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Coseismic landsliding during the M_w 7.1 Darfield (Canterbury) earthquake: Implications for paleoseismic studies of landslides

Timothy Stahl [a,*], Eric L. Bilderback [a,b], Mark C. Quigley [a], David C. Nobes [a], Chris I. Massey [c]

[a] Department of Geological Sciences, University of Canterbury, PB 4800, Christchurch 8140, New Zealand
[b] United States National Park Service, Geologic Resources Division, P.O. Box 25287, Denver, CO, USA
[c] Institute of Geological and Nuclear Sciences, PO Box 30368, Lower Hutt, New Zealand

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ABSTRACT

The head scarp of the Harper Hills landslide consists of ground cracks with vertical displacement and extension that opened during the 2010 Darfield (Canterbury) M_w 7.1 earthquake. The geomorphology of the cracks, regional geology and ground penetrating radar indicate that the landslide formed by bedding-controlled translation and joint-controlled toppling, and suggest incipient deep-seated movement. Crack depth and displacement along the head scarp vary along the ridge; maximum values are located where the head scarp is closest to the local ridge line. Increased seismic shaking due to topographic and geometric amplification of seismic waves is suggested as an explanation for this relationship. An excavation across the head scarp revealed no evidence of prior slip events over a time period that is likely to exceed the return period (1000–2500 years) of peak ground accelerations experienced at this location in the Darfield earthquake. We suggest that specific seismologic attributes of the Darfield earthquake may have influenced the location of landsliding in this instance. Studies of paleolandslides must consider crack preservation potential as well as complex source/site effects that may complicate estimates of acceleration return periods from the subsurface investigation of individual landslide head scarps.

1. Introduction

Earthquake induced landslides are a major hazard in susceptible regions. The understanding of seismic conditions under which landslides are triggered is assisted by empirical data from past landslides. Characteristics of strong ground motion may be ascertained by combining geological and geomorphologic studies with simple back-analysis models of slope stability (Jibson and Keefer, 1993; Jibson, 1996, 2011). These studies are of interest to paleoseismologists because landslides have the ability to provide a history of earthquake-induced strong ground motion at a site independent of fault studies.

Where deep-seated landslides have been preserved in the landscape, geomorphic mapping and trenching can yield information on ground failure (e.g. Nikonov, 1988; Nolan and Weber, 1992; McCalpin and Irvine, 1995; Nolan and Weber, 1998; Onida et al., 2001; McCalpin and Hart, 2002; Gutiérrez et al., 2010a; Hart et al., 2012; Moro et al., 2012; Carbonel et al., 2013). Trench studies allow determinations of landslide kinematics and movement rates that can help distinguish whether motion is episodic or progressive (Agliardi et al., 2001; Johnson and Cotton, 2005; Gutiérrez et al., 2008, 2010b). Without a detailed inventory of mechanical rock properties, ground water conditions, and a range of possible seismic inputs and site-response characteristics, unambiguous evidence of a seismic origin is often difficult to obtain. In areas of active faulting, the determination of a seismic or aseismic origin, and the causative fault source, has a significant impact on determining hazard.

In this paper, we present a geomorphic and subsurface study of ground cracks that opened coseismically during the 2010 Darfield earthquake in New Zealand. Trenching and ground penetrating radar (GPR) are used to investigate the kinematics, morphology, and failure mechanism of the landslide. We conclude with suggestions for incorporating subsurface records of strong ground motion from landslides into paleoseismic analyses.

2. Geologic and tectonic setting

2.1. Darfield earthquake

The M_w 7.1 Darfield (Canterbury) earthquake (henceforth the Darfield earthquake) in New Zealand was caused by rupture on a series of previously unrecognized faults underlying the low relief Canterbury Plains (Fig. 1; Beavan et al., 2010; Quigley et al., 2010; Gledhill et al., 2011; Beavan et al., 2012; Elliott et al., 2012; Quigley et al., 2012). The earthquake initiated on the steeply dipping, reverse Charing Cross fault which triggered predominantly strike-slip motion on three to four E–W to NW–SE striking Greendale Fault segments. Two other strike-slip faults intersecting the main Greendale Fault traces and a

* Corresponding author. Tel.: +64 212861202.
E-mail address: stahl.geo@gmail.com (T. Stahl).

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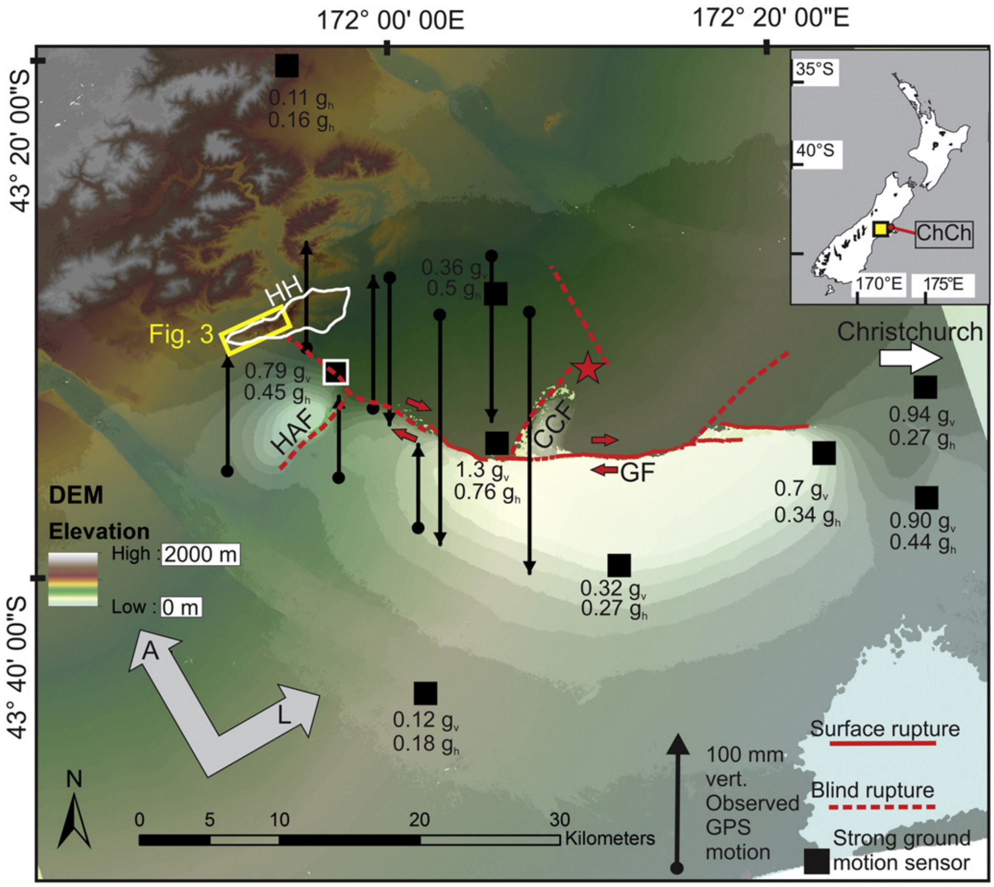

Fig. 1. Map and study site location. 15 m Digital Elevation Model (DEM) showing (i) Location of faults involved in the 2010 Darfield earthquake: Greendale fault (GF), Hororata anticline fault (HAF), Charing Cross Fault (CCF) and other unlabeled structures from Beavan et al. (2012); ii) DInSAR interferogram showing relative motion of faults with respect to the satellite heading direction (A) and satellite look direction (L). Lighter areas moved towards the satellite (up or in the direction of L), and darker areas moved away; iii) selected GPS stations with absolute motions; iv) selected strong ground motion sites with vertical and horizontal PGAs reported from Bradley (2012). White outlined station is HORC (see text for discussion); and v) location of the Harper Hills (white outline on the DEM) and the field area (Fig. 3).

second high-angle, blind reverse fault to the West (the Hororata Anticline Fault, HAF) also ruptured (Beavan et al., 2012; Elliott et al., 2012; Jongens et al., 2012). Differential interferometric synthetic aperture radar (DInSAR) (Fig. 1) highlights the relative motions of the major fault planes towards (lighter) and away from (darker) the line of sight of the recording satellite (Beavan et al., 2010). GPS measurements and other survey techniques indicate a maximum of 1.4–1.6 m vertical, normal displacement on the western segment of the Greendale Fault at the surface and 0.4 m uplift on the intersecting HAF, both NW-side up (Beavan et al., 2010, 2012; Duffy et al., 2013).

Peak ground accelerations on the Canterbury Plains reached a maximum of ~1.3 times that of gravity (g) near the Greendale Fault (Gledhill et al., 2011; Bradley, 2012). Finite-element modelling of uninstrumented ridge-tops in the Port Hills (east of the Greendale Fault) where boulders were displaced in the Darfield earthquake indicates frequency-dependent amplification of PGAs of up to 80% greater than at the base of the hills (Khajavi et al., 2012). The multiple-fault rupture contributed to complex and varying waveforms at recording stations, though in general accelerations recorded within 25 km of the Greendale Fault all exceeded 0.1 g (horizontal and vertical over 0.01–10.0 s period) with 5–95% significant durations of 20–30 s (Bradley, 2012).

2.2. Harper Hills

The Harper Hills are located 20 km west of the epicenter of the Darfield earthquake and 9 km northwest of the up-dip projection of the HAF (Fig. 1). The south-western 5 km of the E–NE trending strike-ridge is located on the hanging wall of both the HAF and the subsurface extension of the Greendale Fault (see Fig. 1). The nearest strong motion seismometer ('HORC', Hororata School, Fig. 1) recorded a peak vertical acceleration of 0.79 g and a peak horizontal accelerations of 0.45 to 0.51 g (using methods of Bradley, 2012 and GeoNet for horizontal accelerations, respectively). The 5–95% significant duration was markedly shorter for HORC (8.7 s) compared with stations further away from the causative faults (Bradley, 2012). Horizontal accelerations were strongest in W–NW/E–SE directions with the highest vertical accelerations recorded in the NW and SE quadrants (Fig. 2; 0.1 Hz high-pass filtered data currently held by GeoNet).

The Harper Hills strike-ridge is asymmetric with a steep scarp slope (40–70°) and gentle dip slope (20–40°) defined by joint and bedding planes, respectively (Figs. 3 and 4). It is one of the easternmost topographic highs in the foothills of the Southern Alps despite the relatively subdued 210 m of relief. The regional geology consists of SE-dipping Cretaceous–Tertiary sandstones, volcanics, and locally-mined beidellite–montmorillonite–bentonite units of the Burnt Hill Group (Carlson et al., 1980; Browne, 1983). On the scarp slope, jointed blocks of the Upper Miocene Harper Hills Basalt can be observed conformably overlying well-bedded Sandpit Tuff. Pliocene gravels overlie the Burnt Hill Group on the dip slope of the field area. North-east of the field area, Forsyth et al. (2008) mapped undifferentiated Quaternary landslide deposits along the dip-slope below the Harper Hills Basalt (Fig. 3). The Hororata Fault (a different structure than the HAF, which ruptured in the Darfield earthquake, Fig. 1) bounds the north-eastern section of the Harper Hills (Fig. 3).

The Harper Hills Basalt is identifiable as a prominent scarp along the length of the Harper Hills. Rolling hills with ~10 m scale local relief,