SITE AMPLIFICATION IN CHRISTCHURCH DURING THE 2010 – 2011 CANTERBURY EARTHQUAKE SEQUENCE, BASED ON REGIONAL FOURIER AMPLITUDE SPECTRA (FAS) MODEL

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ABSTRACT

The 2010 – 2011 Canterbury earthquake sequence produced some of the strongest ground motions recorded globally (exceeding 2 g) leading to extensive structural damage, landslides and liquefaction in the city of Christchurch. Ground motions were locally variable due to local site effects arising from local soft soil deposits and topography. Here, we take advantage of the wealth of repeated recordings at strong motion sites within Christchurch (corresponding to earthquakes of Mw 4 – 7.1) to first quantify locally variable linear site amplification using generalized spectral inversion. We then use the resulting simple regional Fourier Amplitude Spectra (FAS) model for Canterbury to investigate nonlinear amplification effects using modeled 'reference' spectra for each source-station combination. This allows us to investigate how the site effect varies under different levels of ground acceleration. In general, significant reduction in site amplification is seen at Christchurch soil sites at PGA values approximately 0.3 g or greater. This effect is particularly pronounced at known soft soil and liquefiable sites. Finally, we employ regional and local ground motion parameters in stochastic ground motion simulations to better capture local ground motion characteristics.

Keywords: *strong motion, site effects, ground motion simulation, nonlinear effects, Fourier amplitude spectra*

INTRODUCTION

The Canterbury earthquake sequence of 2010 - 2011 produced some of the highest recorded near-field ground motions globally. The maximum recorded peak ground acceleration (PGA) exceeded 1 g in four earthquakes of the sequence, including the Mw 7.2 Darfield mainshock in September 2010, the destructive Mw 6.2 earthquake in February 2011 and two further aftershocks of Mw 6.0 (June 2011) and Mw 5.8 (December 2011). Damage to the city of Christchurch was considerable, resulting in 181 fatalities, severe liquefaction and landslides, and ongoing rebuilding of infrastructure (Kaiser et al. 2012).

Ground motions in Canterbury are thought to have been strongly influenced by several regional factors, including high stress drop sources (e.g. Fry & Gerstenberger 2011) and strong and variable site effects (e.g. Fry et al. 2011; Bradley 2012). Much of Canterbury is situated on flat-lying plains formed by braided river systems, and is underlain by thick sedimentary sequences (~1km deep) and locally variable near-surface Quaternary stratigraphy. Quantifying how these regional factors influence ground motion amplification at different levels of shaking is important for future hazard assessment in the region. In Canterbury, seismic hazard is expected to be elevated above background levels for at least the next decade (Gerstenberger et al. 2014), with an Mw 5.7 aftershock occurring on February 14th 2016 providing a timely reminder of the ongoing potential for strong shaking in Christchurch.

Here, we present a new Fourier Amplitude Spectra (FAS) model for the Canterbury region derived from spectral inversion of ground motion data from the Canterbury earthquake sequence (Oth & Kaiser, 2014; Kaiser et al., 2013). This model allows us to approximate S-wave FAS at any given location for any scenario event in the region. Where site-specific amplification is unknown, the average site amplification for the appropriate site classification of the New Zealand design standard (NZS1170.5; Standards New Zealand, 2004) can be adopted. We also investigate how site amplification varies at selected Christchurch stations under increasing levels of peak ground acceleration (PGA). Finally, we use regional ground motion parameters, including site-specific amplification functions, to improve site-specific stochastic modeling of regional broadband ground motions.

SPECTRAL INVERSION

The Canterbury earthquake sequence was well recorded by the GeoNet strong motion network and provides an ideal dataset to apply spectral inversion methods to determine regional ground motion parameters. We use the non-parametric generalized inversion technique (GIT) of Oth et al. (2011) to separate and quantify source spectra (*S*), frequency-dependent path attenuation (*A*) and site amplification (*G*) in the Canterbury region by solving the linear equation:

$$\log_{10} FAS_{ij}(f, M_i, R_{ij}) = \log_{10} S_i(f, M_i) + \log_{10} A(f, R_{ij}) + \log_{10} G_j(f) \tag{1}$$

where the FAS of the *i*th earthquake and *j*th station is a function of frequency (*f*), moment magnitude (*M*), and source-station distance (*R*).

The GIT has been applied to a Canterbury S-wave spectral dataset consisting of 2416 records from 205 earthquakes recorded at 64 regional strong motion stations. Kaiser et al. (2013) provide a brief overview of the Canterbury GIT results and linear site amplification results and Oth & Kaiser (2014) present a more detailed discussion of the spectral dataset and source characteristics. Here, we briefly summarise the FAS model for Canterbury resulting from this work, and use it to examine site response under increasing levels of ground acceleration.

The S-wave spectral dataset spans an approximately one-and-a-half year period following the 4 September 2010 Darfield earthquake and includes earthquake magnitudes ranging from Mw 2.9 – 7.2. We use the root-mean-square (RMS) average of the two horizontal component spectra in the inversion. The vertical component spectra derived from the equivalent S-wave window are also inverted separately, in order to quantify the vertical site amplification at each station. Records with PGA greater than 0.15 g were excluded from the spectral inversion dataset, to avoid biasing of the site amplification functions from nonlinear effects. Thus, the resulting site amplification functions are valid for linear ground motion conditions.

The GIT approach is based on that of Castro *et al.* (1990), but solves equation (1) for all three functions simultaneously (one-step approach). Source spectra (Fig. 1a) are calculated at 5 km hypocentral distance and are fit well by the omega-squared model (Brune 1970), with a median stress drop of ~5 MPa (Oth & Kaiser, 2014). Frequency-dependent attenuation functions are constructed relative to this reference distance of 5km (Fig. 1b). Attenuation is constrained only to be a smoothly varying function with distance, with no pre-determined functional form. This approach is better able to capture the complexity of observed attenuation without bias. Site amplification is calculated relative to the average of three chosen rock reference stations in Canterbury (D14C, RPZ, and MQZ); the average amplification at the reference stations is set to unity in the inversion. Further details of the method and constraints can be found in Oth & Kaiser (2014).

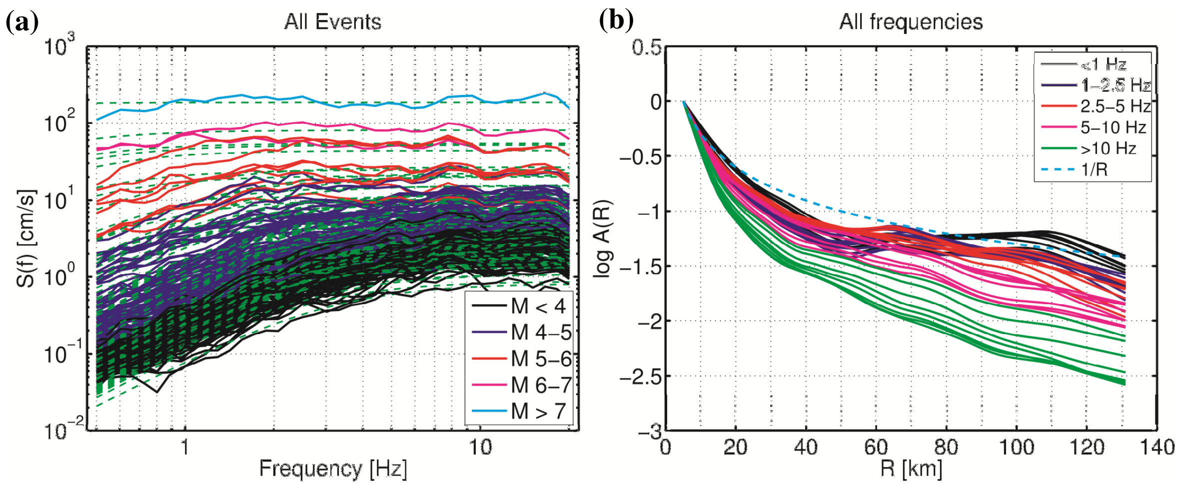

Figure 1 Source and path terms derived for the Canterbury region. (a) Acceleration source spectra at a reference distance of 5 km. Green dashed lines show the best-fitting omega-square models. (b) Non-parametric frequency-dependent attenuation functions give relative to the reference distance of 5km. For reference, the dashed line presents spectral amplitude decay of 1/R.

Linear site amplification

Horizontal (H) and vertical (Z) site response functions are calculated with respect to the average horizontal reference component following the approach outlined in Kaiser et al. (2013). Figure 2 shows examples of site response functions at stations within each site classification used in New Zealand design codes (NZS1170.5 Site Class; Standards New Zealand 2004). The GIT frequency-

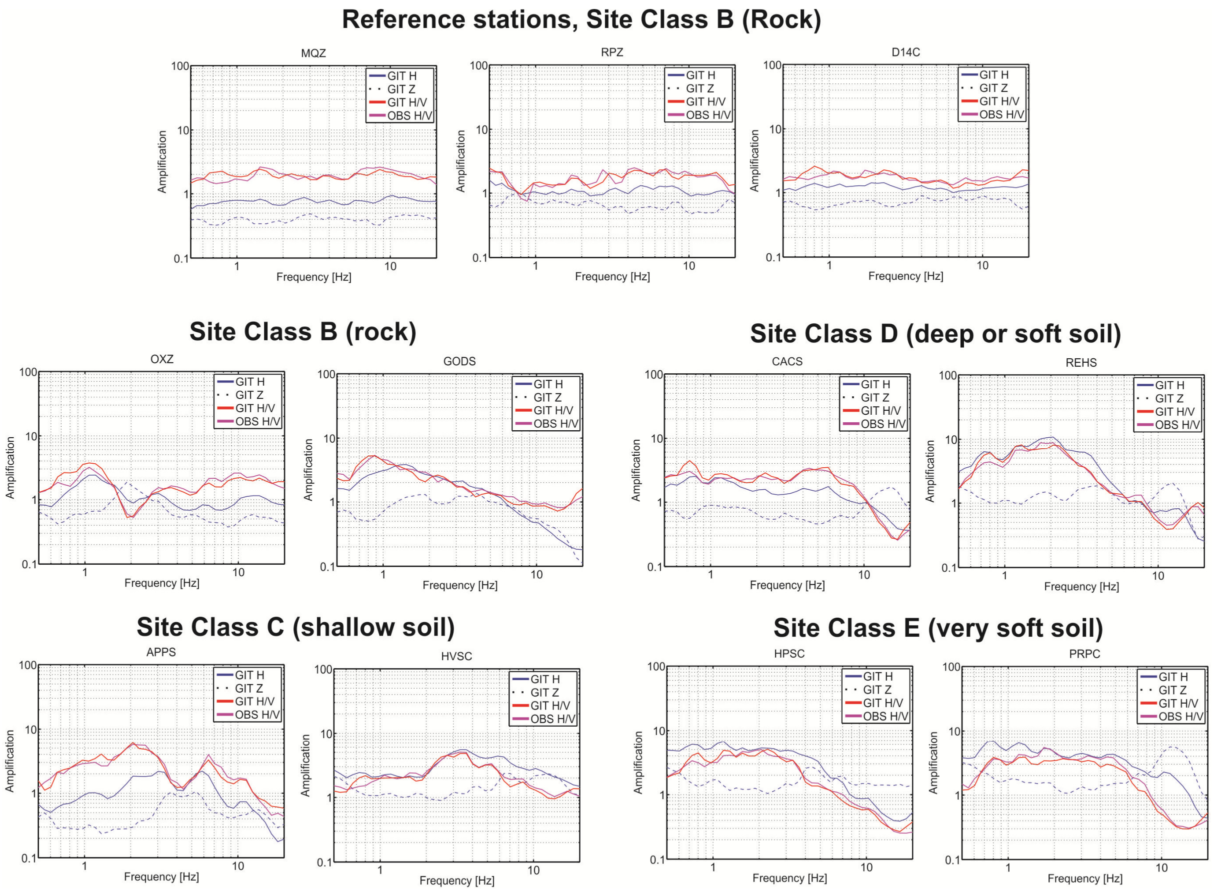

Figure 2 Examples of site amplification functions at stations representing each New Zealand Site Class. GIT results are plotted relative to the average reference horizontal component.

dependent amplification curves (solid and dashed blue lines for H and Z component respectively) are compared with the horizontal-to-vertical (H/V) spectral ratio calculated from the GIT results (red line) and directly from the observed spectra (pink line). In general, there is a very good match between the GIT results and observed H/V ratios. In some cases, the GIT results are better able to capture the true amplification at the site, given that H/V ratios can be biased by amplification or deamplification of the vertical component. For example, at station OXZ, a vertical amplification peak at ~2 Hz is clearly shown in addition to the horizontal peak at ~1.2 Hz.

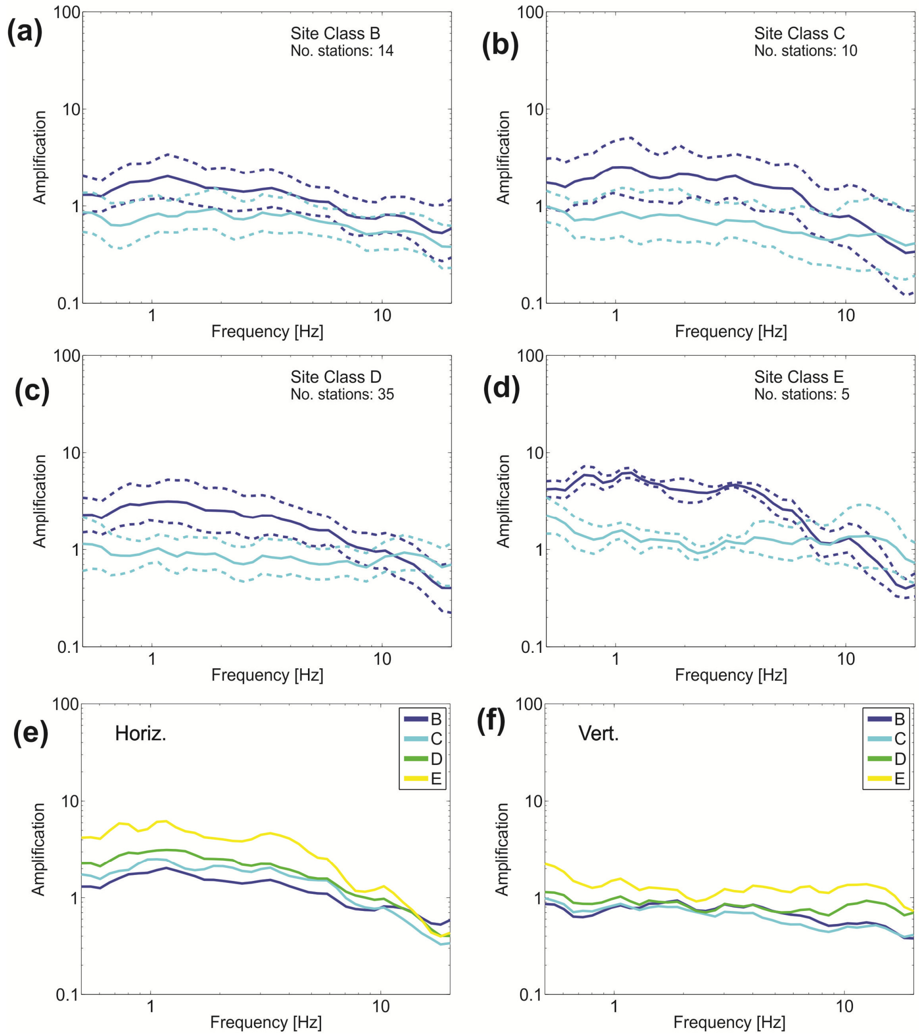

Figure 3 Mean site amplification for each GeoNet Site Class classification (B – E) according to the New Zealand design standards. (a) – (d) show geometric mean horizontal (dark blue solid line) and vertical (light blue solid line) amplification relative to the average reference horizontal component. One standard deviation above and below the mean are shown as dashed lines. (e) and (f) show comparison of average amplification functions across site classes for horizontal and vertical components respectively.

We quantify the mean and standard deviation of linear site amplification curves within each New Zealand site class category in Figure 3. As expected, average vertical amplification is flat and approximately equal to one for all site classes, with the exception of very soft soil sites (Class E). Average horizontal amplification increases with decreasing site stiffness below 10 Hz, and again is particularly pronounced for Class E sites. However, site amplification within each category is highly variable, particularly for Site Class C (shallow soil) sites. We also note, that in general rock sites in Canterbury (Class B) tend to exhibit some degree of amplification (see also Figure 1 for individual examples) and only a few good reference stations exist. This is inferred to be due to a combination of topographic effects and the weak nature of the rock and overlying cover (e.g. Kaiser et al. 2014).

CANTERBURY REGION FAS MODEL

A Canterbury regional FAS model can be constructed based on equation (1) and the source, path and site contributions quantified using spectral inversion. This model can be used to estimate S-wave FAS for the frequency range 0.5 – 20 Hz for any given earthquake and site in Canterbury. The model has some limitations in the near-field, given that source directivity effects and site nonlinear effects are not directly considered.

The FAS model can also be applied to earthquakes and site locations not represented in our spectral inversion dataset by assuming appropriate regional average parameters. For earthquake scenarios not represented in our spectral dataset, a theoretical Brune source spectra can be approximated based on the median stress drop value of ~5 MPa. Similarly, where site-specific amplification functions are not available, the average site amplification function for the appropriate site class (Fig. 3) can be adopted. For calculation of reference spectra, the site function is set to unity across the entire frequency range.

NONLINEAR SITE AMPLIFICATION

The Canterbury strong motion dataset is notable for capturing very strong near-field ground motions on multiple occasions throughout the sequence. At many locations, particularly in eastern Christchurch, multiple liquefaction effects at a single site were observed (e.g. Quigley et al. 2013, Cubrinovski et al. 2012). This makes the dataset ideal to investigate the effect of nonlinear site amplification with increasing levels of ground shaking.

We calculate the site response of each strong motion record at a given site relative to a ‘modelled’ reference spectra based on equation (1) with site amplification set to unity. The resulting site amplification functions are plotted for each site colored by peak ground acceleration of the observed record and compared to the average linear site amplification (Fig. 4). Note that directivity effects are not considered in this simple model, but may nonetheless be present during the largest earthquakes, and are a source of potential bias.

For many Christchurch stations, a consistent trend of reduced site amplification at large PGA values is clearly visible, although some scatter exists in the results. This trend is particularly pronounced at Class E sites known to have soft and liquefiable soil layers (e.g. HPSC, PRPC). Station HPSC in particular lies close to the Avon River channel and experienced strong liquefaction during multiple earthquakes of the sequence. We also note, that although the current GeoNet site classification for stations REHS, CCCC and CBGS is Class D, Wotherspoon et al. (2014) show that the preferred classification based on recently conducted shear-wave velocity profiles is in fact Class E (GeoNet site classes are currently being revised accordingly). In general, attenuation occurs at Christchurch soil stations at frequencies greater than 1 Hz at PGA levels above approximately 0.3 g.

SITE-SPECIFIC GROUND MOTION SIMULATIONS

The Canterbury region source, path and site parameters generated here are also being used to improve site-specific broadband ground motion simulations. Holden & Kaiser (2016) generate synthetic time histories and response spectra using the stochastic EXSIM method (Motazedian & Atkinson 2005), and regional parameters (source stress drop, attenuation model and linear site-specific amplification functions) derived from the Canterbury FAS model.

Observed and synthetic time histories for the Mw 5.9 December 2011 earthquake are compared for selected Christchurch stations in Figure 5. Synthetic motions generated using the site-specific amplification functions (red lines) are better able to capture the character and amplitude of the observed motions. A good match between observed and synthetic motions is generally obtained for stations on rock (LPCC, D14C, GODS, PARS) or shallow soil (HVSC), and stations on deep or soft soil (CMHS, REHS, RHSC, SHLC, CACS) under weak or moderate accelerations as illustrated in the example. However, we note, that this simple approach to modeling of time histories does not take into account nonlinear effects or fully capture the complexity of site amplification through time, particularly at deep or soft soil sites subject to strong accelerations. We will focus on improving these aspects with ongoing research work.

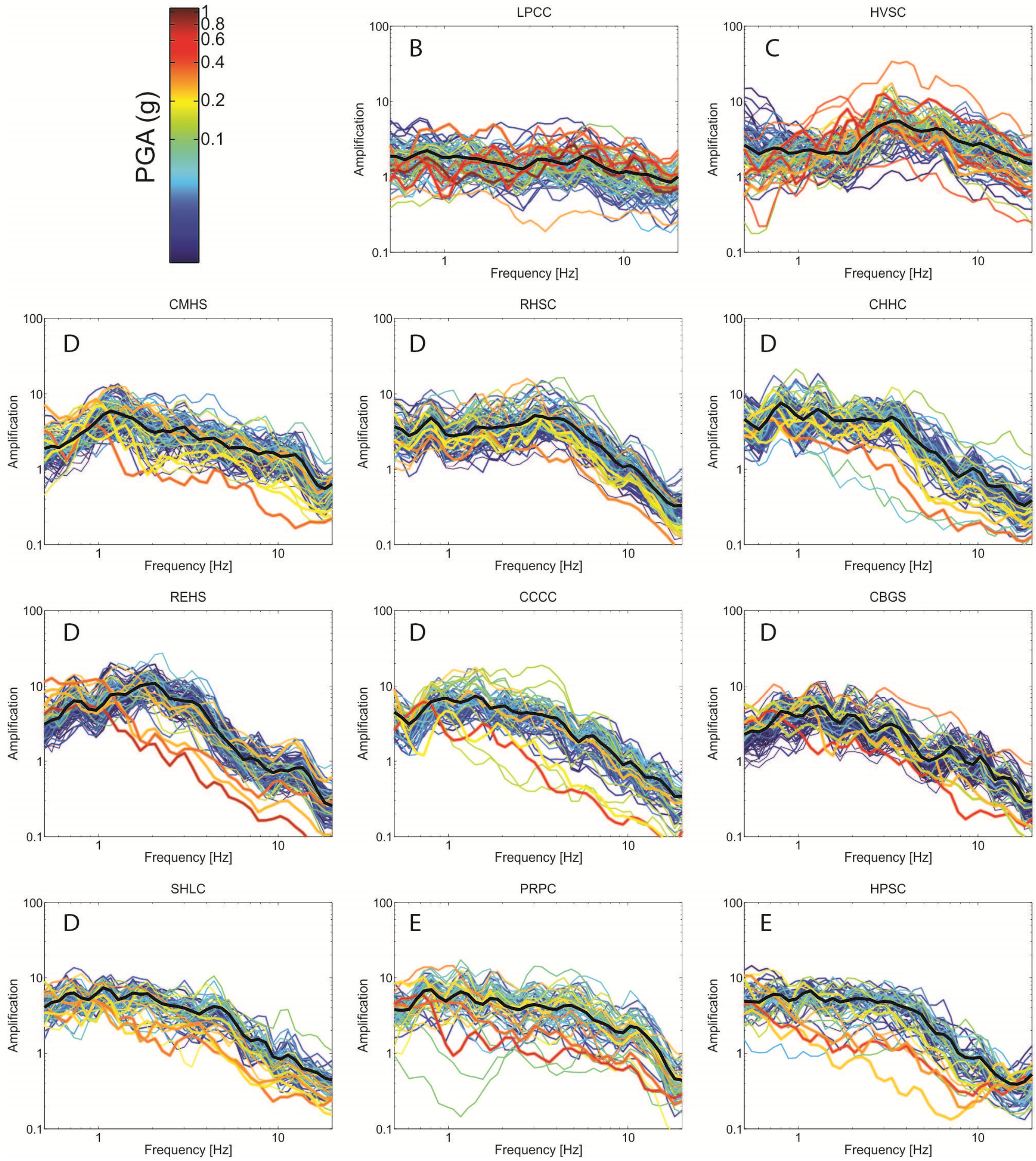

Figure 4 Site response (H component) calculated at Christchurch stations for individual earthquakes of the Canterbury sequence. Amplification corresponds to the observed spectra relative to the modeled average horizontal reference spectra at that location. Amplification ratios are colored by maximum recorded horizontal PGA. Ratios corresponding to the four largest events (Mw 7.2, 6.2, 6.0 and 5.9 are plotted as thick coloured lines; average site response is plotted as thick black line). The New Zealand site classification of each station as currently defined by GeoNet is indicated in the top left corner of each plot.

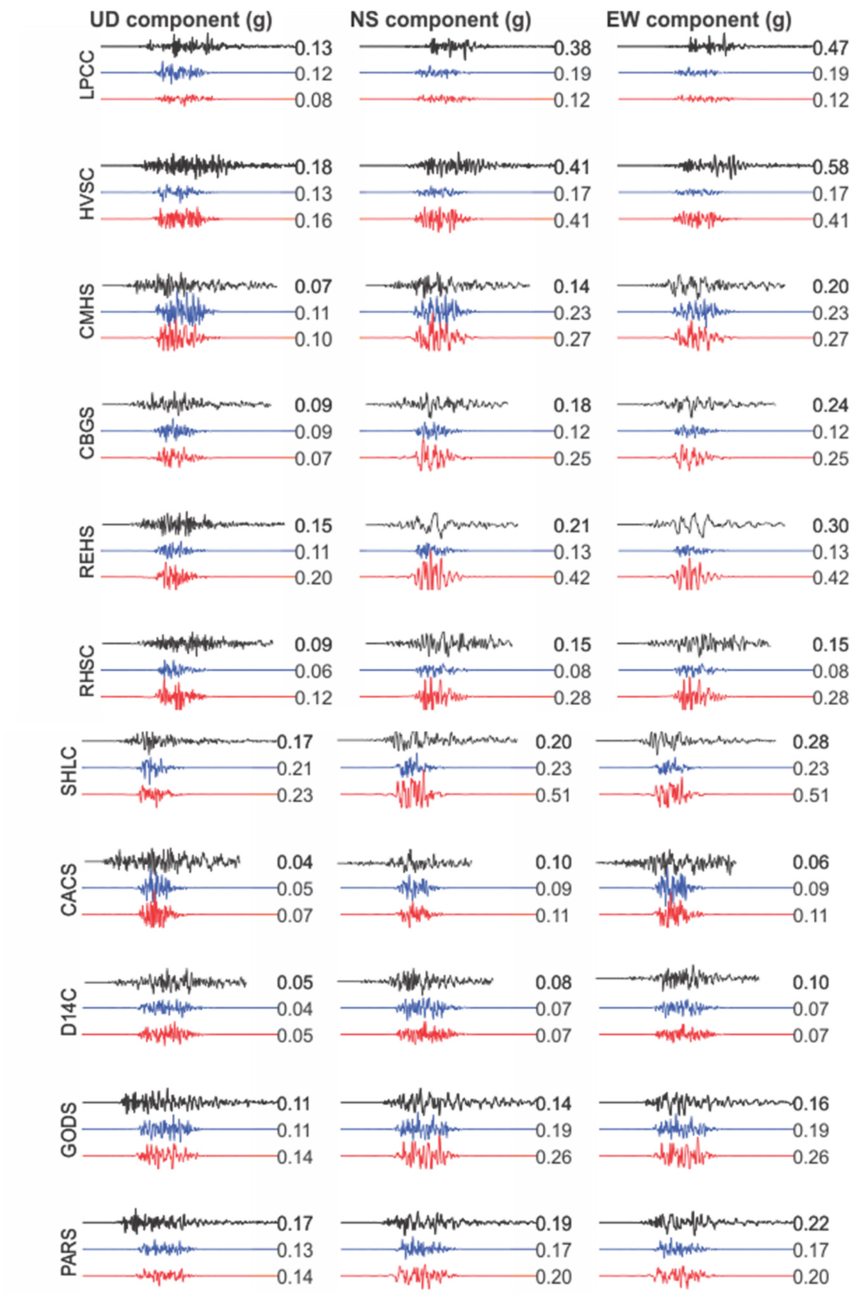

Figure 5 Example of stochastic ground motion simulations of Holden & Kaiser (2016) calculated for the 23rd December 2011 Mw 5.9 Christchurch aftershock, using regional parameters derived from the spectral inversions. Black seismograms represent observed accelerations at selected near source (<20 km distant) GeoNet strong motion stations, blue represent synthetic motions for a rock reference site at the station location, and red represent synthetic motions calculated using linear site-specific amplification functions derived here. PGA values (g) for each time history are shown to the right of each plot.

CONCLUSIONS

Ground motions during the Canterbury earthquake sequence were locally variable in part due to site effects arising from local soft soil deposits and topography. Using spectral inversions of ground motion data, we quantify linear site amplification and derive average site amplification for each of the site classifications in the New Zealand design standard. We also use a regional Fourier amplitude spectra (FAS) model for Canterbury, based on the spectral inversion results, to investigate site amplification under levels of shaking. In general, significant reduction in site amplification is seen at Christchurch soil sites at PGA values approximately 0.3 g or greater. This effect is particularly pronounced at known soft soil and liquefiable sites. Finally, we employ regional and local ground motion parameters in stochastic ground motion simulations in order to better capture local ground motion characteristics. When compared against observed data, the use of site-specific amplification function leads to better prediction of PGA amplitudes and acceleration characteristics.

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