

PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

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PEER Report No. 2018/05

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Disclaimer

The opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the study sponsor(s), the Pacific Earthquake Engineering Research Center, or the Regents of the University of California.

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ABSTRACT

Pseudo-spectral acceleration (PSA) is the most commonly used intensity measure in earthquake engineering as it serves as a simple approximate predictor of structural response for many types of systems. Therefore, most ground-motion models (GMMs, aka GMPEs) provide median and standard deviation PSA using a suite of input parameters characterizing the source, path, and site effects. Unfortunately, PSA is a complex metric: the PSA for a single oscillator frequency depends on the Fourier amplitudes across a range of frequencies. The Fourier amplitude spectrum (FAS) is an appealing alternative because its simple linear superposition allows effects to be modeled as transfer functions. For this reason, most seismological models, i.e., the source spectrum, are developed for the FAS. Using FAS in conjunction with random-vibration theory (RVT) allows GMM developers to superimpose seismological models directly, computing PSA only at the end of the process. The FAS-RVT-PSA approach was first used by the Hollenback et al. team in their development of GMMs for the Next Generation Attenuation Relationships for Central & Eastern North-America (NGA-East) project (see Chapter 11 of *PEER Report No. 2015/04*). As part of the NGA-East project to support the Hollenback et al. team and similar efforts, the current report summarizes a systematic processing algorithm for FAS that minimizes computational requirements and bias that results from the RVT approximation for median GMM development.

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1 Introduction

Random-vibration theory (RVT) is a method to statistically represent earthquake ground motions that allows for the calculation of the expected time-domain peak value with one calculation. It has been used by seismologists and engineers for decades for a wide range of applications (e.g., Hanks and McGuire [1981], Boore and Joyner [1984], Campbell [2003], and Rathje et al. [2005]). In the context of quantifying ground motions, RVT is used to compute pseudo-spectral acceleration (PSA), starting from a statistical representation of the Fourier amplitude spectrum (FAS) and an associated measure of duration. Pseudo-spectral acceleration is the most commonly used metric in earthquake engineering. Because it is a simple predictor of structural response for many types of systems, ground motion models (GMMs) have been developed for PSA; however, PSA is a highly nonlinear metric. It depends on various bandwidths captured by different single-degree-of-freedom (SDOF) systems, which makes it difficult to translate seismological effects directly to PSA. Thus, most seismological models have been developed for FAS, one of the fundamental building blocks of the frequency domain representation of ground motions. Using FAS in conjunction with the RVT process allows GMM developers to superimpose various seismological models directly and computes PSA only at the end of the process. Although this process cannot account for all the time-dependent effects of recorded ground motions, it presents the advantage of relative simplicity for integrating complex seismological models into median PSA computations.

The RVT approach was considered for the development of GMMs for the Next Generation Attenuation Relationships for Central & Eastern North-America (NGA-East) project. This report provides an overview of the basic concepts of the RVT method, discusses previously proposed methods, and summarizes methodologies adopted for use by the NGA-East project.

1.1 MOTIVATION AND CONSTRAINTS

Traditional GMMs are used to compute the expected PSA—as well as other intensity measures (IMs)—for a given scenario event (defined by an earthquake magnitude and source–site distance measures). The response spectrum was selected as the IM of choice because it is generally a good predictor of the dynamic response of a wide range of structures. Each frequency of the response spectrum corresponds to the peak time-domain response of a SDOF system with a specific natural period and damping. The SDOF response depends on the frequency content and timing (or phasing) characteristics of the ground motions. The response is largely controlled by

amplitudes in the frequency range near to and lower than the natural frequency of the SDOF system. Thus, for a high-frequency system, the oscillator response is dependent on nearly all of the frequency content of the ground motion. As a result, changes in the ground-motion response spectrum are dependent on the frequency content of the input motion (i.e., spectral shape). Spectral shape refers to the trace of any amplitude metric as a function of frequency. This report applies this concept of spectral shape to both PSA and FAS. The dependence on spectral shape on the oscillator response complicates the development and functional form of GMMs.

The FAS has one main advantage over the PSA spectrum: the amplitude at each frequency is independent of the amplitudes of adjacent frequencies. The same site amplification, distance attenuation, site attenuation, etc., is applicable to any motion regardless of the spectral shape. The primary disadvantage of the FAS is that it is not a useful IM for engineering design. The RVT solves this problem by providing a method to compute the expected peak response in the time domain (e.g., PGA, PGV, etc.). By coupling RVT with the SDOF transfer function, it becomes possible to calculate the expected acceleration response spectrum that corresponds to the FAS. The GMM development can therefore be completed in FAS space—where many processes are linear—with the PSA computed using RVT theory models.

The RVT relies on extreme value statistics, which describe the distribution of peak values of the underlying time-varying seismogram. Because of complexities inherent in a seismogram, there is no exact solution. Instead, there are a number of proposed solutions, each with their own advantages and disadvantages. The NGA-East project required that the RVT procedure provides accurate results over the widest frequency range possible. The NGA-East GMMs were developed for reference-rock site conditions that were paired with site-amplification models to address site response. To maintain consistency between the GMM and site-amplification model development, the selected RVT approach should also be applicable to site response analyses.

This report is structured as follows: (1) it presents an overview of the RVT approach; (2) discusses the selection of peak factors to use for the GMM development application; (3) introduces a down-sampled orientation-independent FAS referred to as the effective amplitude spectrum (EAS); and (4) discusses alternative duration models that are consistent with the RVT process. The down-sampled smoothed EAS was applied and included as data products for the NGA-East, NGA-West2, and NGA-Sub databases.

2 Random-Vibration Theory: Fundamentals

In practice, RVT can be separated into a theoretical framework that relates the frequency content and duration of the motion to the distribution of peak time-domain response; empirical corrections are used to improve the accuracy of RVT where assumptions begin to limit the methodology. This chapter discusses the methodology used to characterize the ground motion and calculate the peak-time response.

2.1 CHARACTERIZATION OF RANDOM-VIBRATION THEORY GROUND MOTION

In RVT, the ground motion is characterized the power spectral density (PSD). For time varying signal $x(t)$, the PSD(f) can be computed by:

$$\text{PSD}(f) = [X(f)]^2 / D \quad (2.1)$$

where $X(f)$ is the FAS, and D is the ground-motion duration (see Section 2.3). Seismology has typically separated the frequency content [i.e., $X(f)$] and the duration instead of being combined into the PSD. If an RVT motion is defined as the average of a set of time series, then the FAS should correspond to the mean power, which is computed by the mean value of the squared Fourier amplitudes [Boore 2003].

The frequency content may be indirectly specified by a response spectrum from which a compatible FAS is developed. While specifying the ground motion in this manner is advantageous due to the general familiarity with the response spectrum, there are challenges associated with ground-motion saturation of the SDOF transfer function. The details of this process of developing a compatible FAS from a target response spectrum is not discussed herein; more information can be found in Vanmarcke [1976], Der Kiureghian [1980], and Rathje et al. [2005].

2.2 CALCULATING THE PEAK RESPONSE

The peak factor (PF) relates the root-mean-squared response to the peak response. The following assumptions of the ground are required for the development of the PF formulations:

- They can be represented by a band-limited white Gaussian noise (amplitudes have random phases) with zero mean.
- It is a stationary stochastic process with no change in the probability distribution over the duration interval.

The ramifications of these proposed assumptions are discussed in Chapter 3.

Consider a time-varying signal $x(t)$ with its associated FAS $X(f)$: the root mean square (rms) value of the signal (x_{rms}) is a measure of the average value over a given time interval, D_{rms} , and is computed from the integral of the time series over that time interval by:

$$x_{\text{rms}} = \sqrt{\frac{1}{D_{\text{rms}}} \int_0^{D_{\text{rms}}} [x(t)]^2 dt} \quad (2.2)$$

Parseval's theorem relates the integral of a time series to the integral of its Fourier transform such that Equation (2.2) can be re-written in terms of the FAS of the signal:

$$x_{\text{rms}} = \sqrt{\frac{2}{D_{\text{rms}}} \int_0^{\infty} |X(f)|^2 df} = \sqrt{\frac{m_0}{T_{\text{rms}}}} \quad (2.3)$$

where m_0 is defined as the *zereth* moment of the FAS. The n th moment of the FAS is defined as:

$$m_n = 2 \int_0^{\infty} (2\pi f)^n |X(f)|^2 df \quad (2.4)$$

and is used to characterize the frequency content of the ground motion. The spectral moments are used to define the frequency of zero crossings (f_z) by:

$$f_z = \frac{1}{\pi} \sqrt{\frac{m_2}{m_0}} \quad (2.5)$$

and the number of zero crossings (N_z) by:

$$N_z = f_z \cdot D_{\text{gm}} = \frac{1}{\pi} \sqrt{\frac{m_2}{m_0}} \cdot D_{\text{gm}} \quad (2.6)$$

where D_{gm} is the duration of the ground motion; this is discussed in more detail in Section 2.3.

Similarly, the frequency (f_e) and number (N_e) of extrema can be computed by:

$$f_e = \frac{1}{\pi} \sqrt{\frac{m_4}{m_2}} \quad (2.7)$$

$$N_e = f_e \cdot D_{\text{gm}} = \frac{1}{\pi} \sqrt{\frac{m_4}{m_2}} \cdot D_{\text{gm}} \quad (2.8)$$

2.2.1 Peak Factor Formulations

2.2.1.1 Cartwright and Longuet-Higgins [1956]

Cartwright and Longuet-Higgins [1956] (abbreviated as CLH56) studied ocean waves and developed functions to predict peak wave height based on characteristics of the wave train. Boore [1983; 2003] modified the PF equation by changing the variables to remove an integrable singularity. The resulting PF equation is:

$$\text{PF} = \frac{x_{\max}}{x_{\min}} = \sqrt{2} \int_0^{\infty} \left\{ 1 - \left[1 - \varepsilon \exp(-z^2) \right]^{N_e} \right\} dz \quad (2.9)$$

where ε is defined as ratio of number of zero crossings (N_z) to the number of extrema (N_e):

$$\varepsilon = \frac{N_z}{N_e} + \sqrt{\frac{(m_2)^2}{m_0 \cdot m_4}} \quad (2.10)$$

The number of zero crossings and extrema are defined in Equations (2.6) and (2.8).

Equation (2.9) assumes a Poisson process in which each peak is statistically independent. For narrow-band motions ($\varepsilon = 1$), the distribution of peaks follow a Rayleigh distribution. For broadband motions ($\varepsilon = 0$), the distribution of peaks follow a Gaussian distribution.

2.2.1.2 Davenport [1964]

Davenport [1964] (abbreviated as D64) simplified Equation (2.9) to the following asymptotic form:

$$\text{PF} = \frac{x_{\max}}{x_{\min}} = \sqrt{2 \ln(N_z)} + \frac{0.5772}{\sqrt{2 \ln(N_z)}} \quad (2.11)$$

which results in faster calculations but at the cost of decreased accuracy; see Section 2.2.2. Note: this approximation does not work if N_z is less or equal to 1.

2.2.1.3 Vanmarcke [1975]

Vanmarcke [1975] (abbreviated as V75) extended the previous PF formulations to include the potential for clustering of peak values in the time domain. This formulation no longer assumes a Poisson process with statistically independent peaks. The cumulative distribution of the peak values from Equation (29) of Vanmarcke [1975] is as follows:

$$F_x(x) = \left[1 - \exp\left(-\frac{x^2}{2}\right) \right] \exp \left\{ - \frac{N_z \left[1 - \exp\left(-\sqrt{\frac{\pi}{x}} \cdot \delta_e \cdot x\right) \right]}{1 - \exp\left(-\frac{x^2}{2}\right)} \right\} \quad (2.12)$$

where δ_e is an empirically defined factor defined as:

$$\delta_e = \delta^{1+b} \quad (2.13)$$

where δ another measure of bandwidth defined by:

$$\delta = \sqrt{1 - \frac{(m_1)^2}{m_0 \cdot m_2}} \quad (2.14)$$

and the value of b was tentatively estimated to be 0.20 based on fitting to numerical simulations. Equation (2.12) does not provide for direct calculation of the expected PF. Instead, it is possible to calculate the expected PF through first computing the analytical or numerical derivative of Equation (2.12) prior to computing the expected value of the probability density function, $[f_x(x)]$, which is defined as:

$$E[x] = \int_0^{\infty} x \cdot f_x(x) dx \quad (2.15)$$

However, because F_x is continuous and only non-negative, the expected value may be computed directly from F_x by^{1,2}:

$$E[x] = \int_0^{\infty} [1 - F_x(x)] dx \quad (2.16)$$

The PF is then computed by substituting Equation (2.12) into Equation (2.16).

2.2.1.4 Der Kiureghian [1980]

Der Kiureghian [1980] (abbreviated as DK80) assessed the Davenport [1964] PF formulation and identified that the Poisson model of crossings tends to overestimate the mean and underestimate the variance of the peak. Der Kiureghian [1980] modified the Davenport [1964] asymptotic equation based on empirical data, and defined the PF as:

$$PF = \frac{x_{\max}}{x_{\text{rms}}} = \sqrt{2 \ln(N_z^*)} + \frac{0.5772}{\sqrt{2 \ln(N_z^*)}} \quad (2.17)$$

Where N_z^* is an equivalent-statistically-independent number of zero crossings and defined as

$$N_z^* = \begin{cases} \max(2.1, N_z) & 0.00 < \delta \leq 0.10 \\ (1.63 \delta^{0.45} - 0.38) \cdot N_z & 0.10 < \delta \leq 0.69 \\ N_z & 0.69 < \delta \leq 1.00 \end{cases} \quad (2.18)$$

and δ is a measure of bandwidth defined by Equation (2.14).

¹ http://en.wikipedia.org/wiki/Expected_value#Formulas_for_special_cases

² <http://stats.stackexchange.com/a/13377/48461>

2.2.1.5 Toro and McGuire [1987]

Toro and McGuire [1987] (abbreviated as TM87) adopted the functional form of Equation (2.11) proposed by Davenport [1964] with two modifications. The first modification introduced the non-stationarity factor (n_f)—discussed in Section 3.2—to address the fact that the oscillator does not reach steady-state conditions during the interval $[0, T_{gm}]$. The second modification addressed the correlation in peaks ignored by the Poisson process assumption and is based on equivalent-statistically-independent number of zero crossings [Der Kiureghian 1980]:

$$N_z^* = \max \left[1.33, (1.63\delta^{0.45} - 0.38 \cdot N_z) \right] \quad (2.19)$$

The PF is defined as:

$$\text{PF} = \frac{x_{\max}}{x_{\text{rms}}} = n_f \left[\sqrt{2 \ln(N_z^*)} + \frac{0.5772}{\sqrt{2 \ln(N_z^*)}} \right] \quad (2.20)$$

2.3 DISCUSSION

To illustrate the differences in the PF formulations, three different events were considered: moment magnitude **M** 3.5 at 5 km, **M** 5.5 at 20 km, and **M** 7.5 at 100 km. Using a point-source source model and Central and Eastern North America (CENA) parameters from Campbell [2003], the associated FAS were computed and are shown in Figure 2.1; SDOF transfer functions with an oscillator natural frequency (f_n) of 0.1, 3.0, and 100 Hz and a damping of 5% were applied to the FAS. The resulting FAS for the three events are shown in Figures 2.2, 2.3, and 2.4. Considering the range of oscillator frequencies, the bandwidth parameters ε and δ are computed using Equations (2.10) and (2.14), respectively. The variation of ε and δ with oscillator frequency is shown in Figures 2.5 and 2.6, respectively. Narrow-band motions were characterized by ε values close to 1 or δ values close to 0.

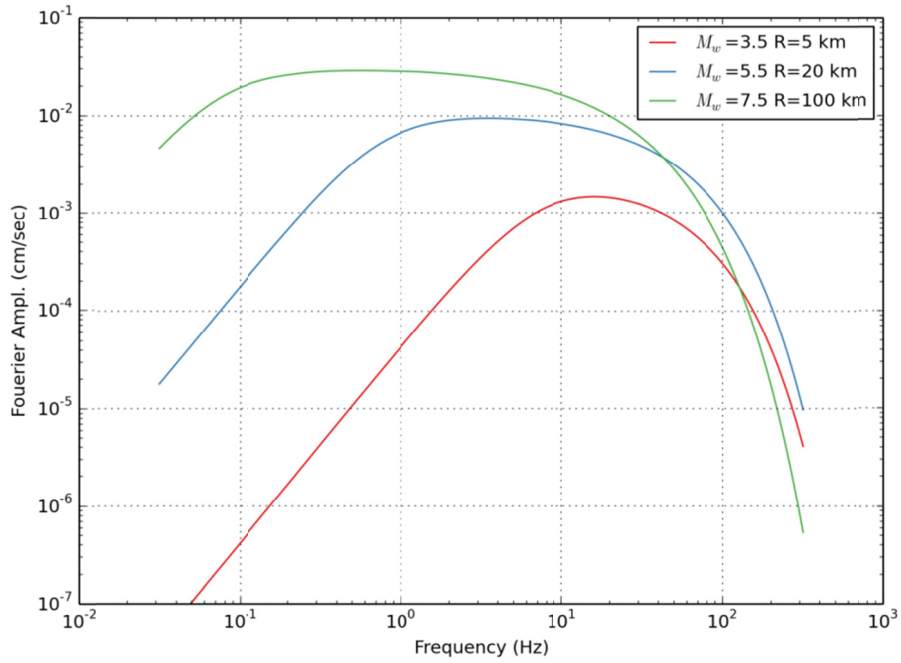


Figure 2.1 The FAS for the M 3.5 event at a distance of 5 km. The FAS with the SDOF transfer function with f_n of 0.1, 3.0, and 100 Hz and 5% damping are also shown.

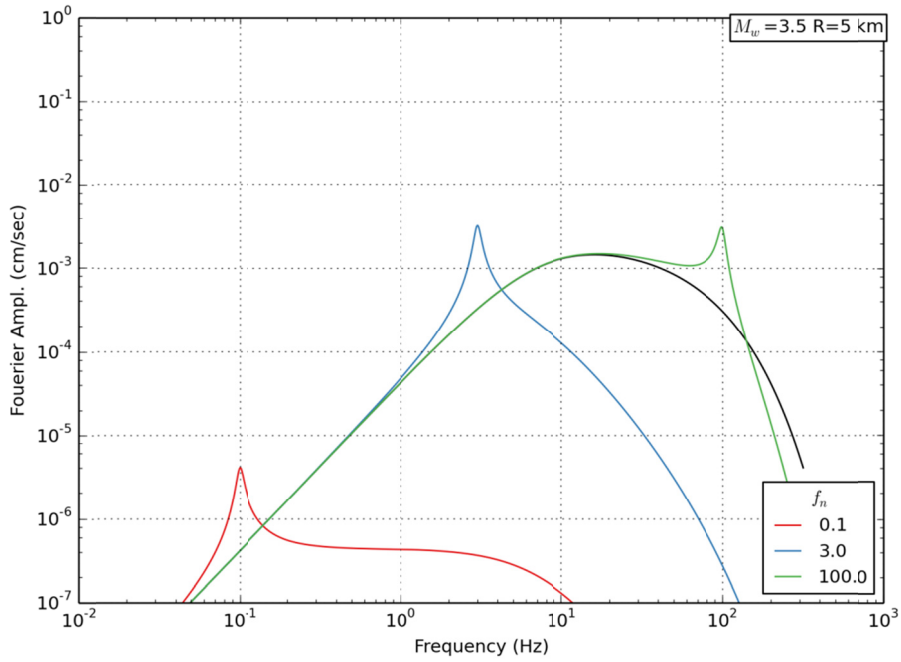


Figure 2.2 The FAS for the M 3.5 event at a distance of 5 km. The FAS with the SDOF transfer function with f_n of 0.1, 3.0, and 100 Hz and 5% damping are also shown.

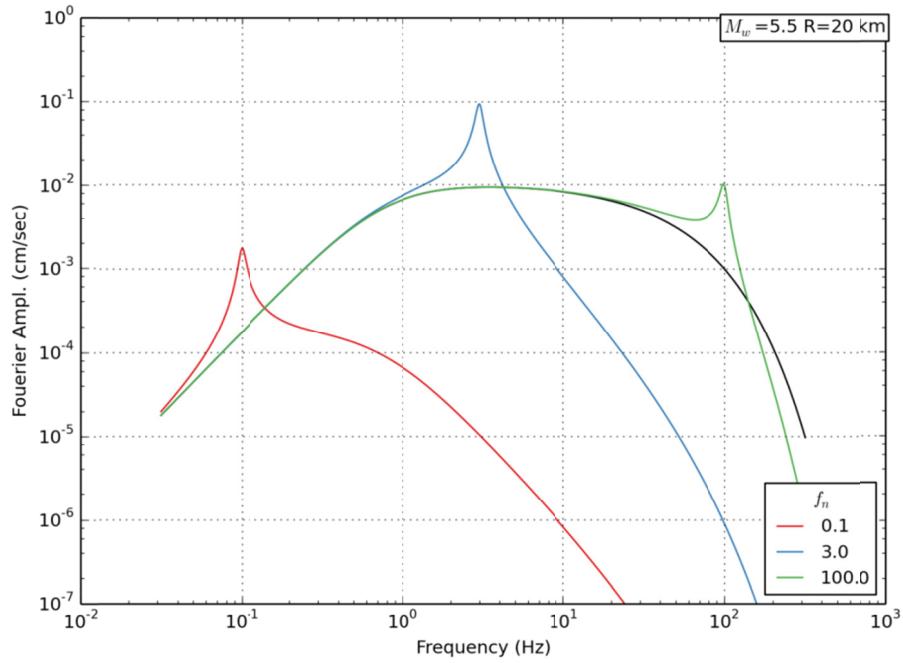


Figure 2.3 The FAS for the M 5.5 event at a distance of 20 km. The FAS with the SDOF transfer function with f_n of 0.1, 3.0, and 100 Hz and 5% damping are also shown.

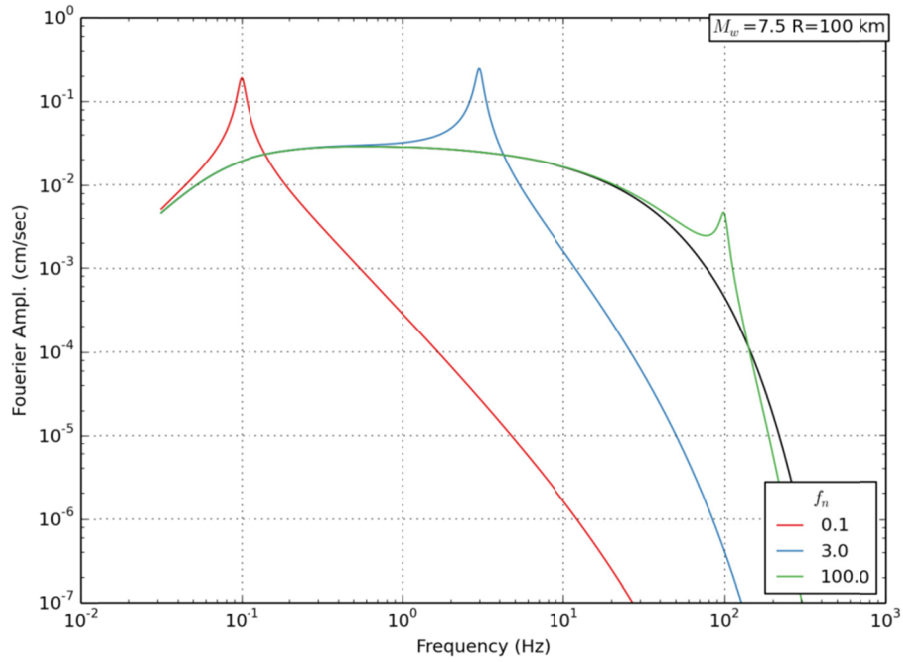


Figure 2.4 The FAS for the M 7.5 event at a distance of 100 km. The FAS with the SDOF transfer function with f_n of 0.1, 3.0, and 100 Hz and 5% damping are also shown.

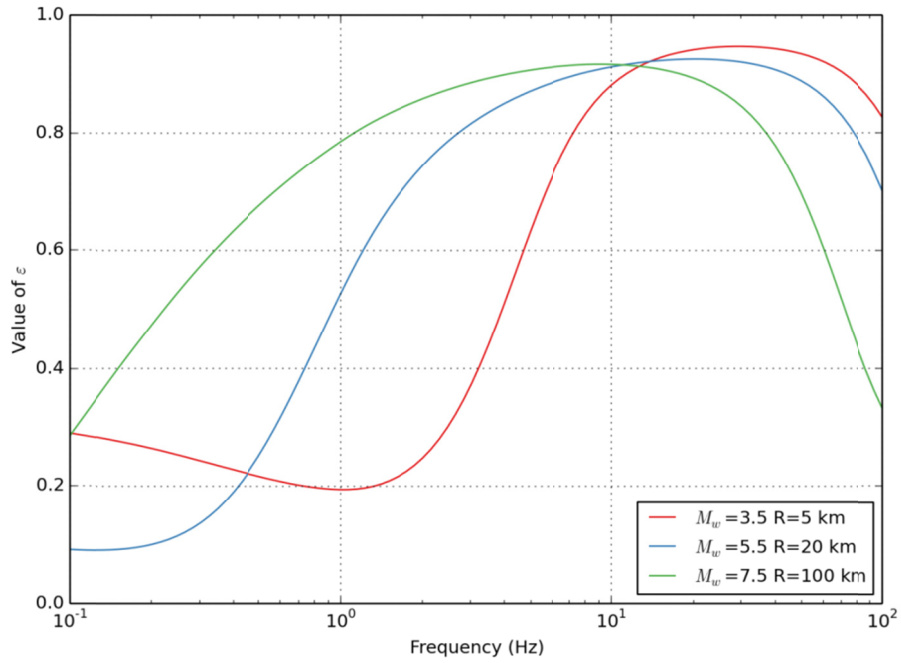


Figure 2.5 Variation of the bandwidth parameter ϵ with oscillator frequency and the three considered events.

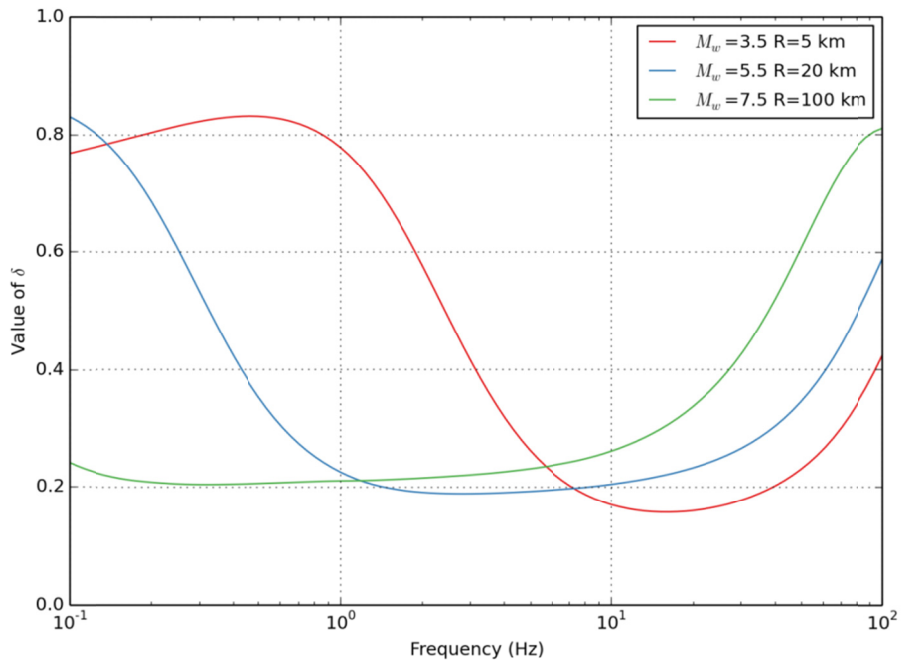


Figure 2.6 Variation of the bandwidth parameter δ with oscillator frequency and the three considered events.

The PF formulations presented in the previous section can be separated into two categories: (1) those based on Cartwright and Longuet-Higgins [1956]; and (2) those based on Vanmarcke [1975]. The Cartwright and Longuet-Higgins [1956] formulation factor assumes statistical independence between the local peaks of a random process, which is a significant approximation for a narrow-band process [Der Kiureghian 1980].

To illustrate the differences between the PF formulations, the PFs were computed for the three scenarios using four different PF formulations: CLH56, D64, V75, and DK85. For these calculations, the N_z was limited to be greater than 1.33. The computed PFs are shown in Figures 2.7, 2.8, and 2.9. The differences between each of the formulations vary with respect to input motion and oscillator frequency. For the **M** 5.5 and 7.5 events (Figures 2.8 and 2.9), the considered PFs are clustered with the CLH56 and D64, and demonstrate relatively consistent behavior. Similarly, the V75 and DK85 provide similar estimates of the PF. These results are not unexpected as the two groups of PFs are based on differing assumptions. For the **M** 3.5 event (Figure 2.7), there are significant differences between the CLH56 and D64 due to the limited range over which the asymptotic approximation is accurate. The limit of $N_z \geq 1.33$ also limits the DK85 PF to be greater than 1.51 for frequencies less than 10 Hz.

The differences between the CLH56 and D64, and V75 and DK85 PF formulations suggest that both PF formulations should be considered. While the CLH56 is based on a simpler statistically model (i.e., Poisson process), this methodology is used by SMSIM [Boore 2003], which has been used extensively within the seismology community. The deficiency of assumed statistical independence was addressed first by Boore and Joyner [1984] and has been revisited by subsequent work through modifications of the duration; see Chapter 3. Although the recommended modifications to the ground motion improve the agreement between time series and RVT response spectra, they fail to address the underlying statistical assumptions. These assumptions may lead to inaccurate results with RVT when it is extended beyond calculation of response spectra. Kottke and Rathje [2013] compared time series and RVT seismic site response analyses, and showed significant differences between the results, which in part was due to differences in duration. Ongoing work by Rathje [*Personal Communication* 2014] has shown that using the Vanmarcke [1975] PF formulation reduces these differences.

Both the Cartwright and Longuet-Higgins [1956] and Vanmarcke [1975] PF formulations are recommended for use by this project. The complete form of the Vanmarcke [1975] formulation is recommended because asymptotic formulations, such as Der Kiureghian [1980], are not accurate over the range of bandwidths considered by this project.

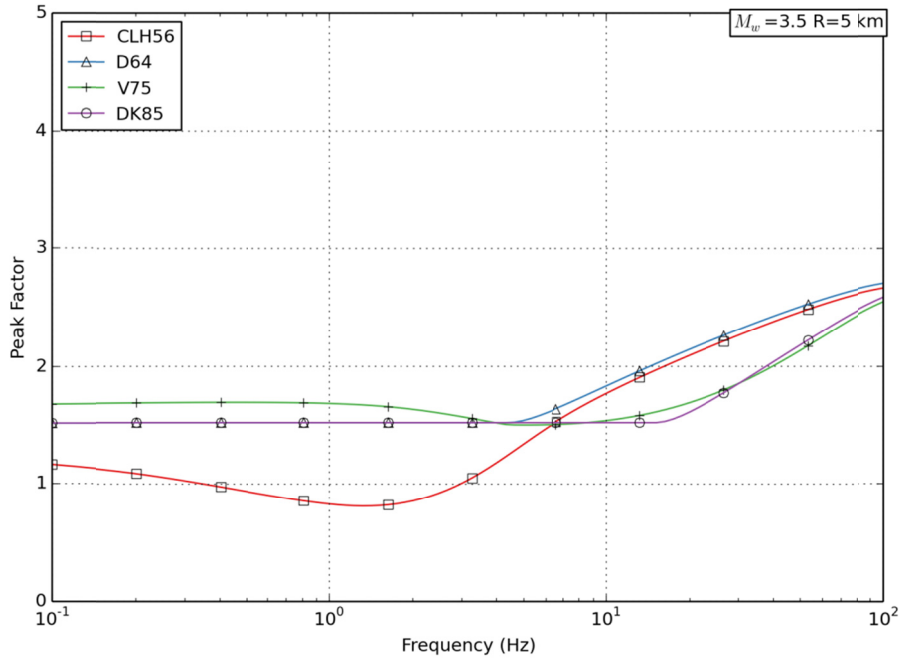


Figure 2.7 The PFs computed by four different PF formulations at various oscillator frequencies for the M 3.5 event at a distance of 5 km.

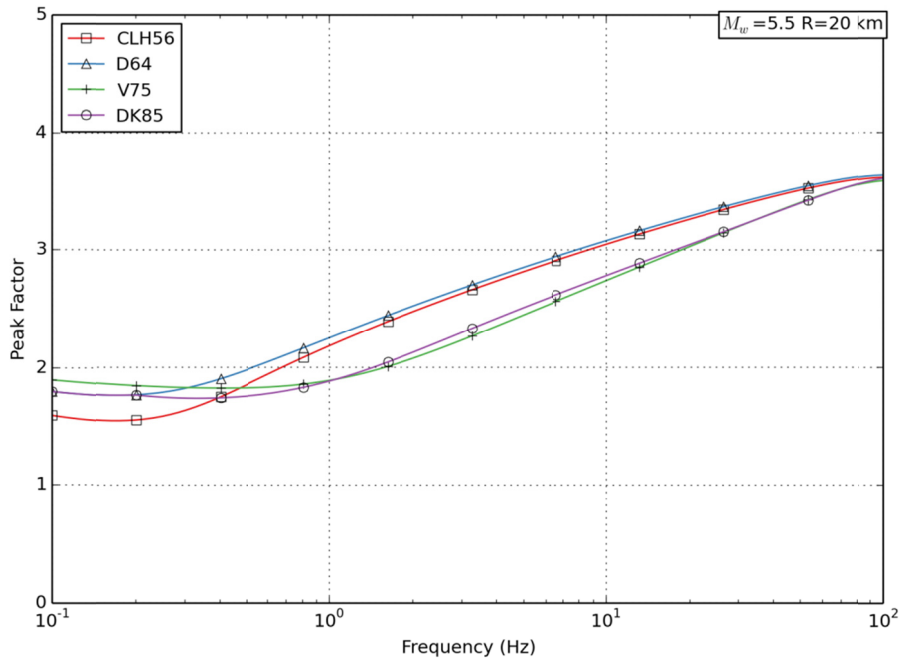


Figure 2.8 The PFs computed by four different PF formulations at various oscillator frequencies for the M 5.5 event at a distance of 20 km.

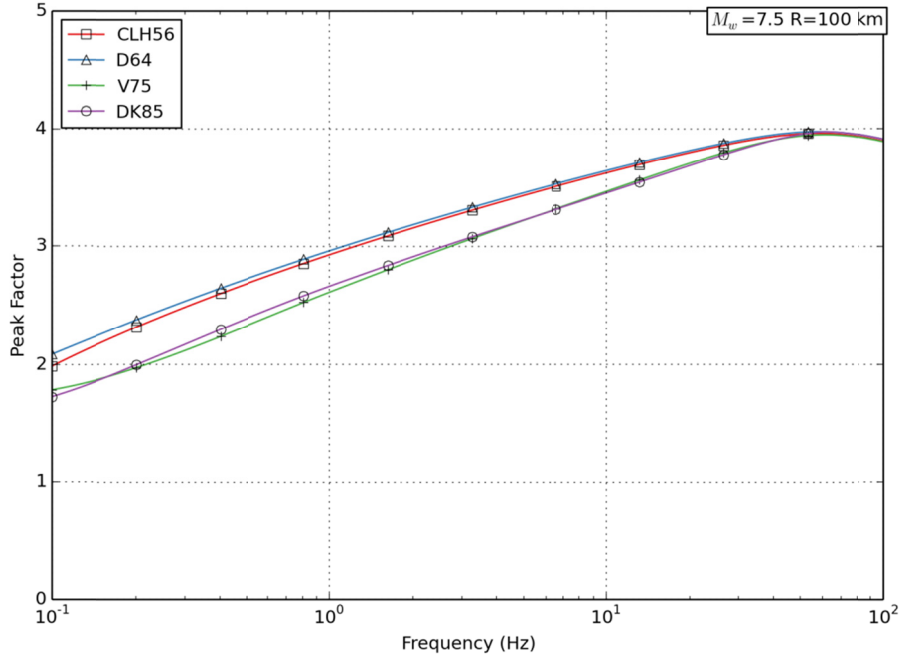


Figure 2.9 The PFs computed by four different PF formulations at various oscillator frequencies for the M 7.5 event at a distance of 100 km.

2.4 GROUND-MOTION DURATION

In the context of ground motions, “duration” is the term used to refer to different definitions of time-length intervals. Whenever discussing ground-motion duration, it is important to understand the specific definition of the metric. In some cases, duration can refer to the actual physical duration of ground motions based on threshold or rules; in other cases, as it is for some RVT applications, it can be a fitted parameter with units of time, but it doesn’t relate to the traditional concept of shaking duration.

2.4.1 Earthquake Source and Path Durations

Ground-motion duration has long been recognized to be inversely related to the earthquake’s corner frequency [Hanks and McGuire 1981]. Herrmann [1985] showed that ground-motion duration also increases with distance. Traditionally, the total ground-motion duration (D_T) is decomposed into two contributing factors: the source duration (D_S) and the path duration (D_P). The source duration for a single-corner frequency model is given by:

$$D_S = 1/f_c \quad (2.21)$$

where f_c is the corner frequency [Hanks and McGuire 1981; Herrmann 1985; and Boore 2003]. The double-corner frequency model is often given as:

$$D_S = 1/f_a \quad (2.22)$$

where f_a is the lower of the two corner frequencies (e.g., Atkinson and Boore [1995] and Atkinson and Silva [2000]). Boore et al. [2014], however, have suggested that the duration should be modeled as a combination of the two corner frequencies, i.e.,

$$D_S = \frac{0.5}{f_a} + \frac{0.5}{f_b} \quad (2.23)$$

As formulated by Hanks and McGuire [1981] and Boore [1983], the ground-motion duration only included D_S . Thus, for a given magnitude, D_T was the same at all distances. Herrmann [1985] noted that this formulation should be limited to short distances because the duration of real ground motions increases with distance. Herrmann [1985] computed synthetic records with a one-dimensional velocity model to illustrate this trend, noting that the ground motion at short distances is simple and pulse-like, while at larger distances surface waves and crustal reflections arrive after the direct S -wave, increasing the duration of shaking. Herrmann [1985] proposed that the path duration could be modeled as:

$$D_p = 0.05R \quad (2.24)$$

where R is the hypocentral distance.

For an assumed source model, the D_p can be computed empirically by subtracting the D_S from D_T , which is typically a function of distance (e.g., Boore [2003]). As discussed below, there are different ways to compute D_T from ground-motion records. The following subsections discuss the different parameterizations of D_T as well as recently developed models for D_p .

2.4.2 Significant Durations

For many ground-motion applications, the significant duration, bracketed duration, and uniform duration are often used to characterize the duration of ground-motion shaking. Herein, only the significant duration as introduced by Trifunac and Brady [1975] will be discussed. It is based on the normalized integral of the squared acceleration (i.e., the Husid curve) and is closely associated with the “rms” acceleration.

The Arias intensity at time t [$I_a(t)$] is computed by:

$$I_a(t) = \frac{\pi}{2g} \int_0^t x(t)^2 dt \quad (2.25)$$

where $x(t)$ is the acceleration at time t in units of gravity (g). The Husid curve [$h(t)$] is defined as:

$$h(t) = \frac{I_a(t)}{I_a(\infty)} \quad (2.26)$$

and varies from zero at the start of a record to one at the end of a record. The significant duration D is defined as the difference in the times at which $h(t)$ for two different percentages of its final

value (Figure 2.10). For example, D_{5-95} refers to the time difference of the 5–95% occurrence of the squared acceleration.

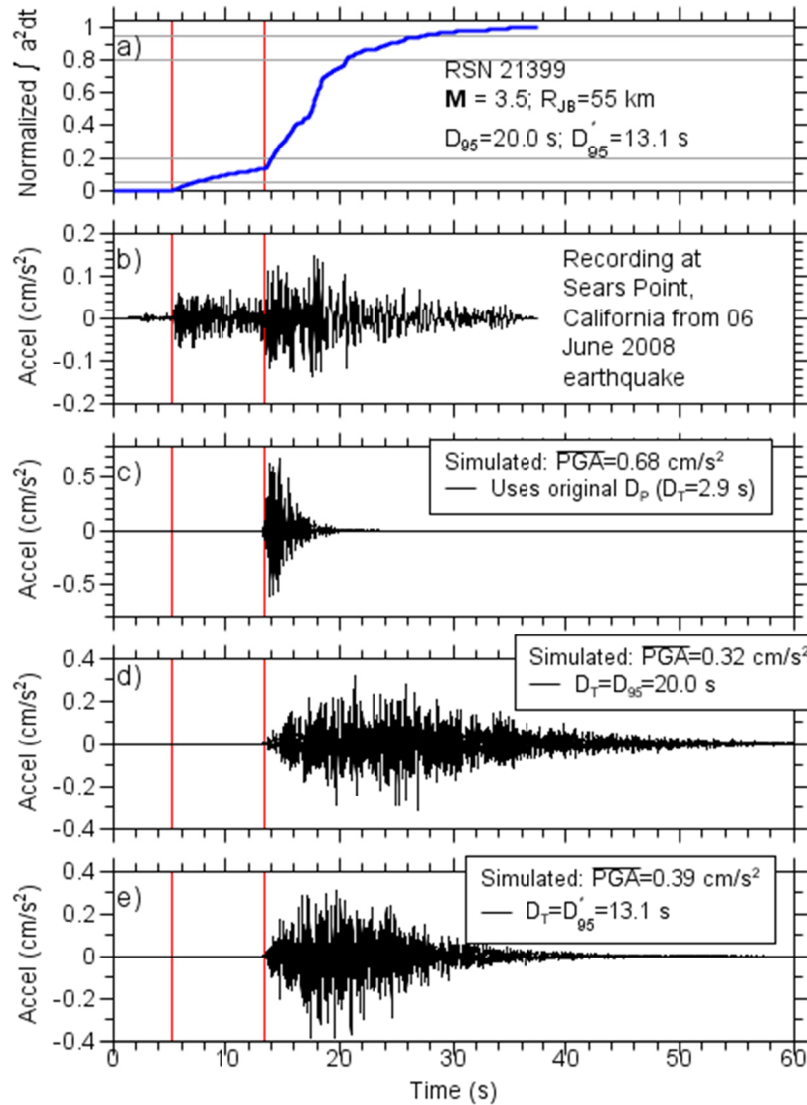


Figure 2.10 The Husid plot (graph a) from the acceleration record shown in graph (b). For this record, the 0.05 level is reached near the *P*-wave arrival. Graphs (c), (d), and (e) show simulations using D_T values equal to the original path duration and the D_{5-95} and D'_{5-95} durations obtained for the recording, respectively. Note the change of the ordinate scale of part (c) compared to the other two simulations. The time series shown for each duration model is the one simulation out of 800 that had a PGA closest to \overline{PGA} . The vertical lines indicate the *P*- and *S*-wave arrivals (the simulations have been aligned on the *S*-wave arrival).

Alternative measures of duration are based on fitting ground-motion IMs calculated from the recorded motions and predicted by RVT. The IMs used in these parameterizations of duration include the PGA [Vanmarcke and Lai 1980], PGV [Atkinson 1993b; 1995], and PSA at a

number of periods [Bora et al. 2014]. This last definition of duration could be interpreted as the most relevant for RVT applications and is discussed in Section 2.3.3.

The stochastic method of ground-motion simulation, as developed by Boore [1983], used D_{5-95} as the total duration of ground shaking and a separate duration to compute peak values (i.e., spectral accelerations), which is a function of the oscillator period. Thus, significant duration may still be preferred as the parameterization for ground-motion duration for use within the Boore [1983] framework for a number of reasons: (1) the duration of ground-motion excitation is conceptually distinct from the duration of a responding oscillator (as in Boore and Thompson [2012, 2015]); (2) it provides consistency and continuity with the Boore formulation [1983; 2003]; (3) the widespread use and availability of D_{5-95} ; and (4) the ambiguity as to which IM to use for IM-compatible durations.

2.4.2.1 Ou and Herrmann [1990]

A fundamental assumption underlying RVT is that the signal is stationary; see Section 2.3.3. Given that, Ou and Herrmann [1990] argued that the duration window should be chosen such that a stationary process can approximate the signal. Their criteria for determining that a time window is near-stationary is that the Husid plot increases approximately linearly throughout that time window. They analyzed records from the Eastern Canada Telemetered Network with epicentral distances ranging from 135–994 km and concluded that the D_{5-75} window is approximately stationary. They validate the use of this window with RVT by comparing the measured peaks to the peaks predicted by RVT, noting that the spectrum should be estimated only from the signal within the D_{5-75} time window when D_{75} durations are used in the RVT calculations.

2.4.2.2 Boore and Thompson [2014]

Boore and Thompson [2014] addressed the non-stationarity of ground motions using a different approach. This approach was developed by Boore and Joyner [1984] whereby the duration of the ground motion is treated independently from the non-stationarity correction. A different duration (termed D_{rms} and discussed in detail later) is used to compute the peak values from the “rms” acceleration, which is a function of oscillator period and accounts for the non-stationarity of the signal. Thus, Boore and Thompson [2014] developed a new parameterization of duration that was guided by two primary factors: (1) the use of D_{5-95} was preferred for consistency’s sake, in particular for defining the Saragoni and Hart [1974] exponential shaping window in the time domain; and (2) the influence of strong P -wave energy and late-arriving surface wave energy should be minimized because the stochastic method is founded upon seismological consideration of S -waves.

The problem of early P -wave energy is illustrated in Figure 2.10. The Husid plot of the recording is given in the top panel, and the record (second to the top panel) is compared to stochastic simulations where all parameters are held constant except for D_T . The arrival times of the P - and S -waves are labeled on each plot, and the simulations are aligned to coincide with the S -wave arrival. The D_T and the median PGA from 800 simulations (PGA) are given for each simulation.

The main purpose of Figure 2.10 is to demonstrate that the 5% level for data is reached substantially earlier than the S -wave arrival in some cases. That said, parts (c), (d), and (e) of the figure also demonstrate the consequences of the different durations for simulated ground motions. Figure 2.10(c) shows that the $D_p = 0.05R$ duration is too short, whereas Figure 2.10(d) shows that using D_{5-95} from the recorded time series overestimates the path duration because of the presence of strong P -wave energy. Figure 2.10(e) shows the duration parameter developed by Boore and Thompson [2014] (defined below as D'_{95}). Note that the simulations can be compared in terms of the total duration but also in terms of their respective $\overline{\text{PGA}}$: the larger the D_T , the smaller the amplitude (by approximately the inverse of the square root of D_T) because the energy is spread across a larger time window. The median PGA (indicated by $\overline{\text{PGA}}$) for the 800 simulations is given in the legends; as expected, the ratios of any two simulations are close to the square-root of the ratio of their durations.

The early start to the duration measure illustrated in Figure 2.10 is incompatible with the assumption that simulations are for the S -wave contribution to the ground motion. Similar problems can occur due to a delay of the time at which the 95% level is reached. These effects imply that the shape of the envelope of ground motion from data may be inconsistent with that assumed in the simulations. To avoid the instability due to the early and late times at which the 5% and 95% levels are reached, respectively, Boore and Thompson [2014] proposed an effective duration D'_{5-95} :

$$D'_{5-95} = 2.0(D_{80} - D_{20}) \quad (2.27)$$

The scale factor of 2.0 is based on the average of the ratio of D_{5-95} to $(D_{80} - D_{20})$ from the simulations.

Boore and Thompson [2014] computed path durations from the NGA-West1 (for active crustal regions [ACRs]) database as $D_p = D'_{95} - D_S$, and fit a piecewise linear function to the data. Boore and Thompson [2015] performed a similar analysis of the NGA-East database (for stable continental regions [SCRs]). The difference in D_p for ACRs and SCRs is shown in Figure 2.11, which plots D_p as a function of distance R_{pS} (which is the adjusted point-source distance to account for finite-fault effects). Figure 2.11 shows the Boore and Thompson [2015] function and median values for SCRs and the Boore and Thompson [2014] function and median data values for ACRs; path durations for individual records for SCR **M** 4–5 data are included to illustrate the scatter in the data. In addition, the path duration used in a number of simulations of Eastern North America (ENA) ground motions (e.g., Atkinson and Boore, [1995; 2006]) is also shown. The longer durations for SCRs compared to ACRs might be the result of the smaller intrinsic attenuation in the cooler crust, which allows the scattered waves to prolong the duration of shaking.

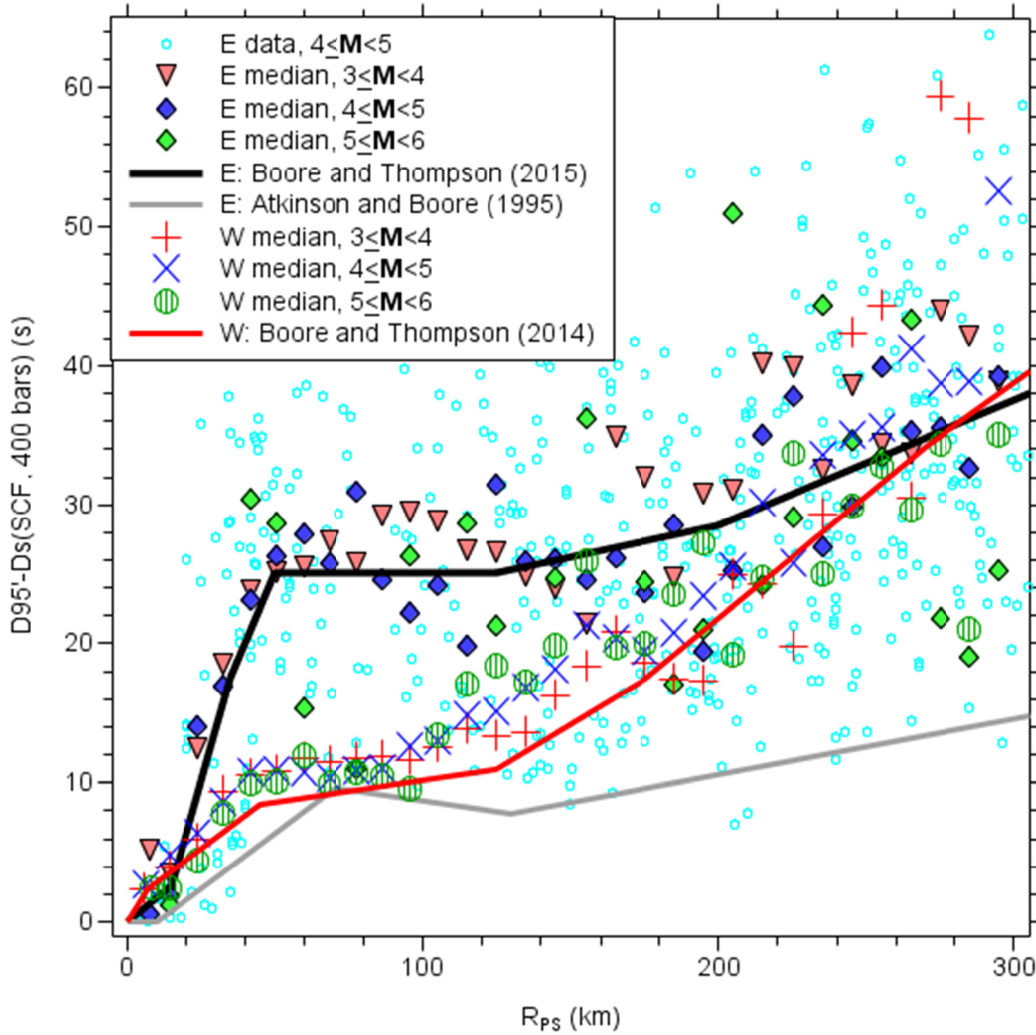


Figure 2.11 The medians in various magnitude and distance bins of $D_p = D'_{95} - D_s$ for data from both from eastern North America (“E”) and active crustal regions (“W”). Path durations computed from individual records for M 4–5 are included to illustrate the scatter in the data. For comparison, D_p functions are included from Boore and Thompson [2014; 2015] and Atkinson and Boore [1995].

2.5 DURATIONS FOR RESPONSE SPECTRUM COMPATIBLE GROUND MOTIONS

An important ingredient in the RVT framework is the duration of ground motion [Hanks and McGuire 1981; Vanmarcke and Lai 1980; and Boore, 1983, 2003]. It enters into calculation of the maximum response:

$$x_{\max} = p_f \cdot y_{\text{rms}} \quad (2.28)$$

both in the PF, p_f , and in the “rms” motion, y_{rms} . Traditionally, different measures of duration based on different criteria (e.g., cumulative energy and bracketed) have been proposed. Based on the application, a suitable duration is selected; however, for RVT it is not entirely clear which duration measure should be used in calculation of response spectra.

Recently, Bora et al. [2014] proposed a duration that is rooted in the RVT framework. It is different from other duration measures: (1) it is not based on an acceleration time series; and (2) it is not a “duration” in a physical sense but a parameter suitable to calculate response spectra using RVT. The duration proposed in Bora et al. [2014] is defined as the duration that minimizes the misfit between the observed response spectrum and the one calculated from the observed FAS and RVT. Thus, in an application that aims to predict response spectra, this duration measure is ideally suited for the RVT framework. Basically, the duration is treated as a parameter that is inverted for using RVT as the model and the response spectrum and the FAS as data. Therefore, one should refrain from associating any physical meaning with this duration: it is to be used as a parameter within RVT to predict response spectra together with the empirical FAS. The advantage of treating the duration as a parameter is that it absorbs any mis-specification of the model.

Equation (2.28) shows the relation between the “rms” duration and the maximum oscillator response. If Davenport’s [1964] PF is used, the relation becomes:

$$x_{\text{max}} = \left(\sqrt{1 \ln N_z} + \frac{0.577}{\sqrt{2 \ln N_z}} \right) \cdot \sqrt{\frac{m_0}{D_{\text{rms}}}} \quad (2.29)$$

with N_z the expected number of zero crossings, and m_k the k th spectral moment: see Section 2.2.1. Because the spectral moments can be calculated from the FAS [i.e., $X(f)$], Equation (2.29) contains only one unknown parameter: the duration D_{rms} . Hence, D_{rms} can be inverted by minimizing the misfit (ξ) between the observed response acceleration spectrum [$S_a(f)$] and the RVT-calculated maximum response [$x_{\text{max}}(f)$]. Since the response spectrum is log-normally distributed, the misfit is calculated as:

$$\xi = \sum_f [\ln S_a(f) - \ln x_{\text{max}}(f)]^2 \quad (2.30)$$

Note: although the idea of an optimized duration is independent of the specific PF formulation, it is important to be consistent. For each PF formulation, an optimized duration can be estimated, but because these two are tied together, forward calculations need to be made with the same assumptions/formulations that were used in the inversion of the duration.

As an example, durations were calculated for two records using both the PF of Cartwright and Longuet-Higgins [1956] and that of Davenport [1964]. One of the records is from the Saguenay event with an epicentral distance of 442 km (record ID 70 in the NGA-East database). The other record is from the Mineral event (record ID 8365 in the NGA-East database). Table 2.1 presents the calculated durations. Figure 2.12 shows the corresponding observed response spectra and the RVT-calculated spectra. The durations based on the different PF formulations vary, but the misfit is close in both cases, and the RVT-calculated response spectra are very

similar. Hence, if the calculations are internally consistent—forward calculations are done with the same PF as the inversion for the duration—the results are close.

Up to this point in the inversion it has been assumed that D_{rms} and the actual ground-motion duration are the same. In application of the stochastic method, an adjustment is needed to match (1) response spectra calculated via RVT and (2) those based on time-domain simulations [Boore and Joyner 1984; Liu and Pezeshk 1999; and Boore and Thompson 2012]. Theoretically, such a model could be incorporated into the inversion process.

When the duration is optimized against response spectra, it is the appropriate duration to use if the goal is to predict response spectra. Therefore, an empirical FAS model as well as a model for the spectrum-compatible duration can be used that predicts the FAS and duration as a function of magnitude, distance, and other source- and site-related parameters. When the predictions are combined via the RVT framework, a response spectrum prediction is obtained. Refer to Bora et al. [2014] for greater detail.

Table 2.1 Optimized durations D_{rms} , calculated for two different PF formulations: Cartwright and Longuet-Higgins [1956] (CLH56) and Davenport [1964] (D64), and the associated misfit ξ .

Record	Formulation	D_{rms} (sec)	ξ
ID 70 (Saguenay)	CL56	34.05	4.32
	D64	34.59	4.33
ID 8365 (Mineral)	CL56	47.80	5.81
	D64	48.85	5.84

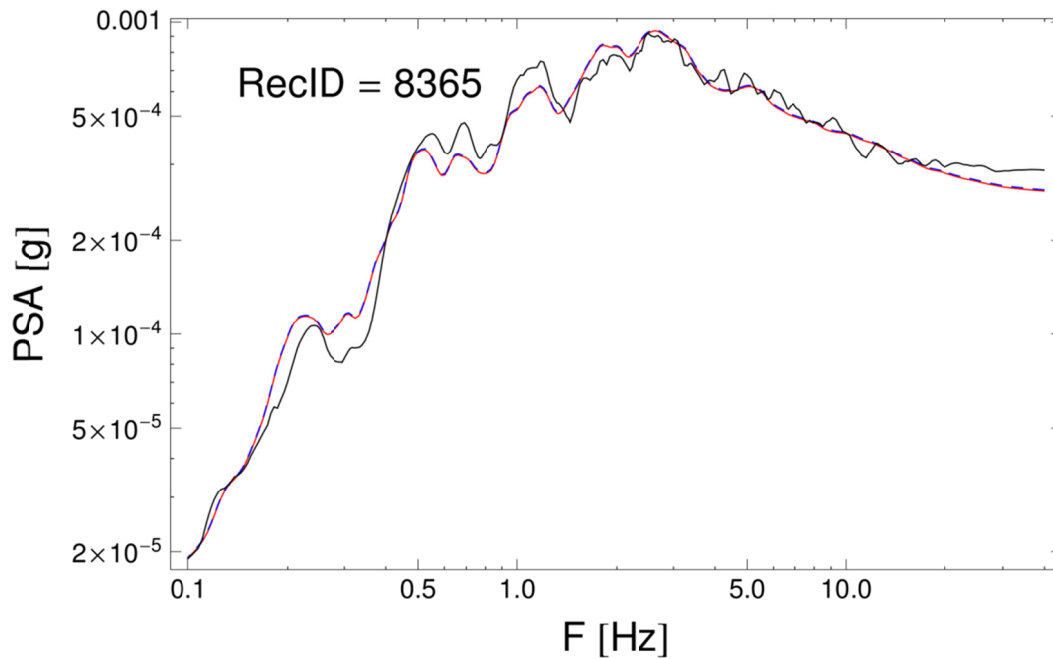
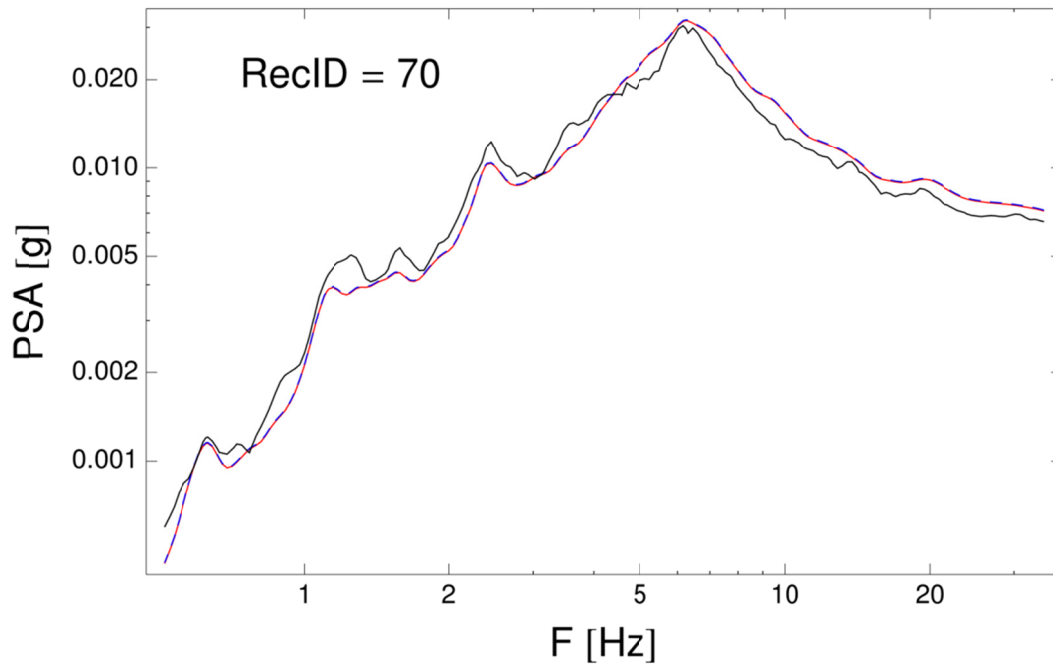


Figure 2.12 Comparison of response spectrum calculated from the time domain (black) and response spectrum calculated via RVT, with the duration inverted using the PF of Cartwright and Longuet-Higgins (blue) and that of Davenport (red). Top: Record ID 70, Saguenay event. Bottom: Record ID 8365 from the Mineral event.

3 Corrections for Non-Stationarity

Ou and Herrmann [1990] demonstrated that for peak values such as PGA and PGV, the careful selection of a window can overcome much of the non-stationarity problem. But for resonant systems, such as SDOF oscillators or layered soils, the problem of non-stationarity is an issue. For these systems, there are two methods for adjusting the PFs to correct for non-stationarity:

- modifying the duration of the motion
- directly scaling the PF

This section presents methods developed to address the non-stationarity of response spectra independent of the ground-motion duration.

3.1 NON-STATIONARITY CORRECTIONS BASED ON DURATION MODIFICATION

3.1.1 Boore and Joyner [1984]

Boore and Joyner [1984] explicitly separated the duration used for computing the number of zero crossings and extrema from the duration used to compute the “rms” acceleration of the ground-motion intensity measure (GMIM). The number of zero crossings and extrema are computed from the characteristic frequency (a function of the spectral moments) and the duration of shaking, which is assumed to be D_T (sometimes termed D_{EX} for the duration of excitation). D_T is inappropriate for computing the “rms” response from the amplitude spectrum of the oscillator because it will continue to respond after the ground motion has stopped. This is illustrated in Figure 3.1 (Figure 19 in Boore [2003]), which shows the response of a 10-sec oscillator to a small (**M** 4) and large (**M** 7) earthquake. Boore and Joyner [1984] found that the following equation captured the interaction between the oscillator’s duration and the ground-motion duration:

$$D_{\text{rms}} = D_T + D_0 \left(\frac{\gamma^n}{\gamma^n + \alpha} \right) \quad (3.1)$$

where $\gamma = D_T/T_0$; T_0 is the period of the oscillator, $D_0 = T_0/(2\pi\zeta)$ is the oscillator duration, and ζ is the fractional damping of the oscillator. Boore and Joyner [1984] selected constants n and α by comparing different values to data and set them to 3 and 1/3, respectively.

3.1.2 Liu and Pezeshk [1999]

Liu and Pezeshk [1999] developed an improved relationship for D_{rms} in which the value of α in Equation (3.1) is replaced by k , which is a parameter calculated from the ground motion by:

$$k = \sqrt{2\pi \left(1 - \frac{(m_1)^2}{m_0 \cdot m_2} \right)} \quad (3.2)$$

where m_i are spectral moments (*zero*th, first, and second are considered here) as defined by Equation (2.4). With this substitution, they also found that a better value for n is 2.

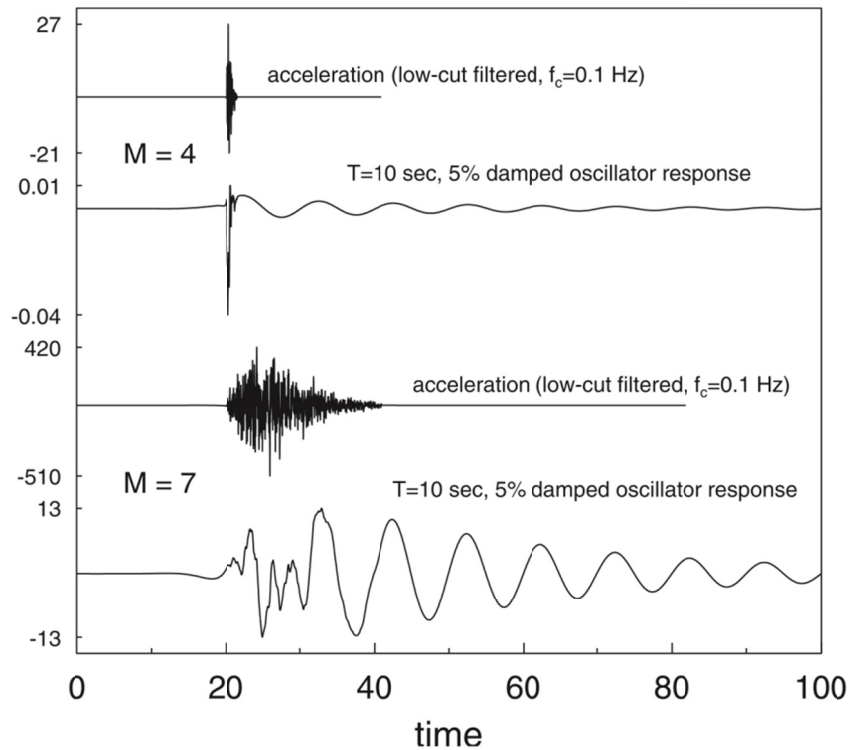


Figure 3.1 Simulated acceleration time series and computed response of 10.0-sec, 5%-damped oscillator for M 4 and M 7 earthquakes at a distance of 10 km. Because the relative shape is important, each trace has been scaled individually (the actual amplitudes are given to the left of the y-axis—acceleration in cm/sec² and oscillator response in cm) (reproduced from Boore [2003]).

3.1.3 Boore and Thompson [2012]

Boore and Thompson [2012] noted that after using the modifications discussed above, clear trends in the GMIM residuals still existed, particularly for small-to-moderate magnitudes and moderate-to-large distances. Therefore, they generalized the D_{rms} equation to be able to model more variations of D_{rms} with magnitude, distance, and period. They noted that D_{rms} can be solved in terms of the time-domain peak values (y_{id}) and the RVT peak values with no oscillator correction (y_{xo} ; i.e., $D_{\text{rms}} = D_T$)

$$D_{\text{rms}} = D_T (y_{xo} / y_{id})^2 \quad (3.3)$$

This equation can be rearranged so that ratio of the durations is equal to the squared ratio of the peaks

$$D_{\text{rms}} / D_T = (y_{xo} / y_{id})^2 \quad (3.4)$$

Figure 3.2 plots the squared peak ratios against period and against period normalized by the ground-motion duration for a range of magnitudes and distances; see Boore and Thompson [2012] for the parameters of the stochastic model used to generate these curves. This figure illustrates the effect of normalizing the period by the ground-motion duration where much of the apparent variability in D_{rms} / D_T is reduced. For this reason, Boore and Thompson [2012] modified the general function form for D_{rms} used by Boore and Joyner [1984] and Liu and Pezeshk [1999] to be

$$\frac{D_{\text{rms}}}{D_T} = 1 + \frac{1}{2\pi\zeta} \left[\eta / (1 + \alpha\eta^n) \right]$$

where $\eta = T_0 / D_T$. Additional terms were then added to better fit the observed ratios:

$$\frac{D_{\text{rms}}}{D_T} = \left(c_1 + c_2 \frac{1 - \eta^{c_3}}{1 + \eta^{c_3}} \right) \left[1 + \frac{c_4}{2\pi\zeta} \left(\frac{\eta}{(1 + c_5\eta^{c_6})} \right)^{c_7} \right] \quad (3.5)$$

In this function, α and n are now free coefficients (c_5 and c_6) to be estimated from the data, and the function approaches $c_1 + c_2$ as η approaches zero and $c_1 - c_2$ as η approaches infinity. Boore and Thompson [2012] fit the coefficients of this equation to the squared ratios $(y_{xo} / y_{id})^2$, where the coefficients vary with magnitude and distance. They developed one set of coefficients from a seismological model that is appropriate for use in SCRs and one that is appropriate for ACRs. Inspection of the squared ratios from these two different sets of simulations clearly indicates that the D_{rms} correction depends upon the seismological model. Additionally, there have been a number of updates to the stochastic method published since Boore and Thompson [2012]; thus the coefficients needed to be updated, as discussed next.

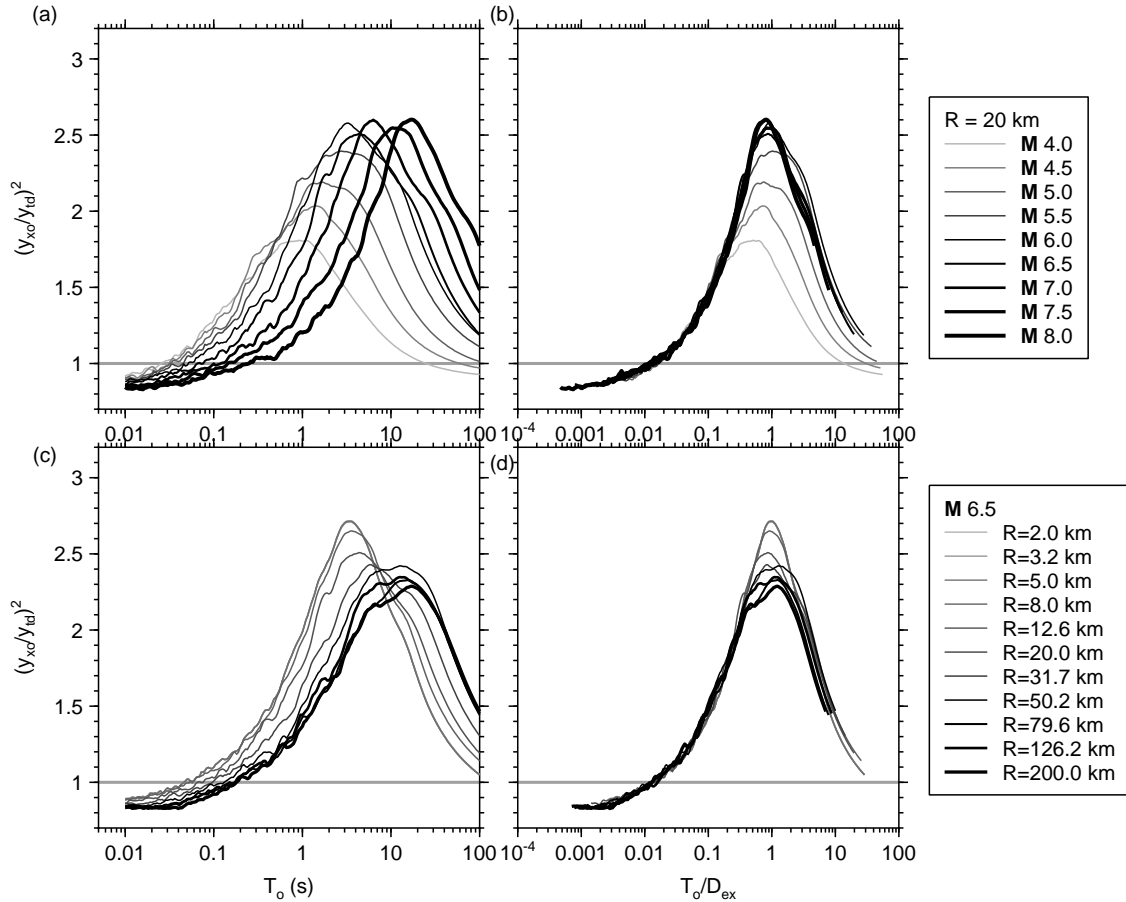


Figure 3.2 Squared ratios of PSA from random-vibration simulations (for which $D_{rms} = D_T$; i.e., no oscillator correction) and time-domain simulations. Note that D_{EX} is synonymous with D_T ; see Boore and Thompson [2012] for details of the stochastic model. Left panels: the squared ratios are plotted against period (T_0). Right panels: the squared ratios are plotted against T_0 normalized by the ground motion duration (T_0/D_T). The top row shows ratios for a fixed distance (20 km) and a suite of magnitudes; the bottom row shows ratios for a fixed magnitude (6.5) and a suite of distances.

3.1.4 Boore and Thompson [2014; 2015] and Update to Boore and Thompson [2012]

Subsequent to Boore and Thompson [2012], a number of important updates have been made to the stochastic method that will affect D_{rms}/D_T . These include:

- Revised path durations [Boore and Thompson 2014; 2015]
- Revised crustal amplifications [Boore and Thompson 2015]
- Generalized double-corner frequency source model [Boore et al. 2014]
- Adjustments to the finite-fault correction factor [Yenier and Atkinson 2014; Boore et al. 2014]

- A new “rms”-to-PF (R2PF) based on Vanmarcke [1975] and Der Kiureghian [1980]

Figure 3.3 shows spectral displacements for a standard SCR model (equivalent to that used in Atkinson and Boore [2006]) computed using TD and RV computations. The bottom row shows ratios of the RV/TD simulations. Although the RV simulations using the Der Kiureghian [1980] R2PF are closer to the TD simulations (which are taken as the correct values) for small magnitudes and short periods than those using the Cartwright and Longuet-Higgins [1956] R2PF, neither R2PF is acceptably accurate; additional curves were added to Figure 3.3 for the Boore and Thompson [2012] D_{rms} model. While the Boore and Thompson [2012] coefficients work relatively well for the CL R2PFs (which were used in the RV simulations by BT12), they do not work well for the DK R2PFs. Thus, the coefficients need to be recomputed for the new R2PF and seismological parameters for SCRs and ACRs.

To check that the coefficients were estimated accurately, the TD/RV ratios were plotted for a range of magnitudes, distances, and periods. Figure 3.4 shows maps of the ratio TD/RV for a SCR model as a function of period and distance for the range of magnitudes used in the simulations (2 to 8). In these figures, period rather than frequency was used to be consistent with the published sources. The top row shows the ratio TD/RV with no adjustment to D_{rms} . The second row shows the ratio when the RV simulations used the value of D_{rms} from Boore and Thompson [2014], which were derived by fitting the ratios in the top row of the figure (note the expanded scale compared with that of the top row of graphs). This indicates that the D_{rms} correction is sufficiently accurate across the magnitude, distance, and periods of interest.

Next, the consistency of the TD/RV ratios was evaluated as reasonable changes were made to the seismological model. Figure 3.5 shows the TD/RV ratios for SCR models with somewhat different parameters than the base model used in deriving the coefficients for D_{rms} . Note the expanded scale used for the graphs (0.9 to 1.1). All of the SMSIM parameter files used in the simulations for the TD and the RV simulations are given in the electronic supplement of Boore and Thompson [2015]. The first and second rows in Figure 3.5 are for the same model used to derive the coefficients (i.e., the base model) but with stress parameters of 100 bars and 1600 bars, respectively, rather than 400 bars. The results imply that the adjustments to D_{rms} are relatively insensitive to the stress parameter. The models used in the third and fourth rows depart even farther from the base model. The third row uses parameters that are consistent with the Atkinson and Boore [2006] model; the most important differences between this model and the base model are path duration, geometrical spreading, and attenuation functions. The graphs in the fourth row use a double-corner-frequency source model given by Atkinson [1993a], but otherwise the parameters are the same as those in the base model. Except for those events that are of little interest (e.g., very small magnitudes or long periods), the results in Figures 3.4 and 3.5 show that relatively accurate results (within about 10% for the examples discussed herein) can be obtained for RV simulations using D_{rms} values obtained for models that are different than the models for which the simulations are being done.

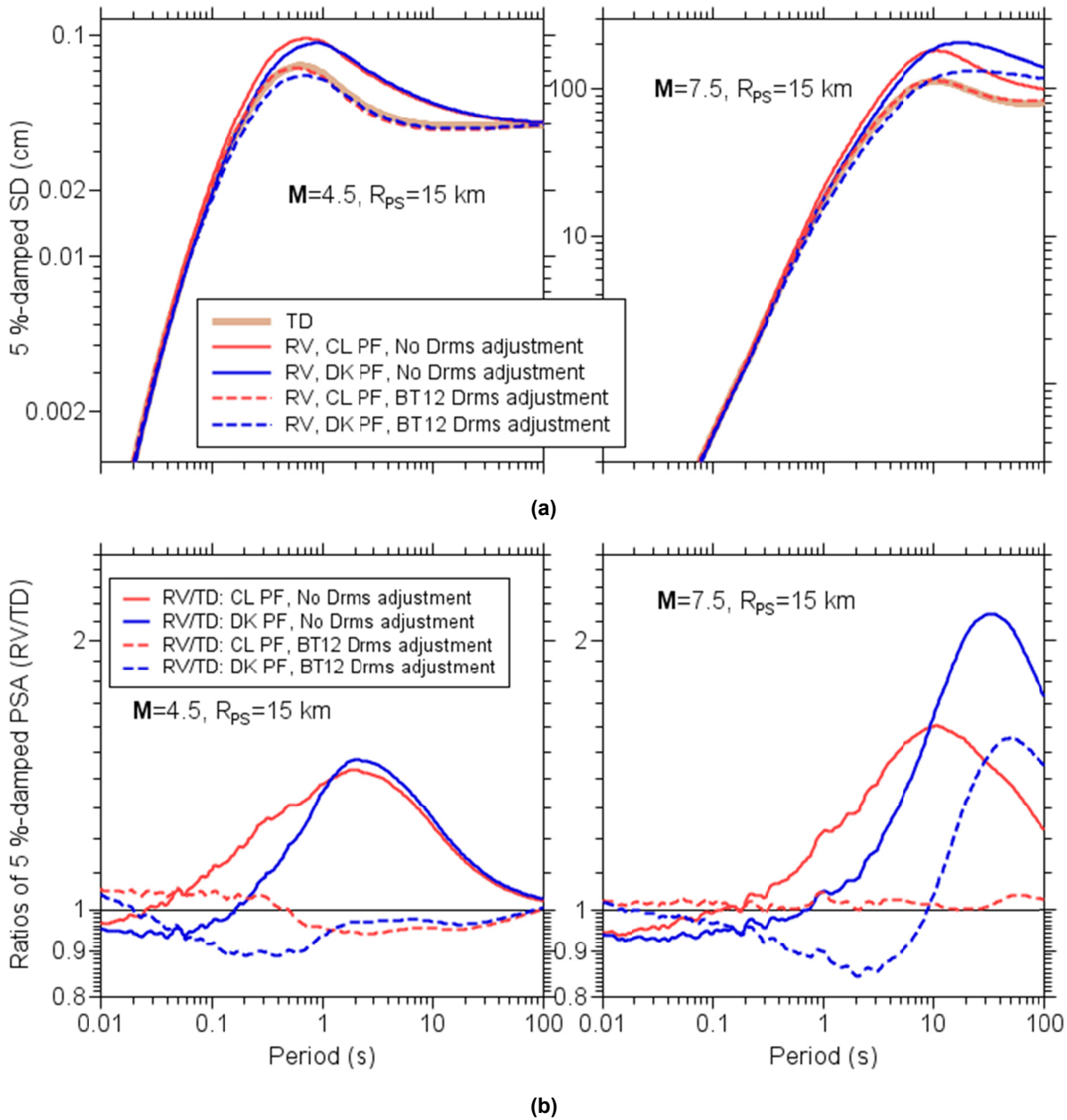


Figure 3.3 (a) Response spectral displacements (SD) from time-domain (TD) simulations and random-vibration (RV) simulations, with and without adjustments for the duration (D_{rms}) used to compute the “rms” of the oscillator response. For the RV simulations, two “rms”-to-PFs were used: Cartwright and Longuet-Higgins [1956] (CL) and Der Kiureghian [1980] (DK); and (b) ratios of the RV and TD response spectra.

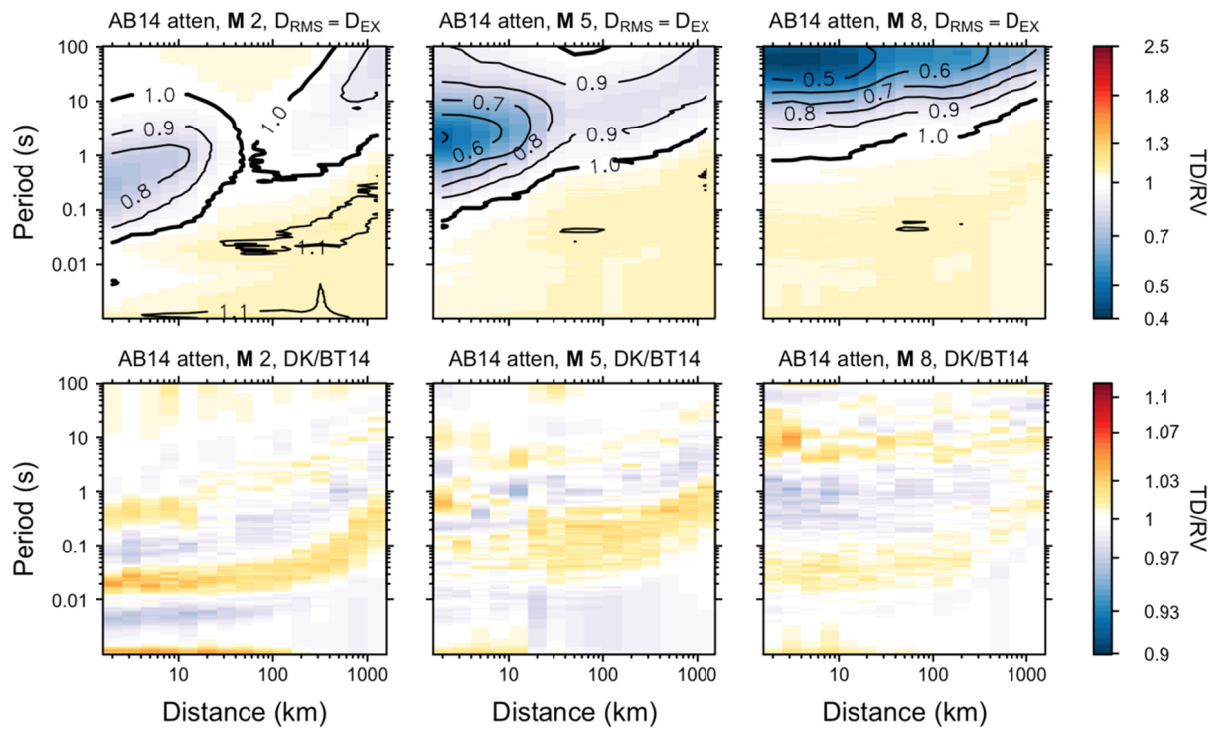


Figure 3.4 Shaded contour plots of the TD/RV ratios; see Boore and Thompson [2015] for the parameters used to generate the TD and RV simulations. The top row shows the ratios when $D_{rms} = D_T$ in the RV simulations, and the bottom row shows the TD/RV ratio using the new adjustments to D_{rms} given in the electronic supplement of Boore and Thompson [2015]. Note the change of scale between the top and bottom rows.

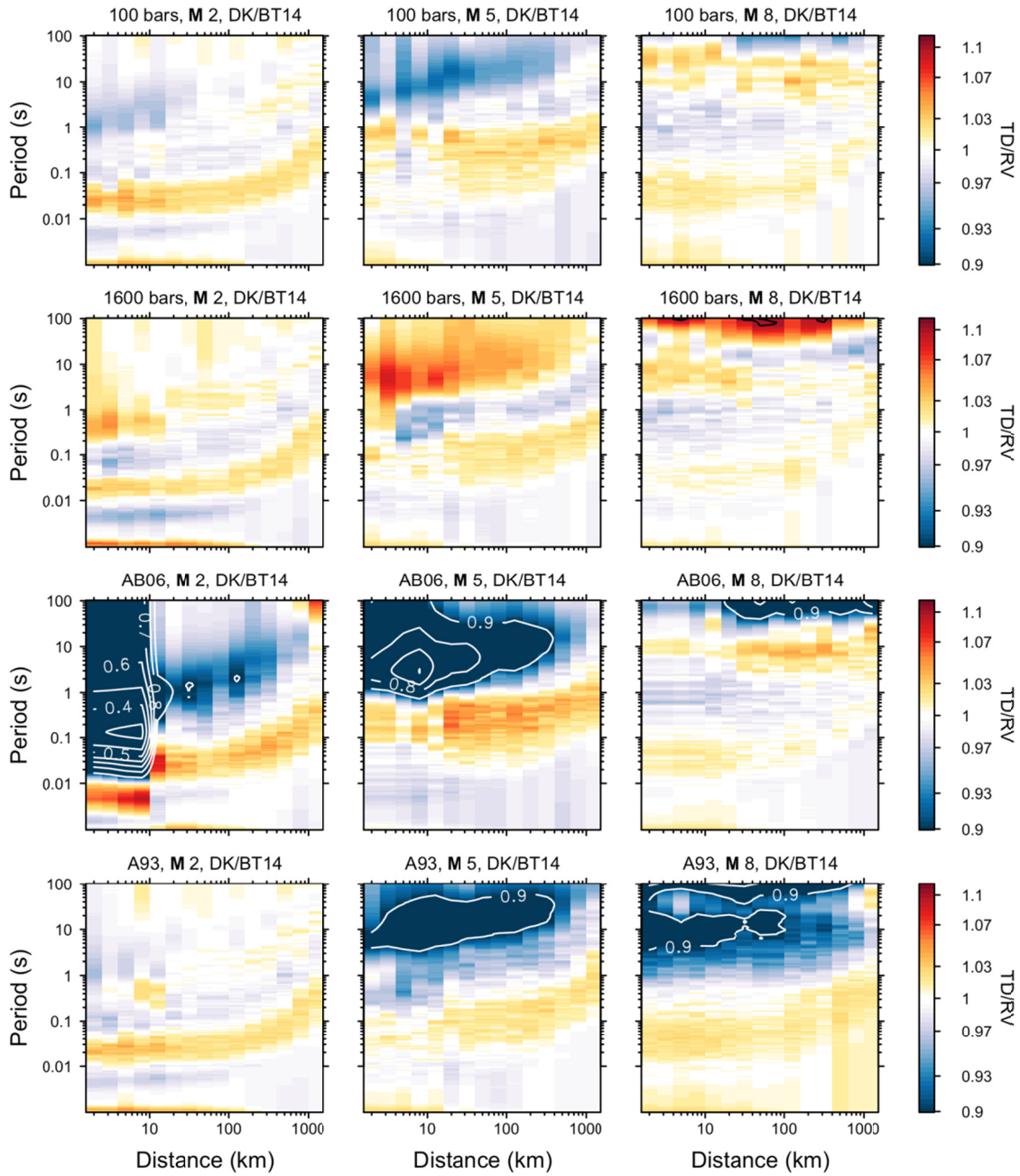


Figure 3.5 Shaded contour plots of the TD/RV ratios for various SCR models not used to derive the coefficients used in the RVT simulations; see text and Boore and Thompson [2015] for discussion and model details. DK = the Der Kiureghian [1980] R2PF; BT14 = the new coefficients for Equation (5) given in the electronic supplement; AB06 = Atkinson and Boore [2006]; and A93 = Atkinson [1993a].

3.2 NON-STATIONARITY CORRECTIONS BASED ON PEAK FACTOR MODIFICATION

Section 8.3.2 of Vanmarcke [1976] considered the time-dependent response of a SDOF oscillator. Integrating the transient squared amplification function over all frequencies yields the following scale factor:

$$n_f = \sqrt{1 - \exp(-4 \cdot \pi \cdot \zeta \cdot f_n \cdot T_{gm})} \quad (3.6)$$

where ζ and f_n are the damping and natural frequency, respectively, of the SDOF transfer function. This non-stationarity factor corrects for the fact that an oscillator may not reach steady-state conditions during the interval from 0 to D_{gm} . The response within the duration of the ground motion [$x_{rms}(T_{gm})$] is related to the steady-state response [$x_{rms}(\infty)$] by Toro and McGuire [1987]:

$$x_{rms}(T_{gm}) = x_{rms}(\infty) \cdot n_f \quad (3.7)$$

3.3 DISCUSSION AND SUMMARY

This section presents two methods for modifying RVT methodology. The influence of these corrections is evaluated by computing the ratio of the oscillator response computed by the corrected and uncorrected approaches presented in Table 3.1. The TM87 method is not represented here because the same corrective factor is used by the V75 formulation. The ratio between corrected and uncorrected oscillator response for the three events considered in Section 2.2.2 are shown in Figure 3.6. For the BT12 “rms”-duration correction, the coefficients for the CENA region were used. For the M 3.5 event, the five different correction methods provide very different estimates. Because the BT12 method only provides coefficients down to M 4, the corrective ratio for BT12 is not shown in Figure 3.6. The least significant ratio (i.e., closest to 1), is the DK85 ratio, although based on modifying the N_z parameter to fit empirical results, it does not explicitly consider non-stationarity. The more significant ratio is the V75, which adjusts directly the PF based on duration required for steady-state response. Unlike the other corrective ratios, the V75 ratio does not return to unity at low frequencies.

As the magnitude increases, all corrective methods show similar shifts to lower periods due to the longer ground-motion duration. Each of the “rms”-duration methods (i.e., BJ84, LP99, and BT12) show similar albeit slightly different corrective ratios.

While the Boore and Thompson [2015] coefficients are very accurate for the rock parameters used to derive the coefficients—and acceptably accurate for reasonable adjustments to the seismological parameters—they will likely not be accurate for simulations using the full-resonance site-response calculations and equivalent-linear nonlinearity (e.g., Kottke and Rathje [2013]). This is because the coefficients do not account for the increased duration of the oscillator due to site response resonances or substantial changes to the spectral shape. This could be addressed by developing an additional parameter that is a function of the site characteristics to adjust the Boore and Thompson [2014] D_{rms} coefficients. Alternatively, new D_{rms} equations can

be developed that account for the impact of the full-resonance site response on the spectral shape and oscillator duration.

Table 3.1 The ratios between corrected and uncorrected PF formulations with respect to non-stationarity.

Corrected	Uncorrected
V75 with n_f	V75 without application of n_f
DK85	D64
CLH56 with BJ84 “rms” duration	CLH56
CLH56 with LP99 “rms” duration	CLH56
CLH56 with BT12 “rms” duration	CLH56

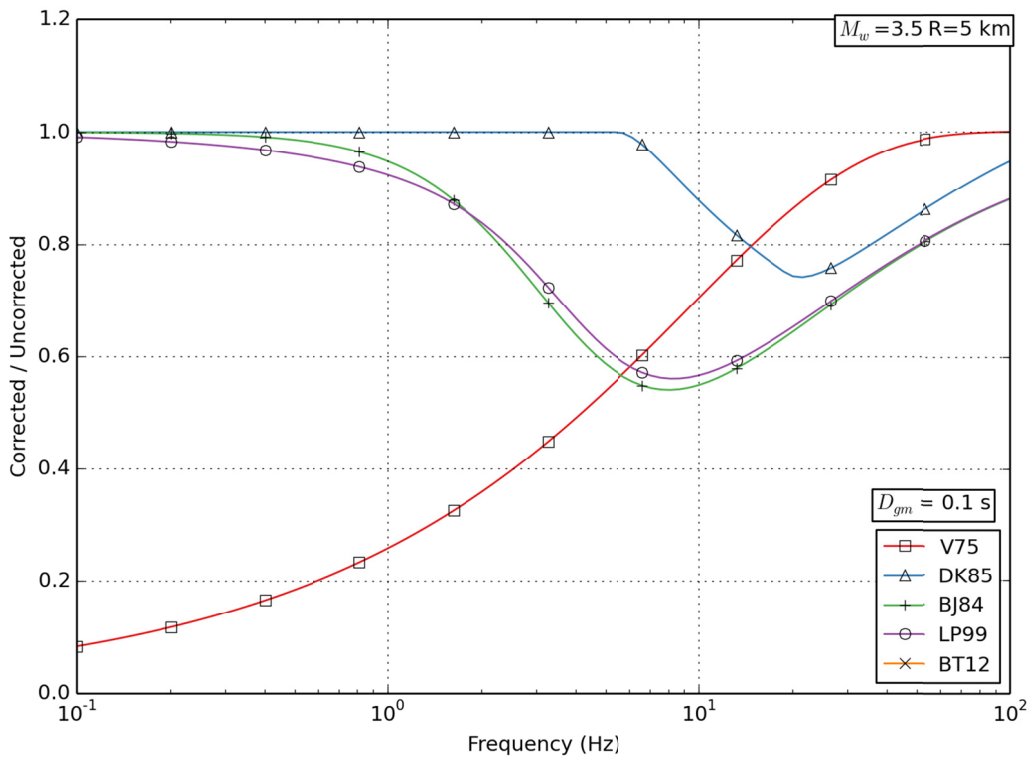


Figure 3.6 The ratio of the correction to uncorrected oscillator response for the M 3.5 event at a distance of 5 km; see Table 3.1 for the definitions of the corrective ratios.

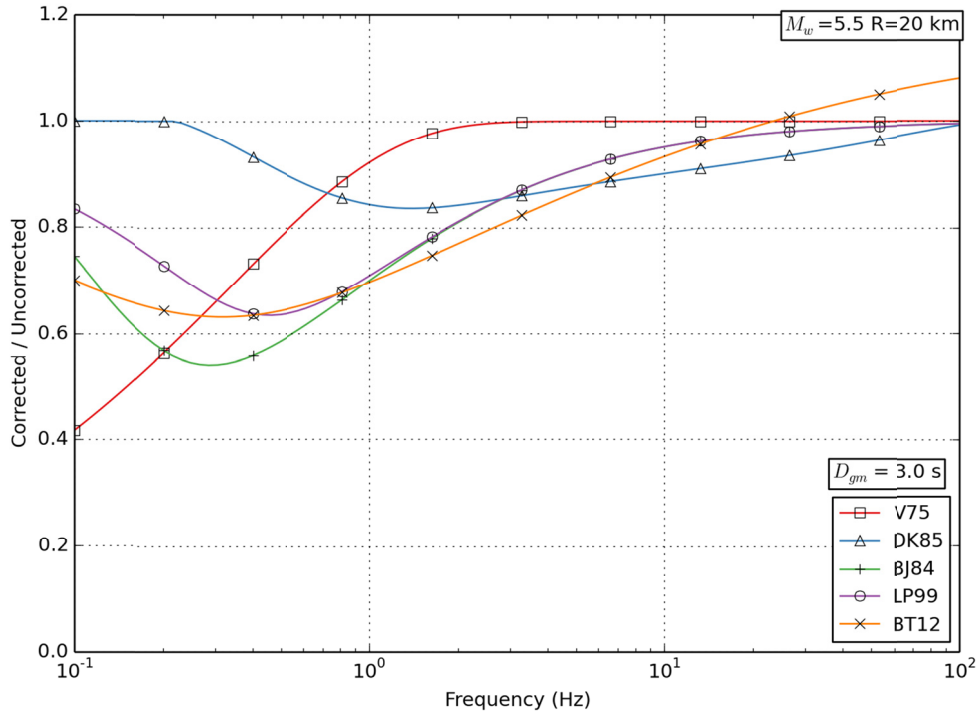


Figure 3.7 The ratio of the correction to uncorrected oscillator response for the $M = 5.5$ event at a distance of 20 km; see Table 3.1 for the definitions of the corrective ratios.

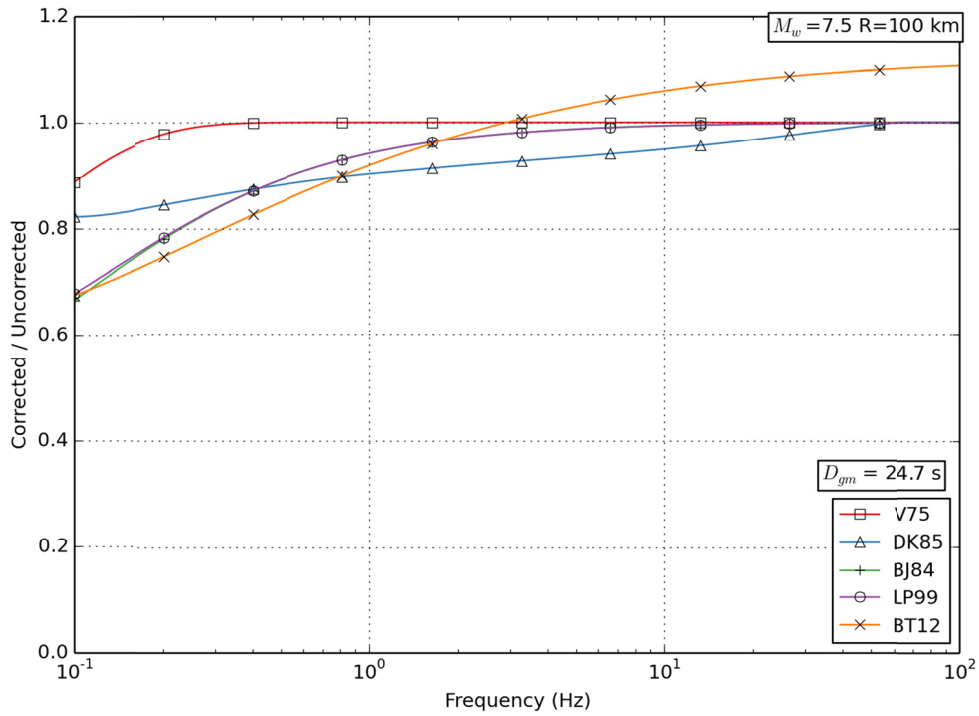


Figure 3.8 The ratio of the correction to uncorrected oscillator response for the $M 7.5$ event at a distance of 100 km; see Table 3.1 for the definitions of the corrective ratios.

4 Processing Ground Motions using the Random Vibration Theory Approach

The records used for ground-motion model (GMM) development per the NGA-East RVT approach (see Chapter 11 by Hollenback et al. in *PEER Report No. 2015/04* for further details on this approach) required additional processing beyond what is described in Goulet et al. [2014]. The two primary additional steps are:

- Definition of an orientation-independent FAS to represent the two as-recorded horizontal components of a record
- Smoothing and down-sampling of the orientation-independent FAS to a reasonable number of frequency points in order to develop a frequency-by-frequency GMM-based FAS

The RVT Working Group's proposed approach for completing these tasks is discussed below.

4.1 ORIENTATION-INDEPENDENT FOURIER AMPLITUDE SPECTRUM

The GMM development (e.g., constraining magnitude scaling and distance attenuation) was performed on the FAS of recorded ground motions. Subsequently, PSA GMMs were defined using this FAS model and a calibrated duration model through RVT. The FAS and duration models were developed from an orientation-independent FAS. We refer to this orientation-independent FAS as the effective amplitude spectrum (EAS), which is defined as

$$\text{EAS}(f) = \sqrt{\frac{1}{2} [\text{FAS}_{\text{HC1}}(f)^2 + \text{FAS}_{\text{HC2}}(f)^2]} \quad (4.1)$$

where FAS_{HC1} and FAS_{HC2} are the FAS of first and second as-recorded horizontal components of a three-component time series. By definition, this is independent of the orientation of the instrument. Figures 4.1 and 4.2 compare the FAS of the two as-recorded horizontal components to the EAS for two records from the NGA-East database [Goulet et al. 2014].

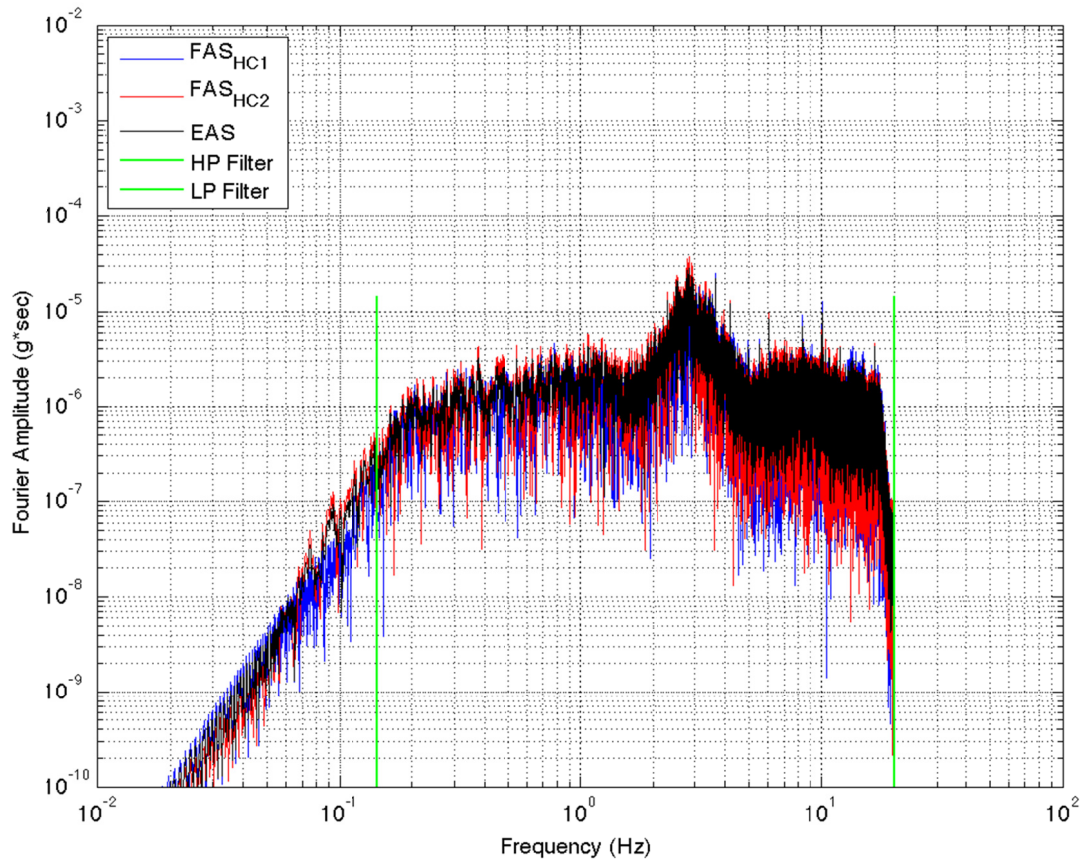


Figure 4.1 Fourier amplitude spectra from the Cap-Rouge event recorded at station US.GOGA. The north and east components (FAS_{HC1} in blue and FAS_{HC2} in red) are plotted along with the effective amplitude spectrum [Equation (4.1) in black]. The green vertical lines represent the high-pass (HP) and low-pass filters (LP) of the record.

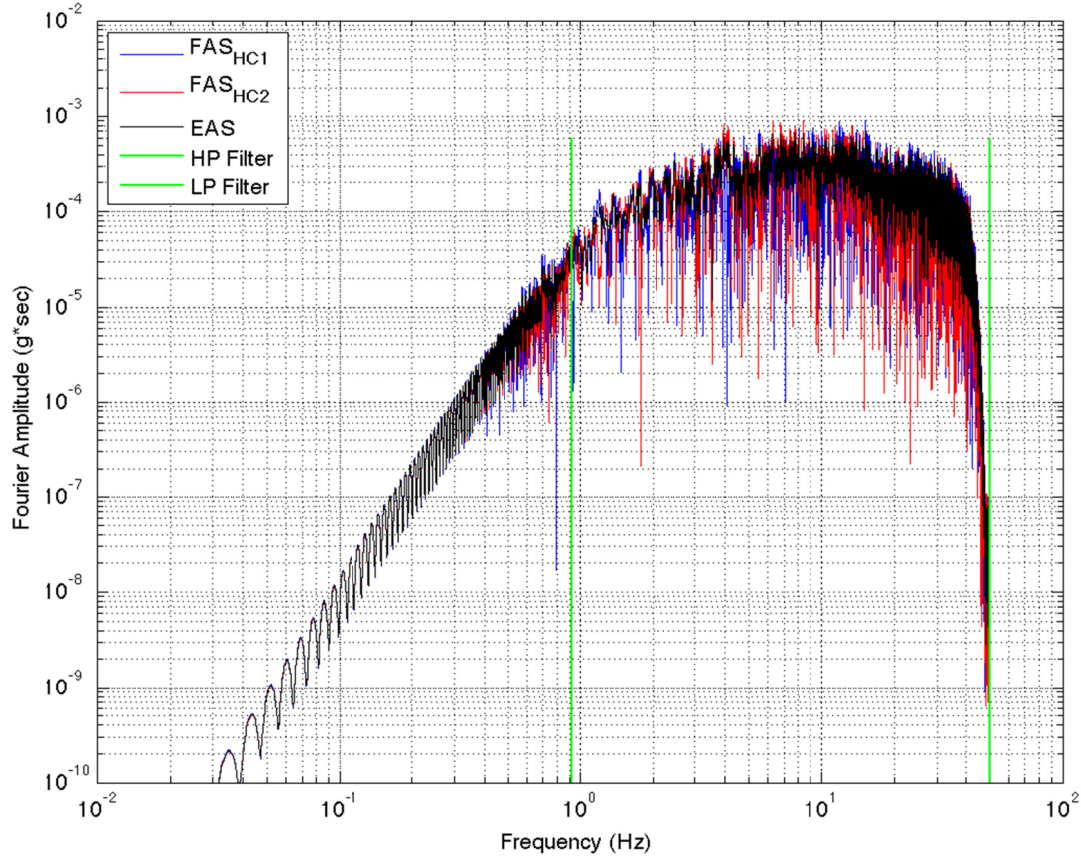


Figure 4.2 Fourier amplitude spectra from the Cap-Rouge event recorded at station CN.A11 (Station ID 8). The north and east components (FAS_{HC1} in blue and FAS_{HC2} in red) are plotted along with the effective amplitude spectrum (Equation (34), in black). The green vertical lines represent the high-pass (HP) and low-pass filters (LP) of the record.

4.2 SMOOTHING AND DOWN-SAMPLING

As part of the NGA-East uniform record processing, all time series were padded to longer durations to make the frequency step, Δf , in the FAS as uniform as possible. The choice of Δf was a compromise between record length and reasonably similar Δf , and resulted in the two Δf defined in Table 4.1. This is a departure from other datasets where Δf is defined by the as-recorded record length.

The resulting FAS for these processed records contain very large numbers of frequency points; records with a high Nyquist frequency have over 100,000 frequency points. This is not a practical number of frequencies to use with the NGA-East FAS modeling approach for developing GMMs in which regression is performed frequency-by-frequency. Therefore, all the EAS in the database were uniformly smoothed and down-sampled to a manageable number of frequency points. A wide range of smoothing operators are available, each allowing different

smoothing levels. The smoothing technique and level must be carefully selected so as to not introduce bias relative to the original dataset.

In the context of RVT performed using the Vanmarcke PFs (see Section 2.2.1.3), there are four FAS quantities controlling the process in addition to duration: the *zero*th spectral moment [m_0 , Equation (2.4)], δ [a measure of the ground motion band width, Equation (2.14)], the frequency of zero crossings [f_z , Equation (2.5)], and the frequency of extrema [f_e , Equation (2.7)]. The smoothing criterion for the current application was as follows: that the smoothed, down-sampled EAS led to similar quantities as the complete EAS for the four properties relevant to RVT.

Several smoothing windows of various widths were considered and tested, including the Hamming, trapezoidal, and triangular windows. Application of such windows to linear sampling of frequencies led to bias in spectral shape, especially at low frequencies, and did not allow a close match to the four quantities listed above. To prevent these issues, the RVT working group selected the Konno and Ohmachi [1998] (KO) smoothing window, which is based on the log10 sampling of frequencies. The KO window weights are defined by:

$$W(f) = \left\{ \frac{\sin[b \log(f/f_c)]}{b \log(f/f_c)} \right\} \quad (4.2)$$

where W is the weight defined at frequency f for a window centered at frequency f_c and defined by window parameter b . Window parameter b can be defined in terms of the bandwidth in log10 units of the smoothing window as:

$$b = 2\pi/b_w \quad (4.3)$$

where b_w is the bandwidth of the smoothing window in log₁₀ units. The KO smoothing window was selected because it resulted in little-to-no bias on the amplitudes of the smoothed EAS when compared to the unsmoothed EAS. Other smoothing windows considered (the Hamming window, trapezoidal window, and triangular window) did not. Figure 4.3 shows the KO smoothing window for $f_c = 5$ Hz and four different values of b_w .

Table 4.1 Frequency sampling of the NGA-East dataset.

NGA-East Data	Type 1	Type 2
sps	10, 20, 40	50, 100, 200
dt	0.1, 0.05, 0.025	0.02, 0.01, 0.005
Duration (sec)	3276.8	2621.44
Power of 2	15, 16, 17	17, 18, 19
Δf	0.00030518	0.0003815

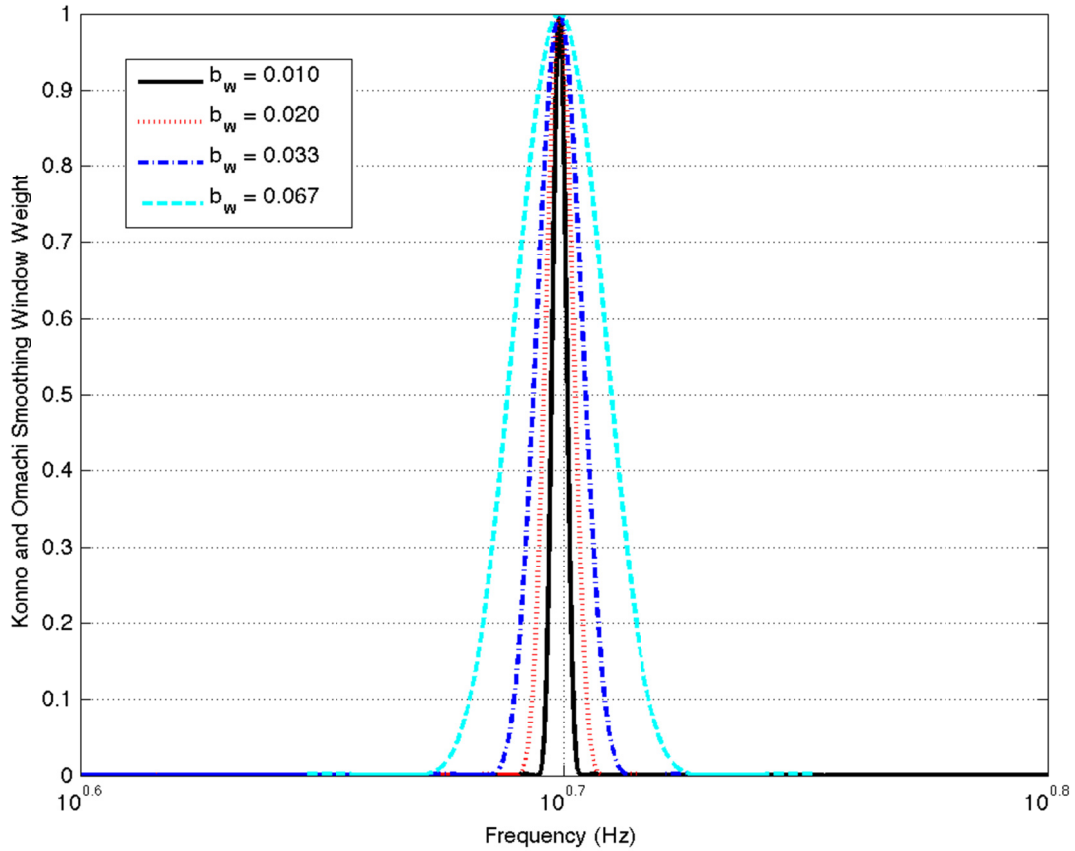


Figure 4.3 Comparison of Konno and Ohmachi smoothing windows with four different smoothing window bandwidths: 0.01, 0.02, 0.033, and 0.067.

The four RVT properties selected for calibration are all functions of several different n^{th} order moments of the oscillator frequency response function, which is a function of the square of the FAS of the ground motion. Thus, the smoothing and down-sampling was performed on the square of the EAS in the NGA-East database.

All EAS in NGA-East database were smoothed and down-sampled for six different combinations of smoothing window bandwidth, b_w , and number of frequency points for down-sampling; see Table 4.2. To determine the combination that would have the least impact on subsequent GMM development, the four properties selected for RVT calibration, m_0 , q , f_z , and f_e , were calculated for the original EAS and the smoothed and down-sampled EAS. The comparison was done at three different oscillator periods and covered the full range of periods to be defined by the GMMs: 0.01 sec, 0.2 sec, and 10 sec. The value of each property from the smoothed and down-sampled EAS was compared to that of the original EAS for all the records and each oscillator period. We quantified the number of records in the database whose smoothed and down-sampled RVT properties fell within a given percentage of the original RVT properties. Table 4.2 lists the percentage of records that had smoothed and down-sampled RVT properties that fell within $\pm 1\%$ of original RVT properties. Based on this criteria, the combination of $b_w =$

1/30 and 100 frequency points per decade was identified as having the least impact on the four RVT calibration properties and were, therefore, selected for smoothing and down-sampling of the NGA-East database. Close inspection of the records falling outside of the 1% range led to the elimination of these records on the basis of a peculiar spectral shape around a limited frequency band. Figures 4.4 and 4.5 compare the original EAS and the smoothed and down-sampled for this selected combination for two different records.

Table 4.2 Percentage of records in NGA-EAST database that have RVT properties of the smoothed and down-sampled EAS within $\pm 1\%$ of the RVT properties of original EAS.

Oscillator period = 0.01 sec					
Number of frequency points per decade	Width of smoothing window, b_w (fraction of a decade)	m_0	q	f_z	f_e
30	1/15	46%	49%	86%	88%
30	1/30	18%	20%	47%	57%
50	1/30	35%	39%	80%	85%
50	1/50	19%	21%	54%	63%
100	1/30	99%	98%	100%	99%
100	1/100	24%	26%	64%	70%

Oscillator period = 0.2 sec					
Number of frequency points per decade	Width of smoothing window, b_w (fraction of a decade)	m_0	q	f_z	f_e
30	1/15	21%	15%	87%	92%
30	1/30	12%	10%	66%	78%
50	1/30	25%	24%	89%	94%
50	1/50	14%	13%	73%	83%
100	1/30	99%	98%	100%	100%
100	1/100	17%	15%	79%	88%

Oscillator period = 10 sec					
Number of frequency points per decade	Width of smoothing window, b_w (fraction of a decade)	m_0	q	f_z	f_e
30	1/15	22%	37%	60%	76%
30	1/30	11%	14%	32%	37%
50	1/30	30%	34%	63%	70%
50	1/50	19%	19%	40%	43%
100	1/30	94%	99%	99%	100%
100	1/100	37%	28%	58%	56%

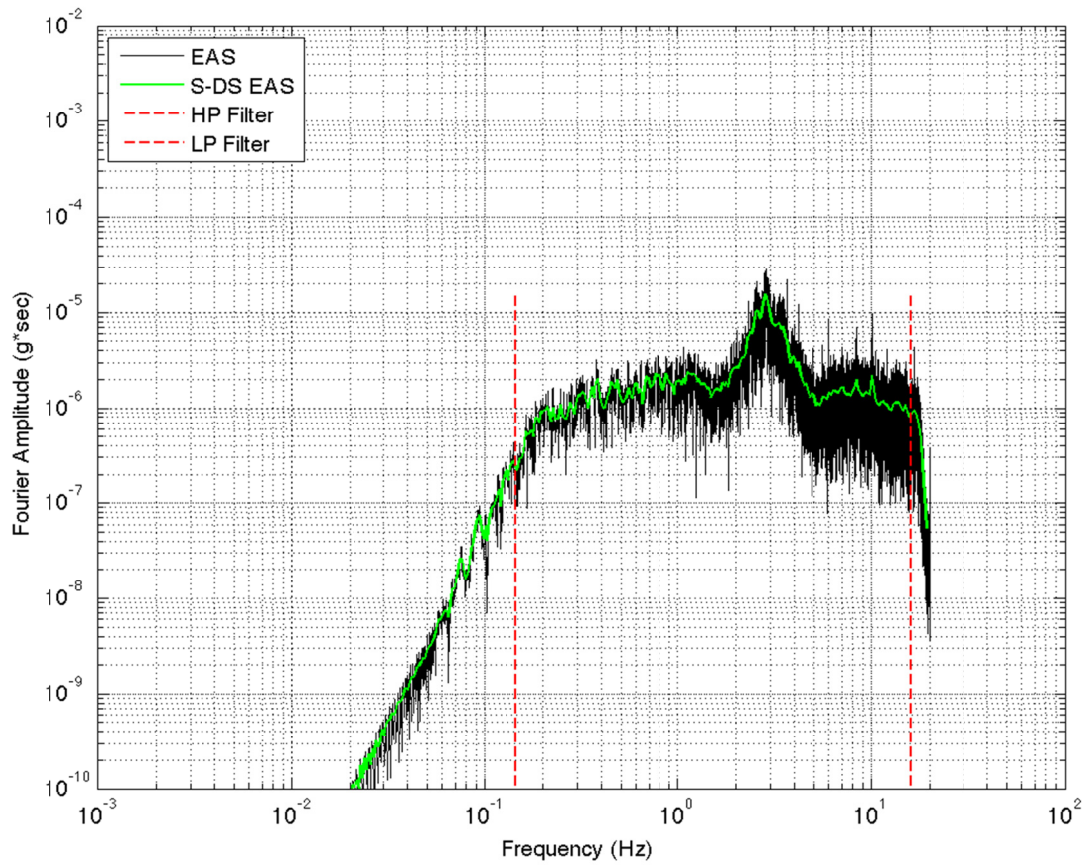


Figure 4.4 Effective amplitude spectra (EAS) and smoothed and down-sampled effective amplitude spectra (S-DS EAS) from the Cap-Rouge event recorded at station US.GOGA. The red dashed vertical lines represent the high-pass (HP) and low-pass filters (LP) of the record.

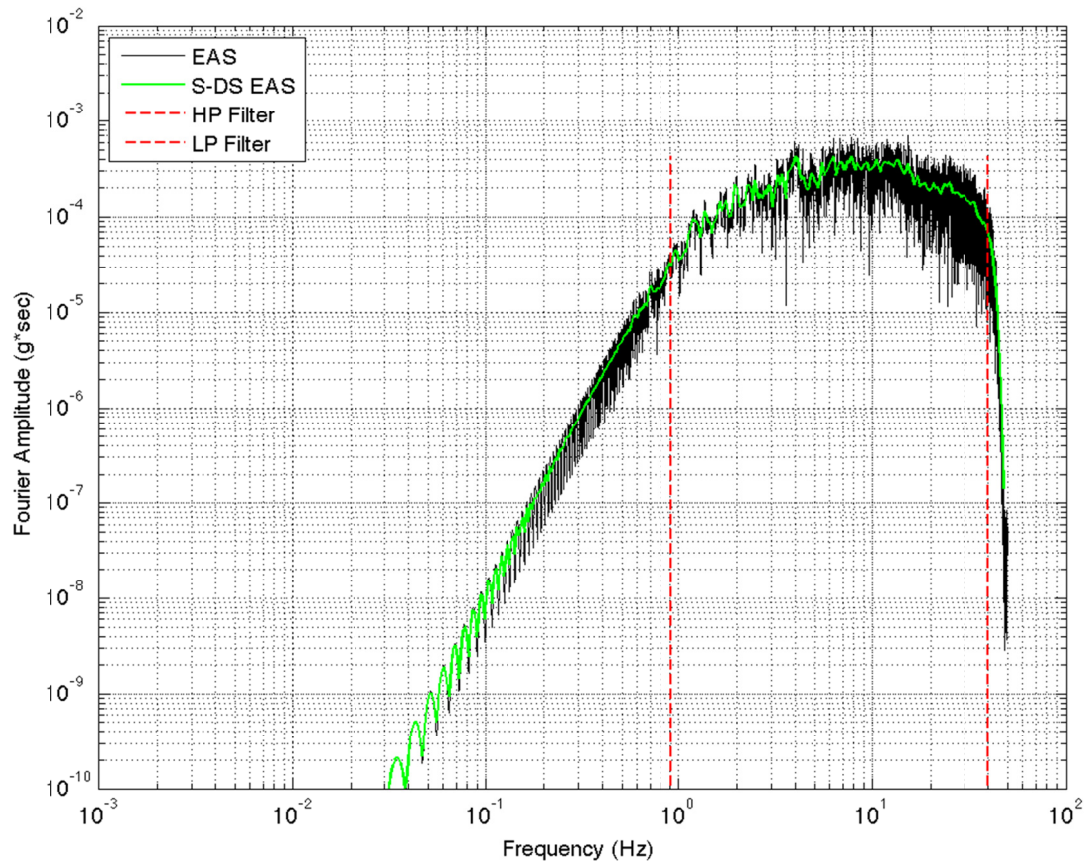


Figure 4.5 Effective amplitude spectra (EAS) and smoothed and down-sampled effective amplitude spectra (S-DS EAS) from the Cap-Rouge event recorded at station CN.A11. The red dashed vertical lines represent the high-pass (HP) and low-pass filters (LP) of the record.

5 Conclusions and Future Work

5.1 CONCLUSION: RECOMMENDED APPROACH

This report evaluated the use of RVT for the purpose of median GMM development. Based on their relevance to engineering and seismology communities, two PF formulations are recommended: (1) Cartwright and Longuet-Higgins [1956], and (2) Vanmarcke [1976]. The associated duration corrections developed by Boore and Thompson [2014; 2015] are recommended when response spectra are being computed. Alternatively, new durations optimized to minimize PSA bias could be computed from a region-specific database; that approach, applied to the NGA-East project, is discussed in Chapter 11 of *PEER Report No. 2015/04*.

The orientation-independent FAS referred to as the effective amplitude spectrum (EAS) is recommended to characterize the frequency content of recorded ground motions. Down sampling of the EAS should be done using a Konno and Ohmachi [1998] smoothing window with a width (b_w) of 1/30 and 100 frequency points per decade. Because this smoothing window was identified as having the least impact on the four RVT calibration properties, it was selected for smoothing and down-sampling of the NGA-East database.

This report was originally developed in 2014 for the NGA-East project to document a basis for the ground motion processing and to provide recommendation on the practices for random vibration theory. Since the original draft of this report, there have been additional studies on random vibration theory that are not included in this report, such as: Wang and Rathje [2016]; Wang and Rathje [2018a; 2018b]; and Van Houtte, Larkin, and Holden [2018].

5.2 FUTURE WORK

Several RVT topics were barely touched-on in this report and we identify selected avenues for future research.

1. RVT for site response. Site response studies such as Kottke and Rathje [2013] have demonstrated the potential misfit between TS and RVT site-response analyses. Evaluating RVT for site response is beyond the scope of this document and has not been considered herein. Future work regarding RVT should consider not only how

the method works on simple SDOF oscillators but also on multi-degree of freedom systems (e.g., site response and SDOF oscillators).

2. Host-target corrections. Host-target corrections have been recently used to correct acceleration response spectrum for different site attenuation parameters (e.g., Al Atik et al. [2014]). These correction factors are dependent on the RVT methodology used. Further research needs to be conducted to ensure that the correct factors are not influenced by the PF formulation selected.
3. Applicable frequency range of RVT. The current RVT procedures use a combination of theoretical and empirical corrections to provide accurate estimates of the peak time-domain response. The empirical nature of the correction might cause the RVT results to be accurate only over a select frequency range. This aspect of the empirical corrections has not been well investigated.

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