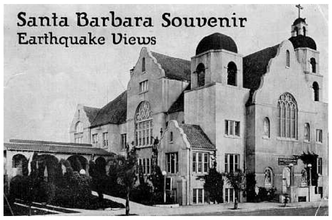

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NONLINEAR SITE RESPONSE OF THE 2010 DARFIELD, NEW ZEALAND EARTHQUAKE SEQUENCE

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ABSTRACT

The September 3, 2010 Darfield, New Zealand M_w7.1 earthquake caused about 29 km surface rupture of the Greendale fault. There were no loss of life and only two serious injuries. In general, residential houses suffered very little structural damage, except for that caused by chimneys falling and in areas of liquefaction. But the aftershock of the February 21, 2011 Christchurch earthquake (M_W=6.3) caused severe damage in the Christchurch area due to the epicenter distance is more close to the downtown area than the mainshock. Severe liquefaction reported in the Christchurch area resulted in subsidence and lateral spreading of the ground. The nonlinear soil response should be occurred during the strong shaking of these events. In this study, the nonlinear site effects during the 2010 Darfield, New Zealand earthquake sequence are identified from the comparison of the H/V spectral ratio of the strong and weak motion records.

INTRODUCTION

Nonlinear site effects, such as an increase in damping and reduction in shear wave velocity as input strength increases, are commonly recognized in the dynamic loading of soils from geotechnical models. During the findings of recent years indicate that nonlinear site effects are more common than previously recognized in strong-motion seismology (Beresnev and Wen, 1996). Direct seismological evidences of nonlinear site effects were reported by using the spectral ratio techniques of soil-to-rock or surface-to-borehole station pair (Wen *et al.* 1994, 1995; Beresnev *et al.* 1995a, 1995b).

A magnitude M_w=7.1 Darfield, New Zealand earthquake occurred on September 3, 2010. It caused the surface rupture along the Greendale fault is about 29 km length. It is a previously unknown fault under the Canterbury Plain (Quigley et al., 2010). During the 2010 Darfield earthquake sequence, Geonet national strong motion network and the Canterbury regional strong-motion network of New Zealand (GeoNet, Fig. 1) obtained a large number of acceleration records from the mainshock (Cousivs and McVerry, 2010) and aftershocks. Therefore, a lot of high quality data had been recorded that triggered by this earthquake sequence. The Darfield earthquake has not caused human life loss, due to less population distribution in the epicenter area, and is approximately 40 km west of the Christchurch central business district (CBD). It caused the largest peak ground acceleration (PGA) of 0.2 ~ 0.3 g in the Christchurch city area. But the aftershock of February 21, 2011 Christchurch earthquake (M_W=6.3) caused severe damage in the Christchurch area due to the epicenter distance is more close to the downtown area (< 10 km). A larger PGA of 1.88 g was recorded in the Christchurch area which is greater than that of the mainshock (Fig. 2). Severe liquefaction reported in the Christchurch area resulted in subsidence and lateral spreading of the ground. From the field surveys, the yellow and brown color areas in Fig. 3 (Tonkin and Taylor Ltd, 2010; Orense *et al.*, 2011; Berryman, 2011) show the soil liquefaction and more severe areas, respectively. It implies that the nonlinear soil response should occur pervasively in those areas. The normal spectral ratio method of a two-station pair can not apply to this large alluvium area. In this study, the horizontal-to-vertical (H/V) method was used to study the nonlinear site response during the 2010 Darfield, New Zealand earthquake sequence.

METHOD USED TO IDENTIFY NONLINEAR SITE RESPONSE

Nonlinear site effects, such as an increase in damping and reduction in shear wave velocity as input strength increases, are commonly recognized in the dynamic loading of soils from geotechnical models. During the findings of recent years indicate that nonlinear site effects are more common than previously recognized in strong-motion seismology. Direct seismological evidences of nonlinear site effects were reported by using spectral ratio techniques (Wen 1994). Nakamura (1989) proposed a hypothesis that microtremor site effects can be determined by simply evaluating spectral ratio of horizontal versus vertical components of motion observed at the same site. Lermo and Chávez-García (1993) shows that this method can use to earthquake record for studying the site effect. Wen *et al.* (2006a) using the horizontal-to-vertical spectral ratio method to identify nonlinear site response. The results show the applicability of H/V technique for nonlinear site response identification. In this study, we calculated the H/V ratios of the 2010 Darfield and 2011 Christchurch earthquakes record at each station and compared the variation of the predominant frequency with time using the moving window spectral ratio method to identify the site response at each station during the Darfield, New Zealand earthquake sequence. The results are compared with the weak motion responses for the same station. Some stations that can find previous weak motion records are compared the H/V ratios for the strong and weak motion records.

RESULTS OF THE NONLINEAR SITE RESPONSE ANALYSIS

H/V Ratios in the Liquefaction Area

Many places had observed soil liquefaction after the 2010 Darfield earthquake sequence (Tonkin and Taylor Ltd, 2010; Orense et al., 2011; Berryman, 2011). It can be seen in Fig. 3 that station REHS located in the liquefaction area during the 2011 Christchurch earthquake, but it was not during the Darfield event. Fig. 4a shows the time-frequency H/V spectra of the station REHS. The ratio did not show dominant frequency shift effect in the strong motion portion of the 2010 Darfield earthquake. Only shows a little de-amplification in the middle frequency band (Fig. 4b). The response on 2011 Christchurch earthquake shows a different response in Fig. 5. Fig. 5a shows the time-frequency H/V spectra of REHS station during the 2011 Christchurch earthquake. The dominant frequency shift to lower frequency is clearly shown in the result of the red window. For the latter portion of weak motion part, the dominant frequency shift back to higher frequency. But it could not back to the frequency as that from previous weak motions due to the soil liquefaction effect (Fig. 5b).

For understanding the dominant frequency variation with respective to time for the station REHS, we collected all the data recorded by the station REHS from 2000. Except the PGA great and equal 60 gals events, all the H/V ratios of the weak motion events with PGA < 60 gals are averaged. The variation of the dominant frequency with time is shown in Fig. 6. Time periods are separated into five periods: before Darfield earthquake (black symbol), during Darfield earthquake (green symbol), before Christchurch earthquake (blue symbol), during Christchurch earthquake (red symbol), and after Christchurch earthquake (purple symbol). Circles means the average results for events with PGA < 60 gals within the time period shown in the x-axis. It is clearly show that the dominant frequency keep around the same from beginning to the period of before the Christchurch earthquake. During the Christchurch earthquake, it shifted to lower frequency and did not move back to the original frequency until March 2011. After April 2011, it shows around the same as that before the 2010 Darfield mainshock. This phenomenon also shown as the shear wave velocity reduction found in the case of the 1995 Kobe earthquake (Aguirre and Irikura, 1997).

Quantitative Analysis Of Nonlinearity

In previous study, the strong and weak motion's H/V spectral ratios are compared to show the nonlinearity qualitatively. Some stations are not easy to clarify it had nonlinear response or not. So, Wen et al. (2006b) identify the nonlinearity, quantitatively, by the deviation between the H/V spectral ratios of strong and weak motions. Which was compared the deviation with the standard deviation of the weak motion and calculated as follow:

$$d(f) = \frac{s(f) - w(f)}{\sigma(f)} * 100\% \qquad (1)$$

where $s(f)$ is the H/V ratio of the strong motion event, $w(f)$ and $\sigma(f)$ are H/V ratio of the weak motion event and its standard deviation. Noguchi and Sasatani (2008) proposed to use the quantitative index of nonlinear site response DNL (Degree of Non-Linear site response) defined as follow:

$$\mathrm{DNL} = \sum \left| \log\left(\frac{R_{strong}(f)}{R_{weak}(f)}\right) \right| \bullet \Delta f \qquad (2)$$

where R_{strong} and R_{weak} are H/V spectral ratio of the strong and weak motions, and sum it from 0.5 to 20 Hz frequency band.

Due to only a few stations have weak motion records before the 2010 Darfield earthquake (we can found from the web recently), we selected the weak motion events before the 2011 Christchurch earthquake to quantitatively analyze the H/V ratios of strong and weak motion for other stations. The DNL values are calculated from the strong motion window (e.g. Red window in Figs. 4 and 5) of the 2010 Darfield and 2011 Christchurch earthquakes. Compared with the liquefaction areas of the Christchurch earthquake in Fig. 3b, we can found that the liquefaction areas located in the high DNL value and high PGA value (Fig. 2) areas.

CONCLUSIONS AND DISCUSSIONS

Liquefaction hazard occurred in the Christchurch area during the 2010 Darfield, New Zealand earthquake sequence. In this study, the horizontal-to-vertical spectral ratio method is used to identify the nonlinear site effects during the earthquake sequence. The preliminary results show that the nonlinear site effects existed in most alluvium area. The DNL between the H/V ratios of strong motion and weak motion are calculated in the frequency band of 0.5~20 Hz (Fig. 7). The liquefaction areas are within the high DNL and high PGA areas. Fig. 8 compares the DNL values and the PGAs for stations near Christchurch area. The DNL value seems has positive relationship with PGA value except some data points.

Due to the strong motion stations of the GeoNet do not have Vs30 information, the DNL value can not compare with the Vs30 now. Fig. 8 also tries to compare the DNL with the site classification of the strong motion station. Most data shown in Fig. 8 are site class D, it cannot show the relationship between DNL and site condition. If it can have more detail information, for example the Vs30, then we can compare the DNL value with Vs30. This information will be useful for engineering application.

ACKNOWLEDGMENTS

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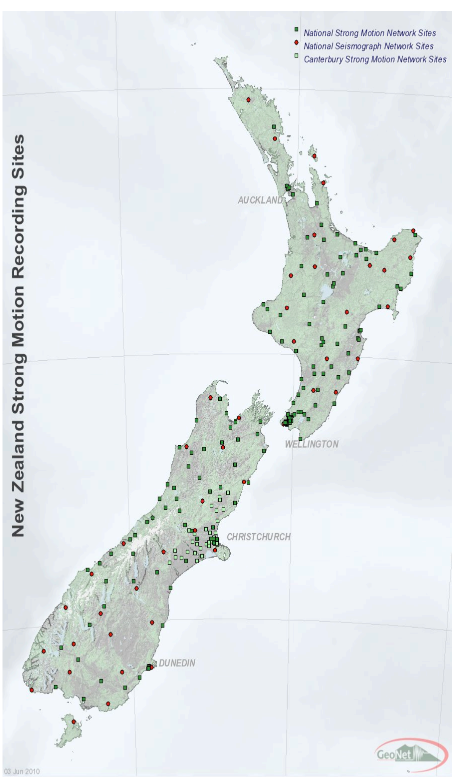
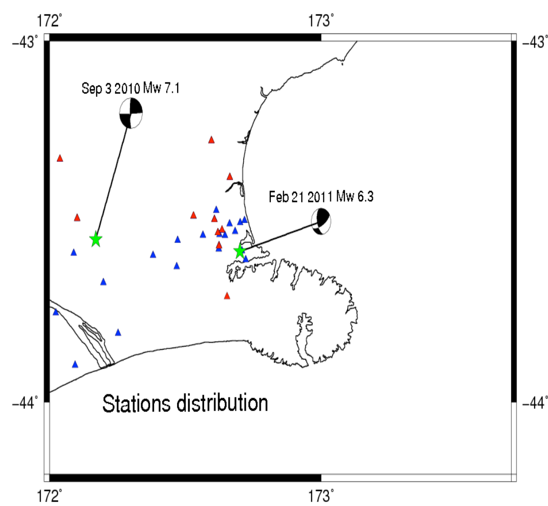
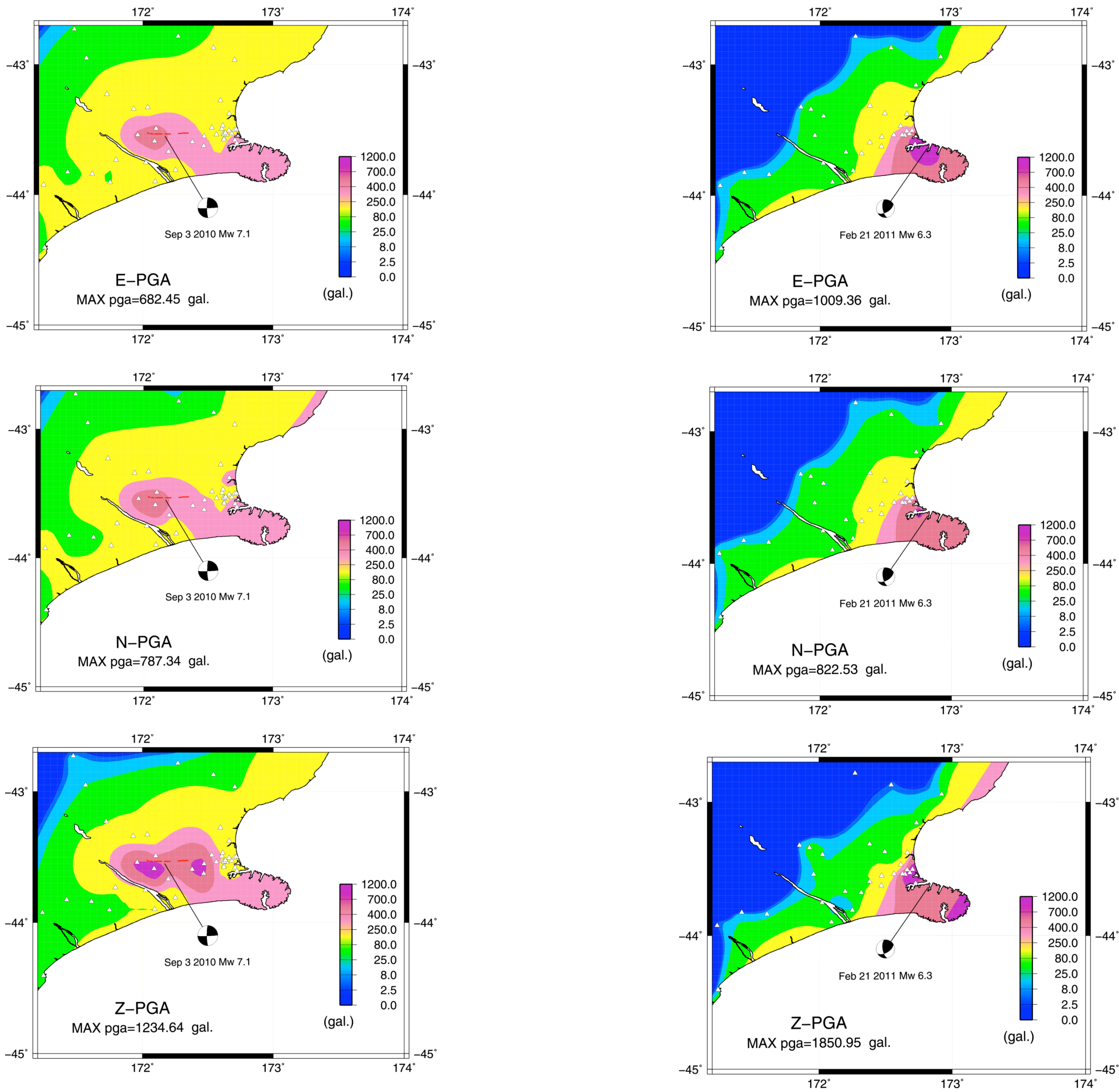


(a)



(b)

Fig. 1. (a) Strong motion station distribution in New Zealand; (b) Strong motion stations near the Christchurch area. Red triangles show the stations recorded more than five events before the Darfield earthquake.



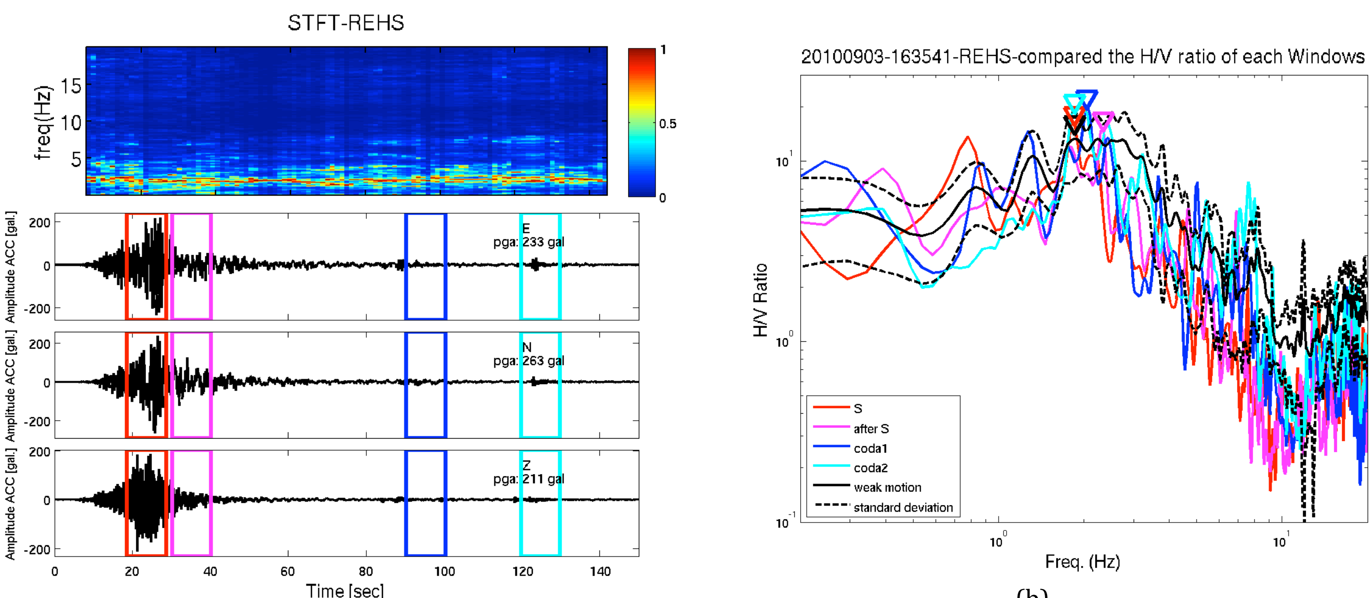
(a)

(b)

Fig. 2. PGA contours for (a) 2010 Darfield earthquake, and (b) 2011 Christchurch earthquake.

(a) (b)

Fig. 3. Liquefaction distribution in the Christcurch area during the (a) 2010 Darfield earthquake and (b) 2011 Christchurch earthquake. Brown color areas are the severe damage areas.



(a) (b)

Fig. 4. The time-frequency H/V spectra of the station REHS during the 2010 Darfield earthquake. (a) Time-frequency H/V spectra; (b) H/V ratios of different windows as shown in Fig. 3a. Black lines are the weak motion results before the 2010 Darfield earthquake.

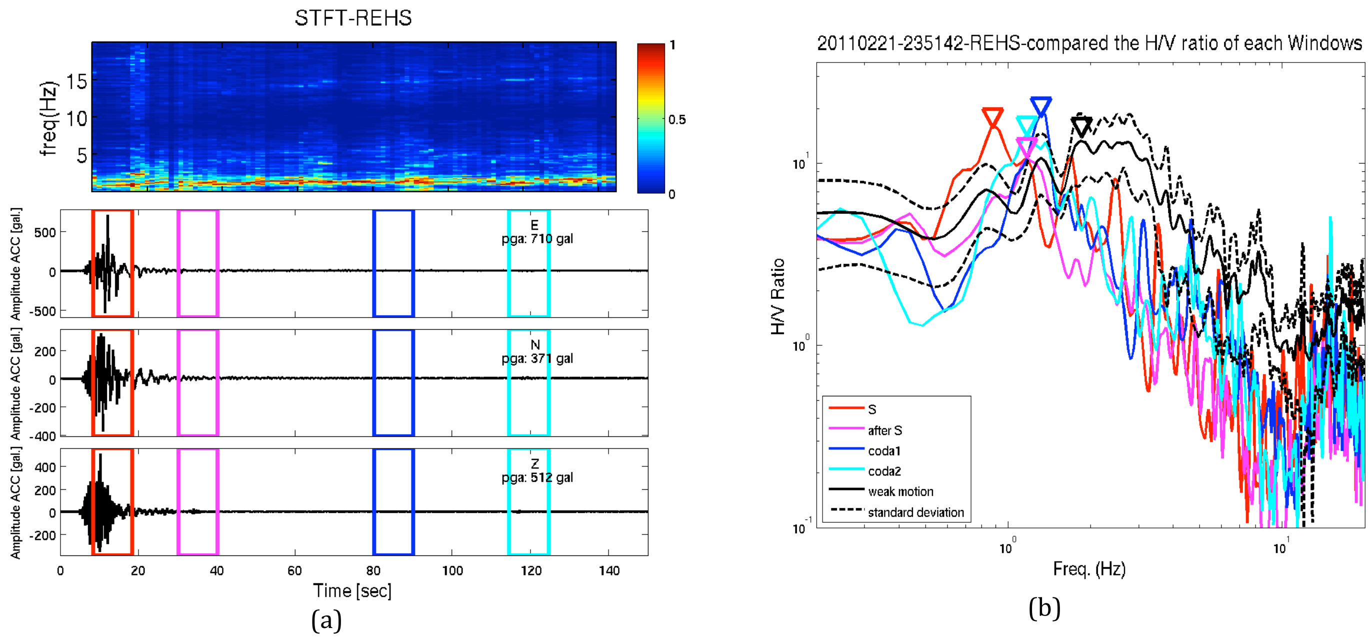


Fig. 5. The time-frequency H/V spectra of the station REHS during the 2011 Christchurch earthquake. (a) Time-frequency H/V spectra; (b) H/V ratios of different windows as shown in Fig. 4a. Black lines are the weak motion results before the 2010 Darfield earthquake.

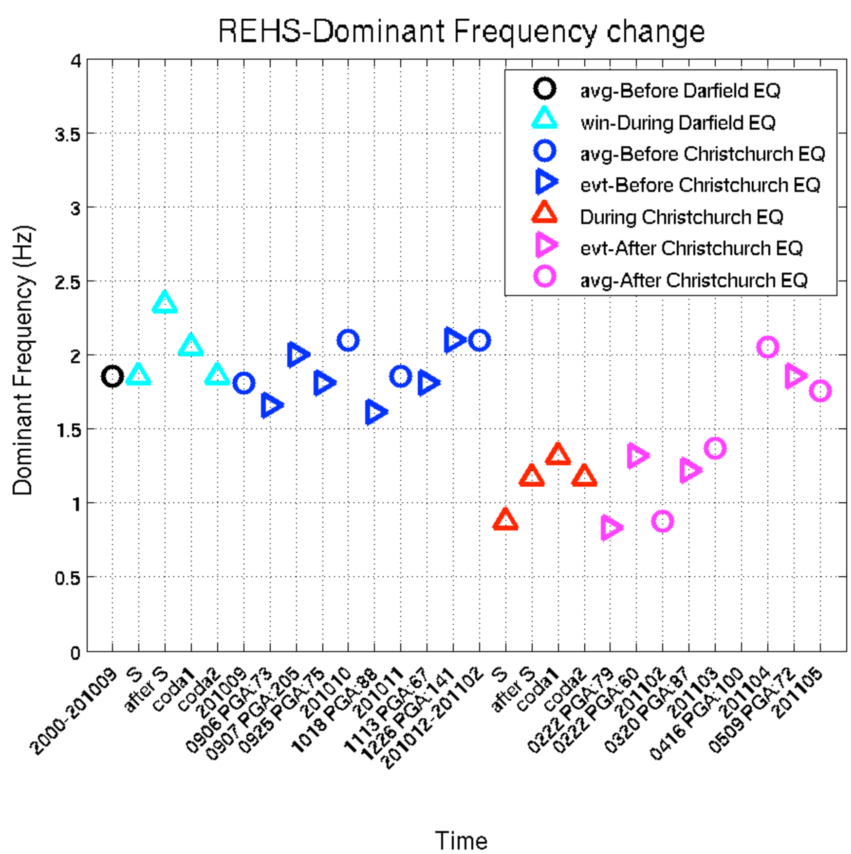


Fig. 6. Variation of the dominant frequency with time for station REHS by using the data from 2000 to May 2011. It clear shows that the dominant frequency shift to lower frequency during the 2011 Christchurch earthquake and back to around the same frequency range after April 2011.

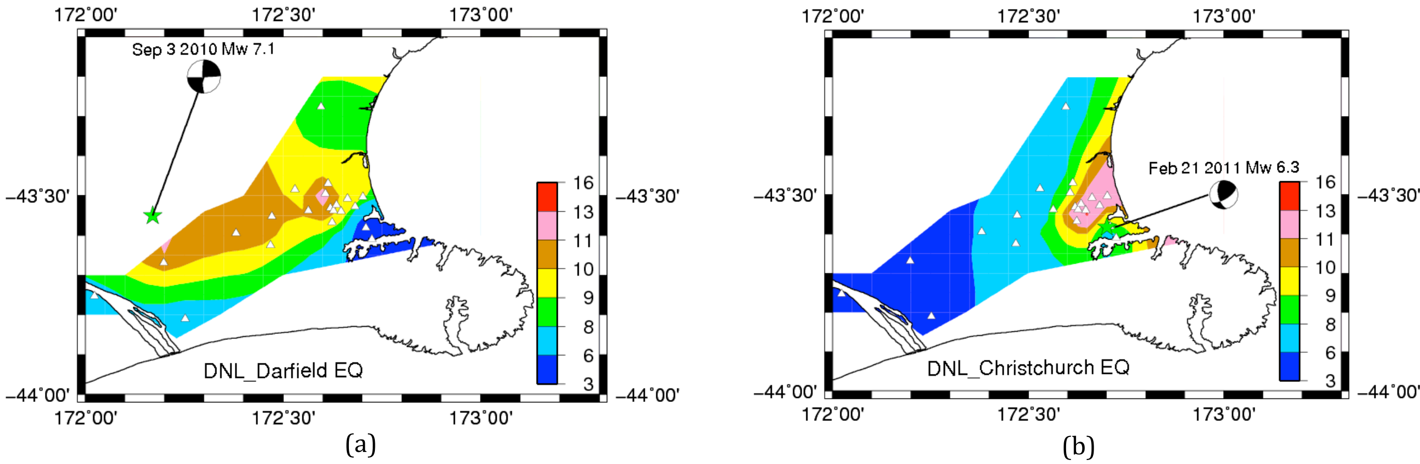


Fig. 7. DNL distribution of the (a) 2010 Darfield earthquake, and (b) 2011 Christchurch earthquake.

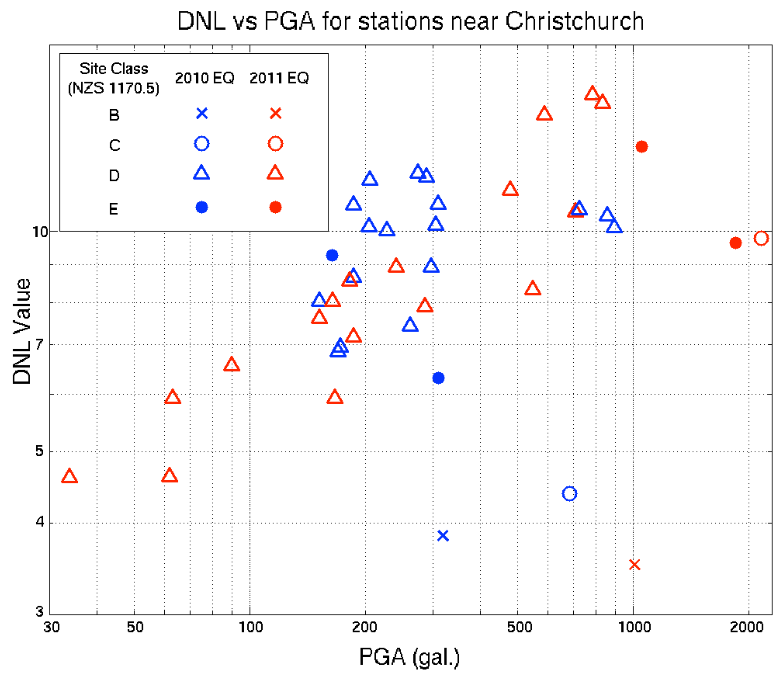


Fig. 8. Comparison of the DNL with the PGA value.