, such as nuclear power plants. For instance, seismic site response analyses need compatible input ground motions with a reference rock horizon. However, defining reference rock conditions (i.e., in terms of V_s and κ_0) has proven challenging for seismic hazard calculations. This paper described the motivation behind site-specific PSHA and provided insights on the role of attenuation and κ in seismic hazard assessments of critical facilities.

Site-specific attenuation is often defined by means of the distance-independent spectral decay parameter κ_0 (Anderson and Hough, 1984), but there is currently no consistent attenuation models for host

and target regions, which are typically required in site-specific probabilistic seismic hazard analysis. The main challenge is the lack of data in low-to-moderate seismicity regions (i.e., the target region), which does not allow the use of the acceleration spectrum methodology to compute individual values of κ in the Fourier Amplitude Spectrum of multiple ground motion recordings (as it is often done for host regions).

The benefits from the estimation of site-specific seismic hazards for stable continental regions such as the CEUS can be many; from obtaining hazard-consistent input motions, more representative damping estimates in the field, to more robust host-to-target adjustments for GMPEs. Understanding the implications and underlying assumptions behind different approaches to estimate κ is necessary before using this parameter in different engineering seismology and earthquake engineering applications; especially in the context of site-specific seismic hazard analysis in low-to-moderate seismicity regions.

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