EQRNet: New Zealand's densest urban seismic monitoring network

H.R.D. Avery, J.B. Berrill & L.F. Damiano
Canterbury Seismic Instruments Ltd, Christchurch.

ABSTRACT

An ultra-dense urban earthquake monitoring and effects management system is presented. We describe our learnings from the 2016 M 7.8 Kaikōura earthquake and how these motivated us to create a globally unique system of ultra-dense sensor networks, a centralised processing system and a wide range of visualisation tools, collectively called EQRNet. A small-scale trial in Christchurch in 2018 confirmed the necessity for ultra-dense sensor placement and the benefits of better data visualisation. Following the trial, a city-wide full-scale deployment of EQRNet was completed in Christchurch, and some preliminary results are presented. We discuss areas of improvement and summarise the state of the work.

1 INTRODUCTION

This paper presents a new earthquake effects management solution: EQRNet.

Following a significant earthquake, a decision-maker has traditionally sought the three knowns: how bad is the damage in the immediate vicinity, how big was the earthquake and how far away? All three pieces of information give no definitive answers to the next steps unless local damage is obvious and significant. From a city-wide perspective, there have been recent examples of both highly localised damage (e.g. Christchurch 2010, 2011), and building-class specific damage (e.g. Wellington 2016). At an individual asset level, some buildings were initially closed only to be later determined safe, whilst other buildings remained occupied until later detailed inspections found hidden damage. Whether at an individual asset or city-wide level, this experience raises significant uncertainty as to the efficacy and appropriateness of the existing immediate response model of source and magnitude as a damage indicator combined with rapid visual inspections of individual assets.

EQRNet's solution to reduce the uncertainty in managing earthquake effects is simple; to measure ground shaking at sufficient density to ensure confident information within the network area and convert it into formats that can be directly compared to each asset's capacity to withstand earthquake shaking. This allows us to immediately determine the first-pass status of every asset within network and flag those that require evacuation and detailed inspection. In addition, the collective city-wide data can be used to drive civil defence response and management of city assets. We believe the EQRNet approach represents the best value compromise between the demonstrably unreliable use of distant source-level information with rapid visual inspection, and installation of expensive comprehensive structural monitoring solutions in every asset.

EQRNet represents a step change to be able to manage immediate earthquake effects in a considered, confident and defensible manner. In this paper we outline the motivation for developing EQRNet, explain how it works, and present some interesting results from our Christchurch network.

2 BACKGROUND

Canterbury Seismic Instruments Ltd (CSI) was founded in 2003 to commercialise the results of a research program at the University of Canterbury School of Engineering. The program developed a novel seismic monitoring device using low-cost solid-state sensors and low-cost internet communications, both of which enabled higher deployment density and lower operational costs to maximise the results with limited budgets.

CSI has since supplied a considerable proportion of the equipment behind the GeoNet strong motion program, both for the free-field seismic and structure monitoring networks. It also supplies equipment to commercial clients, critical infrastructure owners such as port, airports and dams nationally and internationally, and other research and response networks such as the Iceland dense seismic arrays and SIATA, the Colombian GeoNet equivalent.

With the start of the Canterbury earthquake sequence in 2010, many organisations began to realise that while much of their earthquake response procedures worked well in very large and very small earthquakes, the implications of moderate earthquake shaking were less clear. Business and production interruptions and costs needed to be balanced against employee health and safety defensibly with a scientific basis. Having clear and simple procedures based on actual local shaking levels, as opposed to distance + magnitude ‘rules’, drove many organisations to seek seismic monitoring equipment. A good example of this was Christchurch International Airport, which, by using local instrumentation with direct data access, maintained continuous operation right through the devastating Christchurch earthquake of February 2011.

However, despite the benefits of local seismic monitoring, these were limited to those who had both the foresight and resources necessary for the installation and operation of instrumentation prior to an earthquake, along with the ability to set engineer-derived shaking thresholds for the decision-making process.

3 M 7.8 KAIKŌURA NOVEMBER 14, 2016

Prior to the Kaikōura earthquake of 2016, CSI was experimenting with better ways to use raw seismic data. At that time, most users with local instrumentation were using peak acceleration as an indicator of building damage. While this information is of value, it usually requires processing based on a good understanding of the building, which in turn requires good planning and relies on expert analysis. An acceleration time-history plot is of little assistance to the engineer standing outside an unfamiliar building at night ready to do an inspection. We had decided to generate ground response spectra plots relative to the New Zealand Building Code (NZS 1170.5) as a better first-pass information output.

When the Kaikōura earthquake struck, we immediately applied this new processing to data from our own sensors in Wellington, as well as to the public data from the limited urban GeoNet stations. Within minutes we had created a picture that we believe would have changed the immediate response for many buildings.

A portion of this data is shown in Figure 1, with the key points being:

- Parts of Wellington city exceeded 100% design capacity even for brand-new buildings at some period bands. However other areas, even very short distances away, did not.
- Many buildings in some areas were likely to have suffered some structural damage

- With few widely spaced sensor points and significant variation between these, it was clear that interpolating or extrapolating between sensors was extremely uncertain. It would be impossible to say with any confidence what was happening between measurement points. This left large areas of the city in an uncertain state until comprehensive inspections were completed.

The effects of the Kaikōura earthquake in Wellington comprehensively dispelled the established paradigm that magnitude and distance could deliver a reliable damage estimate (Figure 2). It conclusively demonstrated there was no substitute for direct, local measurement of earthquake effects to capture a rapid snapshot of likely consequences to our infrastructure.

However, it was also clear that if the shaking was known at sufficiently many points such that the unknowns between stations were eliminated, a comprehensive and timely image of the likely effects of any given earthquake could be created, greatly reducing the uncertainly in managing earthquakes at both city-wide and at individual building level.

4 THE VISION

Within CSI, the information we generated from the Kaikōura earthquake compelled us to completely rethink our approach to earthquake effects management. We had a vision that by combining the data from our existing clients, from public sources, and by installing new sensors in the gaps in between, we could create real-time 'heatmaps' of shaking in previously unobtainable resolution that would not just benefit single commercial users, but the public infrastructure and the people of our cities as well. Another aspect we determined as vital was the processes to get this information to the end-users in simple and easily understood metrics, so that each type of user (councils, civil defence, building owners, tenants and the public) could make best-practice decisions in a timely and useful manner.

Several critical developments have been key to enabling such an approach:

- We developed new technology and installation methodology to reduce the size, cost and installation effort to enable the great number of sensors that are required to accurately know what happened at every point. Previously, the cost and time to install such a network would have been prohibitive.
- A centralised cloud data capture and processing system was created to reduce equipment and operation cost. By centralising the powerful processing required to convert raw data into a wide range of formats, including ground response relative to NZS 1170.5, subsurface movement displacement, velocity and acceleration etc., we could reduce the complexity and hence cost of the sensors.
- By overlaying the shaking information over pre-determined information relative to the buildings and assets within the network we could instantly determine how severe the shaking was relative to each asset.
- We developed infrastructure and channels to send the information in relevant and easily understood formats to the different types of users in an expected and timely manner.

We named our network of sensors and data capture tools EQRNet, and the information delivery service to our commercial users is branded Sentinel.

We believe that EQRNet is globally unique in its combination of sensor numbers, density and focus on earthquake effects on the urban built environment. It is a fundamentally different approach when compared to traditional national geohazard monitoring platforms such as New Zealand's local GeoNet platform. We consider EQRNet as a complimentary companion to such networks, which were originally developed to provide data for hazard and risk estimation for long term future societal benefit such as improved building codes. This complimentary nature is readily apparent when comparing the locations of the sensors of the two networks in New Zealand. GeoNet is optimised to achieve geographic coverage whereas EQRNet is focused on the urban environment (Figure 3).

5 TRIAL AND DEPLOYMENT IN CHRISTCHURCH

With the support of Smart Christchurch (Christchurch City Council's smart cities programme) and several local businesses, we installed and operated a demonstration network of eight closely spaced sensors in central Christchurch for several months in 2018. To this demonstration network we added data from the four closest GeoNet sensors, which surrounded the outer boundaries of the CBD. Across several small earthquakes, this network confirmed:

- There was significant variation in ground shaking across the city (e.g. a factor of 5 or more in response spectral amplitude).
- That significant shaking variation was observable at scales of ~200m
- That extrapolation or interpolation was not reliable in terms of estimating how the shaking varied
- That the pattern of shaking variation was not repeated – every earthquake was different

Figure 4 shows a typical example from the demonstration. On the back of these results, we pushed forward the development of the full scale EQRNet system and associated tools, along with the launch of the Sentinel service. Christchurch City Council, through Smart Christchurch, became our anchor subscriber and supported the roll-out of the first dense network in Christchurch. EQRNet has been fully operational since January 2019 and we are now expanding this system nationwide.

6 INITIAL RESULTS

6.1 Spatial shaking variation

Large scale deployment has confirmed the experience of the demonstration network. A typical example, for an earthquake close to the city centre, is shown in Figure 5. Although there is a general reduction in ground response shaking as distance from the epicentre increases, distance alone is not a reliable predictor. There is significant variation across the general city area. At the scale of a city block, as shown in Figure 6, shaking variation remains clearly observable.

Figure 7 shows the ground response shaking from an earthquake of similar size and epicentral location to that in Figure 5. Despite the nominal similarity between the two earthquakes, the pattern of variation remains significant, and the spatial distribution of peaks is quite different between the two.

6.2 Shaking variation v source location

Figure 8, Figure 9, Figure 10 and Figure 11 each show four different earthquakes of similar size located at varying distances and locations around the central city. From this we observe no obvious simple connection between the location of the earthquake source and the ground shaking ultimately experienced in the city centre.

6.3 Damage indicator variation

In addition to spectral ground response, EQRNet simultaneously calculates a range of other damage indications. Figure 12, Figure 13, Figure 14, and Figure 15 show the distribution of peak ground response, peak horizontal acceleration, peak horizontal velocity and peak horizontal displacement respectively for a single earthquake. There appears to be no direct relationship between the location of the maximums of each damage indicator – that is, the location of peak acceleration does not necessarily coincide with that of peak displacement, or peak spectral response. This is significant in terms of damage indicator interpretation, in that the locations of maximum movement (e.g. damage to underground infrastructure) may not be the same locations as maximum peak acceleration or peak response spectra (damage to above-ground plant and structures respectively).

7 UNCERTAINTIES AND FURTHER WORK

Given the lack of larger earthquakes (and hence high spatial density data associated with these) it is unclear to what extent the pattern of high variability associated with observed smaller events is repeated when the scale of shaking grows. However, from the information gathered from the few stations in the 2016 Kaikōura earthquake, even in large scale events, the variation is known to be significant in some areas, and without measurement at higher spatial density the uncertainty remains.

We acknowledge that EQRNet is a ground-motion based approach and does not provide any detail as to what has happened with individual assets; it assumes assets are built to, and meet, estimated code compliance. While CSI and others can provide much more comprehensive structural monitoring within assets, we believe EQRNet represents a sensible balance between cost and performance.

In addition to expanding EQRNet network coverage, we have initiated further work into several areas;

- Increase the range of damage indicators, particularly those that can applied to area wide summary information
- Improve the quality and resolution of key parameters (for example soil class) in the spectral ground response calculation – currently some information is not available at the same resolution as the sensor density.
- Fundamental research around the factors which influence shaking variation at small spatial scales to formalise a robust methodology for inter-sensor spacing decisions and hence network coverage requirements. We expect that in some areas the density may need to be increased, and in others it could be decreased.
- Research the effect of soil-structure interaction, and thereby understand what limitations might exist in the application of information from a sensor in one structure to those structures around it. Currently most EQRNet sensors are free field, but it may be possible to incorporate additional sensors that are currently within structures.
- We currently produce short-window earthquake early warning using sensors within our local networks (seconds of warning). We are working toward full nationwide coverage.

8 CONCLUSIONS

We believe EQRNet represents a new and improved approach to managing the effects of earthquake shaking on the built environment.

EQRNet eliminates the current reliance on the presumed relationship between magnitude and distance for damage estimation. Instead it provides direct measurement of local and asset-specific effects in metrics relevant for the type of infrastructure, be that below-ground, plant or buildings.

EQRNet implements a range of damage indicators that are useful for all asset classes, both above and below ground. It provides highly granular differentiation between areas of high potential damage for each asset class, rather than applying simplifications or averages across an area.

The network density provides confidence for civil defence and emergency services to manage city-wide deployment of resource in a targeted manner to ensure those that need it most get it first. This is a significant advance compared to the current practice using wide area estimates and/or waiting for reconnaissance teams to report based on visual indicators. The experience in Wellington following the Kaikōura earthquake later showed this to be a poor indicator of actual building status because it took considerable time for many earthquake damaged buildings to be identified.

We have developed a proven, simple and scalable techno-commercial model that enables city-scale deployment of a system that gives users and stakeholders of all classes to access to better and real-time earthquake effects management information.

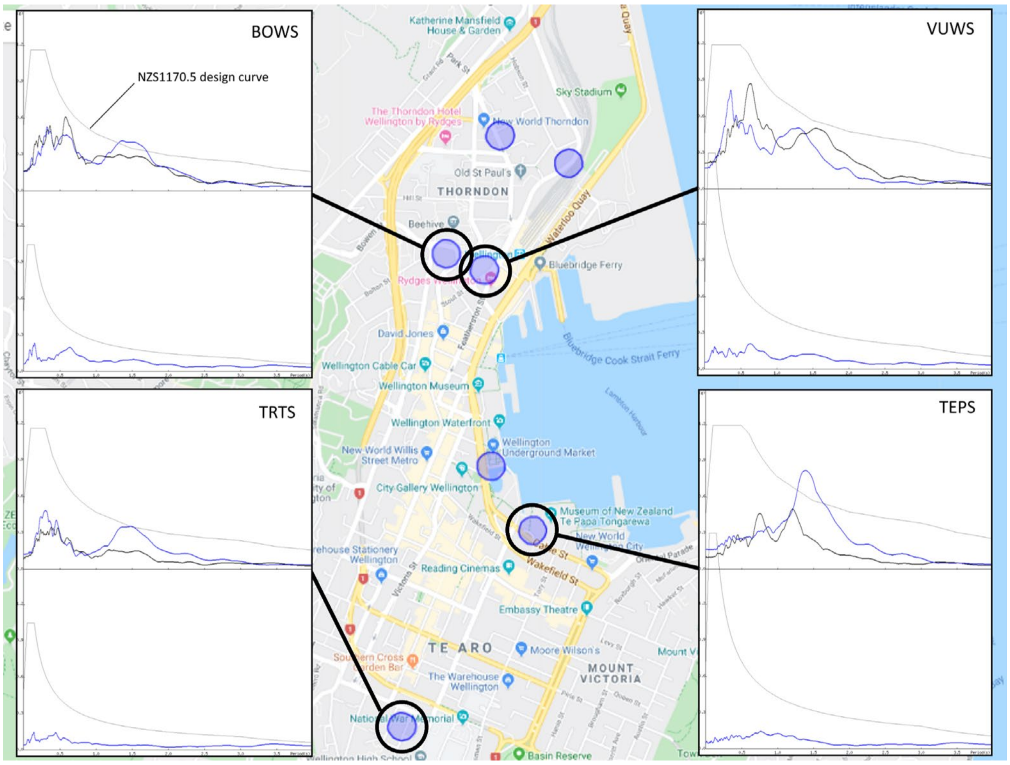

Figure 1 Kaikoura earthquake 2016-11 spectral ground response in Wellington

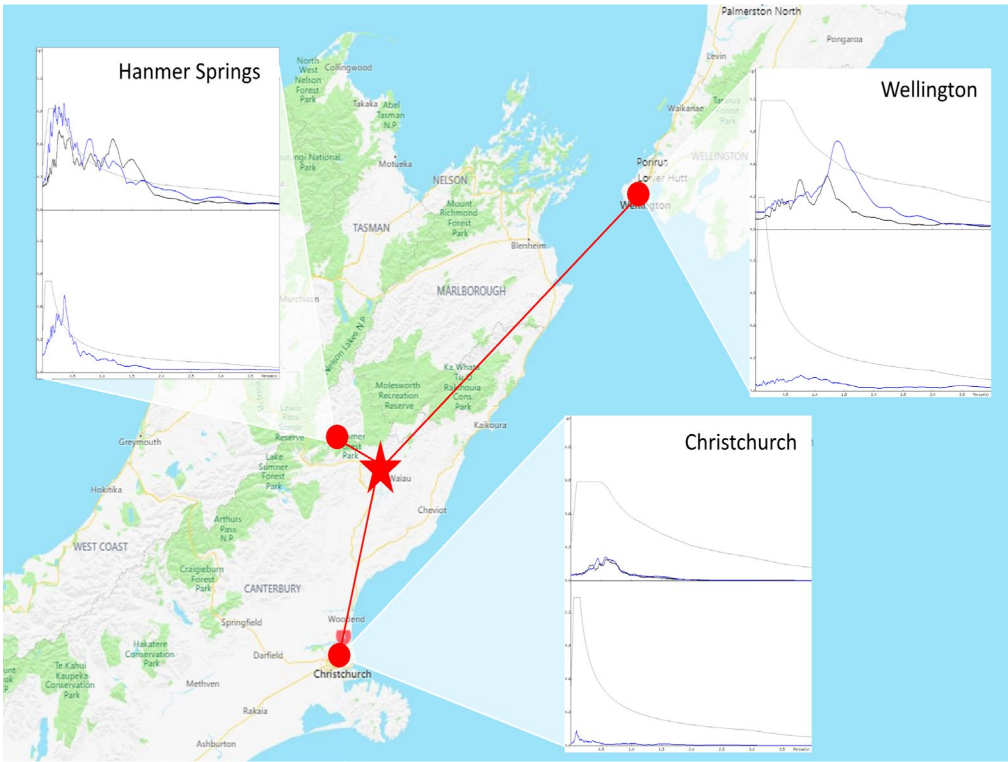

Figure 2 Kaikoura earthquake 2016-11 spectral ground response relative to distance from epicentre

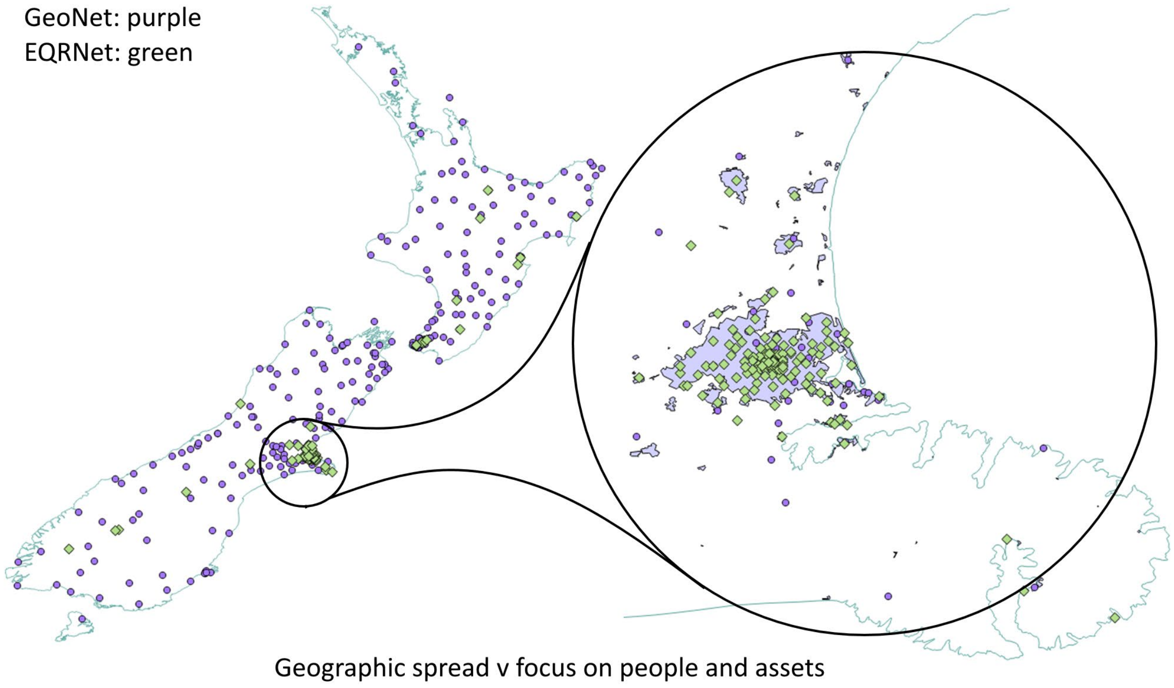

Figure 3 Sensor distribution EQRNet relative to GeoNet

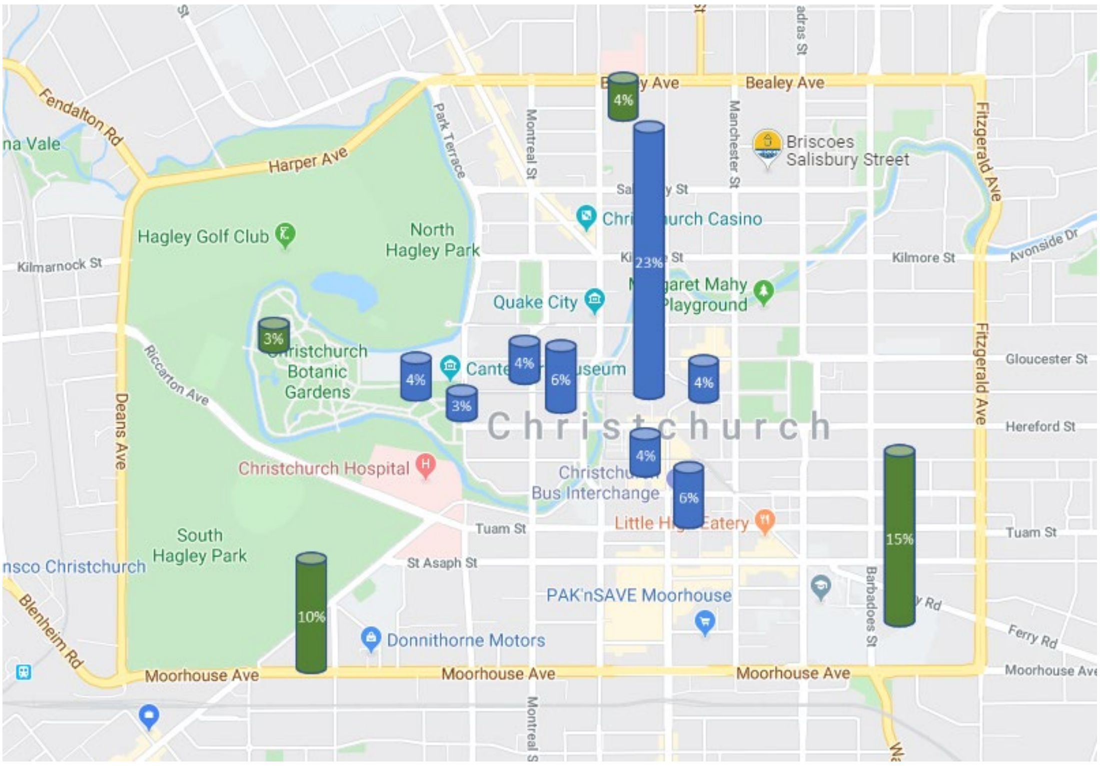

Figure 4 EQRNet pilot January 20 2018 M4.0 5 km SE of Christchurch, peak spectral shaking relative to NZS 1170.5 ULS (IL2, soil class D).

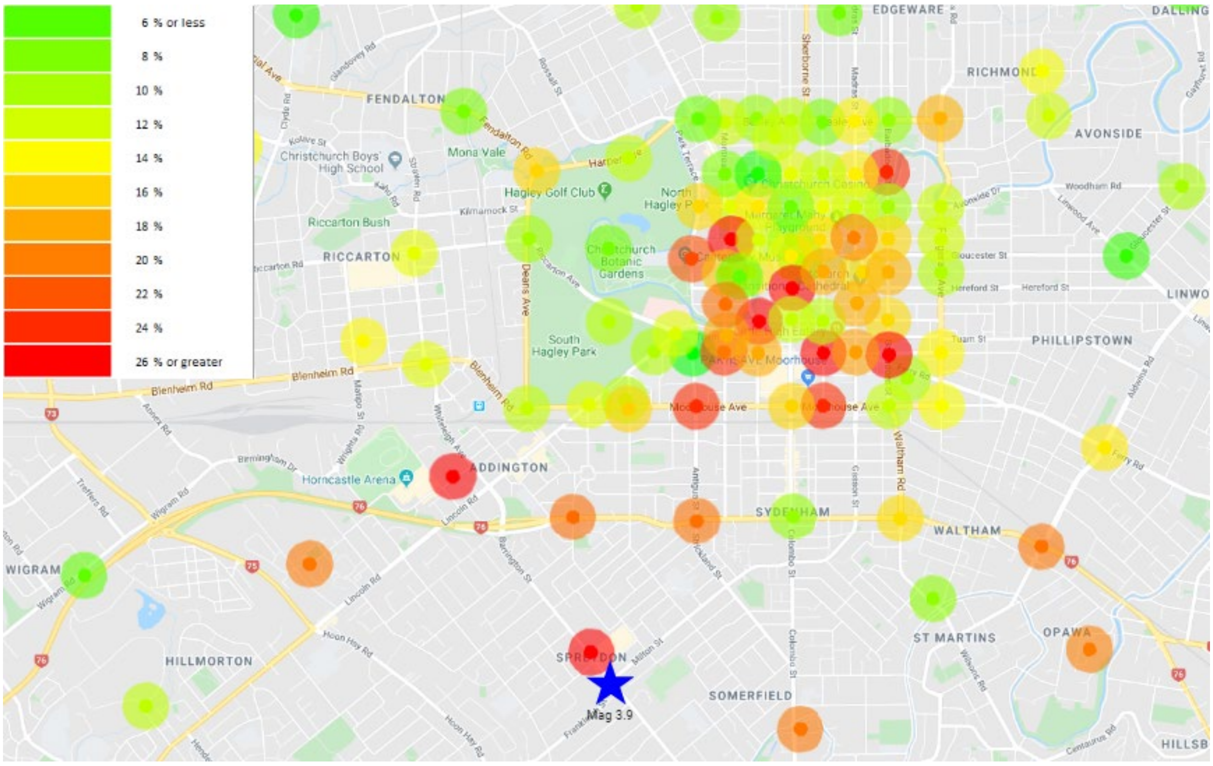

Figure 5 July 22 2019, M3.9 near Spreydon, peak spectral shaking relative to NZS 1170.5 ULS (IL2, soil class D).

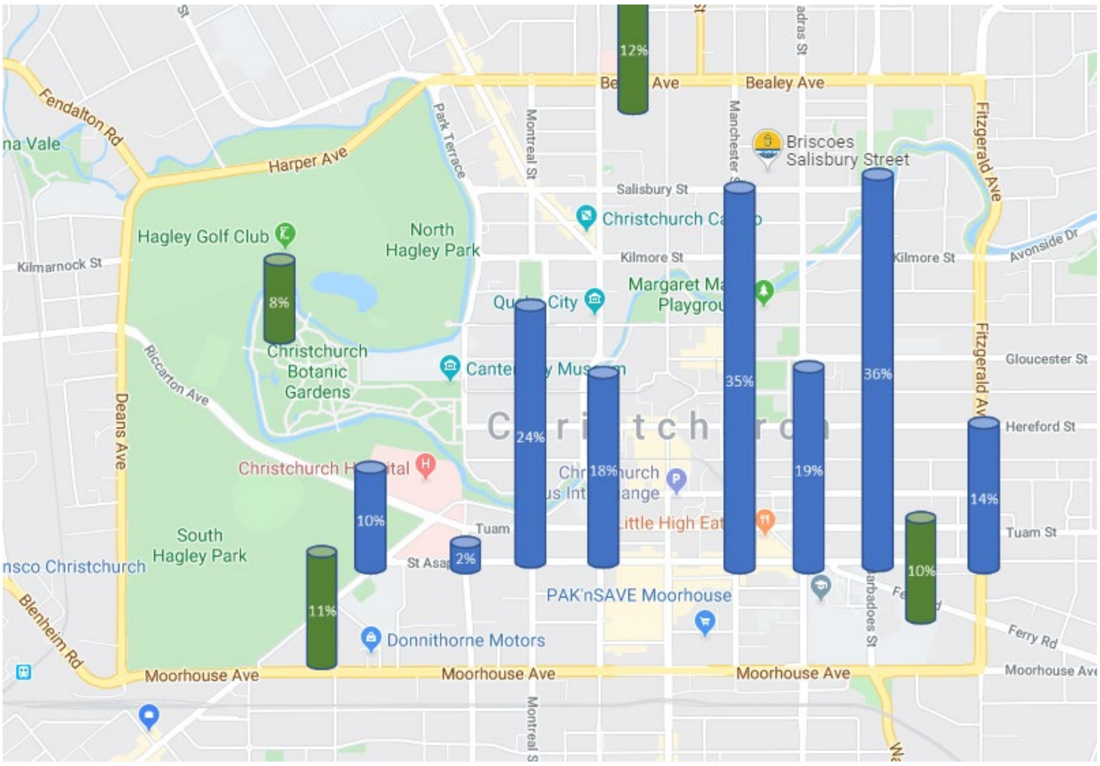

Figure 6 Event detail along St Asaph St, July 22 2019, M3.9 near Spreydon, peak spectral shaking relative to NZS 1170.5 ULS (IL2, soil class D).

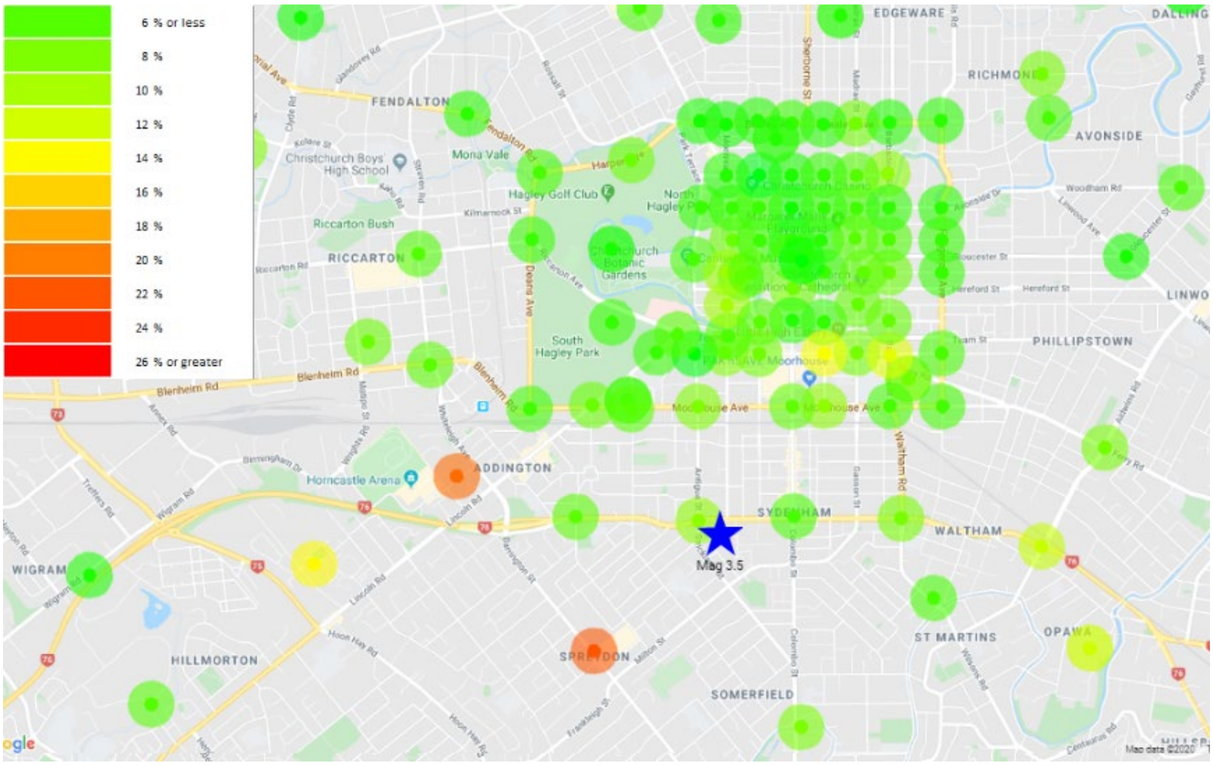

Figure 7 July 20 2019, M3.5 near Sydenham, peak spectral shaking relative to NZS 1170.5 ULS (IL2, soil class D).

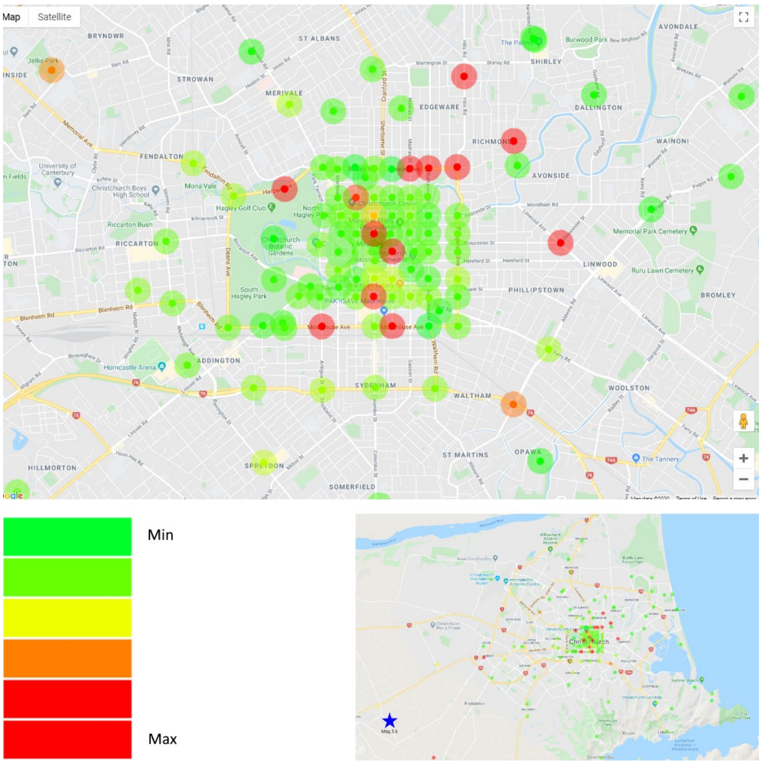

Figure 8 23 April 2019, M3.6 near Rolleston, peak spectral shaking relative to NZS 1170.5 ULS (IL2, soil class D).

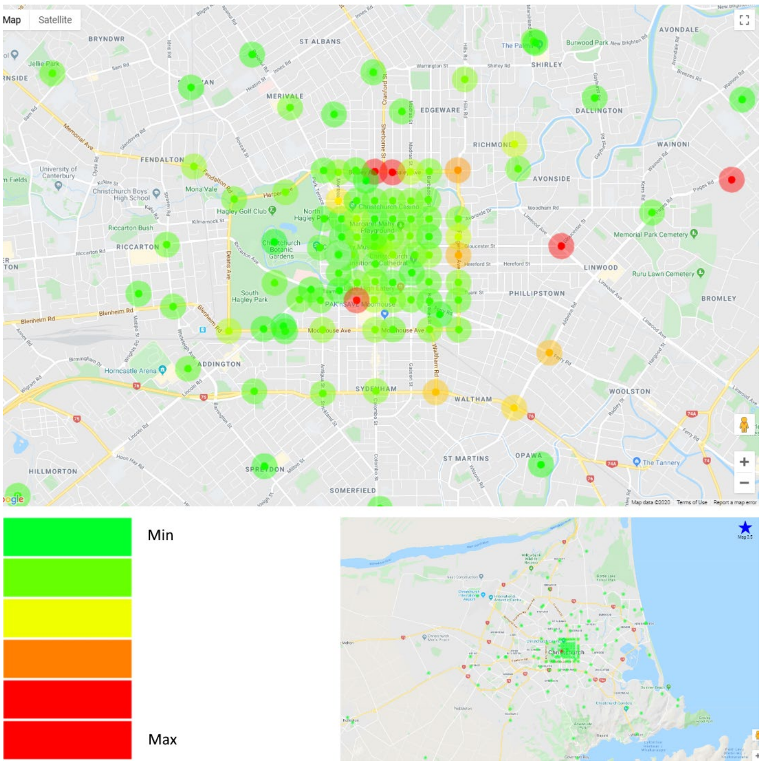

Figure 9 1 May 2019, M3.5 in Pegasus Bay, peak spectral shaking relative to NZS 1170.5 ULS (IL2, soil class D).

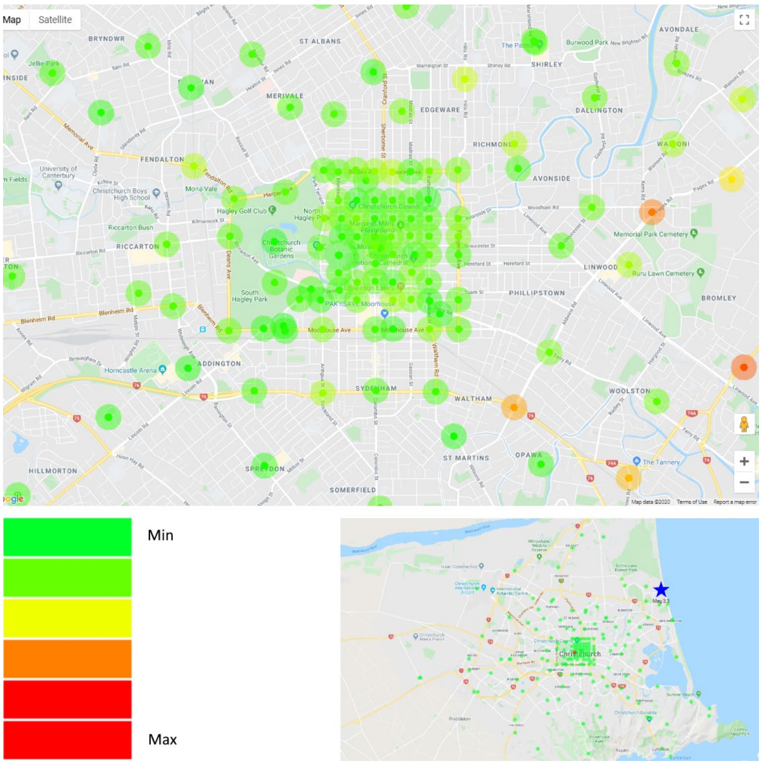

Figure 10 15 July 2019, M3.3 near Bottle Lake, peak spectral shaking relative to NZS 1170.5 ULS (IL2, soil class D).

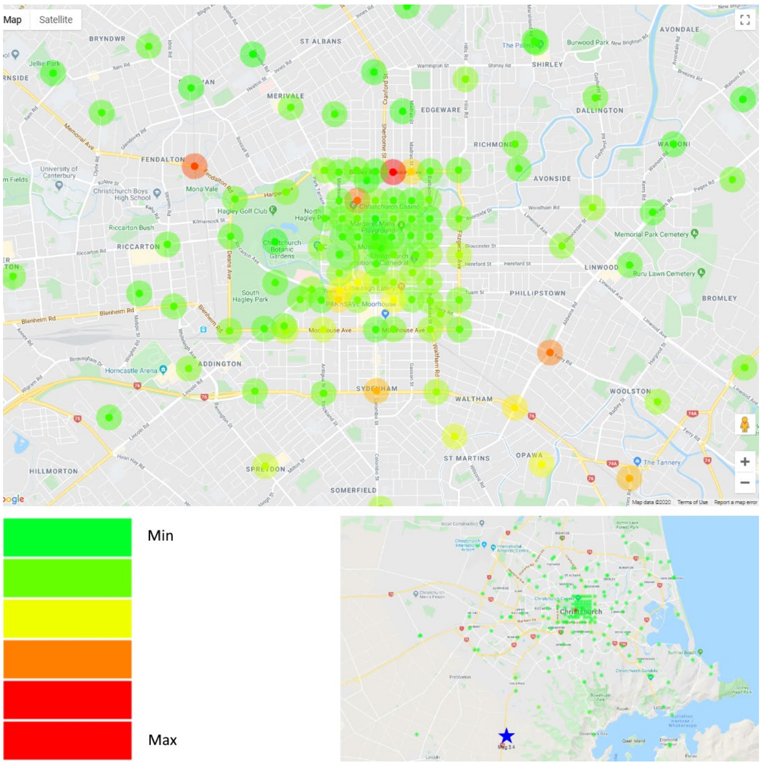

Figure 11 28 July 2019, M3.4 near Tai Tapu, peak spectral shaking relative to NZS 1170.5 ULS (IL2, soil class D).

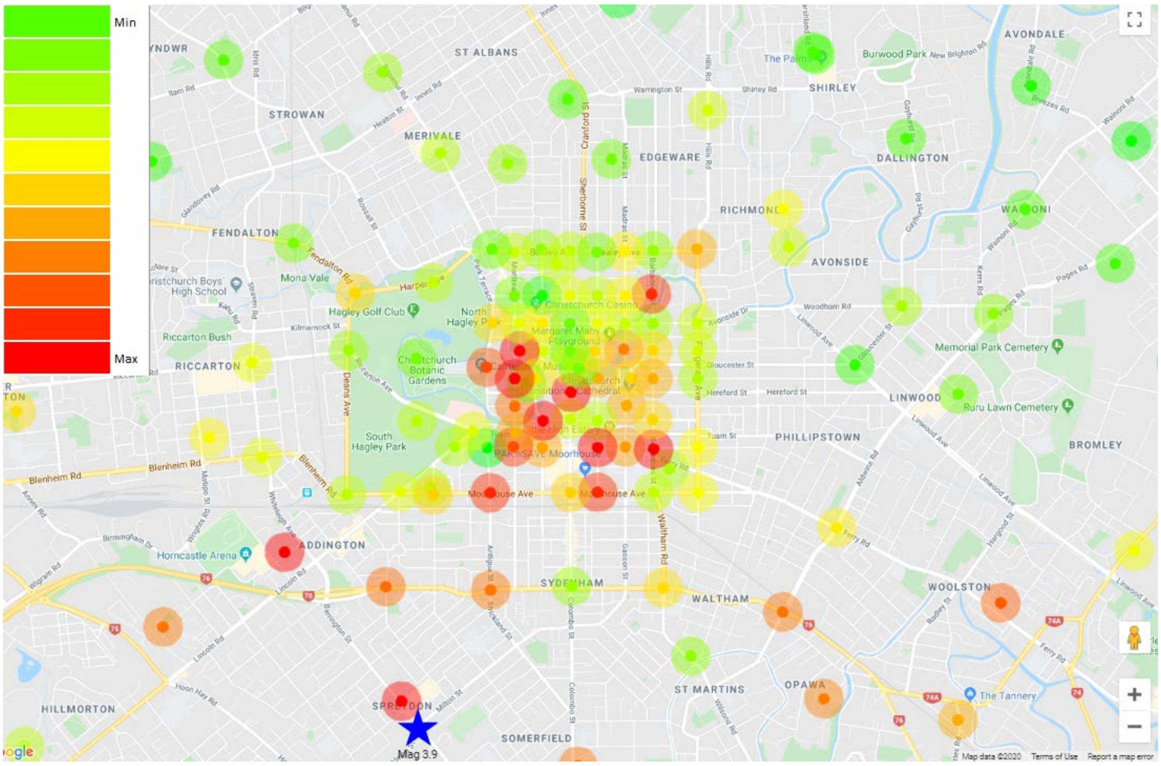

Figure 12 July 22 2019, M3.9 near Spreydon, peak spectral shaking distribution

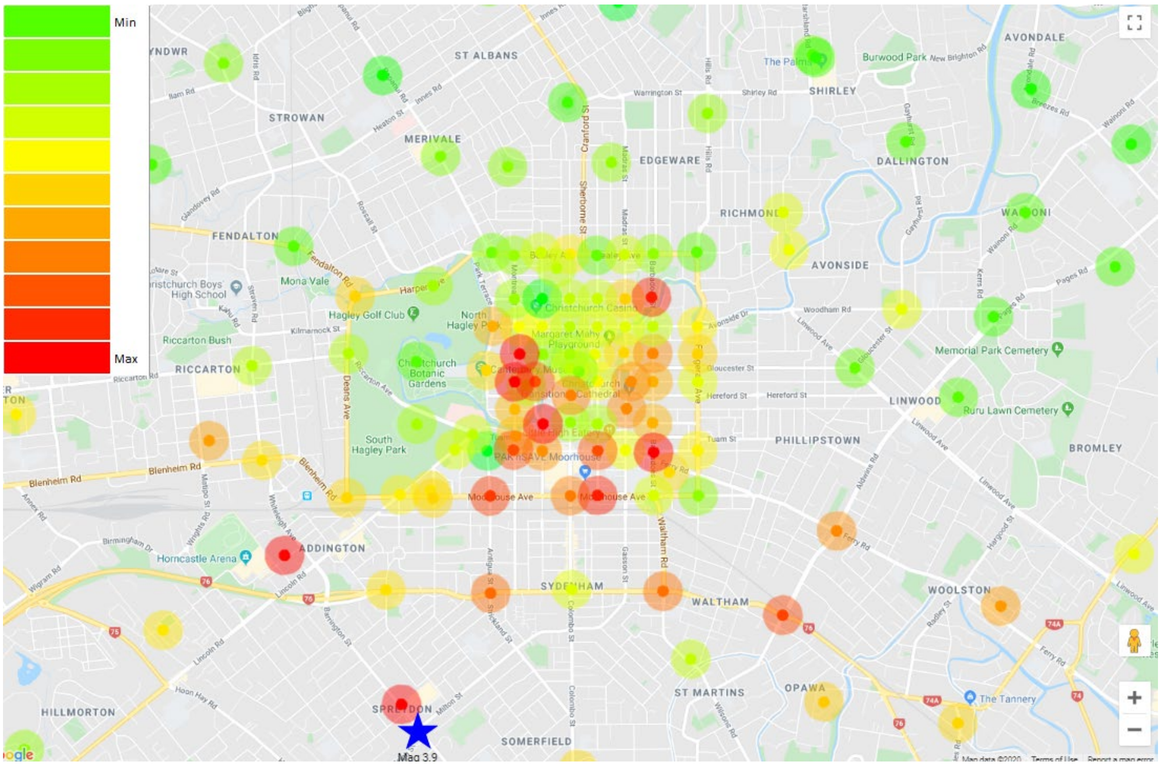

Figure 13 July 22 2019, M3.9 near Spreydon, peak horizontal acceleration distribution

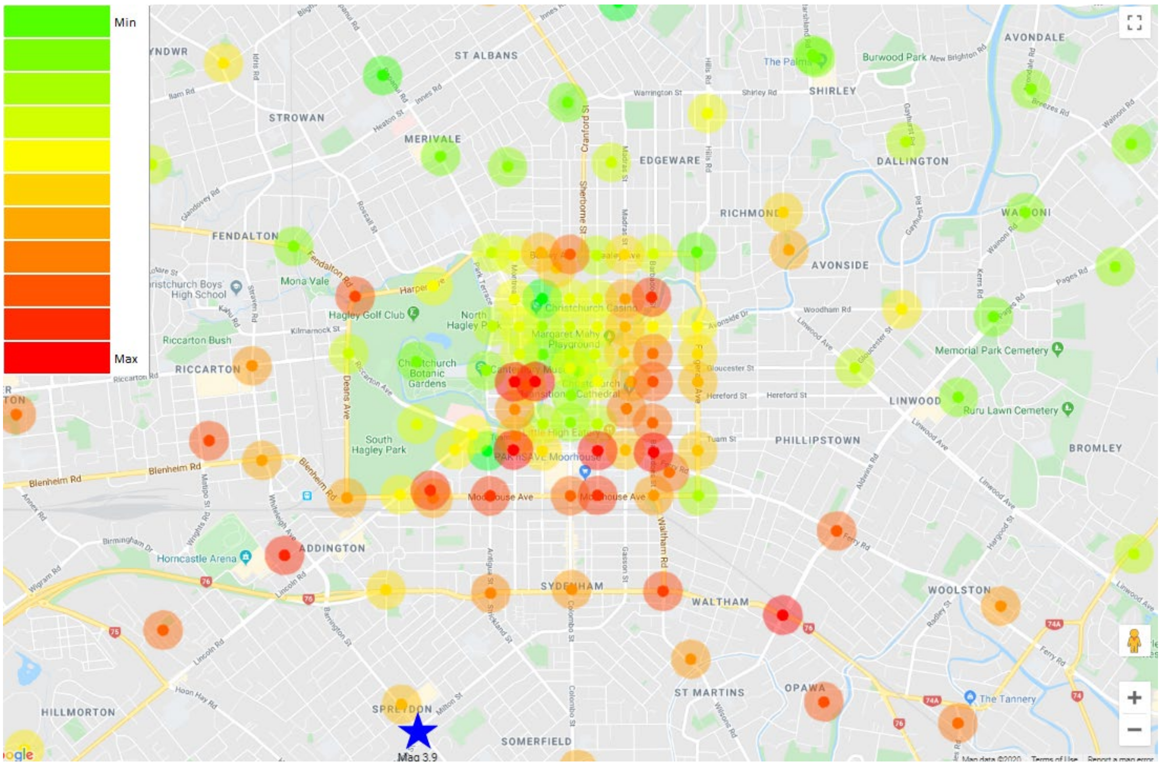

Figure 14 July 22 2019, M3.9 near Spreydon, peak horizontal velocity distribution

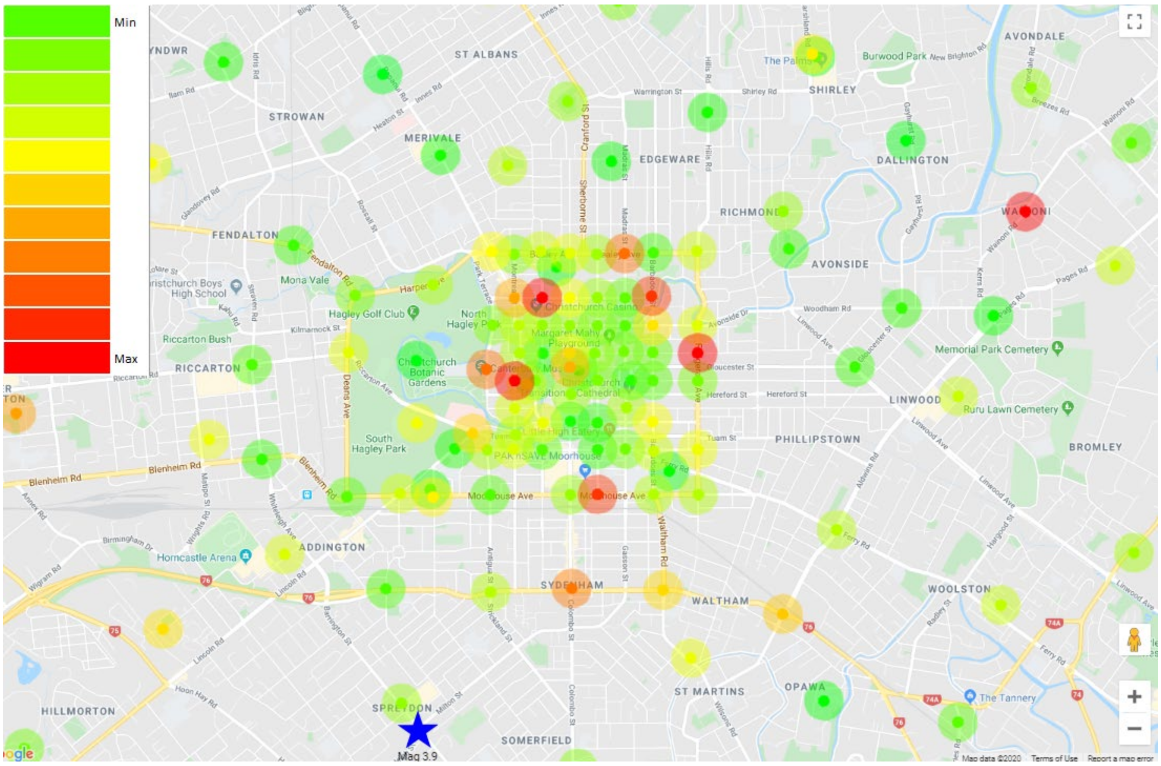

Figure 15 July 22 2019, M3.9 near Spreydon, peak horizontal displacement distribution