Variation in Seismic-wave Attenuation Along the Cascadia Subduction Zone
Determined from Tectonic Tremor

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Introduction

Many subduction zones worldwide host large, devastating earthquakes, such as the 2011 M9 Tohoku-Oki earthquake. To increase resilience to such events, earthquake engineers utilize what is known as Ground Motion Prediction Equations (GMPEs) that quantify ground motion during an earthquake. GMPEs relate ground motion to a number of physical parameters such as earthquake magnitude, fault mechanism, local site characteristics, and, namely, attenuation. Seismic-wave attenuation is the decay in amplitude of seismic waves as a function of distance from the earthquake source.

In addition to fast, seismic slip many subduction zones also host slow, largely aseismic slip. These “slow slip earthquakes” occur on timescales of weeks to months and are often accompanied by an episode of weak seismic signals known as “tectonic tremor,” or simply “tremor.” Tremor behaves differently than regular earthquakes in that it is comprised of many small earthquakes that radiate low-frequency seismic energy and originate at the plate interface downdip of where large earthquakes typically occur (Beroza and Ide, 2011) (Figure 1). This behavior is thought to reflect variation in frictional properties, effective stress, or both in between the seismogenic and aseismic sections of the plate interface. Because tremor events have such a weak seismic signal and occur on long timescales relative to ordinary earthquakes, we typically do not feel them.

Our goal is to quantify seismic wave attenuation in Cascadia and determine its spatial variations using tectonic tremor. By inverting tremor ground motion data for an attenuation parameter, we can analyze how our results vary spatially in Cascadia and attempt to relate these variations to lithology and/or other physical properties.

Ground Motion Prediction Equations (GMPEs)

Ground Motion = (Source) x (Path) x (Site)

Here, we’re looking at Path Effects:

- Describes the amplitude of the seismic wave at a certain station as combination of the initial source amplitude, geometrical spreading (following a 1/R relationship) and attenuation.
- Amplitude follows a 1/R relationship with distance, where R is the hypocentral distance from the earthquake to the station. However, attenuation causes the energy of the wave to dissipate more quickly along its path.
- We define the anelastic attenuation parameter as $c_2 = 1/R_f$, according to Baltay and Beroza (2013).

Ground Motion Prediction Equations (GMPEs)

$A_g = A_{g0} \exp\left(-\frac{\lambda R_f}{Q}\right) \frac{1}{R_f}$

$\lambda = \text{Geometrical spreading of energy}$
$\text{R_f} = \text{Hypocentral distance}$

The Data

- For the tremor episodes of 2009, 2012 and 2015-2016:
- We obtain data from the Pacific Northwest Seismic Network (PNSN) and Incorporated Research Institutions for Seismology (IRIS).
- Ground motion data are waveforms containing the amplitude versus time of individual earthquake tremor events that comprise the tremor episode (Figure 3). Data are corrected for instrument response, filtered in the 1-10 Hz frequency range and converted to velocity, acceleration and displacement.
- We utilize the Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV) as amplitude measures in our inversion. These are taken as the peak amplitude in each one-minute time window for acceleration and velocity, respectively.

Preliminary Results

- Table 1. Initial source amplitude, geometrical parameter, we can analyze if and how our results vary spatially in Cascadia and attempt to relate these variations to lithology and/or other physical properties.

Figure 2. Cross-section of a subduction zone. The pink circle indicates where slow slip earthquakes and associated tremor are generated, downdip of the seismogenic zone where larger earthquakes occur. Schwartz and Rokosky, 2007.

Figure 3. Typical waveform of an individual tremor event. Displayed is acceleration ($\ddot{x}$) versus time.

Inversion Scheme to Obtain the Attenuation Term

Starting from our original equation, $A_g = A_{g0} \exp\left(-\frac{\lambda R_f}{Q}\right) \frac{1}{R_f}$
we take the natural log and rearrange the term to solve for a preliminary $c_2$ value, and designate a $c_1$ term; describing the initial amplitude for each event:

$\ln A_{g1} = c_1 - c_2 \times R_f - \ln R_f$

We use differential ground motion amplitudes by comparing the amplitude of each event at two different stations. Subtracting the amplitude of event $i$ at station 1 and the amplitude of event $i$ at station 2, for all possible station combinations:

$c_2 = \frac{(\ln A_{g1} - \ln A_{g2}) + (\ln R_f - \ln R_f)}{(R_f - R_f)}$

We compute a $c_2$ term for each event and each station combination, then substitute our preliminary $c_2$’s to determine the $c_1$ terms for each event:

$c_1 = \frac{1}{R_f} \sum_{i} \ln A_{g1} + \ln R_f + c_2 \times R_f$

Plugging back in to recover site terms for each station:

$\ln S_i = \sum_{j} \ln A_{g1} - c_1 + \ln R_f + c_2 \times R_f$

And there we have it! We use all of our previously determined terms to find our final attenuation parameter:

$c_2 = \ln S_i - \ln A_{g1} - c_1 - \ln R_f$

Figure 4. (Above) PGA c1-terms are indicative of the relative magnitude of each individual tremor event. Figure 4 displays the c1 terms over the duration of the 2016 tremor episode, illustrating the dependence on the time of day. Day hours exhibit consistently larger amplitudes, amplified during the daytime due to noise from humans! (Below) Normal distribution of PGA c2-terms for the 2016 tremor episode.

Figure 5. (Above) Final $c_2$ values for each year, computed using both PGA and PGV. The similarity between the mean and median $c_2$ values is what we expect for the normal distribution as shown on the right, and indicates that these are relatively stable results.

What’s Next?

Quantifying seismic-wave attenuation allows a straightforward way of determining its spatial variations in Cascadia. Next, we will repeat our analysis regionally to determine if the attenuation parameter experiences significant changes. Changes in seismic-wave attenuation could result in significantly different ground motions in the event of a very large earthquake, hence quantifying attenuation may help to better estimate the severity of shaking in densely populated metropolitan areas such as Vancouver, Seattle and Portland.

References

Field, Edward H. Probabilistic Seismic Hazard Analysis (PSHA) · A Primer, OpenSHA