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Seismically induced boulder displacement in the Port Hills, New Zealand during the 2010 Darfield (Canterbury) earthquake

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An analysis of boulders displaced during the September 2010 M_W 7.1 Darfield (Canterbury) earthquake provides non-instrumental constraints on the variability, distribution and origin of strong ground motion during major earthquakes. Boulders ranging in mass from 10 to 5000 kg were displaced 8–970 cm laterally from hosting soil sockets of <1 cm to 50 cm depth at several sites in the Port Hills, roughly 35 km southeast of the earthquake epicentre. Boulder displacement was observed on N-striking (000–015°) ridges above c. 400 m elevation but not on NE-, NW- and SE-striking ridges. The prevailing boulder horizontal displacement azimuth of $250 \pm 20°$ is subparallel with the direction of instrumentally recorded transient peak ground horizontal displacements. Boulder displacement distance has no correlation with displacement azimuth, boulder mass or soil socket depth and has a partial correlation with slope angle. The lateral displacement of many boulders from low slope ($<10°$) ground surfaces on ridge crests exceeds nearby instrumentally recorded peak ground displacements at lower elevations by up to an order of magnitude, implying that seismic waves were amplified at the study sites. Preliminary 2-D FLAC modelling suggests that topographic amplification may explain this observation. The co-existence of displaced and non-displaced boulders at proximal (<1 m spacing) sites also suggests small-scale ground motion variability and/or varying boulder-ground dynamic interactions relating to shallow phenomena such as variability in soil depth, bedrock fracture density and/or microtopography on the bedrock–soil interface. Remapping of boulders following the February 2011 M_W 6.2 Christchurch earthquake reveals no subsequent relocation despite locally recorded horizontal and vertical ground accelerations well in excess of the Darfield earthquake and pervasive rockfalls and landslides elsewhere. This study successfully identifies some of the major controls on spatial ground motion variability at non-instrumented locations and highlights the complexity of ground response at different spatial scales and for different earthquake characteristics.

Keywords: Christchurch earthquake; Darfield earthquake; displaced boulders; FLAC; ground motion; New Zealand; Port Hills; site effects; topographic amplification

Introduction

Measurements of earthquake strong ground motion are important for understanding the spatial distribution, intensity and origin of seismic shaking, with relevance for the engineering of earthquake-resistant structures. In areas lacking dense seismometer arrays, it is necessary to use independent techniques to characterise earthquake ground motion. Coseismically displaced boulders may provide non-instrumental proxies of earthquake motion (Oldham 1899; Clark 1972; Bolt & Hansen 1977; Umeda et al. 1987; Iio & Yoshioka 1992; Ohmachi & Midorikawa 1992; Bouchon et al. 2000).

Several studies have concluded that local peak vertical ground accelerations (PVAs) must have exceeded 1 *g* in order to cause the observed lateral boulder displacements (e.g. Umeda et al. 1987; Iio & Yoshioka 1992; Bouchon et al. 2000). Shaking table experiments and numerical arguments based on empirical data, on the other hand, suggest that boulder 'upthrow' can be produced by strong horizontal ground motion alone, due to the impact and dynamic interactions of boulders with the sidewalls of ground sockets (e.g. Ohmachi & Midorikawa 1992). Many other studies have similarly concluded that lateral boulder displacements used to infer the 'upthrow' of objects do not require vertical ground accelerations in excess of 1 *g* (e.g. Newark 1973; Clark 1972; Bolt & Hansen 1977; Ohmachi & Midorikawa 1992).

There is a general paucity of comparisons between coseismic boulder displacement data (distance and azimuth), boulder characteristics (e.g. mass), site conditions (e.g. slope, soil thickness, socket depth, elevation, hosting ridge orientation) and seismologic attributes (earthquake magnitude, peak ground acceleration data, frequency content, etc.) that are necessary for providing insights into the relationships among displaced boulders and strong ground motion characteristics.

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Supplementary file: Part 1: Tables 1 and 2, including characteristics of displaced boulders, rockfalls, and non-displaced boulders in the Port Hills; Part 2: FLAC modelling methodology; and Part 3: complete results of four analysed profiles.

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Table 1 Seismic characteristics of Darfield and Christcurch earthquakes. PHDs, PVDs and PHGDs are peak horizontal displacements, peak vertical displacements and permanent horizontal ground displacements, respectively. Station codes are CRLZ, Canterbury Ring Laser; LPCC, Lyttelton Port Company; and HVSC, Heathcote Valley Primary School.

Earthquakes	Fault	Distance to study site (km)	PHAs and PVAs (g) CRLZ	PHAs and PVAs (g) LPCC	PHAs and PVAs (g) HVSC	PHDs and PVDs (mm) CRLZ	PHDs and PVDs (mm) LPCC	PHDs and PVDs (mm) HVSC	PHGD (mm)
Darfield	Strike-slip	39	0.12, 0.07	0.37, 0.15	0.66,0.28	75, 13	70, 41	87, 38	115–145 at study site
Christchurch	Dextral-reverse	5.6	–	1,0.41	1.5, 1.47	–	126, 59	149, 119	N/A

The M_W 7.1 Darfield (Canterbury, New Zealand) earthquake of September 2010 occurred on a previously unknown fault network beneath the Canterbury Plains approximately 40 km west of the Christchurch central business district (CBD) at a depth of c. 11 km (Quigley et al. 2010, 2012; Gledhill et al. 2011). An M_W 6.2 aftershock (Christchurch earthquake) occurred on February 2011 at depth of 5 km on a dextral-reverse fault network approximately 5 km southeast of the Christchurch CBD (Beavan et al. 2011). The seismological attributes of these earthquakes relevant to this study are presented in Table 1.

The Darfield earthquake generated an array of coseismic geomorphic features in the Port Hills south of Christchurch (Fig. 1) including displaced boulders, shattered ridges, landslides and other forms of ground damage (Fig. 2). The locations, physical attributes, hosting socket geometries, displacement directions and displacement azimuths of displaced boulders were mapped at several sites starting approximately two weeks after the Darfield earthquake, and key sites were revisited from two days following the Christchurch earthquake. In this study we present boulder displacement data, site characteristic data, seismologic data and preliminary results from finite difference models (Fast Lagrangian Analysis of Continua (FLAC) 6.0) in order to obtain non-instrument constraints on the intensity, spatial variance and origin of strong ground motion during the Darfield earthquake.

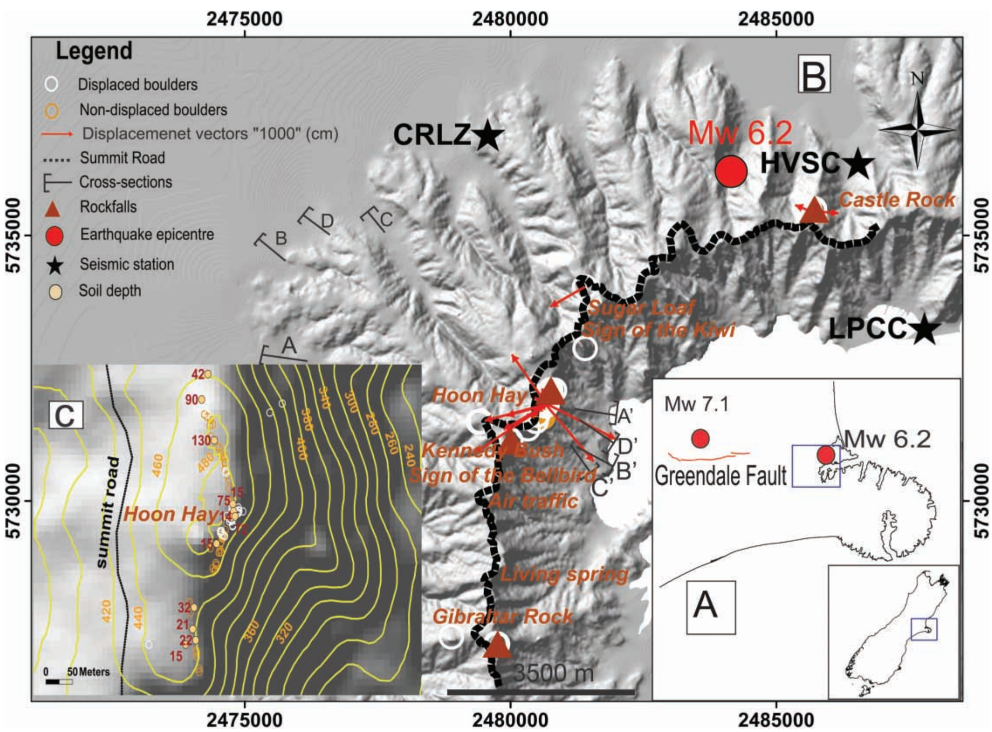

Figure 1 General view of the Port Hills. **A,** Location of study area is shown by a blue square on map of the Canterbury region and within South Island of New Zealand. **B,** 10 m hillshade model of the Port Hills showing the distribution of displaced boulders, rockfalls and seismic stations. Vectors show the 1000 × exaggerated horizontal displacement of boulders displaced from flat to gently sloping ground. **C,** Ridge crests of two modelled sites have been magnified to show the details.

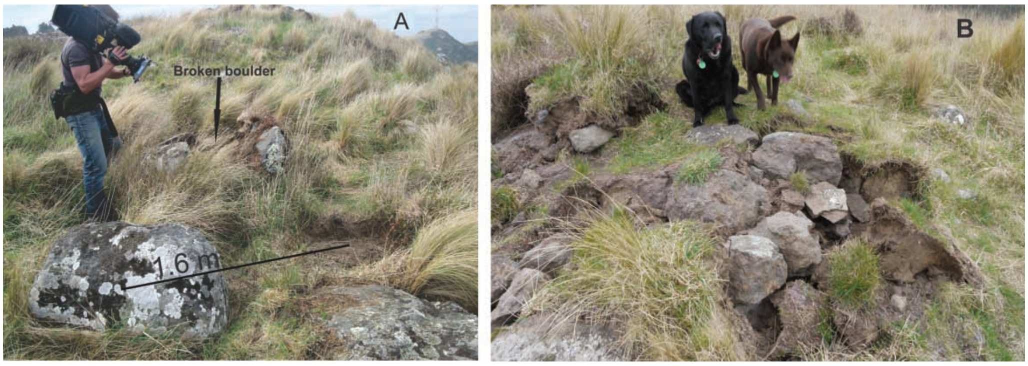

Figure 2 Displaced boulders at Hoon Hay site. **A,** Displaced boulder on the flat ground at ridge crest; turf between socket and boulder remained without damage. **B,** Coseismic shattered ridge; turf was torn up and boulders and soil were thrown away.

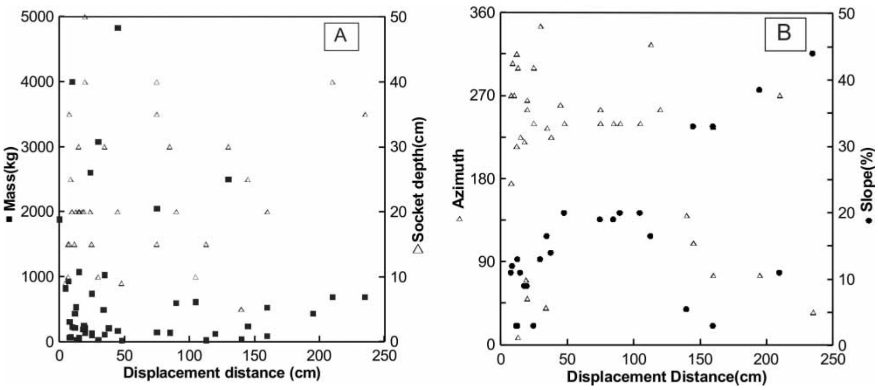

Figure 3 Plots of displacement distance of boulders versus **A,** Mass and socket depth and **B,** azimuth and slope.

Boulder displacement in the Darfield earthquake

Methodology

Fifty-four displaced basaltic boulders and tens of non-displaced boulders were mapped at various locations in the Port Hills following the Darfield earthquake (Figs 1, 2). Net displacement distances were measured from the centre of the identifiable pre-earthquake boulder location (soil socket) to the centre of the present resting position of the boulder. As most boulders were relocated at small distances (<2.5 m) on gentle ($<10°$) slopes, the reported displacement distances are primarily horizontal displacements. Boulder displacement azimuths were recorded and boulder dimensions (length, width and height) were combined with a basaltic density of 2.85 g/cm^3 to derive boulder masses (Figs 3A, 3B). Soil socket depths were measured in the field and estimated from field photographs, local slopes were measured using a clinometer (Figs 3A, 3B) and soil thicknesses were derived using a soil penetrometer. The orientations of ten linear segments of ridgeline crests in the Port Hills were measured and it was noted whether these ridges contained displaced boulders or not (Table 2).

Field observations

Thirty-eight (two-thirds) of the identified displaced boulders were concentrated at a prominent ridge crest c. 488 m a.s.l. in Hoon Hay Scenic Reserve (Fig. 1). Some of these boulders were displaced 0.75–1.6 m from flat or gently sloping (0–10°) ground with no geomorphic evidence of

Table 2 Azimuth measurements in ten places along the Port Hill ridgeline. Existence of displaced boulders or ground damage is indicated with ‘Yes’ or ‘No’.

Number	Location	Ridge azimuth	Displaced boulders
1	Hoon Hay	040	No
2	Hoon Hay	014	Yes
3	Kennedy Bush	015	Yes
4	East of Gibraltar	000	Yes
5	Castle Rock Ridge	013	Yes
6	Sign of the Kiwi	034	No
7	South of Castle. R	129	No
8	Sign of the Bellbird	026	No
9	Air traffic control	028	No
10	Living spring	343	No

sliding, rolling or being overturned on the surface (Fig. 2A). Other evidence for strong ground shaking at this site included cracks, rockfalls, a 23 m^2 area of shattered and disturbed turf and soil (Fig. 2B) and some boulders, weakened by pre-existing joints, that were broken and/or rotated in situ and split open. The largest crack to develop, located on the western flank 5 m below the ridge crest and oriented parallel to the topographic contour, measured 1.5 cm in width and was 3.25 m long. A rockfall and a slump occurred on the eastern flank of the ridge with volumes of c. 10.7 m^3 and 4.8 m^3 respectively. On an adjacent ridge (c. 450 m a.s.l. and c. 300 m south), only one big spheroid boulder was ejected from the ridge flank and the only ground damage at the crest was minor gaps formed between surface turf and rock outcrop.

Displaced boulders were observed, but to a limited extent, at several other sites around the Port Hills. At Kennedy Bush Scenic Reserve and Gibraltar Rock, where spurs are perpendicular to the Port Hills ridgeline (Fig. 1), several boulders were displaced from sloping ground. A big rockfall, sourced from a steep (c. 87°) NE-facing slope, caused ground damage, disturbed vegetation and crossed a walking track. Several smaller rockfalls were noted at Gibraltar Rock. At Castle Rock spur, displaced boulders were found on the flanks (Fig. 1). Rockfalls were also common at a steep outcrop along this spur, presumably because of the influence of well-developed columnar jointing. A rockfall sourced from the NE face of weathered and jointed basalt outcrop, with estimated volume of c. 1300 m^3, is considered to be the biggest rockfall triggered by the Darfield earthquake in the study site.

Non-displaced boulders with similar morphologies and in close proximity to displaced boulders are observed at all sites; this indicates small-scale (c. 1–5 m) spatial variability in ground motion or other conditions favourable for boulder displacement. Many boulders were observed to have millimetre to centimetre scale gaps between the boulder edge and the formerly flush edge of the soil socket indicating transient, but not necessarily permanent, coseismic boulder displacement.

All previously described sites were re-inspected 2 days after the Christchurch earthquake except for Castle Rock, which was inaccessible due to numerous rockfalls and slips blocking the road. Neither previously displaced boulders nor other boulders were relocated at any of the study sites. This is despite the Christchurch earthquake producing greater damage to road cuts in the area and higher accelerations being recorded by nearby seismic stations (Table 1). Landslides were considerably more numerous than the Darfield earthquake but were mainly distributed in the north-northeast part of the study area, closer to the earthquake epicentre (Hancox et al. 2011).

Analysis of displacement data

Coseismically displaced boulders in the Port Hills were only observed on ridges with azimuthal orientations of 000– 015° (Table 2). Many of these ridges comprise similar bedrock lithology and elevation, implying that ridge orientation may have played a role in generating the conditions required for boulder dislocation. Displaced boulders were only observed at elevations > 400 m a.s.l. with the exception of Castle Rock (360–420 m a.s.l.).

Boulders ranging in mass from 10 to 5000 kg were displaced 8–970 cm laterally from hosting soil sockets of < 1 cm to 50 cm depth (Fig. 3A). The prevailing boulder displacement azimuth is $250 \pm 20°$, although isolated displacement azimuths were recorded over a full 360° range. Displaced boulders at the Hoon hay site appear to exhibit bimodal displacements of 8–50 cm and 70–160 cm along an azimuth of 215–270°. Soil thickness varies over the range 15–32 cm on the site without displaced boulders and 14–130 cm on the Hoon Hay site, which includes most of the displaced boulders (Fig. 1). Further investigations are required to document whether small-scale thickness variations exist beneath each boulder displacement site.

No clear relationship is observed between displacement distance and mass, socket depth and displacement azimuth (Figs 3A, 3B). A partial correlation exists between slope and displacement distance, although significant exceptions exist with some of the largest displacements recorded on gentle (≤ 15°) slopes.

Field investigations suggest that boulders were either (a) ejected from a socket of soil (5 cm ≤ socket depth ≤ 40 cm) on sloping or relatively flat ground, with the largest travelling distances of 45–970 cm among the others or (b) were not ejected, but either slid along the local slope or became unattached within their soil sockets due to severe shaking. The displacement distance of group (b) was generally smaller (8–85 cm), but recorded as 130–160 cm where ground was steeper (slope > 30°).

The prevailing SW-directed boulder displacement azimuth range is subparallel with the NE–SW direction of instrumentally recorded transient peak horizontal ground displacements from the closest strong ground motion seismographs (Canterbury Ring Laser or CRLZ and Heathcote Valley Primary School or HVSC; Fig. 4, Table 1) and at high angles to the NW-orientated net permanent horizontal displacements interpolated for the study site from GPS and differential InSAR data (J. Beavan, pers. comm., 2012). Observed boulder displacements are therefore attributed to the dynamic phase of ground motion, occurring around the largest amplitude of the ground velocity (Iio & Yoshioka 1992) rather than the permanent tectonic deformation. Several measured boulder horizontal displacements, including boulders that show no geomorphic evidence for rolling or sliding (Fig. 2A), exceed the maximum instrumentally recorded horizontal displacements by an order of magnitude

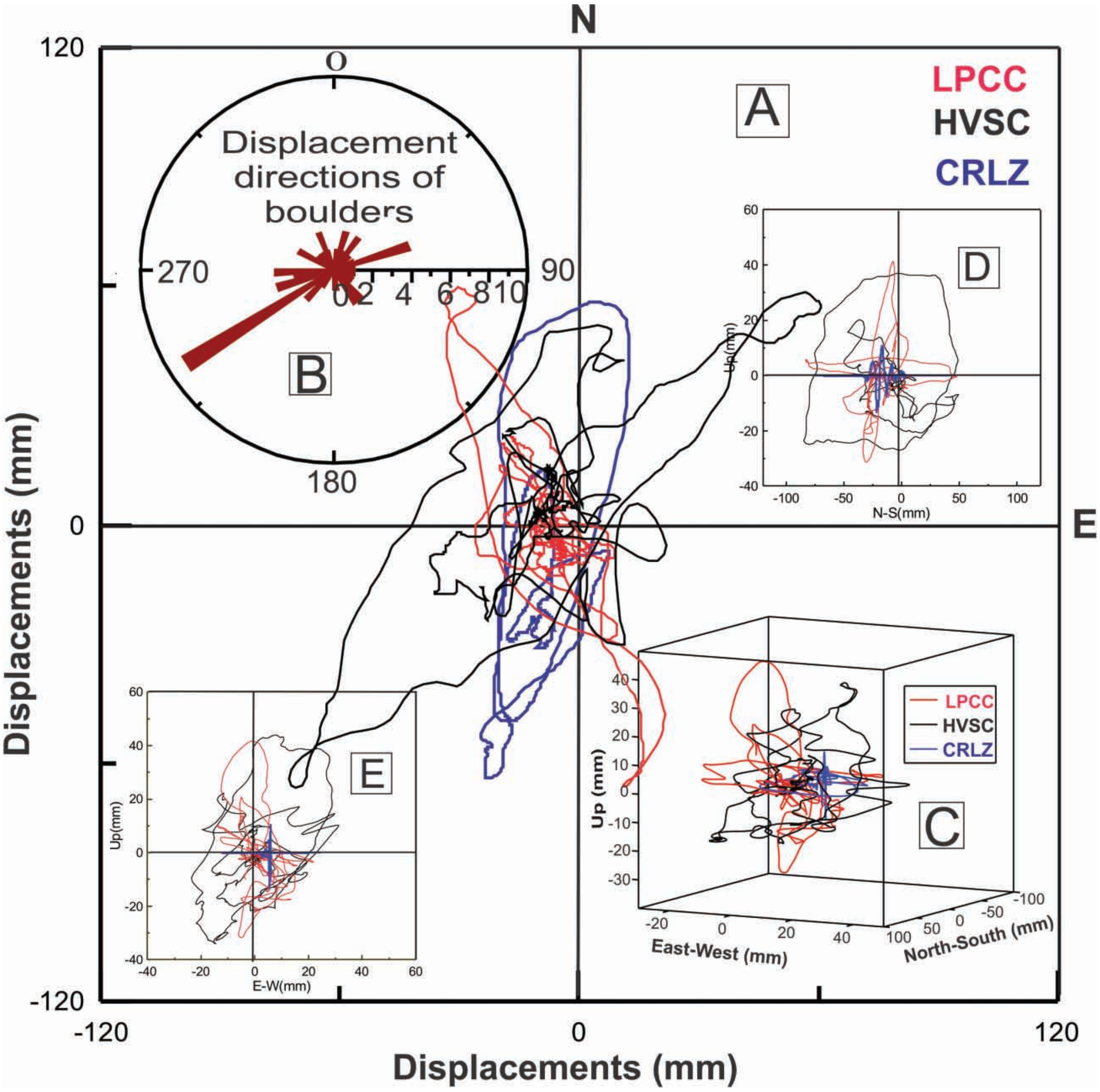

Figure 4 A comparison of observed and instrumentally recorded displacement directions. **A,** Horizontal displacement records of three seismic stations (LPCC, HVSC and CRLZ) for Darfield earthquake; **B,** rose diagram shows displacement directions of boulders measured in the field; **C,** 3D diagram of displacements; **D,** sectional view (up versus north–south); and **E,** sectional view (up versus east–west).

(Table 1) however; this implies greatly enhanced horizontal ground accelerations at the study site. Other studies on seismically induced boulder displacements have indicated that topographic amplification may have been important because of the distribution of displaced boulders being concentrated on ridge crests (e.g. Umeda et al. 1987; Iio & Yoshioka 1992). To investigate whether the topography of the Port Hills may have amplified the shaking response in the Darfield earthquake, we used 2D FLAC modelling.

Possible role of topographic amplification

Methodology

To assess whether ridge shape and earthquake frequency spectra may have influenced variation in displaced boulders, a 2D explicit finite difference program (FLAC 6.0) is used to model the shaking response at two sites: one for which boulders were displaced during the Darfield earthquake only, and the other for which boulders were present but not displaced during either earthquake. The methodology used follows that of McColl et al. (2012).

Both sites are on the crest of the semi-circular ridgeline defining the western skyline of the Lyttelton Harbour. They are within close proximity to each other and have almost similar ridge-crest orientation. For each site, two cross-sections (AA'-DD'; Fig. 1) were made using a 10 m digital elevation model (DEM) and data were imported into the FLAC software to define the model free surface for each site. The cross-section orientations were approximately perpendicular to the ridge crest to provide a range of likely topographic amplification. Null (zero stress) zones were applied above the free surface and an isotropic elastic constitutive material model represented the volcanic rock (modelled as homogenous basalt). To account for potential deviations from generic properties for basaltic rock masses at the locations, upper and lower bounds were selected and modelled separately.

Seismic inputs used in the model were based on the horizontal ground motion data available from the GeoNet website (www.geonet.org.nz) and applied as vertically propagating horizontal shear waves. Records of the Lyttelton Port Company (LPCC) seismometer for the Darfield and Christchurch earthquakes and records of the CRLZ seismometer for Darfield earthquake (no data were available from this seismometer for the Christchurch earthquake) were applied. Each model was run for both components of horizontal motion separately and for the upper and the lower bound rock properties to provide a range of likely ground motion amplifications.

The output from the models included peak ground velocities and accelerations (vertical and horizontal) recorded at the modelled ridge crest and slope base to assess the effect of topographic amplification of seismic shaking.

Results and interpretation

The results of topographic amplification analyses along profiles AA′ and BB′ for upper-bound rock properties have been selected as an example (Fig. 5). Amplification of horizontal ground velocity and acceleration at the ridge crest occurs at all sites, with a maximum amplification of around 80% of the ground motion at the base of the hill. The amplification factor varies significantly between seismic inputs, reflecting frequency-dependent response. Amplification of horizontal velocities and accelerations are higher for all seismic inputs at the site with displaced boulders (Fig. 5). It is difficult to determine what specific topographic conditions caused this difference, except to note that the elevation of the site with displaced boulders was slightly higher. On the contrary, greater vertical amplifications were modelled at the site without displaced boulders for three of the seismic inputs (Fig. 5). However, vertical accelerations presented here are merely a secondary product of horizontal motion of the hill and not representative of the real vertical ground motion, which is a result of additional wave forms not modelled here.

Discussion

A comparison of field measurements with seismologic data indicates that the predominant direction of coseismic boulder displacement in the Port Hills was governed primarily by the orientation of peak transient horizontal ground displacement during the Darfield earthquake. As variations in the timing and height of object upthrow and directions of object displacement are observed even in shaking table experiments with uniform objects, constant socket depths and purely horizontal seismic input (e.g. Ohmachi & Midorikawa 1992), it is not surprising that some variability is observed in both the displacement and displacement direction of the boulders we describe. The overall consistency between these datasets suggests that the displacement azimuths of coseismically displaced boulders have the potential to provide insights into the prevailing direction of transient peak ground deformation during major earthquakes in some instances.

In the absence of geomorphic evidence for rolling or sliding, the lateral displacement of some boulders on low-slope (<10°) surfaces exceeds instrumentally recorded transient peak horizontal ground displacements by more than an order of magnitude. This implies that horizontal ground displacements at the sites with displaced boulders

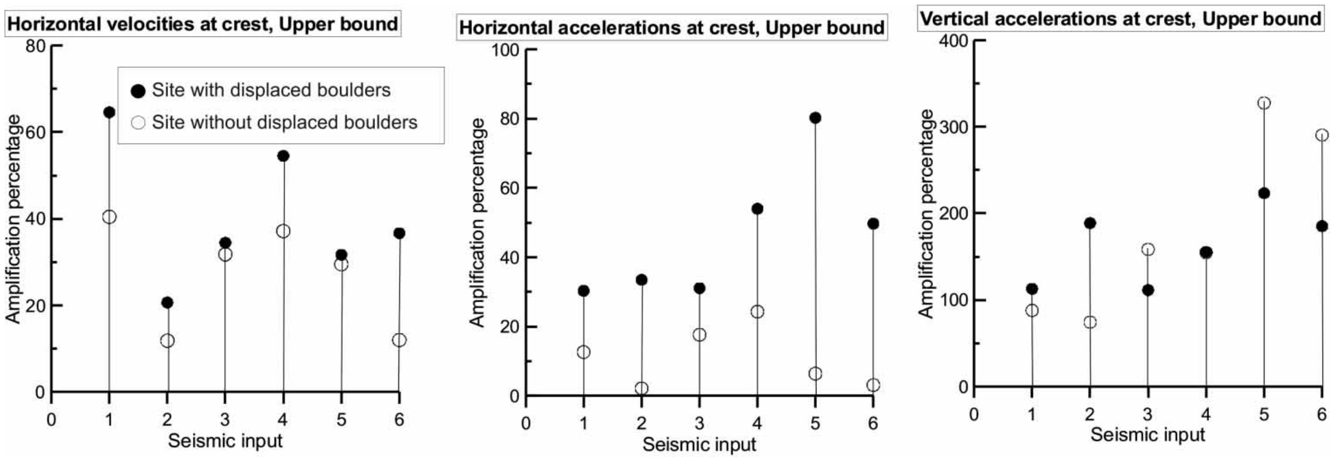

Figure 5 Results of topographic amplification modelling along profiles AA’ and BB’. Numbers 1–6 on the *x* axes show the different seismic inputs. 1, 2: LPCC data of S80W and N10W components recorded for the Darfield earthquake; 3, 4: CRLZ data of east and north components for the same earthquake; 5, 6: LPCC data of similar components recorded for the Christchurch earthquake.

were amplified relative to the seismometer sites. Field observations and FLAC modelling indicate that both ridge orientation and shape are likely to have amplified ground motions. The rather narrow azimuthal range in ridge orientations with displaced boulders is at a high angle to the seismic wave propagation direction from the Darfield earthquake, which is likely to have amplified incoming seismic waves at these sites.

The lack of correlation between boulder displacement, mass and socket depth is somewhat surprising, given that heavier boulders with deeper (or more cohesive) soil sockets might be expected to have smaller displacements. Beyond a threshold level, soil socket geometry and depth must play a role in influencing the ability of a boulder to be ejected and displaced; an extensively deep socket and/or an enclosing, highly concave-up socket geometry (e.g. a buried boulder) would prohibit a boulder becoming dislodged and ejected in an earthquake. In this instance however, for boulders that were ejected from a socket the depth of the socket does not seem be relevant in influencing the finite displacement distance.

The lack of a correlation between displacement, boulder mass and socket depth (Fig. 3A), together with the general lack of clearly distinguishable boulder impacts on the edges of some major sockets, suggests that some boulders may have been ejected from sockets due to PVAs $\geq 1\ g$ (Iio & Yoshioka 1992). Under such circumstances the mass of the boulder would be theoretically irrelevant to lateral transport distance, but shape, ground slope and transient vertical and horizontal ground motions at landing time of the boulder would be critical factors to determine the final displacement distances. At this stage we cannot resolutely prove that Darfield earthquake PVAs exceeded 1 *g* based on our observations. It remains possible that amplified peak horizontal accelerations (PHAs) and ground displacements at the study sites with PVAs $< 1\ g$ may have driven boulder displacement through impacts and 'ramping' of boulders against soil sockets and/or other dynamic site effects (Clark 1972; Newmark 1973; Bolt & Hansen 1977; Ohmachi & Midorikawa 1992).

The co-existence of morphologically similar displaced and non-displaced boulders in close proximity (Fig. 2A) suggests small-scale variability in boulder–ground dynamics and/or the frequency and intensity of strong ground motion relating to site effects. Microtremor measurements reveal that boulders on soft ground have differing vibration characteristics from the ground due to dynamic boulder–ground interactions (Ohmachi & Midorikawa 1992), and we suspect that these complex interactions may be partially responsible for the variability in displacement we observe here. Shallow site conditions such as variability in soil depth, bedrock fracture density and/or microtopography on the bedrock–soil interface may be possible sources to explain both differential site responses. The subsequent lack of boulder displacement at these sites in the Christchurch earthquake, despite higher recorded PHAs and PVAs at the closest seismometers (Table 1), highlights some of the challenges in directly inferring earthquake characteristics using 'non-instrumental' techniques such as displaced boulders. The shorter shaking duration of the Christchurch event, differing frequency contents (Fig. 6) and different source characteristics (e.g. location, depth and focal mechanism) are all factors that may have contributed to generating circumstances less favourable to boulder displacement in this earthquake.

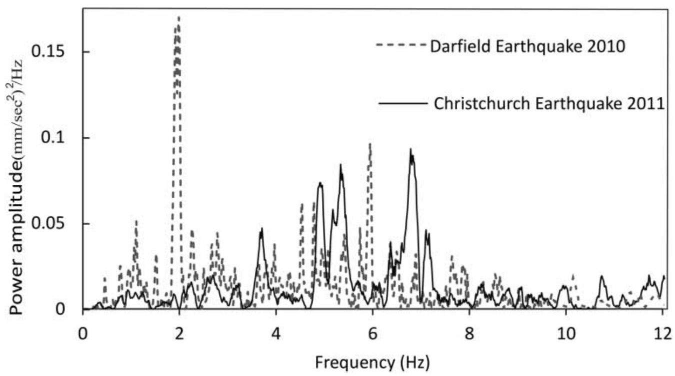

Figure 6 Seismograms in the frequency domain for Darfield and Christchurch earthquakes at LPCC site. This record is for the east–west component of ground motion. Power spectra analyses were performed using SeismoSignal 4.3.0.

Supplementary files

Supplementary file: Part 1: Tables 1 and 2, including characteristics of displaced boulders, rockfalls, and non-displaced boulders in the Port Hills; Part 2: FLAC modelling methodology; and Part 3: complete results of four analysed profiles.

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