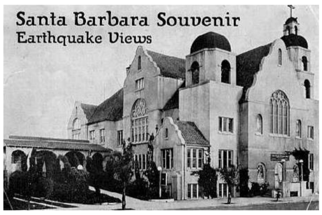

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ESTIMATING SEISMIC SITE RESPONSE IN CHRISTCHURCH CITY (NEW ZEALAND) FROM DENSE LOW-COST AFTERSHOCK ARRAYS

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ABSTRACT

The Mw 7.1 September 2010 Darfield earthquake, New Zealand, produced widespread damage and liquefaction ~40 km from the epicentre in Christchurch city. It was followed by the even more destructive Mw 6.2 February 2011 Christchurch aftershock directly beneath the city's southern suburbs. Seismic data recorded during the two large events suggest that site effects contributed to the variations in ground motion observed throughout Christchurch city.

We use densely-spaced aftershock recordings of the Darfield earthquake to investigate variations in local seismic site response within the Christchurch urban area. Following the Darfield main shock we deployed a temporary array of ~180 low-cost 14-bit MEMS accelerometers linked to the global Quake-Catcher Network (QCN). These instruments provided dense station coverage (spacing ~2 km) to complement existing New Zealand national network strong motion stations (GeoNet) within Christchurch city.

Well-constrained standard spectral ratios were derived for GeoNet stations using a reference station on Miocene basalt rock in the south of the city. For noisier QCN stations, the method was adapted to find a maximum likelihood estimate of spectral ratio amplitude taking into account the variance of noise at the respective stations. Spectral ratios for QCN stations are similar to nearby GeoNet stations when the maximum likelihood method is used. Our study suggests dense low-cost accelerometer aftershock arrays can provide useful information on local-scale ground motion properties for use in microzonation. Preliminary results indicate higher amplifications north of the city centre and strong high-frequency amplification in the small, shallower basin of Heathcote Valley.

INTRODUCTION

Christchurch (population ~377 000; location in Fig. 1), New Zealand's second largest city, has been severely impacted by the Mw 7.1 2010 Darfield earthquake and subsequent aftershock sequence that included the devastating Mw 6.2 Christchurch earthquake. The earthquake sequence occurred in a region of relatively low historical seismicity, ~140 km from the plate boundary, and contained low-recurrence, high-impact events. The Darfield main shock occurred on 3 September 2010 (UTC time) within 40 km of the city (Gledhill et al. 2011). The earthquake produced a ~30-km surface rupture on a previously unidentified fault, now named the Greendale Fault (Barrell et al. 2011, Quigley et al. 2010). Widespread liquefaction and building damage were observed throughout the Canterbury region. In Christchurch city, damage was locally variable, with older brick and masonry buildings in the city centre particularly affected. Areas of liquefaction were concentrated in the northeast and southwest suburbs (Cubrinovski et al. 2010). Ground motions in Christchurch city during the Darfield event ranged up to 0.3 g in the city centre and up to 0.6 g city-wide. Earthquake response spectra exhibited local variability in amplitude and frequency (Cousins and McVerry 2010), suggesting that local site effects influenced ground motions. Assessing the spatial variability of ground motions on a local scale is important for mitigation of seismic hazard. This is especially critical in Christchurch given the ongoing elevated seismic hazard in the region and future efforts to rebuild the city.

To investigate local site response, we deployed a temporary array of ~180 low-cost 14-bit MEMS (Micro-Electro-Mechanical Systems) accelerometers following the main shock, providing block-by-block station coverage (spacing ~2 km) within Christchurch city, and sparser spacing in outlying regions (Fig. 2). These instruments form part of the global Quake-Catcher Network based in California (QCN; Cochran et al. 2009). The aftershock array was designed to complement the temporary deployment of standard strong motion recorders and the ~13 permanent New Zealand national network seismic stations (GeoNet, including the regional CanNet network) located within Christchurch city.

Since the Darfield earthquake, more than 7000 aftershocks have been located by GeoNet in the Canterbury Plains region (Fig. 1). In addition, the temporary QCN network has generally successfully recorded aftershocks of magnitude > 4, although many smaller events with lower signal-to-noise ratio have also been detected (Cochran et al. 2011). The devastating Mw 6.2 Christchurch earthquake, the largest aftershock (to date) of the sequence, occurred on 21 February 2011 (UTC time) at shallow depth with an epicentre just ~6 km from the city centre (Kaiser et al. 2011). The effects of the Christchurch earthquake were severe, including 181 fatalities, building collapse and liquefaction in large swaths of the city. Around ~40 QCN stations were still operating at the time of this earthquake (although many were affected by power outage following the event). This earthquake was followed by a Mw 6.0 aftershock on 13 June 2011 at the southeastern fringe of the city.

To date, the QCN aftershock data has been used to test and develop rapid earthquake detection algorithms (Lawrence et al. 2011). In this study, we enhance standard spectral ratio estimation methods to enable use of the relatively noisy low-cost QCN data in site response studies for Christchurch. We present preliminary estimates of spectral ratios on a dense local scale derived from aftershock data at permanent research-grade and temporary QCN seismic stations in Christchurch city. Finally, we briefly discuss the potential influence of local site effects on ground motions recorded in the recent large Canterbury earthquakes.

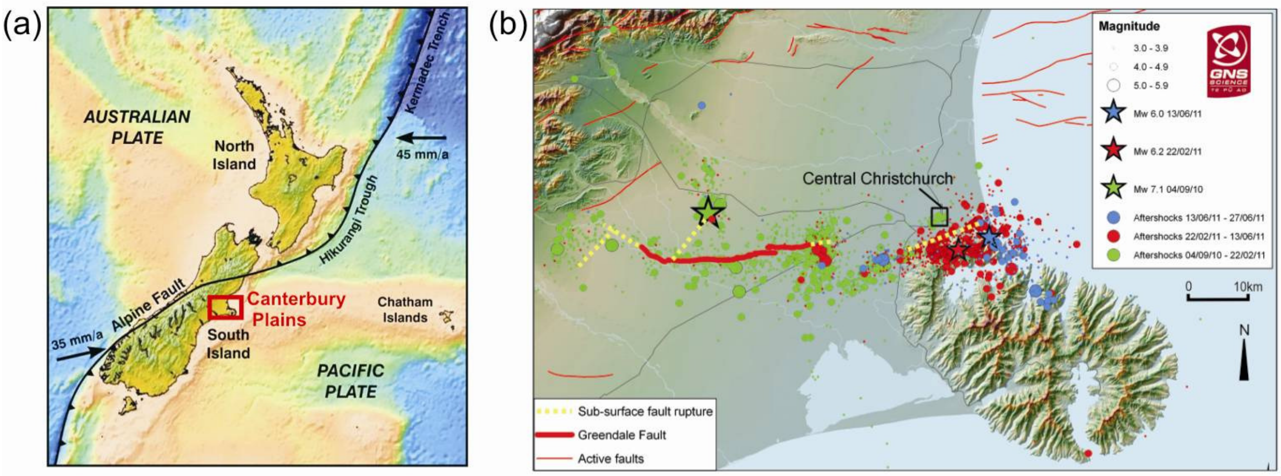

Fig. 1. (a) Tectonic setting of New Zealand showing the location of the Canterbury Plains. (b) Zoomed map of the Canterbury Plains area showing earthquakes of the Canterbury sequence from 3 September 2010 to 27 June 2011. The Darfield earthquake (epicentre shown by the green star) ruptured the surface along the Greendale Fault (thick red line). Aftershocks prior to the Christchurch Earthquake used in this preliminary study are shown in green. Graphic courtesy of Rob Langridge and William Ries of GNS Science.

GEOLOGICAL SETTING

In the central South Island of New Zealand oblique continental convergence of ~ 38 mm/yr is accommodated between the Pacific and Australian plates (Fig. 1; DeMets et al. 2010). The plate boundary is delineated by the Alpine Fault ~140 km to the west of Christchurch, which links two subduction zones of opposite polarity to the north and south. Up to three quarters of the relative plate motion is taken up in a narrow zone along the Alpine Fault (Norris and Cooper 2007, Sutherland et al. 2006). In the northern South Island plate motion is increasingly being taken up by the strike-slip faults of the Marlborough Fault System. The zone of active plate boundary deformation has widened eastwards into the Canterbury Plains during the Quaternary (Forsyth et al. 2008). The residual contractional strain rate within the Canterbury block, extending from the Porters Pass Fault in the foothills of the Southern Alps eastward to Christchurch, is estimated from GPS-derived velocity fields to be ~2 mm/yr, or ~5% of the plate motion budget (Wallace et al. 2007).

Prior to the Darfield earthquake, the Canterbury Plains had historically been an area of relatively low seismicity for New Zealand. Nevertheless, national seismic hazard models had identified earthquake source regions capable of generating significant shaking in Christchurch city (Stirling et al. 2008). Although the potential for local earthquakes had been recognized in the Canterbury area (e.g., Pettinga et al. 2001), no active faults had previously been mapped in the immediate Christchurch region.

Christchurch lies at the eastern edge of the Canterbury block. Large gravel-laden braided river systems draining eastward have deposited large quantities of postglacial alluvium forming the Canterbury Plains. This alluvium lies over sedimentary and interbedded volcanic deposits dating back to the late Cretaceous and greywacke bedrock (Forsyth et al. 2008). Geology of the immediate Christchurch regions is described by Brown and Weeber (1992). Miocene volcanic rocks outcrop at the extinct volcano of Banks Peninsula (active 6 -12 Ma) to the south of the city. Volcanic flows resulting from Banks Peninsula volcanism likely underlie Christchurch at about 600m depth in the central city. These flows are roughly 200 m thick and define the effective lower boundary of the basin, although it is uncertain if older alluvium immediately underlies the volcanic flows above the greywacke basement. In Christchurch, a history of flooding, erosion and sedimentation has created a complex sequence of flat-lying sedimentary layers (up to ~1 km thick) in the shallow subsurface. The depth of sediment and complex near-surface conditions are likely to cause enhanced shaking and significant ground motion variability due to site effects (including nonlinear soil response and liquefaction).

DATA FRAMEWORK

The Canterbury aftershock sequence was well recorded by national network GeoNet and temporary QCN stations (Fig. 2). Following the Darfield main shock, ~180 temporary 14-bit MEMs accelerometers were deployed as part of the Quake-Catcher Network rapid earthquake response (RAMP) program. The sensors are hosted by volunteer members of the public in their homes, transmitting data by network computing through their home internet connection (further details in Cochran et al. 2009). The positive response from the Christchurch public allowed us to deploy ~180 sensors in the region within 11 days of the main shock. Most residential dwellings in Christchurch are 1-storey houses with concrete slab or pile foundations, ideally suited for this type of deployment.

The network of ~180 instruments spans a 60-km-wide region (Fig. 2a). In contrast to previous QCN deployments, the Christchurch array provides particularly dense coverage over a small urban area with most sensors deployed within a 10-km radius of the central city (Fig. 2b). Figure 3 shows a summary of the QCN network data; note, that because of the dependence of data logging and transfer on volunteer networked computers at the host sites, not all sensors will return records for every aftershock. Around ~40 volunteer sensors were still recording 6 months after the main event.

Although noisier than research-grade seismometer, the QCN accelerometers generally produce clear 3-component signals from aftershocks greater than magnitude 4. The observed time series, peak ground motion amplitudes, and spectral characteristics of seismograms are similar between closely located QCN and GeoNet stations, suggesting they are representive of true ground motions (Cochran et al. 2011).

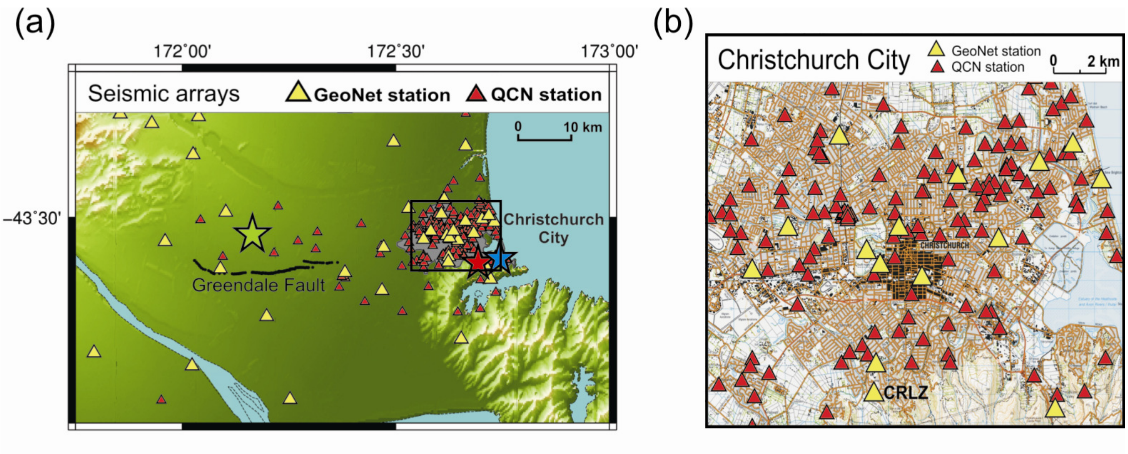

Fig. 2. Locations of permanent GeoNet stations (yellow triangles) and a temporary array of QCN accelerometers (red triangles) in place following the Darfield Earthquake.

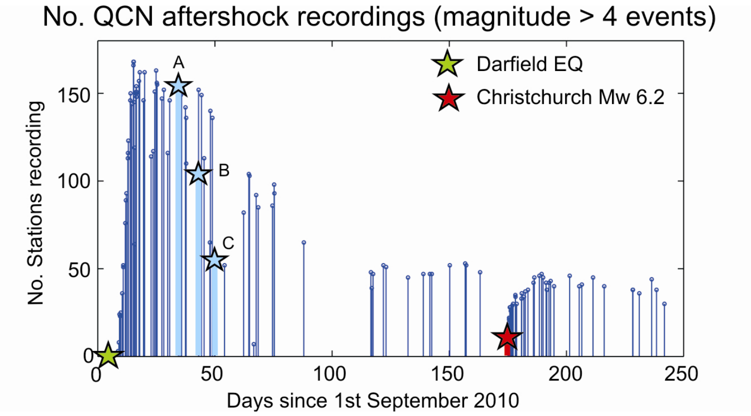

Fig. 3. Stemchart showing the number of QCN recordings per aftershock until end of April 2011. The magnitude 5 aftershocks shown in Fig.4 are labeled A-C. Installation of the array was completed over a 10-day period following the Darfield main shock.

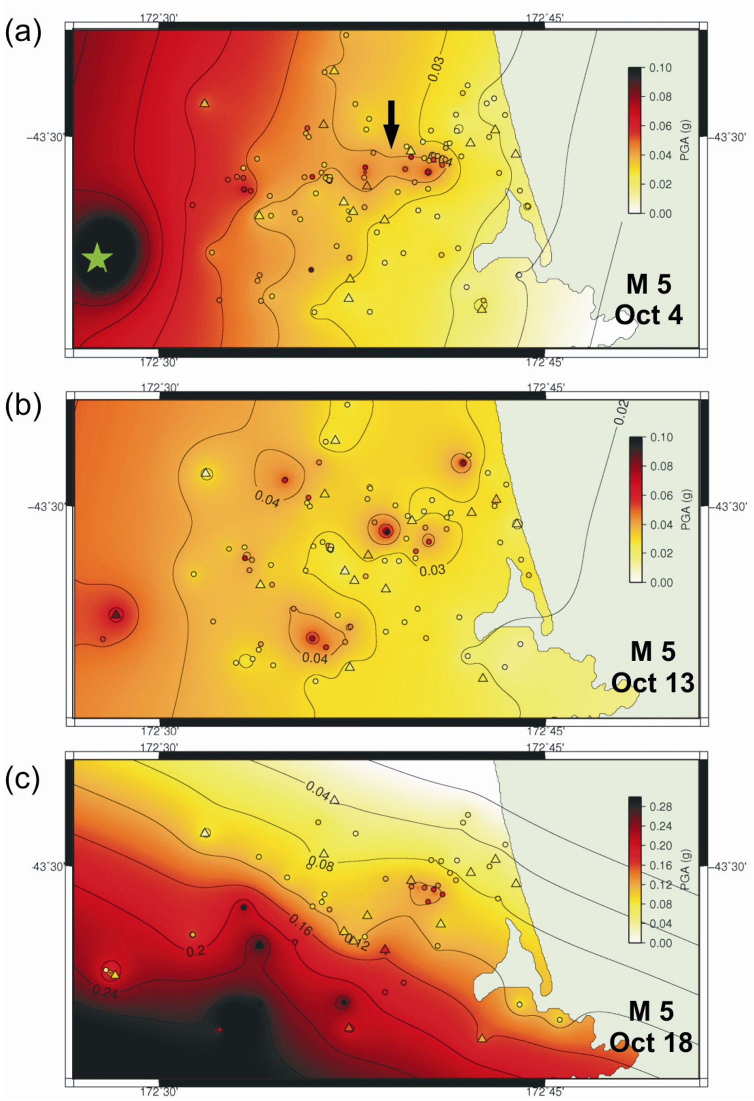

Fig. 4. Contoured maximum peak ground acceleration (3D vector maximum) at GeoNet and QCN stations (triangles and circles respectively) for three magnitude 5 aftershocks. The epicentres of the earthquakes are located (a) 15 km west (green star), (b) 20 km west and (c) 12 km southwest of the city centre respectively (epicentres lie outside the mapped area for the latter two earthquakes).

Figure 4 shows peak ground accelerations (PGA) in the Christchurch region from several of the larger magnitude 5 aftershocks. PGA values show reasonably good agreement between GeoNet and QCN stations, with some consistent variations in PGA trends. In particular, an area of consistently higher PGA values is observed just north and northeast of the city centre (marked by black arrow in Fig. 4a).

SPECTRAL RATIO CALCULATIONS

In order to better isolate and quantify the average site amplification utilizing the larger aftershock data set, we have made preliminary estimates of the spectral ratio of Christchurch stations relative to a reference station in the southern Port Hills (CRLZ in Fig. 2b). Ideally, a reference station would be located on unweathered horizontal bedrock, such that ground motions are as free as possible from any site effects due to soft surface material and/or topography. The CRLZ reference station is located on Miocene-aged basalt at the base of a broad ridge leading up to Banks Peninsula. Although it is possible that this station may be influenced by site effects (potentially at higher frequencies due to topographic effects), inspection of earthquake time series and spectra at various stations show that the CRLZ station has lower amplification and shorter signal duration than observed at other Christchurch stations. We therefore conclude that it is the best available reference station in the Christchurch urban area.

Preliminary spectral ratio estimates were derived from the database of magnitude 4 - 5 aftershocks through to the end of 2010 (the full aftershock database will be used to refine results at a later stage). Typically, between 6 – 20 events were used per station (not all events were recorded by each station). A tapered 10 s time window beginning at the onset of the S-wave was used in the calculations (e.g. Fig. 5). Fourier spectra were smoothed using a weighted average before the ratio calculation and again after the average Fourier spectral ratio was determined. No corrections for path differences or attenuation were made in these preliminary calculations.

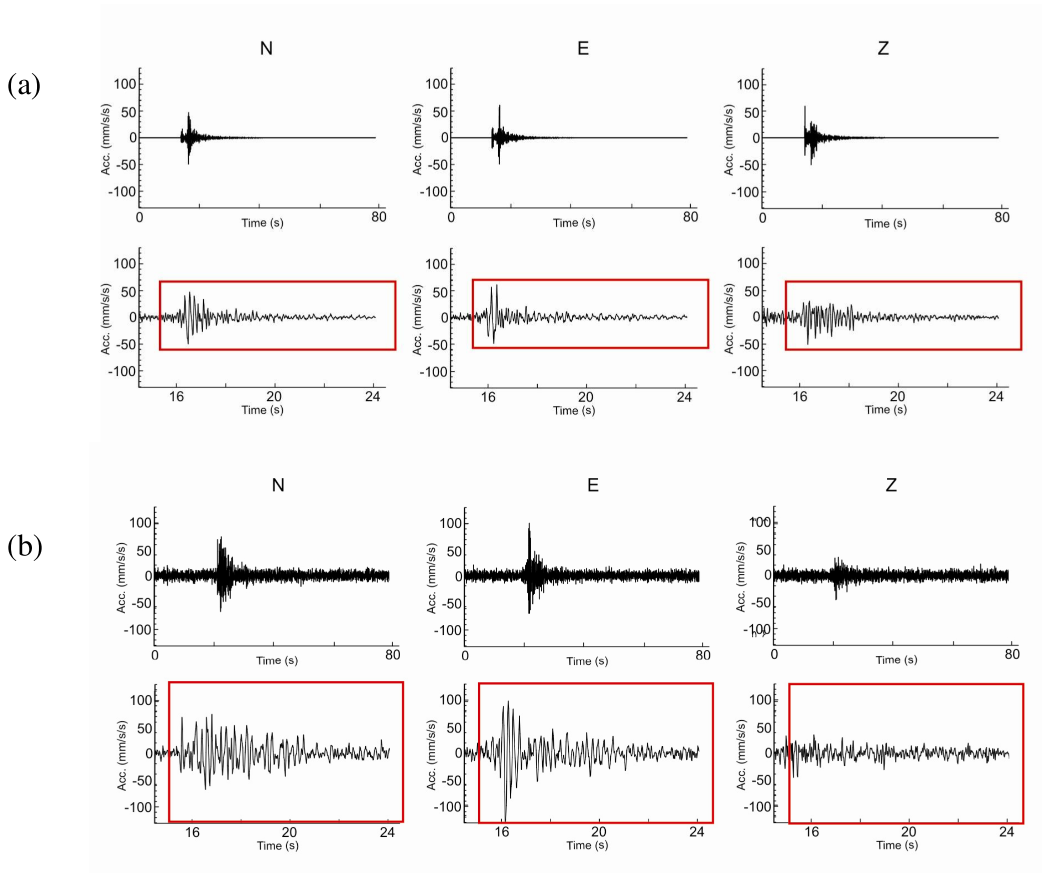

Fig. 5. Acceleration seismograms from a typical aftershock at (a) reference station CRLZ and (b) a QCN station on soft sediments. Bottom plots show zoomed in windows of the top seismogram plots. Red box shows the time window used in the spectral ratio calculations.

Standard spectral ratio methods produced well-constrained estimates of spectral amplification for research-grade GeoNet stations using CRLZ as a reference station. However, the much noisier QCN data meant that spectral ratios with respect to CRLZ could not be extracted using the standard method. Preliminary trials showed the high levels of noise (illustrated in Fig. 5) led to unconstrained and overestimated spectral ratios.

To correctly treat noise in the spectral ratio calculations, we have implemented the statistical approach outlined in Aki and Richards (1980) and derived by Pisarenko (1970). Here the noise is assumed to follow an independent Gaussian distribution at each station in the calculation. Hence, assuming the noise has zero mean, the spectral ratio can be written as:

$$re^{i\theta} = \frac{\langle C_k^{(2)} \rangle + i\langle S_k^{(2)} \rangle}{\langle C_k^{(1)} \rangle + i\langle S_k^{(1)} \rangle} \tag{1}$$

where r is the amplitude ratio, θ is the phase difference, $\langle C_k^l \rangle$ and $\langle S_k^l \rangle$ are means of the cosine and sine transform of the *k*th data at station *l* respectively (where l=1 represents the reference station and l=2 represents the site under investigation). Pisarenko (1970) derives a formula for the maximum likelihood estimates of amplitude ratio and phase difference based on a probability density function formulation:

$$\theta = \tan^{-1} G/F, \tag{2}$$

$$r = \frac{V - ZU}{2(F^2 + G^2)^{1/2}} + \sqrt{\left(\frac{(V - ZU)^2}{4(F^2 + G^2)} + Z\right)} \tag{3}$$

where

$$U = \frac{1}{n}\sum_{k=1}^{n}[(C_k^{(1)})^2 + (S_k^{(1)})^2],$$

$$V = \frac{1}{n}\sum_{k=1}^{n}[(C_k^{(2)})^2 + (S_k^{(2)})^2],$$

$$F = \frac{1}{n}\sum_{k=1}^{n}[C_k^{(1)}C_k^{(2)} + S_k^{(1)}S_k^{(2)}],$$

$$G = \frac{1}{n}\sum_{k=1}^{n}[C_k^{(1)}S_k^{(2)} - C_k^{(2)}S_k^{(1)}],$$

and Z is the variance of cosine and sine transforms of the noise at station 2 divided by the same variance at station 1.

Solving for the maximum likelihood estimate of spectral ratio amplitude at QCN stations relative to the reference station CRLZ using equation (3) leads to more reasonable spectral ratio estimates for QCN stations. Furthermore, comparisons of these QCN spectral ratios compare well to those at nearby GeoNet stations derived using standard spectral ratio methods (Figure 6). The comparisons show that amplifications are present at similar frequencies for adjacent stations, although the amplitude of amplification is not always comparable.

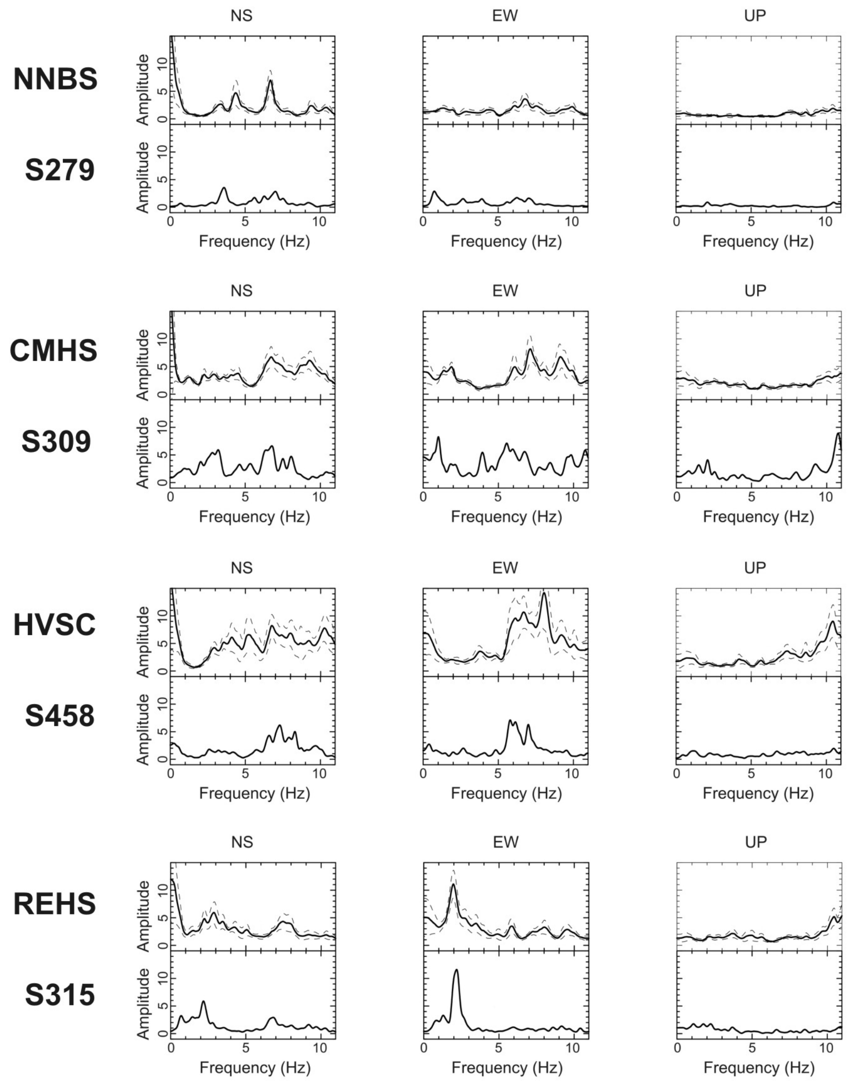

Fig. 6. Spectral ratios for pairs of nearby GeoNet and QCN stations. Spectral ratios for GeoNet stations are derived using standard methods; one standard deviation above and below the mean are indicated by dashed lines. Spectral ratios for QCN stations are derived based on the maximum likelihood spectral ratio amplitude outlined in equation (3).

AMPLIFICATION RESULTS

To investigate the spatial variation in amplification for microzoning purposes, we have mapped the maximum ratio amplitude in the frequency band 1 – 9 Hz for GeoNet stations and a subset of QCN stations with a high number of aftershock recordings (Fig. 7). The size of the aftershocks used in this study (and dominant source frequencies) did not permit well-constrained spectral ratio estimates at frequencies below 1 Hz. Hence, here we do not consider low-frequency amplification effects arising from deeper basin structures, although we note that such amplification has been observed in the Mw 7.1 Darfield and Mw 6.2 February Christchurch earthquakes (Cousins and McVerry 2010; Kaiser et al. 2011).

Figure 7 shows lower amplification at basalt rock sites to the south of the city (e.g. S332, S267) and areas of high amplification on the Canterbury Plains. Strong high-frequency amplification (> 3 Hz) at Heathcote Valley (HVSC, S458; spectral ratios in Fig. 6) is consistent with the high spectral accelerations measured in the Darfield main shock and February Christchurch earthquakes at this site (detailed in Cousins and McVerry 2010; Kaiser et al. 2011). The amplification likely arises from a shallow basin effect within Heathcote Valley.

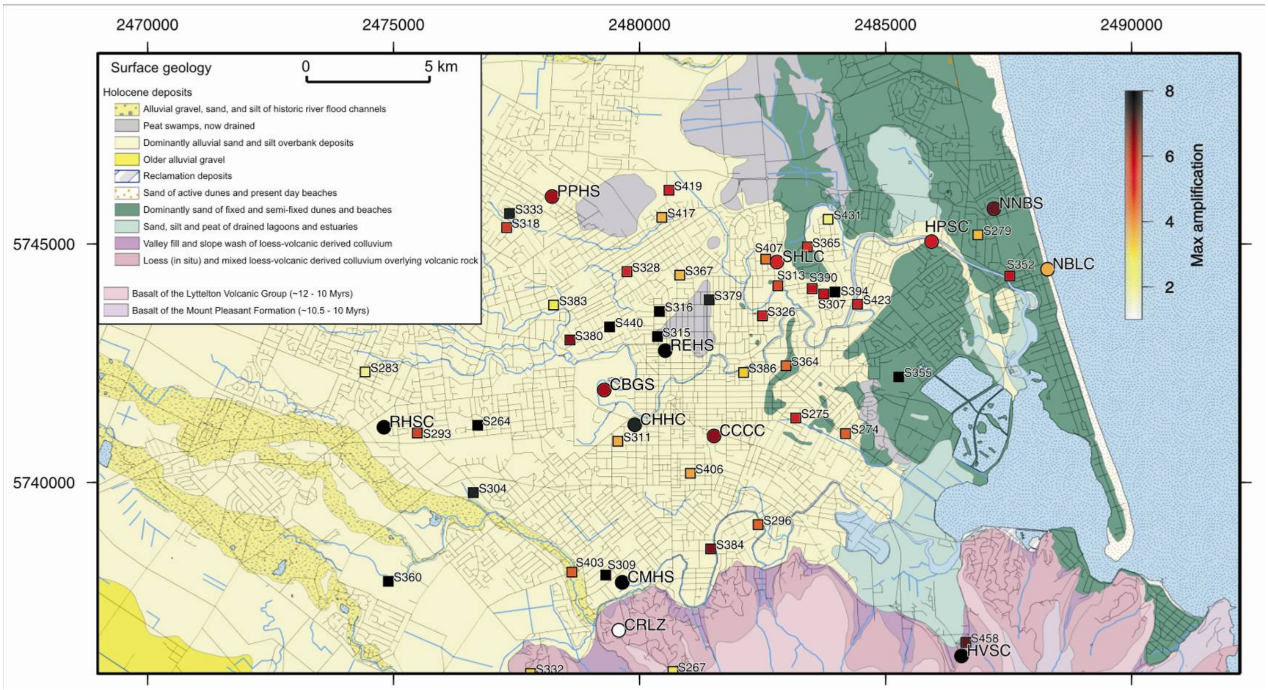

Figure 7. Maximum amplification in the 1 - 9 Hz frequency band derived from spectral ratio calculations at GeoNet stations (circles) and QCN stations (squares). Warmer station colours indicate higher amplifications relative to reference station CRLZ. Background map shows surface geology of the Christchurch area following Brown and Weeber 1992). Coordinates are New Zealand Map Grid given in metres.

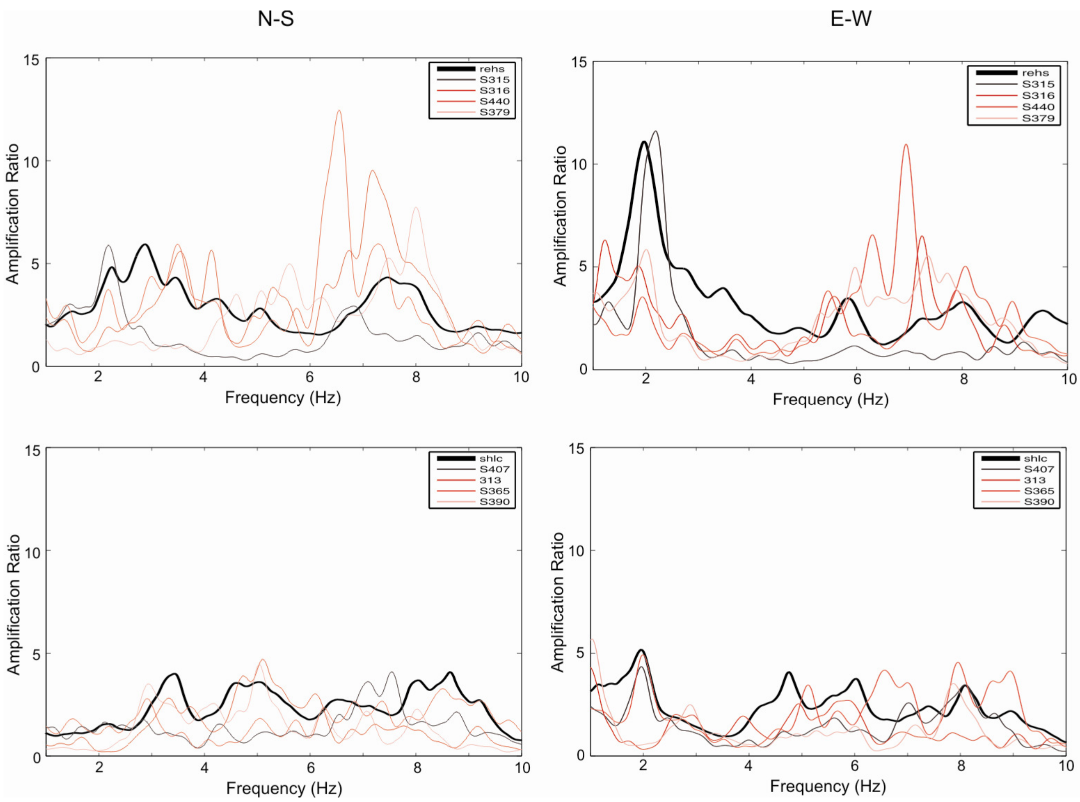

Fig. 8. Comparison of horizontal component spectral ratios in two localized areas surrounding GeoNet stations REHS (above) and SHLC (below). Lighter colours indicate greater distance from the selected GeoNet station.

A ~5 km-wide area of large amplifications surrounding station REHS just north of the city centre (also seen in Fig. 4) is evident in Figure 7. To investigate the amplification in this area, we compare spectral ratios from two groups of nearby stations in Fig. 8. The first group (in the vicinity of station REHS) exhibits high amplification, whereas the second group (in the vicinity of station SHLC further northeast) exhibits moderately high amplification in the 1 – 9 Hz frequency band. Figure 8 shows that spectral ratios are reasonably similar for nearby sites in each group and show more similarity for more closely spaced stations. A prominent peak at 2 Hz is present in the site response at stations REHS and S315, and is dominant on the E-W component. Amplification for other stations in the group is also elevated on the E-W component, but is generally higher at 6 – 8 Hz. We suggest the high amplifications surrounding REHS just north of the city are caused localized soft soils, potentially related to the peat swamp deposits shown in Fig. 7.

The higher amplifications at stations close to the flanks of the Port Hills in the south of the city (e.g. CMHS, S309) may be related to basin edge effects. However, the large amplifications at stations at the southwest edge of the city may be artificially high due to the influence of several larger aftershocks close to this side of the city in the spectral ratio calculations. The spectral ratio at GeoNet station RHSC in this area is more poorly constrained than at other GeoNet stations.

We make a qualitative comparison of the spectral ratios at selected GeoNet stations with the spectral shapes of strong motion data recorded during the Darfield earthquake, ~40 km to the west of the city centre. The observed ground motion will result from of a mixture of source, path and site effects, whereas the spectral ratio is an estimate of site response alone. Furthermore, nonlinear effects (including liquefaction) may modify ground motions on soft sediments, such that the site response may vary between large earthquakes and the smaller events (with linear ground motions) used to derive the spectral ratios. Nevertheless, the frequencies of some spectral peaks in the observed strong motion data correlate with peaks in spectral ratio amplitude. This indicates that strong ground motions observed during the Darfield earthquake were also strongly influenced by local site amplification effects manifest at > 1 Hz. Site effects arising from complex phenomena in the near-surface (i.e. a ‘trampoline’ effect as well as liquefaction) have been put forward to explain some of the characteristics of the Christchurch accelerations during the February 2011 earthquake (Fry et al. 2011). We note, that the proximity of the February earthquake to Christchurch means that such nonlinear behavior as well as strong near-field source effects had a greater influence on the variability of ground motions in Christchurch city than during the Darfield event, such that assessing the contribution of local amplification effects is more challenging.

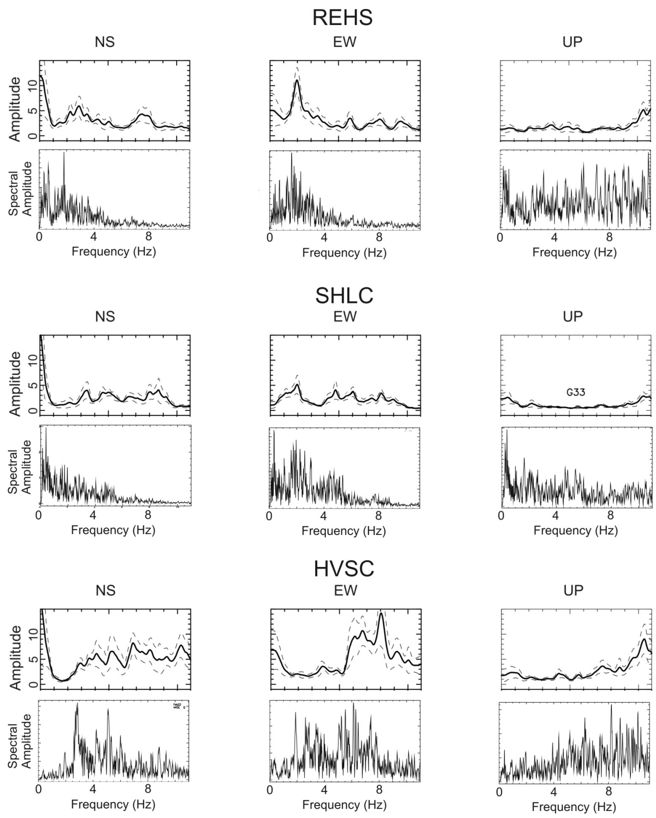

Figure 9. Qualitative comparison of spectral ratios with observed strong motion Fourier spectra at three GeoNet stations (REHS, SHLC, HVSC). Top plots show spectral ratio relative to CRLZ and bottom plots show spectral shape of ground motion recorded during the Darfield earthquake ~40 km west of central Christchurch.

CONCLUSIONS

We have investigated local site response in the Christchurch urban area using spatially dense aftershock arrays. Research-grade strong motion stations (GeoNet) were complemented by a dense array of low-cost MEMs accelerometers installed in residential homes and connected to the global Quake-Catcher Network (QCN). Preliminary spectral ratios were obtained at frequencies > 1 Hz using magnitude 4-5 events. Standard spectral ratio calculations produced well constrained spectral ratio estimates at GeoNet stations, but poorly constrained estimates at noisier low-cost QCN stations. An adapted maximum likelihood spectral amplitude algorithm allowed us to extract much improved estimates of spectral ratio relative to the reference station that were consistent at nearby GeoNet and QCN stations.

Both peak ground accelerations and preliminary spectral ratio results obtained in this study provide evidence for spatially variable site effects due to the complex near-surface geology. In particular, a localized ~5 km-wide area of high amplification was identified north of the city centre. In addition, high-frequency amplification was observed in the small basin in Heathcote Valley and at the edges of the Port Hills. Observed strong motion data from the Mw 7.1 Darfield earthquake shows evidence for spectral peaks at similar frequencies to those seen in the spectral ratio estimates, suggesting that site effects are important for understanding and mitigating severe ground shaking in Christchurch city.

Our study shows that dense low-cost aftershock deployments can be effectively utilized to provide useful estimates of site response for microzonation purposes. Ongoing work using rigorous spectral ratio analyses (employing the full database of aftershock data) and spectral inversions for site response will likely further refine and improve our estimates of local site response in Christchurch city.

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