Engineering application of high frequency ground motions in Christchurch

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ABSTRACT: Consideration of high frequency ground motion is important for the earthquake resistant design of lifelines, non-structural elements of buildings, critical facilities and military installations. The rate of decay of the high frequency content of earthquake ground motions can be parameterised by κ ("kappa"), the spectral decay parameter, which represents the intense attenuation of the high frequency energy of seismic waves near the ground surface. κ is a key parameter when adjusting ground motion prediction equations (attenuation relations) from one region to another using the host-to-target method of Campbell (2003, 2007). This study gives preliminary κ estimates for six rock stations in the Port Hills and Banks Peninsula, south of Christchurch. These κ estimates are a first step to gather the data required for a site-specific hybrid empirical ground motion prediction equation for Christchurch, which may reduce the epistemic uncertainty for future probabilistic seismic hazard assessment (PSHA) in Christchurch. The κ values from Christchurch are similar to those found in Western North America for similar geological conditions.

1 INTRODUCTION

For typical buildings, most of the damaging effects of earthquakes are due to low frequency ground shaking close to the natural frequency of the structure and/or soil profile. High frequency ground motion can control the seismic hazard for other infrastructure such as pipes, lifelines, non-structural elements of buildings and, in particular, important structures built on rock. These important structures (usually nuclear reactors, nuclear waste disposal sites, or military facilities) require very detailed site-specific ground motion prediction, where the target design spectrum may have a probability of exceedence as low as 10^{-7}. These facilities are usually built on rock sites, where earthquake ground motions have more high frequency content than those on soil sites. While the probability of exceedence of the target design spectrum is small, the consequences of failure are very significant, therefore these buildings need to be designed to resist the expected level of high frequency ground motions.

One important characteristic observed on acceleration records is that the amplitude of the Fourier spectrum decreases rapidly from a certain frequency onwards. Hanks (1982) named this frequency f_{max} and considered that after that, the acceleration spectrum 'crashed'. In practice, we are not only interested in knowing at which frequency the decrease begins, but also its rate. This high frequency decay is usually modelled as exponential, after Anderson and Hough (1984). That means that if the amplitude of the Fourier acceleration spectrum, $A(f)$, is plotted in natural logarithmic scale versus frequency in a linear scale, then the decay is linear. The acceleration Fourier spectrum can be modelled as:

$$A(f) = A_0 exp(-\pi\kappa f) \qquad \text{for} \quad f > f_E \qquad (1)$$

where A_0 is a source- and path-dependent amplitude, f is the frequency and f_E is the frequency above which the decay is approximately linear on a plot of log(A) against f. κ controls the rate of high frequency decay, or the slope of the spectrum (Anderson & Hough, 1984). **Figure 1** shows examples of computation of the high frequency κ factor, fitted to two Fourier spectra from the M5.9 Pegasus Bay earthquake of 23 December, 2011.

It should be noted that the frequency band to calculate κ should be selected to avoid any local amplification peaks, as site attenuation and site amplification are two different mechanisms that are usually analysed separately (Purvance & Anderson, 2003). The fundamental frequencies for the GODS and HVSC stations are in the 1-10 Hz range (Van Houtte et al., 2012), therefore the κ slopes in Figure 1 are picked above 10 Hz.

Most studies show that κ is path- and site-dependent (e.g., (Hough & Anderson, 1988; Hough et al., 1988; Anderson, 1991; Campbell, 2009; Fernández et al., 2010; Ktenidou et al., 2013). While the dependences may be modelled in different ways, a simplified approximation (e.g., Ktenidou et al., 2013) is given by equation (2):

$$\kappa = \kappa_0 + m \cdot r \qquad (2)$$

where r is the distance from the epicentre, m is the linear slope of the $\kappa(r)$ trend, and κ_0 is the zero-distance spectral decay parameter. According to Anderson and Hough (1984), m is related to the seismic quality factor, Q. Under certain assumptions, Q can be computed as $1/\beta m$, where β=3.5 km/s is the average V_S of the crust. Therefore m is considered a regional effect. κ_0 represents the local attenuation of high frequency seismic energy directly beneath the site. The cartoon in **Figure 2** illustrates this equation and these two parameters. κ_0 (rather than κ), known as the zero-distance, site-specific component of κ) has since become the chosen high frequency attenuation parameter for several applications, including the host-to-target method of adjusting ground motion prediction equations.

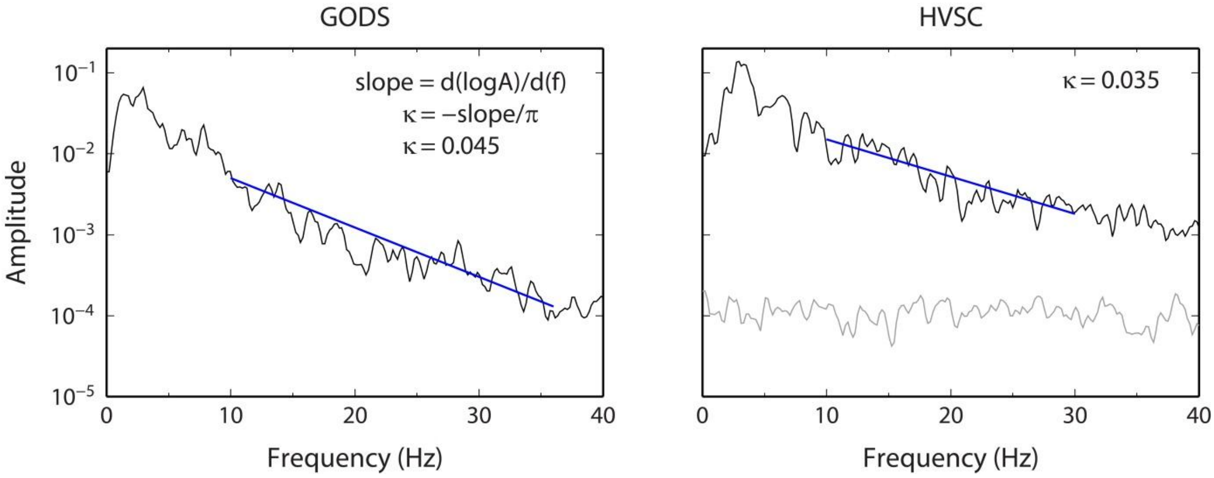

Figure 1 - Example spectra showing high frequency attenuation for the M5.9 Pegasus Bay earthquake at the (a) GODS and (b) HVSC stations. Black curves indicate S-wave acceleration Fourier spectra. Grey curve in (b) indicates noise spectrum.

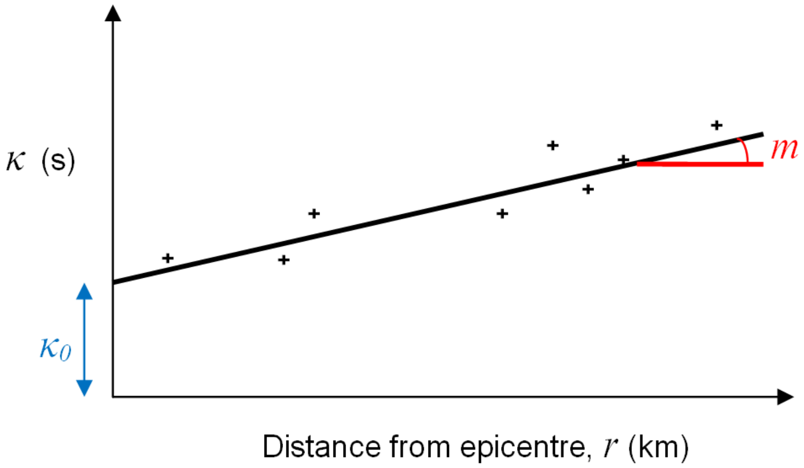

Figure 2 - Cartoon showing a simplified κ parameterisation into the zero-distance site attenuation parameter, κ_0, and the slope (m), related to regional anelastic Q attenuation.

2 AN ENGINEERING APPLICATION: THE HOST-TO-TARGET METHOD

Important structures such as nuclear power plants are usually located on rock to mitigate site amplification effects. Difficulties arise when estimating the ground motion for sites located in areas of low to moderate seismicity, where there are few previous earthquake recordings to develop an empirical ground motion (attenuation) relation. A robust ground motion relation (hereafter referred to as a ground motion prediction equation, or GMPE) is required to calculate the target design spectrum in probabilistic seismic hazard assessment (PSHA) at the given site (Stepp et al., 2001).

Where a robust local empirical GMPE is unavailable, a common solution is to adjust a well-constrained GMPE from a foreign region with a vast amount of data (including large magnitude data), such as Western North America. This method, known as the hybrid empirical method or host-to-target method (Campbell, 2003; Cotton et al., 2006; Douglas et al., 2006; Campbell, 2007; Van Houtte et al., 2011), involves adjusting the well-constrained, or "host" GMPE to the "target" (design) area based on various seismological parameters, including stress drop ($\Delta\sigma$), seismic quality factor (Q), the time-averaged shear-wave velocity in the top 30 metres below ground surface (V_{S30}) and the site attenuation parameter κ_0. Estimates of these seismological parameters in the target region are required, many of which have already been obtained for Canterbury using a non-parametric broadband spectral inversion (A. Kaiser, pers. comm.). This study focuses on calculation of κ_0, just one of the parameters required for the GMPE adjustment. Past studies have shown that κ_0 is one of the parameters that the host-to-target method is most sensitive to (Campbell, 2007).

Currently there are two GMPEs in New Zealand (McVerry et al., 2006; Bradley, 2010). A proposed adjusted foreign GMPE using the host-to-target method may reduce the epistemic uncertainty in PSHA associated with the adopted ground motion prediction model. Therefore the motivation for this study is to begin to gather the local seismological parameters that are required for a potential adjusted GMPE for Christchurch.

3 DATA AND RESULTS

Six rock or stiff soil strong motion stations in the Port Hills and Banks Peninsula were selected for this study. These stations are:

- Akaroa School (AKSS);
- Canterbury Ring Laser (CRLZ);
- Kennedy Bush Reserve (D14C);
- Godley Drive (GODS);

- Heathcote Valley (HVSC); and
- Mount Pleasant (MTPS).

The locations of these stations are shown in **Figure 3**. CRLZ, GODS, D14C, MTPS are classified as class B rock sites according to geological maps (Forsyth et al., 2008), while HVSC and AKSS are stiff soil (class C) sites. Details of these site classifications can be found in NZS1170.5:2004 (Standards New Zealand, 2004). Most events in the Canterbury earthquake sequence were located within an epicentral distance of 30 to 40 km from the strong motion rock stations, with few events located further afield. As the dataset from these events is not well-distributed with distance, it is difficult to quantify any path-dependence of κ (the slope, m, shown in equation (2) and Figure 2). Hence we make a simplification. We assume that for all event recordings with an epicentral distance of less than 30 km we can neglect the path attenuation effects, and thus each individual near-field κ measurement corresponds to a zero-distance κ_0. This way, instead of regressing the κ values and extrapolating them to r=0 to get κ_0, we only need to process all values statistically, treating them as possible κ_0 values with a normal distribution, and get an average.

The processing scheme applied is the following. Recordings are baseline-corrected, then time windows for S-wave shaking and pre-event noise are selected. Time windows are selected to encapsulate the main portion of S-wave signal, with the minimum window length being four seconds to ensure a minimum spectral resolution of 0.2 Hz. Noise windows are selected either from pre-event noise, or if this was unavailable, from the last part of the trace to minimise any wave reflections in the noise window. Both signal and noise windows are cosine-tapered (5%) and Fourier transformed. As per the criteria of Ktenidou *et al.* (2013), records with a signal-to-noise ratio (SNR) of less than three in the frequency range of interest (typically 10 to 30 Hz) are discarded. This criterion led to the rejection of the Lyttelton Port Company sensor (LPCC), for which most records have a very low SNR. **Table 1** shows the number of events recorded at each station with an epicentral distance less than 30 km, and for which a clear κ could be picked from the Fourier spectrum. Histograms of the calculated κ_0 values for each station are shown in **Figure 4**, with the median and standard deviations displayed above. The normal distribution is a fair assumption for our measurements. To test the near-field assumption of this study, κ values for $10 < r < 30$ km were compared to κ values for r <10 km. It was found that median κ values are very similar for these two subsets, and therefore the assumption to neglect the path effects of κ for distances less than 30 km is reasonable.

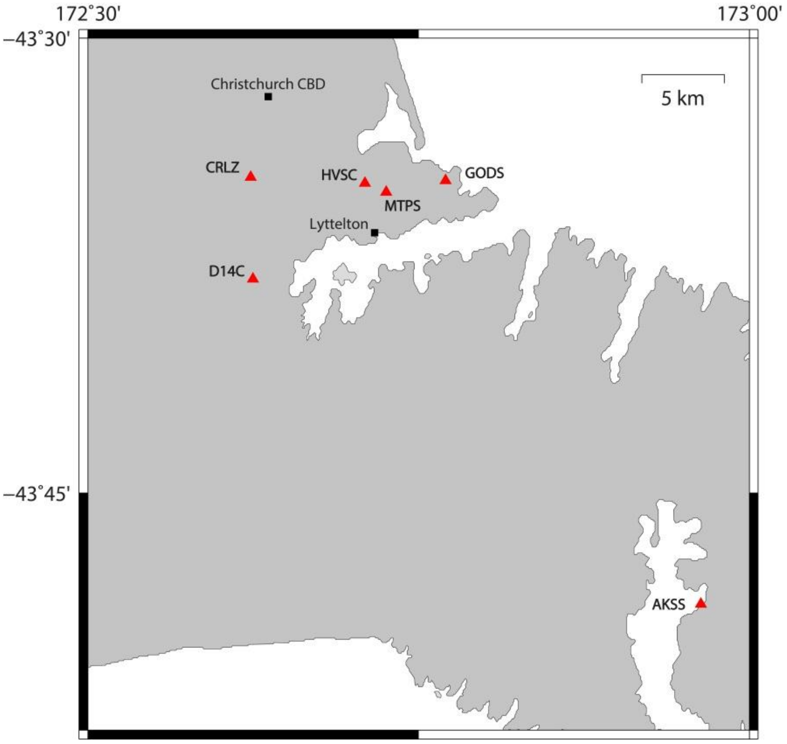

Figure 3 – Map of study area; red triangles indicate GeoNet strong motion stations selected for this study.

Table 1. Number of events recorded at each station, and their corresponding median and standard deviation.

Station	Site class	Number of recordings	Median κ_0 (s)	Standard deviation
AKSS	C	46	0.038	0.005
CRLZ	B	143	0.032	0.006
D14C	B	104	0.072	0.016
GODS	B	106	0.050	0.010
HVSC	C	34	0.052	0.010
MTPS	B	90	0.039	0.006

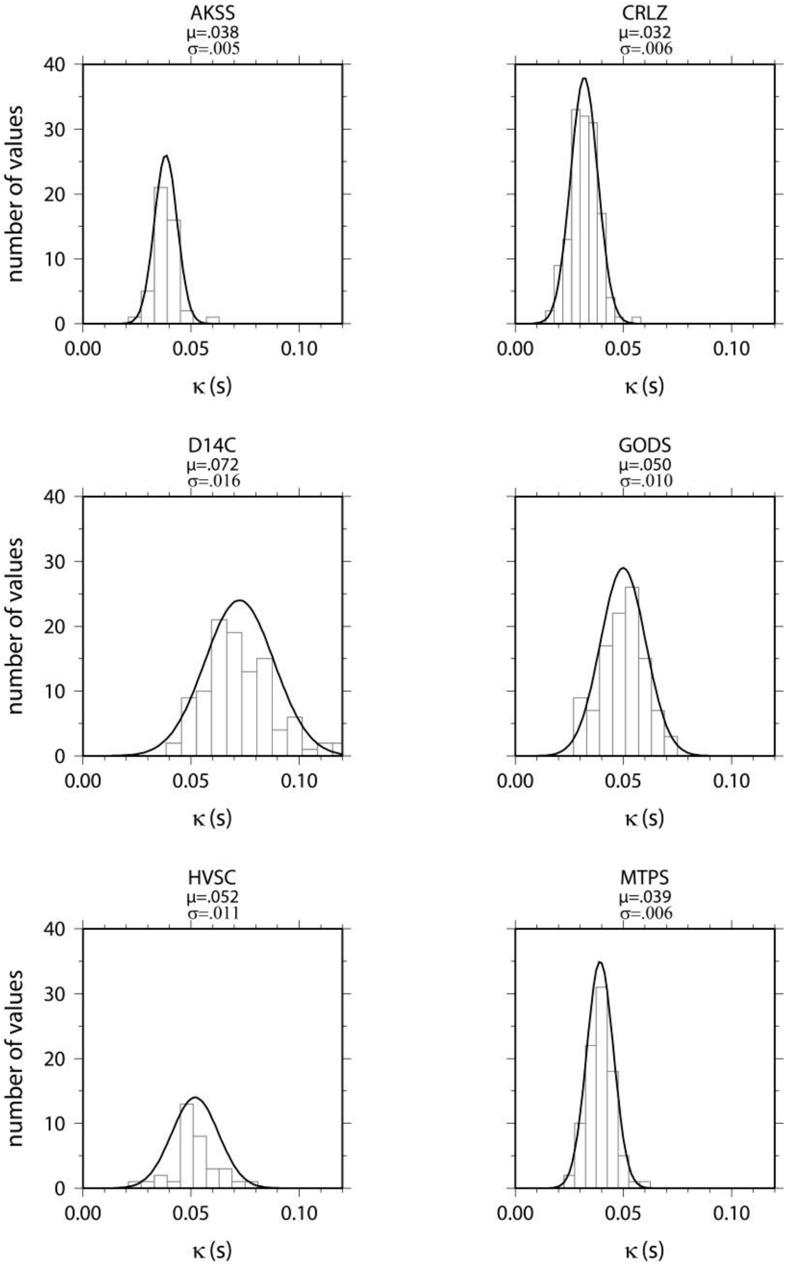

Figure 4 - Histograms of κ_0 estimates at each station for epicentral distances less than 30 km. Station codes, median and standard deviation values are shown above each frame. Each best fit Gaussian curve is also indicated (black curves).

Many studies attempt to correlate κ_0 with V_{S30}, for use in GMPE adjustments (Silva et al., 1998; Drouet et al., 2010; Van Houtte, et al., 2011). It is generally expected that the sites with a lower V_{S30} will have a higher average κ_0 value (in this case, a higher $\kappa(r < 30$ km) value).

The AKSS and HVSC stations, which are tentatively classified as class C sites, exhibit a somewhat higher κ_0s than CRLZ and MTPS but they do not show higher median κ_0s compared to the GODS and D14C. As these site classifications are mainly indicative, it is clear that shear-wave velocity profiles at these stations are required to interpret the results better. While efforts have been made to characterise many soil sites in the Christchurch CBD (Wood et al., 2011), unfortunately there are no V_S profiles or V_{S30} estimates available for any of the rock sites used in this study. Efforts are currently being made by the authors to obtain estimates of these V_S profiles from geophysical investigations.

The standard deviations of the κ_0 measurements are also different at each station. This may be due to the near-source events causing oblique wave arrivals at the stations, rather than vertically propagating. As the events are located at a wide range of azimuths from each station, it may be that the waves sample a different geological structure on the path to the site. The additional scatter at some stations is probably a site effect that depends on the 3D geology around the site. High frequency site effects may not be out of the question at some of the stations.

Initial observations suggest that sites in the Port Hills/Banks Peninsula have similar κ_0 values to Western North America (~0.035 s for V_{S30}=620 m/s) (Boore & Joyner, 1997), while being significantly higher than Central and Eastern North America (~0.005 s for V_{S30}>2000 m/s) (Atkinson & Boore, 2006). This suggests typical rock profiles in the Banks Peninsula (i.e. the intraplate volcanic structures) have similar attenuating properties to typical rock profiles in Western North America, despite belonging to two different tectonic regimes.

4 CONCLUSIONS

This study calculates preliminary κ_0 values using the Anderson and Hough (1984) method, where κ is the high frequency slope of the spectrum in log-linear space. Due to the many near-source recordings, the regional attenuation effect has been neglected and it is assumed that every κ measurement from a recording within 30 km of the earthquake epicentre corresponds to the zero-distance site attenuation parameter κ_0. The absolute values of the initial κ_0 estimates presented here are similar to those in Western North America.

These initial estimates are a first step towards better characterising New Zealand rock conditions. This is a necessary step towards adjusting GMPEs from other active regions to the Canterbury region, to better predict ground motion. A good understanding of κ is critical for the PSHA of important structures such as large power plants.

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