Recurrent liquefaction in Christchurch, New Zealand, during the Canterbury earthquake sequence

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ABSTRACT

Continuous observational monitoring of a study site in eastern Christchurch, New Zealand, following the 2010 Mₜ 7.1 Darfield earthquake has recorded ten distinct liquefaction episodes in the mainshock–aftershock sequence. Three nearby accelerometers allow calibration between the geological expressions of liquefaction and the intensity of earthquake-induced surface ground motion at the site. Sand blow formation was generated by Mₚ 5.2–7.1 earthquakes with Mₜ 7.5–normalized peak ground accelerations (PGAₜ) of ≥ 0.057 g (acceleration due to gravity). Silt drapes between successive sand blow deposits provide markers for delineating distinct liquefaction-inducing earthquakes in the geologic record. However, erosion quickly modifies the surface of sand blows into alluvial and aeolian forms that complicate geologic diagnosis. The two feeder-dike generations identified in subsurface investigations significantly underrepresent the number of liquefaction-inducing earthquakes due to extensive dike reactivation. New constitutive equations enable PGAₜ variations to be estimated from the thickness and areal extent of sand blows.

INTRODUCTION

Cyclic shearing of loosely compacted, fluid-saturated sediments during earthquake-induced ground motion results in excess pore-water pressure and reduced shear strength in the affected media. Liquefaction occurs when excess pore pressures reach the initial vertical effective stress and is commonly accompanied by significant vertical (i.e., subsidence) and/or lateral (i.e., lateral spreading) ground movement. Liquefaction-induced ground deformation may result in severe infrastructure damage (e.g., Youd, 1986) and associated financial loss. Understanding the seismologic and geologic conditions under which liquefaction occurs and the preservation potential of liquefaction-induced features in the geological record are important for reducing societal vulnerability to earthquakes (e.g., Sims and Garvin, 1995; Green et al., 2005).

The ongoing Canterbury earthquake sequence (CES) in New Zealand’s South Island includes the 4 September 2010 Mₜ 7.1 Darfield mainshock, and 45 Mₚ ≥ 5.0 and 3 Mₚ ≥ 6.0 subsequent aftershocks (Fig. 1A). The most damaging aftershock was the 22 February 2011 Mₜ 6.2 Christchurch earthquake that caused 185 fatalities. Land and infrastructure damage due to spatially extensive and recurrent liquefaction (Fig. 1B) resulted in a central government buyout of thousands of residential properties in eastern Christchurch at an estimated cost of over NZ$1 billion (http://www.stuff.co.nz/the-press/news/6489488/Red-zoned-homes-could-ve-been-saved). The lead author lived in one of these properties during the CES and photographically documented (Fig. 2) and mapped (Fig. 3) the areal extent of sand blows at this location following each successive liquefaction-inducing earthquake. Subsequent trenching investigations were conducted to reveal
the subsurface architecture of sand blows and feeder-dike systems (Figs. DR1 and DR2 in the GSA Data Repository1). In this paper, detailed geologic investigations are combined with proximally derived strong ground motion data to infer the approximate liquefaction-triggering threshold and geological controls on the surface manifestation of liquefaction at the study site. These data are further used to investigate the feasibility of obtaining robust seismologic information from the geologic record of paleoliquefaction.

GEOLOGIC AND SEISMOLOGIC SETTING

The city of Christchurch (population 360,000) is predominantly located on a low-relief, low-elevation (0–20 m above sea level [asl]) alluvial landscape (Fig. 1A). Much of the central and eastern city is built upon alluvial silt and sand deposits, drained peat swamps and estuaries, sand of stable to semistable dunes, and underlying marine sands (collectively referred to as the Christchurch Formation) that formed as sea levels transgressed then regressed from a mid-Holocene highstand that reached to ~1 km west of Hagley Park at 6.5 ka (Fig. 1B) (Brown et al., 1995). High water tables (typically 1–2 m depth) and the loose, consolidated nature of Holocene fine-grained sands and non- and low-plastic silts limit soil cementation and aging effects. These sediments pose a long-recognized liquefaction hazard for Christchurch (Elder et al., 1992) that was dramatically confirmed during the CES (Fig. 1B) (Cubrinovski et al., 2012).

At least five earthquakes since A.D. 1869 have generated Modified Mercalli Intensities (MMIs) ≥6 in central Christchurch (Downes and Yetton, 2012). The CES initiated with the rupture of at least seven distinct faults in the Charing Cross–Greendale fault system during the Darfield earthquake (Fig. 1A) (Beavan et al., 2012; Quigley et al., 2012). An energetic aftershock sequence including the 22 February 2011 earthquake cluster (M 6.3, 5.8, and 5.9 earthquakes within 2 h), the 13 June earthquake cluster (M 5.6 and 6.4 earthquakes within 1 h 20 min), and the 23 December earthquake cluster (M 5.8 and 6.0 within 1 h 20 min) followed (Fig. 1A).

METHODS

The study site is located at 11 Bracken Street, Avondise, in eastern Christchurch, within...
overbank silt and fine-grained sand surface deposits (Fig. 1B). The residential dwelling at the study site was occupied by the lead author through the CES until August 2011, and subsequently revisited following aftershocks with recorded peak ground accelerations (PGAs) of ≥ 0.1 g on local accelerometers. New sand blows were identified and photographed (Fig. 2) within 3 h of individual earthquakes or earthquake clusters. The study site was cleaned of all CES earthquakes in the sand blow–feeder dike system (Fig. DR2).

Strong-ground-motion data for 38 $M_s \geq 4.5$ earthquakes was obtained from accelerometers at distances of 1.61 km (GeoNet station PRPC), 1.78 km (station SHLC), and 2.33 km (station CCCC) from the study site using the GeoNet Strong Ground Motion database (http://info.geonet.org.nz/display/appdata/Strong-Motion+Data) (Fig. 1B). Recorded two-component PGAs were linearly interpolated for the study site using distance-weighted averaging and converted to geometric mean PGAs. The effect of shaking duration and frequency content were accounted for using a magnitude scaling factor, MSF. The equivalent PGA for a $M_s 7.5$ event ($PGA_{7.5} = PGA \times 1 / MSF$) was computed, which is directly proportional to the peak shear stress induced in the soil deposit (Yould et al., 2001). Cumulative $PGA_{7.5}$ values were determined for $M_s > 5$ earthquakes that occurred within 1–3 h of temporally adjacent events assuming no drainage as sand blow formation is likely to have occurred in each of these events. $PGA_{7.5}$ is plotted against earthquake $M_s$ for liquefaction-inducing events (Fig. 4A). Individual or cumulative $PGA_{7.5}$ is plotted against $AE$ and $ST$ to derive constitutive equations for the study site that may also apply to sites with similar geotechnical properties (Fig. DR4). $AE$, $ST$, and $PGA_{7.5}$ were normalized against maximum $AE$, $ST$, and $PGA_{7.5}$ values recorded in the 22 February earthquake to produce constitutive equations to compare relative changes in $AE$ and $ST$ ($AE^\star$, $ST^\star$) to relative changes in $PGA_{7.5}$ ($PGA_{7.5}^\star$) (Fig. 4B). Seismologic (Table DR1) and geotechnical data (Figs. DR4 and DR5) for the study site are available in the Data Repository.

RESULTS AND DISCUSSION

Seven distinct episodes of earthquake-induced sand blow deposition were photographed and mapped at the study site, and an additional three episodes were inferred after corroboration between the observations of local residents and the instrumental record (Fig. 4A; Table DR1). Although compound sand blows and feeder dikes have been recognized and attributed to closely timed earthquakes in earthquake sequences (Sims and Garvin, 1995; Tuttle et al., 2002), documentation of recurrent liquefaction to this detail and extent, including the recording of ten distinct liquefaction-related sedimentation events during a single mainshock–aftershock sequence, is unprecedented.

Mapped vent distributions reveal persistent reactivation across distinct northeast-oriented alignments (Figs. 2 and 3) that are subparallel to the closest section of the Avon River ~120 m to the northwest of the study site (Fig. 1B). This indicates that near-surface cracking and sand blow venting occurred perpendicular to the direction of lateral spreading toward the closest “free face” at the river bank edge, with transport facilitated by basal glide within the liquefiable layer at depths of 2–5 m (Figs. DR2 and DR4). Vent zones established in the Darfield earthquake were repeatedly reactivated in successive events with exception of a small sand blow in the northwest corner of the study site (Fig. 3). This location showed no evidence for sand blow deposition after the Darfield earthquake, at which time a small (~10 cm diameter) hole was cored to depths of ~2 m, where the liquefiable layer was encountered. This hole gradually closed at the surface prior to the Christchurch earthquake, but erupted as a source conduit for sand blow formation in the 22 February, 13 June, and 23 December earthquakes, with the highest observed sediment flux rate on site in the 13 June earthquakes (Video DR1 in the Data Repository). This confirms that preexisting zones of weakness in the near surface (e.g., higher-permeability fracture

![Figure 4](https://example.com/figure4.png)

**Figure 4.** A: Peak ground acceleration normalized to $M_s 7.5$ earthquake ($PGA_{7.5}$) versus $M_s$ and relationship to approximate liquefaction-triggering threshold for selected $M_s \geq 4.5$ earthquakes. Liquefaction-triggering threshold of 0.056 g $PGA_{7.5}$ is shown. B: Sand blow areal extent ($AE^\star$), maximum stratigraphic thickness ($ST^\star$), and $PGA_{7.5}^\star$ normalized to 22 February 2011 earthquake maxima ($AE^\star$, $ST^\star$, $PGA_{7.5}^\star$), and corresponding power-law Equations 3–6.
zones or conduits through otherwise low-permeability layers overlying the liquefiable layer) exert a first-order control on the vent distribution of sand blows by providing more-efficient pathways for liquefied material to move vertically.

The liquefaction limit, as defined by the minimum PGA_{7.5} threshold for sand blow formation, at the site is ~0.057 g (Fig. 4A). The highest recorded PGA_{7.5} without surface expression of liquefaction was the 25 December 2010 earthquake with PGA_{7.5} of 0.056 g. An isolated small (~1 m^2) sand blow was observed following the 21 June 2011 earthquake at a PGA_{7.5} of 0.032 g, well below the proposed threshold. The water table at the study site (~1 m depth) is at a similar elevation to the Avon River, which undergoes minor (~50 cm) tidal fluctuations at this location. We thus infer that major changes in groundwater tables from earthquake to earthquake are unlikely and that the liquefiable layer remains saturated regardless of seasonal conditions. However, it is possible that temporarily high winter water tables after extensive rainfall and/or the close timing (~1 week) between the 21 June and the 13 June 2011 earthquake sequences may have resulted in formation of a shallow-water interlayer within pockets of shallower liquefiable sediment that was remobilized in this earthquake despite a below-threshold PGA_{7.5}. The lack of surface liquefaction ejecta in the 25 December 2010 earthquake could conversely be attributed to slightly lower summer water tables and/or a relatively longer lapse time between the previous liquefaction-inducing earthquake (~4 mo). Clearly these factors are only relevant at near-threshold PGA_{7.5} values, as indicated from the pronounced liquefaction in the Christchurch and 23 December 2011 earthquakes that occurred under similar (summer) weather conditions.

Shallow trenching of a sand blow where four sand blow depositional events were observed (Figs. 2D–2F; Fig. DR1) reveals four distinct fine-sand ejecta units that each grade from a reddish-colored, oxidized basal sand to a lighter-gray, clean, fine-grained sand capped by a thin (<0.5 cm) coarse-silt to very-fine-sand drape (Fig. 2G) that formed from suspended sediment as ejected groundwater drained following the liquefaction event (Fig. 2E; Video DR1). The top layer (23 December 2011-b) contains evidence for erosion and sediment remobilization such as postdepositional channel formation on sand blow flanks (Fig. 2F), cross-bed sets in remobilized deposits near ejecta pocket tops (Fig. 2G), and microrilling (Fig. 2H). After 2.5 mo, significant erosion of sand blow features was observed, including vent degradation, crusting and breakup of the silt drape, and formation of ripples and parabolic microdunes (Fig. 2I).

Deeper trenching of the feeder dike system to >1 m depth (Fig. DR2) reveals only one clear crosscutting relationship (two discernible dike generations) despite at least eight liquefaction events sourced through this system. Our observations indicate that sand blow sequences can provide robust geologic archives of successive liquefaction-inducing earthquakes, particularly where capping silt drapes are well preserved (e.g., Tuttle et al., 2002). Because surface features may erode into alluvial and aeolian forms rapidly (e.g., weeks to months), silt drapes that aid in distinguishing different sand blow pulses are more likely to be preserved during temporarily clustered earthquake sequences (e.g., mainshock–aftershock or otherwise triggered events over months to years) rather than recurring mainshocks on the same fault (return times of ~10–10^-1 yr). The number of distinguishable feeder dike generations should be treated as an absolute minimum estimate of, and may significantly underrepresent, the number of liquefaction-inducing earthquakes at a given site (e.g., Sims and Garvin, 1995).

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PGA_{7.5} = 5773.2 \times AE^{2.5187} \quad (R^2 = 0.9853) \quad (1)
\]

\[
PGA_{7.5} = 125.87 \times ST^{1.1165} \quad (R^2 = 0.9513) \quad (2)
\]

Equations 1 and 2 enable PGA_{7.5} to be estimated from paleoearthquake sedimentary layer that liquefied in this instance for this and other sites with comparable geologic, hydrologic, and geotechnical characteristics. By normalizing the values from the smaller CES events to the maximums associated with the 22 February 2011 event, we derive new constitutive power-law equations of relative AE and ST variations as a function of relative PGA_{7.5} variations (Equations 3–6 in Fig. 4B). Where compound sand blow sequences are identified in the geologic record, these equations enable the characterization of relative PGA_{7.5} values in the absence of any major interevent changes to liquefaction susceptibility. Any changes in the sedimentary layer that liquefied in this instance do not appear to have influenced the liquefaction susceptibility during the CES. This empirical data set provides information relevant to paleoearthquake studies, liquefaction susceptibility, and land-use planning in New Zealand and elsewhere.

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