Source, path and site effects influencing ground motions during the Canterbury earthquake sequence, determined from spectral inversions

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ABSTRACT: The Canterbury earthquake sequence beginning with the 2010 Mw 7.2 Darfield earthquake is one of the most notable and well-recorded crustal earthquake sequences in a low-strain-rate region worldwide. Ground motions in Canterbury during the aftershock sequence were thought to have been influenced by several factors, including strong and variable site effects and high stress drop sources. Understanding the particular influences on ground motion is crucial in assessing ongoing seismic hazard in the region and informing the rebuild process.

We present results from a generalized spectral inversion approach utilising the rich GeoNet accelerogram database. This approach allows us to separate and quantify site, path and source contributions to ground motion specific to the Canterbury region. Results were obtained using a regional data subset of > 200 earthquakes (Mw 3.3 – 7.1) and > 2400 source-stations paths. We identify pervasive strong attenuation at frequencies > 5 Hz for Canterbury as well as low-frequency path effects associated with the unusual mid-crustal structure. Source spectra indicate higher than average stress drops for the region. We examine and quantify the local linear site response at Christchurch stations spanning a range of rock and soil conditions. Based on our inversions, we also model and quantify the nonlinear site response during the four largest Canterbury earthquakes. Strongest nonlinear response over all events was seen at station HPSC, along the Avon River.

1 INTRODUCTION

Earthquake ground motion is influenced by the earthquake source, wave propagation path and local site conditions. During the Canterbury earthquake sequence, beginning with the M7.2 Darfield earthquake, ground motions were thought to be strongly influenced by several specific factors. These included strong and variable site effects and high stress drop sources (e.g. Bradley 2012; Kaiser et al. 2012; Fry & Gerstenberger 2011). Understanding these influences on ground motion is ultimately essential for accurate ground motion prediction and hazard analyses in the region.

Our goal is to use spectral inversion to separate and quantify the influences of source, path (including basin) and site effects during the earthquakes of the Canterbury sequence, with the ultimate goal of informing updates to regional seismic hazard models and design standards. This approach utilises the wealth of available strong motion data to efficiently separate and quantify the relative influences on ground motion over the entire Canterbury sequence. By inverting for all three factors together (source, path and site), a deeper understanding of the interplay of these factors can be gained than by investigating any given factor in isolation, such as for instance site effects via H/V ratios only (e.g. shown by previous studies in Japan; Oth et al. 2010, 2011a).

In this contribution, we briefly present the main observations from source and path contributions to ground motion, before focussing in more depth on the effects of local site conditions (both linear and nonlinear).

2   SPECTRAL INVERSION METHOD

Earthquake Fourier amplitude spectra (FAS) can be represented as a product of frequency-dependent source (S), path (A) and site (G) functions (equation 1).

$$U_{ij}(f, M_i, R_{ij}) = S_i(f, M_i) \cdot A(f, R_{ij}) \cdot G_j(f) \qquad (1)$$

Where U_{ij} indicates the S-wave FAS of the i-th event at the j-th station, R_{ij} is the source-station distance, M_i is the magnitude and f is frequency.

To solve for the individual source, path and site functions, we have applied a nonparametric generalized inversion technique (GIT) based on Castro et al. (1990) and following the implementation of Oth et al. (2011b). In this approach, no particular functional form is assumed for attenuation, but results are constrained only to be a smooth function with distance; a detailed description of the method is presented in Oth et al. (2011b). We run the inversion for both the horizontal and vertical ground motion component in order to investigate both horizontal and vertical site amplification effects.

3   DATASET

The Canterbury earthquake sequence was well-recorded by the GeoNet strong motion network. Here, we used a data subset consisting of > 200 events (ranging from magnitude 3.3 – 7.2) and > 2400 source-station paths (Figure 1).
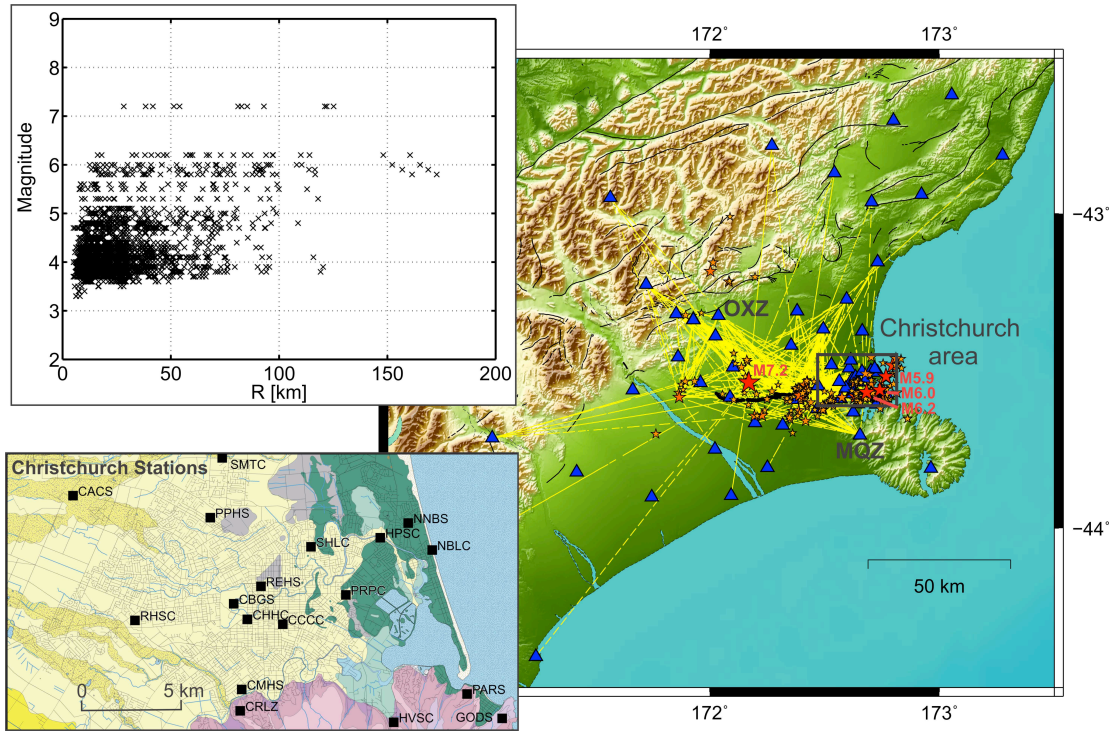

Figure 1: Canterbury earthquakes (stars), stations (blue) and source-station paths (yellow) used in the spectral inversions. Reference station MQZ and the epicentres of the largest four events are labelled. Top inset shows the dataset plotted in terms of magnitude and distance. Bottom inset shows the locations of Christchurch strong motion stations analysed here. Colours correspond to geology: Dark green = dominantly sand; Light green = sand, silt, peat of drained lagoons/estuaries; Pale yellow = Alluvial sand/silt overbank deposits; Dark Yellow = Alluvial gravel; Pinks = Basalt or loess overburden.

FAS used in the inversion were computed based on selected S-wave windows ranging from 5 – 18 s (chosen to include 80% of the record's energy) and smoothed using a Konno and Ohmachi (1998) windowing function. The horizontal spectra are calculated based on the root-mean-square average of the two recording components. Records with peak ground acceleration (PGA) > 0.15 g were excluded from the inversion to minimize contamination by nonlinear and near-source effects.

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In the inversion it is necessary to define one or more reference station(s) for which the average amplification can be considered to be negligible (i.e. flat over the full range of frequencies). Many Canterbury rock stations are imperfect reference stations and exhibit their own site response (Van Houtte et al. 2012). In order to choose the best reference station, we considered both the H/V ratio (calculated directly from the FAS used in the inversions) and inspection of results from trial runs using various reference stations. Due to the trade-off between source and site functions, an imperfect reference station will not only result in systematically biased site response functions, but also in biased source spectra that deviate from the expected omega-squared model. We concluded that MQZ was the most appropriate reference station for our purposes.

4 ATTENUATION & SOURCE FUNCTIONS

Figure 2a shows nonparametric attenuation functions derived for the horizontal motions. These functions represent the average attenuation in the Canterbury region and remain robust over a range of inversion parameters and choice of reference stations.

Attenuation appears to be significantly frequency-dependent, with high frequencies showing very strong attenuation specific to the Canterbury region. This high-frequency effect could be introduced in the near-surface by the shallow water table and then mapped into our attenuation functions, given that these soil conditions are pervasive for most of the Canterbury stations. A significant change in low-frequency attenuation with distance occurs at ~50 km hypocentral distance (R). This is consistent with waves travelling longer distances sampling significantly faster, less attenuating material and fits the model of Reyners (2012), who infers that a former ~100 Myr plate boundary lies at depths of $12-15$ km beneath the region.

Figure 2b shows source spectra derived from our inversions for all individual earthquakes, colour coded by magnitude. These source spectra are generally well fit by the omega-square source model (see green dashed lines for each event). This also indicates that our choice of reference station is reasonable (because of the trade-off between source and site components of ground motion in the inversion). From the best-fitting omega-squared models (Aki 1967; Brune 1970) and their associated corner frequencies, values for stress drop in each event can be calculated following the approach described in Oth et al. (2010). Preliminary results for Canterbury suggest the median stress drop value is ~4 MPa. These values are somewhat higher than global averages and results for crustal earthquakes in Japan (~1.1 MPa) using this methodology. The characteristics of attenuation and source in Canterbury will be discussed in greater detail outside this paper.
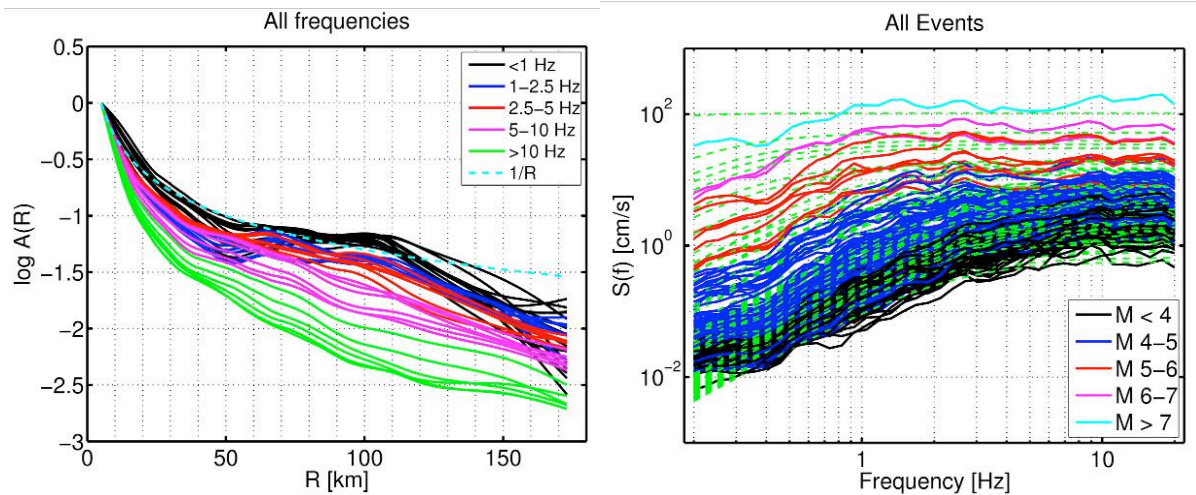

Figure 2: (a) Non-parametric frequency-dependent attenuation functions derived for the Canterbury region. Attenuation is given relative to the reference distance of 5 km. (b) Source spectra derived at reference distance 5 km for events of the Canterbury sequence. Green dashed lines show the best-fitting omega-square source models.

5 SITE RESPONSE FUNCTIONS

5.1 Linear Site Response

We have calculated relative horizontal (H) and vertical (Z) site response functions for the 66 GeoNet strong motion stations used in the inversion with respect to the reference station MQZ. The H/V site response calculated from the GIT H and Z amplification results is also compared to the observed H/V ratio calculated directly from the FAS data. Here, we present results for a selection of Christchurch stations with subsurface conditions ranging from soft soil to rock (Figure 3).

Figure 3 shows the site response results when amplification ratios are calculated relative to the same component recording at MQZ (as in standard spectral ratios). Although MQZ is a rock station with a relatively flat observed H/V ratio, it nevertheless shows relative amplification of the horizontal component over the whole frequency spectrum, for some frequencies to a factor of > 2. For this reason, the GIT H/V ratio is systematically biased downwards from the observed H/V ratio, although they follow similar spectral shapes. In Figure 4 we seek to remove this effect by correcting the GIT H/V ratio and GIT H amplification by the amplification shown by the reference station observed H/V. This figure is now effectively showing amplification relative to the reference station Z component and assuming that the H/V ratio at the reference station is due solely to amplification on the horizontal component (i.e. negligible vertical amplification at the reference station). This assumption effectively removes the biasing effects of the reference station in our horizontal site response functions and better isolates the amplification peaks (see Figure 4 compared to Figure 3). MQZ shows consistently low vertical amplification and is therefore considered a good reference site in this respect.

Our new site response functions (Figure 4) clearly highlight the horizontal and vertical amplification effects at Canterbury stations and are a useful tool in understanding local site effects. In this contribution, we summarize the general features only. Horizontal motions at deep soil stations are amplified by large factors (up to 30 relative to reference station Z component) at frequencies ranging up to ~5 Hz. This includes a systematic increase in amplification at the lowest frequencies (0.4 Hz) that we infer is associated with basin waves (and possible contamination by Rayleigh waves). At frequencies greater than 5 Hz, strong high-frequency diminution effects are apparent and amplitude decreases significantly. Vertical motions are also amplified (by factors up to 10), but not are not affected by attenuation at high frequencies relative to the reference site. These observations are a strong regional characteristic likely associated with the pervasive shallow water table (Fry et al. 2011). S-P conversions may be the reason for a transfer of energy on the vertical component at frequencies higher than the fundamental one (Parolai and Richwalski, 2004), while high-frequency S-wave energy is efficiently damped on the horizontal components under these conditions.

Local resonances associated with shallow structure also exist for Christchurch soil stations, most notably REHS with a strong resonance at ~2 Hz that is not present to the same extent at other central city sites (top panel, Figure 4). The high-frequency amplification at the shallow soil site of HVSC, which lies in a local narrow N-S trending valley, is also clear. The spectral inversion results suggest that HVSC is in fact amplified over a broader range of frequencies than indicated by the observed H/V ratio, which is likely affected by vertical amplification in the higher frequency range.

Local amplification effects are also apparent on most rock stations (with the exception of D14C). Results at CRLZ illustrate a complex pattern of opposing H and Z amplification and deamplification trends. This station lies in a cavern ~30 m below the surface, so we infer these effects could be related to destructive interference from downgoing waves. Station OXZ exhibits a significant vertical amplification at ~2 Hz following the horizontal amplification peak at 1 - 1.5 Hz that was not directly clarified by the H/V ratio. Rock stations PARS and GODS are located on top of local NE-SW trending spurs at the northern edge of Banks Peninsula. Polarization of ground motions (based on azimuthal H/V analyses not shown here) indicate motions are preferentially amplified in the NW-SE direction, consistent with topographic amplification. Hillsides in this area suffered considerable damage in the February 22 and June 13 Christchurch earthquakes and local boreholes reveal the presence of thick layers of low-velocity poorly consolidated lava breccia (Z. Bruce, personal communication) such that amplification effects are likely enhanced by the lithology.
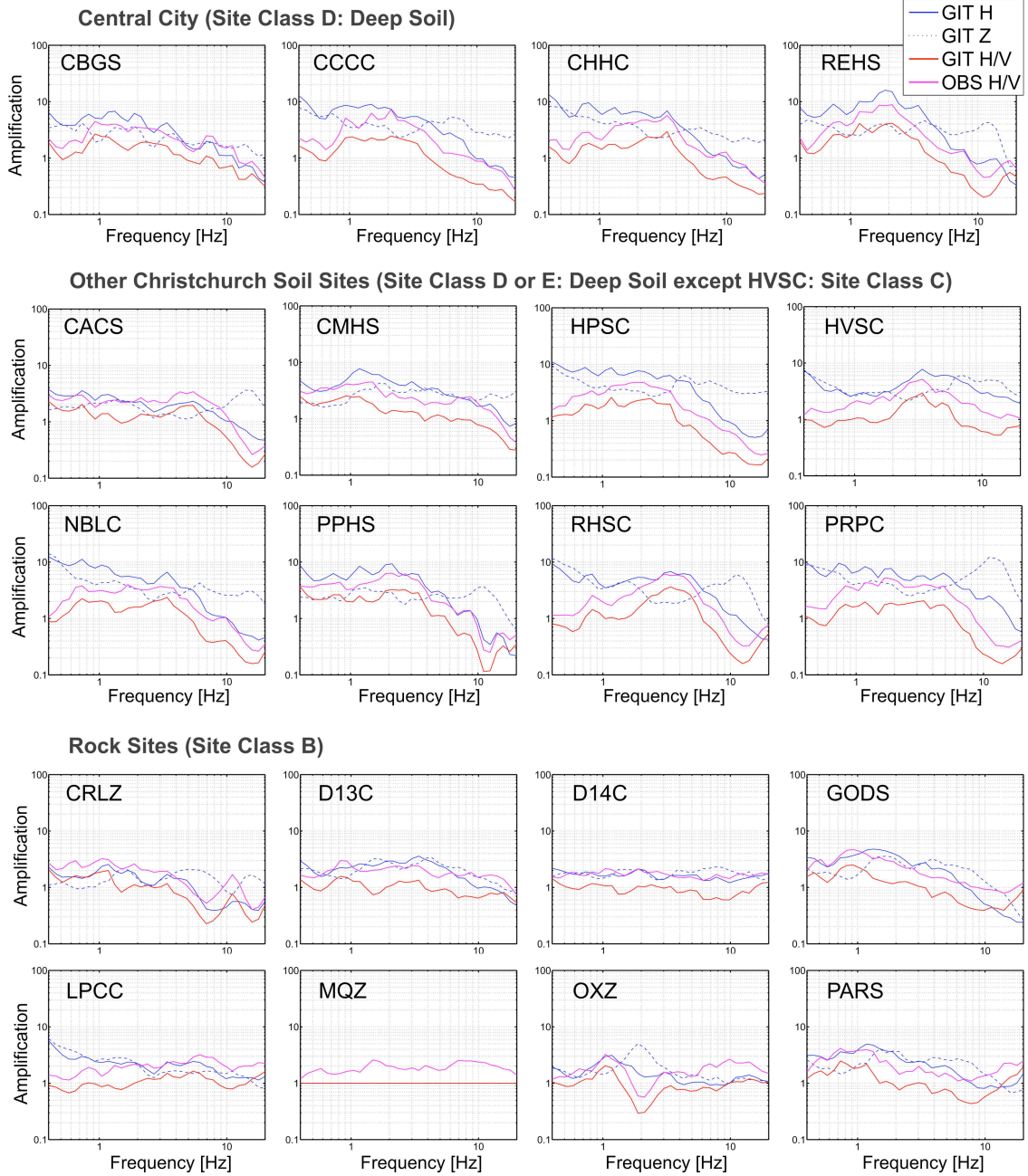
Figure 3: Site response relative to MQZ for a selection of Christchurch stations. GIT H and Z component amplifications are shown as solid and dashed blue lines respectively. GIT and observed H/V ratios are shown as red and pink lines respectively.

5.2 Nonlinear Site Response

During the largest events of the Canterbury sequence (M 7.2 Darfield 2010; M 6.2 February 2011; M 6.0 June 2011; M 5.9 December 2011) ground motions in Christchurch reached levels significantly greater than 0.15 g. Strong nonlinear effects are likely to occur with these accelerations and indeed severe liquefaction was observed in parts of the city in all four earthquakes (e.g. Cubrinovski et al. 2012). To model nonlinear effects, we calculate the site response relative to a 'modelled' reference motion calculated from equation (1) and based on the source spectra and attenuation functions determined by our inversions (similar to the approach of Kawase 2006). This allows us to isolate the response characteristics of a given site during a given earthquake. Under linear soil conditions, this site response should show a similar behavior to the average site response obtained from the spectral inversion (within some scatter range), and no systematic bias. Note that directivity effects are not considered in this modelling, but may nonetheless be present during the largest earthquakes.
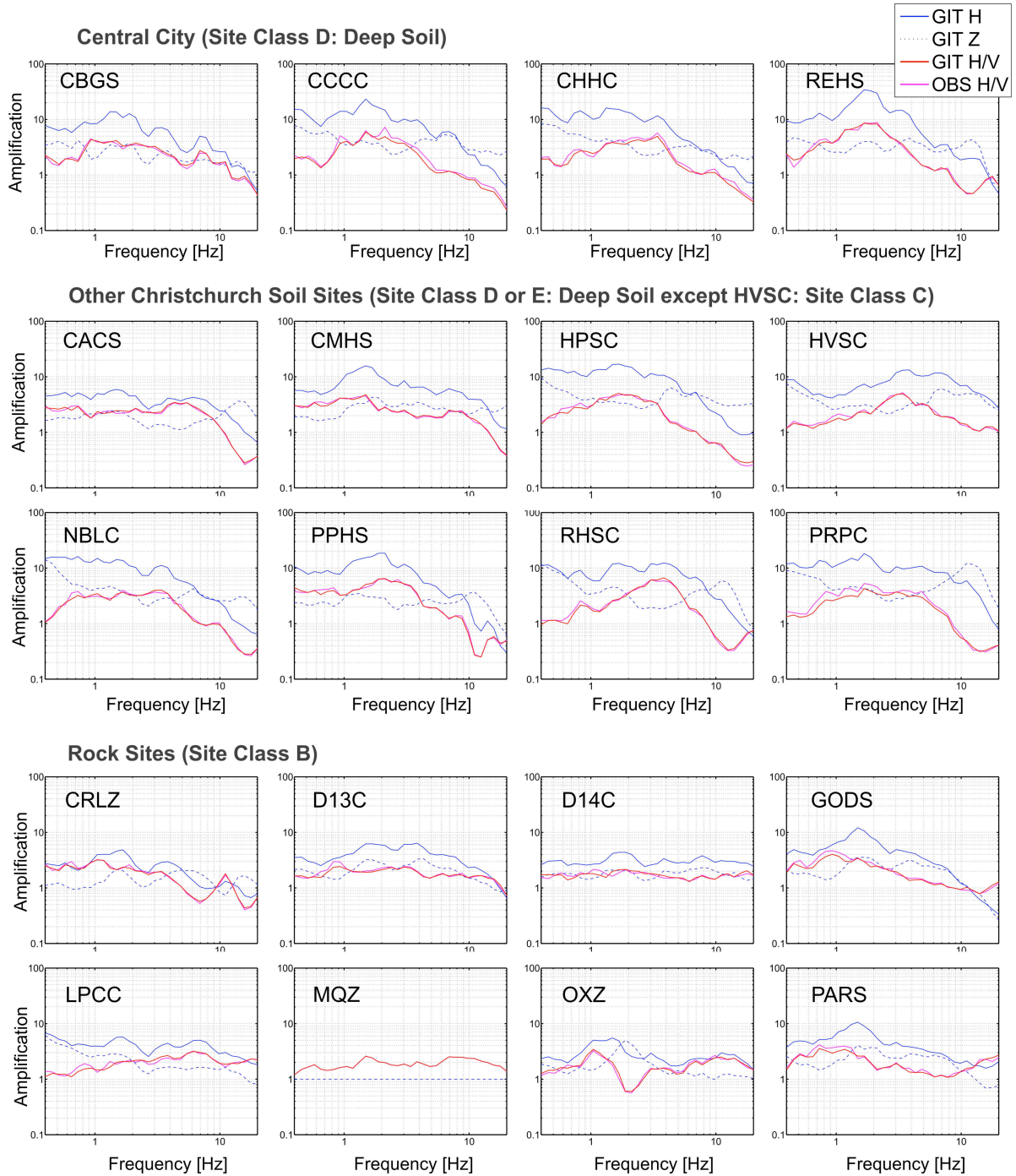
Figure 4: Spectral ratios as for Figure 3, but now all GIT ratios (H, Z and H/V) are given relative to the Z component of the reference station MQZ only as described in the text.

In Figure 5, we compare the results for the largest earthquakes to the average linear site response at both soil and rock stations. As expected, at rock stations (bottom two panels), site response remains roughly constant regardless of the event in question, indicating a lack of nonlinear behaviour. However, at HPSC strong nonlinear effects are apparent during the February, June and December earthquakes. For these events, motions at frequencies > 1 Hz are strongly attenuated, while low-frequency motions remain unchanged. These results are consistent with the fact that station HPSC (close to the Avon River channel) experienced strong liquefaction during multiple events. Nonlinear effects are also evident at most Christchurch soil stations, but as expected are significantly reduced for western stations (e.g. RHSC, CACS) lying on stiffer gravel units. Interestingly, during the Darfield earthquake, strong nonlinear response is not identified, despite the fact that shaking was of longer duration and PGA at central city sites was comparable to that recorded in June and December.

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Considered across the entire dataset, site functions examined over a large range of recorded events can help to isolate the threshold necessary for strong nonlinear effects to occur at each site.
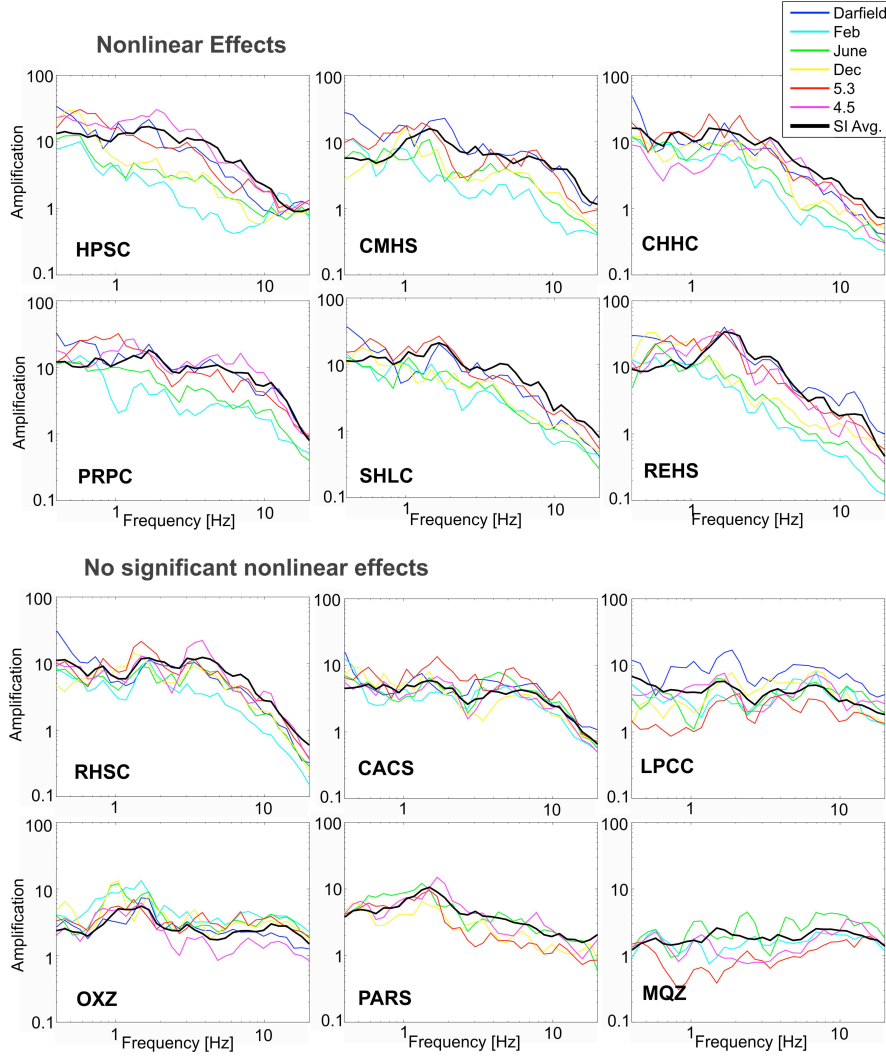

Figure 5: Modelled site response (H component) in the largest Canterbury earthquakes at a selection of sites. Average linear site reponse and site response in two smaller events expected to have a linear site response are included as reference. Site response is corrected for reference station H/V ratio.

6 CONCLUSIONS

We have investigated the factors influencing ground motion specific to the Canterbury region using generalized inversion of recorded acceleration spectra.

Significant attenuation exists at high frequencies (> 5 Hz) associated with near-surface effects, likely to the shallow water-table. These effects are pervasive across Canterbury stations situated on soil. Attenuation is also influenced by the specific crustal structure of the Canterbury region at mid-crustal depths (10 -15 km), where more rigid material associated with a former plate boundary is found.

Source spectra derived in the inversion lead to estimates of stress drop (median ~4 MPa; calculated according to the Brune source model) that are higher than world-wide averages, including for crustal earthquakes in Japan. This means sources in the region are more compact, rupturing stronger crust with higher velocities and leading to potentially higher ground motions.

Site response functions are locally variable and show large amplification effects for particular soil stations (e.g. REHS, HVSC). Vertical amplification effects are also identified at some stations using our approach (e.g. OXZ and CRLZ). Furthermore, we are able to quantify the dominant nonlinear site

response during the four largest earthquakes using theoretical reference spectra calculated from our models.

The observations we present here are important to consider when revising or developing new ground motion prediction models or ground motion simulations to assess future hazard in the Canterbury region.

REFERENCES

Aki, K. 1967. Scaling law of seismic spectrum. *Journal of Geophysical Research,* 72: 1217-1231.

Bradley, B.A. 2012. Ground motions observed in the Darfield and Christchurch earthquakes and the importance of local site response effects. *N. Z. Journal of Geology and Geophysics,* Vol 55(3): 279-286.

Brune, J.N. 1970. Tectonic stress and the spectra of seismic shear waves from earthquakes. *Journal of Geophysical Research,* 75: 4997-5009.

Castro, R.R., Anderson, J.G., Singh, S.K. 1990. Site response, attenuation and source spectra of S waves along the Guerrero, Mexico, subduction zone. *Bulletin of the Seismological Society of America,* Vol 80: 1481-1503.

Cubrinovski, M., Robinson, K., Taylor, M., Hughes, M., Orense, R. 2012. Lateral spreading and its impacts in urban areas in the 2010-2011 Christchurch earthquakes. *N. Z. Journal of Geology and Geophysics,* Vol 55(3): 255-269.

Fry, B. & Gerstenberger, M. 2011. Large apparent stresses from the Canterbury earthquakes of 2010 and 2011. *Seismological Research Letters,* Vol 82(6): 834-839.

Fry, B., Benites, R., Kaiser, A. 2011. The character of accelerations in the Mw 6.2 Christchurch earthquake. *Seismological Research Letters,* Vol 82(6): 846-852.

Kaiser, A., Holden, C., Beavan, J., Beetham, D., Benites, R., Celentano, A., Collet, D., Cousins, J., Cubrinovski, M., Dellow, G., Denys, P., Fielding, E., Fry, B., Gerstenberger, M., Langridge, R., Massey, C., Motagh, M., Pondard, N., McVerry, G., Ristau, J., Stirling, M., Thomas, J., Uma, S.R., Zhao, J. 2012. The Mw 6.2 Christchurch earthquake of February 2011: preliminary report. *N. Z. Journal of Geology and Geophysics,* Vol 55(1): 67-90.

Kawase, H. 2006. Site effects derived from spectral inversion method for K-NET, KiK-net and JMA strong-motion network with special referene to soil nonlinearity in high PGA records. *Bulletin of the Earthquake Research Institute, University of Tokyo,* Vol 81: 309-315.

Konno, K. & Ohmachi, T. 1998. Ground-motion characteristics estimated from spectral ratio between horizontal and vertical components of microtremor. *Bulletin of the Seismological Society of America,* 88: 228-241.

Oth, A., Bindi, D., Parolai, D., Di Giacomo, D. 2010. Earthquake scaling characteristics and the scale-(in)dependence of seismic energy-to-moment ratio: Insights from KiK-net data in Japan. *Geophysical Research Letters,* Vol 37: L19304.

Oth, A., Bindi, D., Parolai, S., Di Giacomo, D. 2011a. Spectral analysis of K-NET and KiK-net data in Japan, Part II: Attenuation characteristics, source spectra, and site response of borehole and surface stations. *Bulletin of the Seimological Society of America,* Vol 101(2): 667-687.

Oth, A., Parolai, S., Bindi, D. 2011b. Spectral analysis of K-NET and KiK-net data in Japan, Part I: Database compilation and peculiarities. *Bulletin of the Seismological Society of America*, Vol 101(2): 652-666.

Parolai, S.,& Richwalski, S.M. 2004. The importance of converted waves in comparing H/V and RSM site response estimates. *Bulletin of the Seismological Society of America* Vol 94, 304-313.

Reyners, M. 2012. The central role of the Hikurangi Plateau in the Cenozoic tectonics of New Zealand and southwest Pacific. *Earth and Planetary Science Letters,* in press.

Van Houtte, C., Ktenidou, O.-J., Larkin, T., Kaiser, A. 2012. Reference stations for Christchurch. *Bulletin of the New Zealand Society for Earthquake Engineering,* Vol 45(4): 184-195.

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