Correlation of Ground Motion Characteristics with Liquefaction in the Christchurch February 2011 earthquake

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ABSTRACT: Hit by two severe earthquakes in September 2010 and February 2011, the city of Christchurch and its environs have suffered extensive damage that has been augmented by phenomena of widespread soil liquefaction and associated ground deformations. This paper has been aimed to find out the quantifiable parameters that could provide a better insight to seismologists and engineers who try to systematically investigate the reasons behind soil failures that occurred in the February shaking correlating the soil behavior to the particular features of the recorded ground motions.

1 INTRODUCTION

The M_w = 6.3 earthquake of February 22 was the strongest seismic event in a series of damaging aftershocks in and around Christchurch after the Darfield earthquake on 4th of September in 2010. The source of the Darfield earthquake was in a sparsely populated area and thus it caused no life losses. Serious damage was mainly due to extensive liquefaction. By contrast, the Christchurch earthquake was generated on a fault in close proximity to the city, culminating in a death toll of 181 people.

The Canterbury Plains are covered with river gravels hiding any evidence of past fault activity in this region. The newly revealed Greendale fault was therefore completely unknown. Only a portion of it was revealed in the ground surface during the Darfield earthquake. Clearly the second fault (of February 2011) appears as a continuation of the first, although no fault structure directly connecting the faults has been recognized.

Thanks to a dense network of strong ground motion stations a large number of records have been obtained, providing valuable information on the event, and offering the possibility to relate damage versus ground shaking. Due to its magnitude, shallow depth and proximity the February earthquake proved particularly destructive for the Central Business District (CBD) of Christchurch, the buildings of which suffered extensive damage. In addition to structural damage due to high spectral accelerations, important soil-related failures have directly affected houses and bridges. Apart from the southern part of the city on the hills and the Lyttelton port area, the city is built on deep estuarine soil, which has been shaped in the last thousands of years with the ever changing riverbed. Fine sands that are the dominant soil type and the high ground water level have contributed to widespread liquefaction in each one or both events. Often accompanied by 'lateral spreading', liquefaction amplified the level of damage, resulting in failure of structures in CBD and surrounding areas.

2 STRONG MOTION RECORDS

Thanks to a dense network of seismographs covering the broader area of Christchurch (Figure 1) a large number of ground motions were recorded during the Christchurch February 2011 earthquake. The CBD area includes four seismic stations, i.e. CBGS, CCCC, REHS and CHHC. The first three records are truly free-field motions. CHHC was located near the base of a 2-story building and its motion may bear to some degree the effect of the structure. These ground motions may not have been the strongest ones recorded in terms of PGA values; however, due to certain features, their effect on structures or soils was detrimental.

There is a certain variation in the recorded acceleration time histories (Figure 1). For instance, the range of PGA values varies within a factor of 2, from 0.34g (CHHC-NS) to 0.72g (REHS-EW). A dominant common feature in all records is the sign of liquefaction: long period cycles with reduced acceleration amplitudes, occurring after a threshold acceleration has been reached. Soil softening due to excess pore water pressures in combination with sufficient acceleration values has led to amplification of large periods affecting a broad category of structures, as indicated by the acceleration spectra. Especially, the spectral amplification at periods exceeding 2 sec is attributed to the fact that once liquefaction has occurred, the overlying soil 'crust' oscillates with very low frequencies, causing the bulges observed in the acceleration spectra for periods of about 3 sec (see Youd & Carter (2005) for similar observations from the then available liquefaction-affected acceleration spectra).

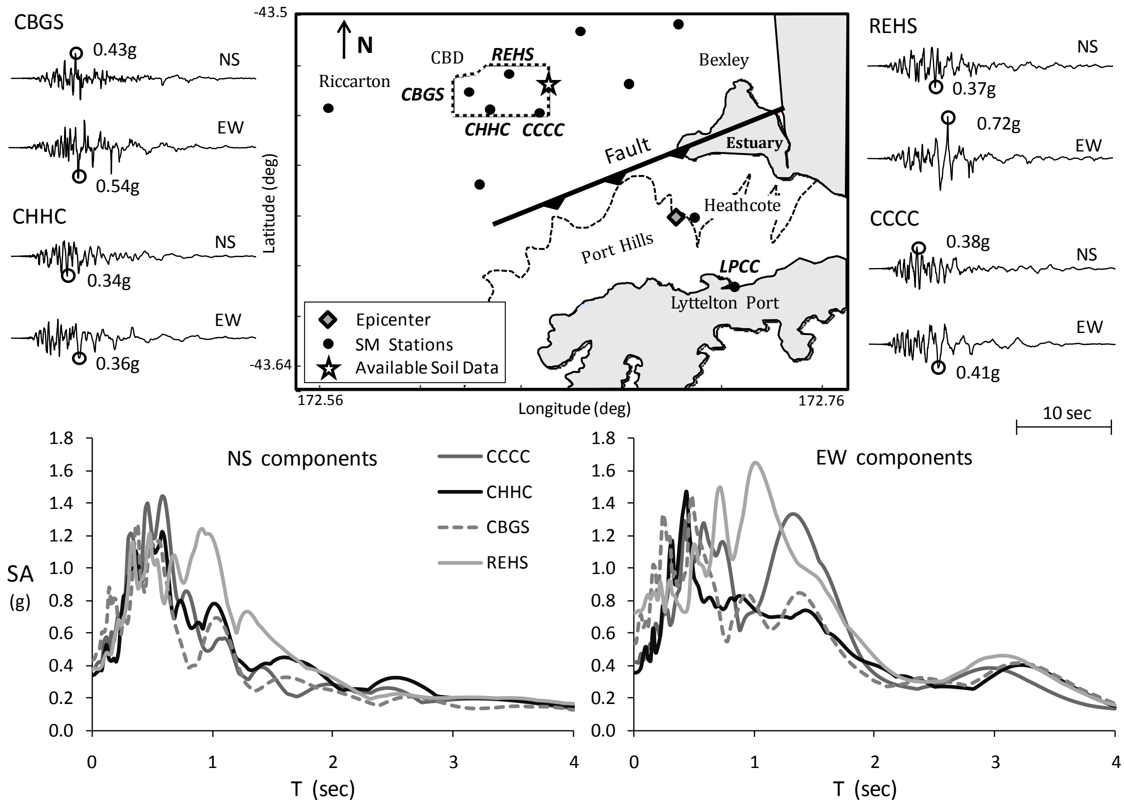

Figure 1. Map of the Christchurch broader area showing the intersection of the fault plane with the ground surface (from GNS Science), the location of the accelerograph stations, the epicenter, and the location with available soil data. Acceleration time histories and spectra of four CBD (Central Business District) seismic stations for NS and EW directions.

3 POLARITY OF THE RECORDED MOTIONS

The two orthogonal components of a record are usually aligned with North-South and East-West (Figure 1), or, ideally, if the faults were known, with Fault-Parallel and Fault-Normal, directions. Mathematically there is at least one specific angle at which a certain ground motion parameter, such as PGA, PGV or PGD, reaches a maximum, indicating the governing direction for that ground motion parameter and revealing a certain polarity of the recorded motion. Polarity plots can be useful in determining the dominant shaking direction of an earthquake and in unveiling any directivity effects (Shabestari & Yamazaki, 2003).

A first index of intensity is the value of peak ground acceleration (PGA), the spatial distribution of which is depicted on the map of Figure 2. Additionally, for the records from the four CBD

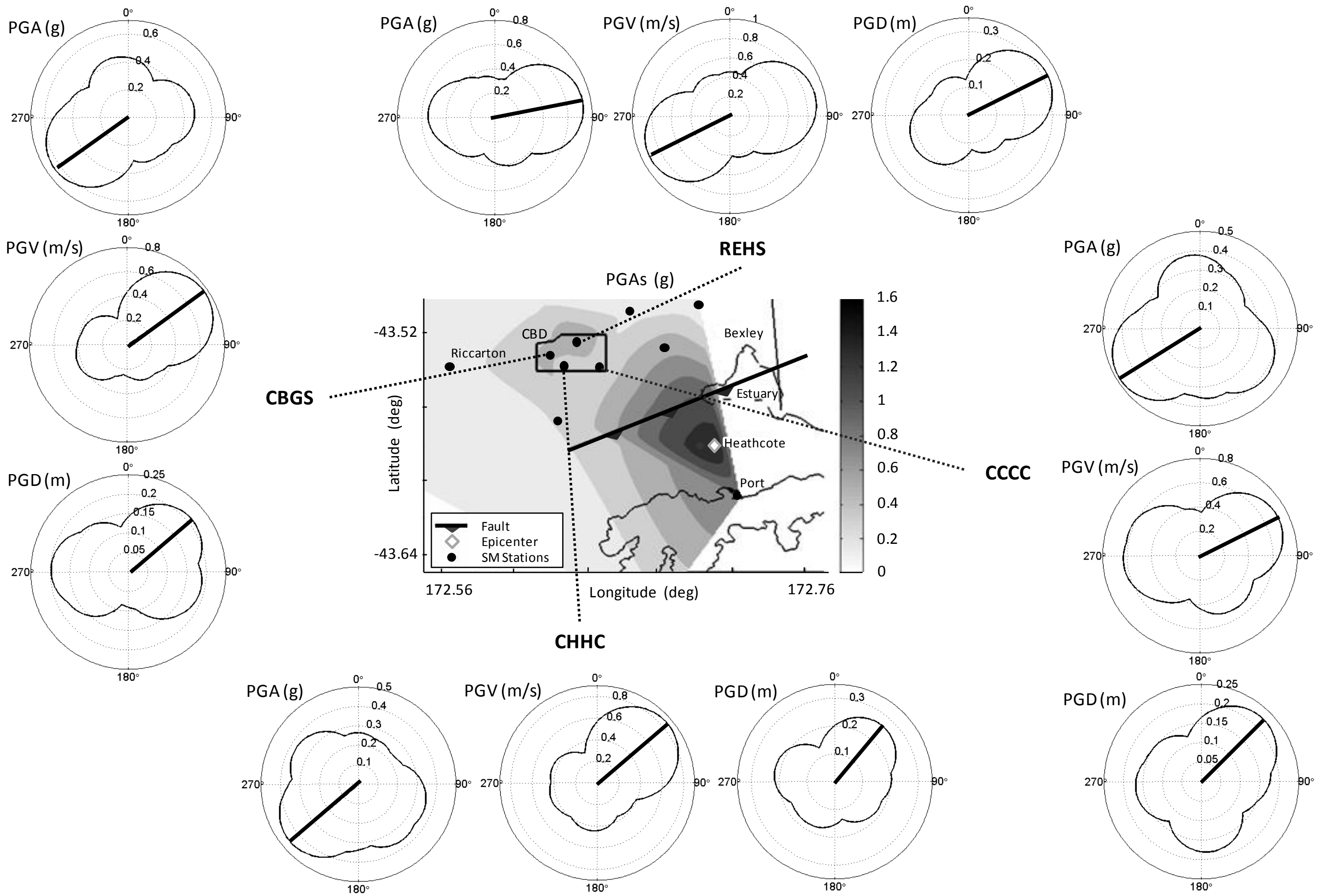

Figure 2. Observed polarity for the records in CBD in terms of peak ground acceleration, velocity, displacement. The contours of PGA on the map were computed by interpolation using all records in Christchurch.

stations (i.e. CCCC, REHS, CBGS and CHHC) the maximum peak values of ground acceleration, velocity and displacement are calculated trigonometrically, by varying the angle by 1^o between 0^o and 180^o, resulting in asymmetric plots of positive and negative maxima (in absolute terms). The graphs consistently exhibit distinct polarity in a direction that practically coincides with that of the fault line. Knowing the polarity of shaking may offer information on the rupture mechanism and insight into the dominant damage observed in the area of CBD.

4 LIQUEFACTION

The Christchurch urban area, extending from Riccarton in the west to Bexley in the east and reaching Heathcote valley and the Port Hills in the south, is located on Canterbury Plains and its dominant geomorphic feature is the river floodplains. In particular, the rivers of Avon primarily and Heathcote (secondarily), originating from various springs in western Christchurch, form endless meanders through the city and the eastern suburbs, as they head to the estuary near the sea. As depicted in Figure 3a, the subsoil in CBD systematically comprises profiles with random variations in layering in the upper 15-25 m (Cubrinovsky et. al, 2010; Toshinawa et al., 1997). The volcanic bedrock is located at an approximate depth of 400 m and emerges on the surface at the southern border of Canterbury Plains, forming the Port Hills of Banks Peninsula. Thick layers of gravel formations overlay the bedrock (Brown and Webber, 1992). The surficial sediments have an average thickness of about 25 m and consist of alternating layers of alluvial sand, silt and gravel. They have been deposited by overbank flooding (Eidinger et al., 2010) — hence, their loose disposition. In CBD, in particular, sand and non-plastic silt with low content of fines are the dominant soil types (Rees, 2010). The latter feature combined with the high ground water level (from 0 to 3 m) below the center of the city, explains the sensitivity to liquefaction.

There is significant variability of soil deposits within short distances that can differentiate the ground motion characteristics. For example, Toshinawa et al. (1997) describe the soil profiles of two characteristic sites 1.2 km distant, one consisting of only sandy gravels and sand close to CBGS seismic station (Figure 1), and the other comprising silt and peat deposits to a depth of 7 m close to REHS seismic station. According to the aforementioned paper, during a 1994 distant earthquake greater amplification was observed at the second site, close to REHS, in agreement with the records of February 2011 (Figure 1). However, both sites belong to the same broader classification of soft soils (class D) for structural design purposes in the New Zealand design standards (NZS 1170.5, 2004). This seems quite reasonable in cases of strong earthquakes, where the response of such type of soft mostly sandy soils is expected to be dominated by the effects of severe liquefaction.

To investigate the soil response in the CBD urban area during accounting for liquefaction effects, a typical "generic" soil profile was chosen (Figure 3a). Soil properties have been obtained from boreholes conducted close to the Fitzgerald Bridge, situated at the eastern part of CBD (see the star sign on the map in Figure 1). Standard Penetration Tests (SPT) values were obtained from Bradley et al. (2009) and Rees (2010). Shear wave velocity, Vs, values were based on empirical correlations with SPT (Dikmen, 2009).

With the "generic" soil profile defined, dynamic effective-stress analyses were conducted in order to capture the excess pore water pressure rise and dissipation, using the finite difference code FLAC (Itasca, 2005). The LPCC ground motion recorded on the volcanic outcrop at Lyttelton Port was selected as the (outcrop) input motion referred to the base of the gravel formations (Figure 3b). The presumption that this rock motion (the only one on [soft] rock in the area) is a suitable candidate for the base of CBD is only a crude approximation. Because, although, the LPCC and CBD stations have the same distance from the about 65°–dipping fault, LPCC lies on the hanging-wall and CBD on the foot-wall of this partly–thrust and partly–strike–slip fault. The NS and EW components of the LPPC record excited the soil column in two different one-dimensional wave propagation analyses. The numerical simulation involves the constitutive law of Byrne (1991) for pore pressure generation which is incorporated in the standard Mohr-Coulomb plasticity model.

In general, as one would expect, the results of the analysis in terms of acceleration time histories and acceleration spectra for the two components (Figure 3b) demonstrate that, as the shear waves propagate from the base of volcanic rock, the soil de-amplifies the low-period components of motion and amplifies those of high period. Moreover, the computed response on top of the dense gravel formation indicates that there is no substantial influence of the gravel layer in altering the input motion, other than de-amplifying the values in the high frequency range (above 5 Hz) and slightly amplifying lower frequencies. In addition, the peak ground acceleration values do not change.

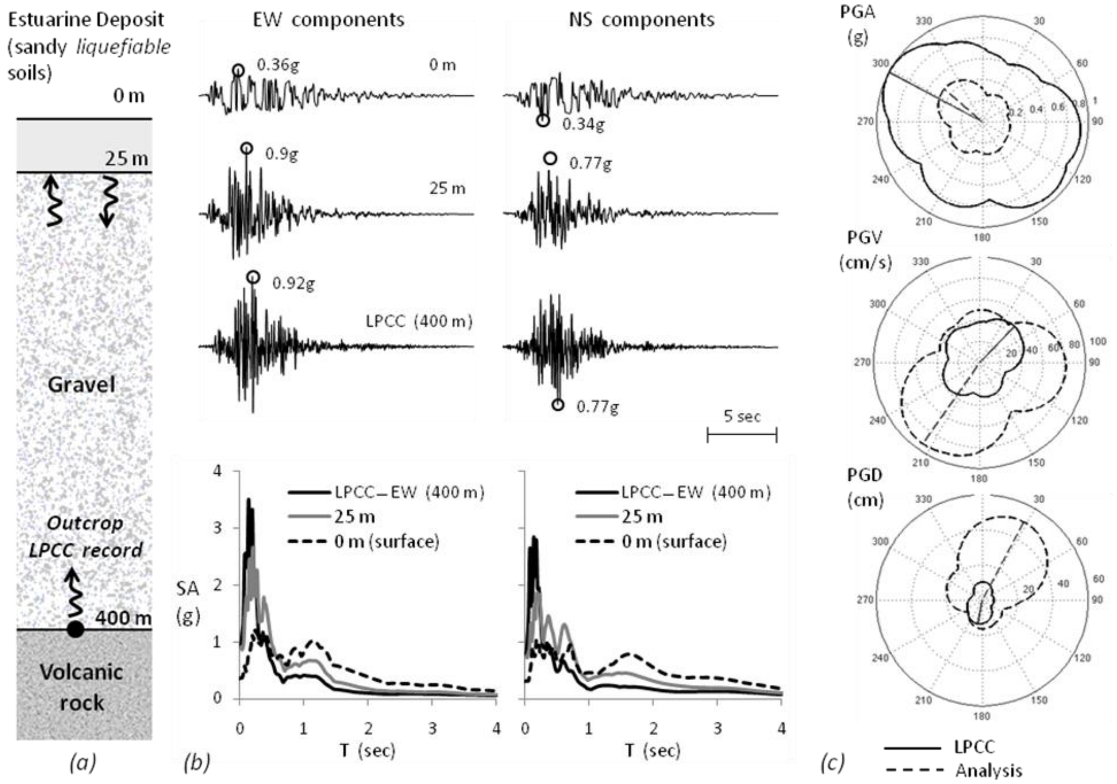

Figure 3. (a) Typical in-depth soil profile on CBD; (b) Accelerograms and response spectra of the LPCC record used as excitation (applied in outcrop), and at two different depths obtained from the analyses; (c) Polarity plots of LPCC record and output of analysis on the ground surface.

In contrast to the minor effect of gravel on the soil response, the surficial soil layers play a dominant role in defining the ground motion characteristics — hardly a surprise: these layers behave as a filter cutting-off the high frequency spikes, while the duration of motion cycles is lengthened. As a result, the peak accelerations have diminished to 0.35 g approximately in both directions. Moreover, in terms of spectral acceleration values, there is considerable spectral amplification to 1 g in the higher period range of up to 1.8 sec. Overall, both components show similar response, with certain disparities in the frequency content, e.g. NS output is richer in higher periods.

Polarity plots have also been constructed for LPCC motion and the computed ground surface motion. They are portrayed in Figure 3c. Evidently, there is no single (common) dominant direction for all PGA, PGV and PGD values, contrary to the consistency in polarity of the CBD records (Figure 2). Especially the PGA principal direction is normal (rather than parallel) to the fault. This discrepancy with CBD polarity might be attributed to the fact that Lyttelton is on the hanging wall side, whilst CBD lies on the foot-wall. For the ‘thrust’ component of faulting this difference may indeed have an effect, but this is an issue that needs further investigation and is beyond the scope of this paper. The polarity of the output diverges only slightly from the polarity of LPCC. The comparison of polarity plots demonstrates clearly the cut-off of PGA values in all directions and increase of PGV and PGD values. Evidently, the liquefied layers play the role of a seismic isolator reducing the acceleration amplitude of the wave components propagating through them.

To validate the analysis, a comparison between real records and numerical results is attempted. The record selected for the comparison, CBGS, is depicted on the map of Figure 1. The CBGS station is located in the Botanic Gardens and the recorder is housed in a really light kiosk (Figure 4a). Visible are the signs of liquefaction sandboils, although they had been cleaned following the earthquake (the picture was taken by our research team in April 2011 (Tasiopoulou et al., 2011)). No other facilities exist in the surroundings ensuring free field conditions. Moreover, the soil profile described by Toshinawa et al. (1997) is appropriate for this location.

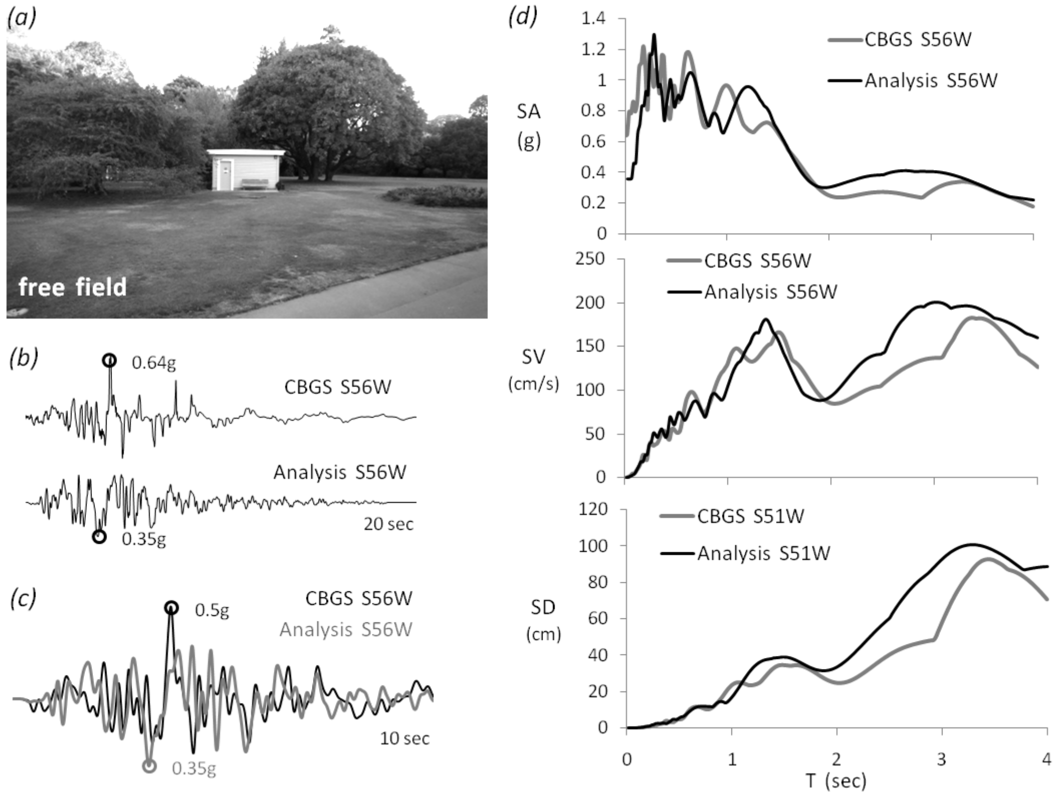

Figure 4. (a) The CBGS seismic station, with the remnants of liquefaction sandboils seen as scars on the grass; (b) acceleration time histories of CBGS: record and analysis; (c) Comparison of (the about) acceleration time histories after filtering them at 4 Hz; (d) Comparison of acceleration 5%–damped spectra between CBGS record and analysis.

As already discussed, LPCC and the four CBD records have different polarity. However, LPCC was the only option in search for a rock outcrop motion to be used as excitation in our analysis. That is why the comparison of spectra has been conducted in the direction of polarity of the CBGS record. For example, the strong PGA and PGV direction (polarity) for CBGS is approximately S56W and its PGD polarity is S51W. The acceleration time histories of the CBGS recorded and computed motions in the direction of S56W are depicted in Figure 4b. Although these time histories seem to differ, especially in terms of PGA values, a closer look reveals that they have certain common features, better depicted in Figure 4c after filtering-out components with frequency above 4 Hz. Notice in particular that the main pulse at 4 sec exists in both time histories. The response spectral SA, SV, and SD are compared in Figure 4d. The agreement of analysis with reality confirms that a realistic insight of the mechanisms of soil response during Christchurch earthquake have been gained from the analysis.

5 CONCLUSIONS

The M_w = 6.3 Earthquake of Christchurch was a surprising and unusual event which occurred in an unknown fault that had already been awakened from the September 2010 stronger earthquake, and it had a strong thrust component and a steeply dipping plane. The study focuses on the basic features of the recorded strong motions connecting the findings to the nonlinear behavior of the soil layers. Liquefaction, a phenomenon that has played a major and devastating role, has been examined through a "generic" downtown soil profile and dynamic effective stress analysis. The LPCC record was applied as the base excitation, being the only one available rock outcrop motion. Despite several uncertainties, the output spectra obtained from the liquefaction analyses and the one recorded in the free field in the Botanic Gardens have shown quite a satisfactory match provided that the compared spectra are aligned with the strong direction of the recorded motion. The dominant direction of the CBGS record is consistently almost parallel to the fault plane whilst the Lyttelton record exhibits more inconsistencies, something that may be related to the effects of the hanging-wall and the steep thrust–fault plane. The governing direction of each record has been found by simply turning the record in every possible direction with one-degree intervals and re-recording the strong motion parameters sought..

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