Contents lists available at ScienceDirect

Anthropocene

journal homepage: www.elsevier.com/locate/ancene

Influence of anthropogenic landscape modifications and infrastructure on the geological characteristics of liquefaction

Josh Borella^{a,b,*}, Mark Quigley^{c,b}, Moses Riley^{d,a}, Sarah Trutner^{d,a}, Harry Jol^e, Maxwell Borella^{a,b}, Sam Hampton^{a,b}, Darren Gravley^{a,b}

^a Frontiers Abroad, 3 Harbour View Terrace, Christchurch, 8082, New Zealand

^b School of Earth and Environment, University of Canterbury, Christchurch, 8041, New Zealand

^c School of Earth Sciences, The University of Melbourne, Victoria, 3010, Australia

^d Geology Department, Oberlin College, Oberlin, OH, 44074, USA

^e Department of Geology, University of Wisconsin-Eau Claire, Eau Claire, WI, 54702, USA

ARTICLE INFO

Article history: Received 18 June 2019 Received in revised form 6 January 2020 Accepted 8 January 2020 Available online 28 January 2020

Keywords: Liquefaction Engineered structures Engineered sediment Canterbury earthquake sequence Ground penetrating radar (GPR) Christchurch

ABSTRACT

Many large cities worldwide are built on natural and engineered geological materials that are highly susceptible to liquefaction and associated ground failure in earthquakes. Constitutive equations describing relationships between sediment geotechnical characteristics, seismological parameters, and liquefaction susceptibility of natural and engineered sediments are well established. What is less understood is the role of anthropogenic landscape modifications (e.g., river channel modifications, sediment engineering and re-distribution) and infrastructure (e.g., buildings, buried infrastructure such as drainage systems) on the spatial distributions and severity of liquefaction and ground deformation. Here we use stratigraphic studies, ground penetrating radar (GPR), and analyses of high-resolution aerial photographs to evaluate surface and subsurface geological manifestations of recurrent liquefaction in anthropogenically-modified landscapes during the 2010-2011 Canterbury earthquake sequence in New Zealand. Engineered fill layers provided low density, high permeability traps that captured fluidized sediment and promoted the formation of a unique assemblage of liquefaction-induced sediment intrusions that differ from those preserved in proximal natural sediment. Subsurface drainage systems imparted significant influence on the location, size and orientations of liquefaction ejecta features. Sediments adjacent to engineered stream channels experienced large lateral strains that are unlikely to have occurred in the absence of channel modifications. Spatial variations in naturally-formed topography and liquefaction-susceptible sediments exerted strong influence on the characteristics of liquefaction hazards, even in highly engineered environments. Collectively, these observations highlight important interactions between natural and engineered environments that should be carefully considered when interpreting the geologic effects of contemporary earthquakes and / or using prehistoric geological records to forecast future hazards.

© 2020 Elsevier Ltd. All rights reserved.

1. Introduction

Within the broader context of global environmental change and increasing urban development, understanding anthropogenic influences on geologic processes and records has emerged as an important scientific issue (Waters et al., 2016; Zalasiewicz et al., 2015, 2011; Lewis and Maslin, 2015; Price et al., 2011: Steffen et al., 2007). Anthropogenic activities may significantly alter the

E-mail address: josh@frontiersabroad.com (J. Borella).

http://dx.doi.org/10.1016/j.ancene.2020.100235 2213-3054/© 2020 Elsevier Ltd. All rights reserved. geological expressions of contemporary earthquake hazards relative to their prehistoric predecessors (Borella et al., 2016, 2019); however detailed studies of how anthropogenic activities and structures influence the spatial characteristics and severity of earthquake hazards are rare (Watkinson and Hall, 2019). This paper attempts to answer the following central research question: *How have anthropogenic landscape modifications and surface and subsurface engineered structures influenced the geological characteristics of liquefaction hazards (surface ejecta, subsurface injections, ground deformation)?*

Liquefaction occurs when saturated, unconsolidated sediments (typically Holocene sands and silts) are subjected to dynamic loading (typically earthquake-induced shear stresses) that initiate







^{*} Corresponding author at: Frontiers Abroad, 3 Harbour View Terrace, Christchurch, 8082, New Zealand.

structural changes within the affected media and increase pore fluid pressures to levels equivalent to overburden pressures. Liquefied sediment loses shear strength and may flow vertically and laterally through sediment profiles. This is commonly manifested as intrusive sedimentary dikes, sills, and bulbous intrusions in the subsurface, and sand blows, ground fissures, and lateral spreading cracks at the surface (e.g., Quigley et al., 2013; Bastin et al., 2015: Villamor et al., 2016: Tuttle et al., 2019). Typical ground deformations in liquefied areas include vertical (subsidence) and horizontal (lateral spreading) components (Hughes et al., 2015). Many large cities in seismically-active settings worldwide (e.g., San Francisco Bay area, Tokyo Bay area, Jakarta, Los Angeles, Manila, Niigata, Dhaka City, Istanbul, Vancouver) are identified as having a high liquefaction hazard, as evidenced from geotechnical analyses of liquefaction-susceptible sediments and, in some cases, historical events. A variety of methods and constitutive equations have been developed to assess liquefaction-related hazards and inform mitigation approaches in these settings and elsewhere (Youd et al., 2001; Kramer and Elgamal, 2001; Bird and Bommer, 2004; Idriss and Boulanger, 2006, 2008; Juang et al., 2003; Seed and Idriss, 1971; Pirhadi et al., 2019; Bartlett and Youd, 1992), including geological investigations of contemporary features and comparison with recorded ground motions (e.g., Quigley et al., 2013) and investigation of paleoliquefaction features (e.g., Tuttle et al., 2019; Bastin et al., 2015; Villamor et al., 2016; Obermeier, 1996).

What is less common are systematic investigations of how anthropogenic (i.e. originating in human activity) landscape modifications and infrastructure have specifically influenced the characteristics of liquefaction hazards at the surface and in the subsurface. Pradel et al. (2012) concluded that much of the liquefaction and lateral spreading damage in the Tokyo Bay region along the Tone River following the 2011 Mw 9.0 Tohuku earthquake occurred in areas modified by anthropogenic historical to contemporary land use changes (primarily levee constructions and infilling of stream channels with engineered sediment) although no subsurface geological investigations were undertaken. Wotherspoon et al. (2012) used historical accounts and maps of the Kaiapoi, New Zealand area to show that much of the most significant liquefaction damage during the 2010 Mw 7.1 Darfield earthquake occurred in areas where river channels had been reclaimed or in old channels where flow had been diverted away. They reported that all underground services, roads, and railways in former channel areas were severely impacted by liquefactioninduced cracking and ground movement, but did not consider, for example, the effect that the underground services may have had on the degree and distribution of liquefaction damage and the characteristics of surface and subsurface phenomena. Other studies have examined the mitigative effects of timber piles (e.g. Stuedlein et al. (2016); Gianella et al., 2015) and gravel columns (e.g. Adalier and Elgamal, 2004) on the engineering performance of buildings and infrastructure. However, this study is the first, to the best of our knowledge, to undertake a forensic multidisciplinary analysis of recurrent surface and subsurface geologic manifestations of liquefaction in areas with natural and engineered sediments that have been subjected to anthropogenic landscape modifications including infrastructure emplacement. The study focuses on surface and subsurface documentation of liquefaction features produced during the 2010–2011 Canterbury earthquake sequence (CES) (Quigley et al., 2016) at two study sites in eastern Christchurch, New Zealand. We provide important insights into the interactions amongst concomitant natural and anthropogenically-modified environments that are highly relevant to forecasting future liquefaction hazards and interpreting geologic (paleoseismic) records of past liquefaction events.

2. Geologic setting

2.1. Christchurch

The city of Christchurch (\overline{O} tautahi) (population ~366,000) is located on the east coast of New Zealand's South Island, set upon the low-relief and low-elevation (0-20 m above sea level) eastern limit of the alluvial Canterbury Plains (Fig. 1A). The eastern suburbs are predominantly underlain by drained peat swamps, fluvial sands and silts, and estuarine, dune, and foreshore sands (Brown and Weeber, 1992) (Fig. 1B,C). Channelized gravels are present within the uppermost several meters and have been attributed to deposition by the braided Waimakariri River that intermittently avulsed through the area prior to European settlement (Cowie, 1957; Brown and Weeber, 1992). To the west of the central city, fluvial sands and gravels predominate. Sediments in eastern Christchurch were deposited during shoreline progradation and marine regression following the culmination of the post-glacial sea level rise, with the shoreline at ~6500 yr BP recorded approximately 3 km west of the present central city (Fig. 1B; Brown and Weeber, 1992). Fluvial sand and silts were deposited by the Avon and Heathcote Rivers. The presence of underlying young unconsolidated fine sands and silts combined with high water tables (1-2m depth) and artesian water pressures define a high liquefaction hazard for eastern Christchurch as confirmed by the CES (e.g. Cubrinovski and Green, 2010; Quigley et al., 2013; Cox et al., 2012; Rutter, 2011).

2.2. Liquefaction during the Canterbury earthquake sequence

The 2010–2011 CES initiated with the Mw 7.1 Darfield earthquake and included major damaging earthquakes on 22 Feb 2011 (Mw 6.2 Christchurch earthquake; 185 fatalities), 13 June 2011 (Mw 6.0 Christchurch earthquake), and 23 December 2011 (Mw 5.9 earthquake) (Quigley et al., 2016). The estimated direct costs due to CES damage are ~NZ\$ 40 B (~US\$ 31 B) (http://www.nbr.co.nz/article/christchurch-quake-costrises-10b-40b-bd-

139278). Liquefaction-induced surface features (sand blows, ground fissures) were identified in highly susceptible areas of Christchurch following at least 10 distinct CES earthquakes (Quigley et al., 2013, 2016. Liquefaction affected ~51,000 residential properties and damaged ~15,000 residential houses in the Christchurch region beyond economic repair. Land and infrastructure damage due to liquefaction resulted in a central government buyout of 7346 residential properties Fig. 1D) at an estimated cost of over NZ\$2.8 billion (see Quigley et al., 2019a, b for reviews of the decision-making process). Surface mapping of CES liquefaction ejecta (e.g. Cubrinovski et al., 2011a, b; van Ballegooy et al. (2014a) v; Quigley et al., 2013; Bastin et al., 2015, 2016; Townsend et al., 2016; Villamor et al., 2016; Almond et al., 2013) highlighted areas of recurrent liquefaction and in some instances identified geological evidence for pre-CES liquefaction events, but did not explicitly examine the impact of anthropogenic landscape modifications and infrastructure on liquefaction hazards. Hughes et al. (2015) and Quigley et al. (2016) described large lateral spreading strains in inner meanders of the Avon River in residential areas of eastern Christchurch (Fig. 1E). Reconnaissance field and imagery-based mapping of liquefaction ejecta around major infrastructure (i.e., Lancaster Park football stadium; Fig. 1F - inset) revealed increased concentrations of ejecta at the edges of heavy structures that Quigley (2015) attributed to enhanced concentrations of transient shear stresses and enhanced structural loading of liquefied sediment, the latter of which was evidenced by localized subsidence of structures of more > 0.3-1 m relative to surrounding areas (green arrow, Fig. 1F). Vertical linear infrastructure such as telephone and electricity poles provided stress



Fig. 1. (A) Site map showing the City of Christchurch and Avondale Park (AP) and Porritt Park (PP) study locations. **(B)** Simplified geological map of the Christchurch area (modified from Brown and Weeber, 1992). **(C)** Light detection and ranging (LiDAR) digital elevation model (DEM) for eastern Christchurch. **(D)** Liquefaction residential technical categories map for eastern Christchurch showing the extent of liquefaction damage resulting from the 4 September 2010, 22 February 2011, 13 June 2011, and 23 December 2011 earthquakes (modified from van Ballegooy et al., 2014). **(E)** Liquefaction-induced horizontal ground displacement vectors in Porritt Park area indicating the direction and magnitude of lateral spreading associated with the CES. **(F - inset)** Aerial photograph of Lancaster stadium Christchurch after the 22 February earthquake. **(F - main)** Differential lidar image including stadium area. [Further information on Fig.1 is provided in supplementary item ST.1, https://doi.org/10.5061/dryad.z612jm67z].

concentrators and vertical conduits for liquefaction ejecta to reach the surface (Fig. 1G).

2.3. Avondale Park and Porritt Park study sites

The Avondale Park and Porritt Park study sites experienced large spatial variations in the severity of land damage during the CES (Fig. 1D; Fig. S.1, https://doi.org/10.5061/dryad.z612jm67z; Bradley and Hughes, 2012a, b; O'Rourke et al., 2012). Avondale Park experienced moderate land damage and was assigned as Technical Category 3 (TC3) land during government decision-making, defined as "where liquefaction damage is possible in future large earthquakes and individual engineering assessment is required to

select the appropriate foundation repair or rebuild" (https://ccc.govt. nz/consents-and-licences/land-and-zoning/technical-categories-

map). Porritt Park experienced severe land damage and was designated by the government as 'red-zoned' land, where "rebuilding may not occur in the short-to-medium term" (see Quigley et al., 2019a; and references therein) (Fig. 1D). Avondale Park (area $\sim 38,000 \text{ m}^2$; average elevation = 4 m asl) is positioned within a distal inner meander bend of the Avon River (Figs. 1C and 2). Porritt Park (area $\sim 127,000 \text{ m}^2$; average elevation = 5.5 m as) is located on an old meander bend of the Avon River that was separated from the main Avon River channel sometime before ~ 1950 (Figs. 1C-E and 2). Porritt Park is currently surrounded by a lightly flowing stream sourced by an overflow pipe connected to

the Avon River. The coastline is located 3.0-3.5 km to the east of the study sites (Fig. 1A-C). The water table is located between 1 and 2 m depth at the study locations but may rise to <0.5 m depth during wet periods (Brown and Weeber, 1992). Both parks are underlain by alluvial sand and silt deposits of the Avon River, along with sand, silt, and peat of drained lagoons and estuaries, and sand of fixed and semi-fixed dunes and beaches (Brown and Weeber, 1992) (Fig. 1B). Radiocarbon ages from correlative alluvial sedimentary sequences at proximal locations yield late Holocene ages (ca. 200-2700 yr B.P.) (Bastin et al., 2015, 2016). The Avondale Park area has probably fluctuated between overbank deposition during flooding events and slower rates of sedimentation in an estuarine setting. Sedimentation at Porritt Park would have been dominated by channel and meander scroll bar deposition prior to the reorientation/widening of the Avon River and isolation of the Porritt Park meander bend. Silby (1856) indicates that swamp and grass swamp with flax rushes, fern, and tutu vegetation predominated in the area during the mid-19th century, prior to development of Christchurch. The location of the Avon River during this time (i.e. \sim 1856) is similar to its present location.

2.4. Anthropogenic history at Avondale Park and Porritt Park

A review of historical aerial photography (1940–2011) indicates there have been significant anthropogenic modifications to both study areas (Fig. 2). The Avondale Park and Porritt Park sites and adjacent area between the Avon River and Wainoni Road remained undeveloped until at least 1949 (Fig. 2A). Changes to the Avon River and the initiation of residential development are evident between 1949 and ~1955-1959 (Fig. 2B), when the north-south oriented section of the Avon River was widened and a new southern extension adjacent to Porritt Park was created, effectively cutting off and isolating the Porritt Park meander bend (Fig. 2B). Between 1965 and 1969 the development of homes continued to the northnortheast (Fig. 2C), suggesting that the majority of anthropogenic fill was probably placed in the area prior to 1965. The 1970–1974



Fig. 2. Historical aerial photographs highlighting the sequence (A–F) of anthropogenic modifications near Avondale Park, Porritt Park, and surrounding residential areas. [Further information on Fig. 2 is provided in supplementary item ST.1, https://doi.org/10.5061/dryad.z612jm67z].

aerial photographs show the continued development and construction of homes in the area moving to the north and northwest (Fig. 2D). At this time, Avondale Park had not been established but homes were constructed to the present-day southern limit. Porritt Park was heavily modified in the 1970s, including the installation of an extensive E-W oriented subdrain system (Fig. 3A). Following the installation of the subdrain system, several playing fields and associated buildings were constructed circa 1974 (Fig. 3A). Aerial photographs indicate that the development of roads, homes, and all parks (as we observe them today) in the area were completed sometime between 1990 and 1994 (Figs. 2E,F). At Porritt Park, a series of solid irrigation pipes were installed in 2002, followed by the construction of several new sport courts in 2004 (Fig. 3B). As a result of damage during the 2010-2011 CES, the playing fields are no longer present and Porritt Park is not maintained, resulting in overgrown vegetation and swampy conditions. The Avondale Park sports field/park (Fig. 3C,D) was established in the late 1990's, with the first irrigation system constructed during this time. Ten centimetres of subsoil was placed beneath the field turf. From 2001-2002, a new field drainage and irrigation system was constructed at Avondale Park (Fig. 3D). Some minor alterations to the surface have been performed following the CES. No grading reports or records documenting fill placement at Avondale Park or Porritt Park were available at the Christchurch City Council.

3. Methods

3.1. Remote sensing and mapping of surface liquefaction features

Desktop mapping of high-resolution aerial photographs following each of the main CES events (4 September 2010, 22 February 2011, 13 June 2011, 23 December 2011) was performed using ArcGIS and Illustrator to map surface liquefaction features (sand blows and sand blow centres) and anthropogenic elements (drain/irrigation lines) at Avondale Park and Porritt Park. The total area for liquefaction surface ejecta was determined for each of the primary CES events at Avondale Park and Porritt Park. The location of individual sand blow centres was mapped at Porritt Park for the February event.

3.2. Trenching

Two trenches were excavated at Avondale Park to investigate the stratigraphy and subsurface morphology of CES and pre-CES



Fig. 3. (A) Porritt Park before CES: 1970–1974 historical aerial photographs showing East-West oriented subdrain system. (B) Porritt Park after CES: Aerial photograph taken on 16 June 2011, a few days after the 13 June 2011 earthquake. Note the locations for the pre-existing subdrain lines and distribution of liquefaction ejecta. (C) Liquefaction ejecta at Avondale Park study site in eastern Christchurch. (D) Surface liquefaction features superimposed on the Avondale Park water irrigation and drainage plan. [Further information on Fig. 3 is provided in supplementary item ST.1, https://doi.org/10.5061/dryad.z612jm67z].

(if present) liquefaction features (Fig. 3C). We used wellestablished criteria for identifying earthquake-induced liquefaction features, including analysis of aerial photography, trenching, and dating of subsurface deposits (e.g. Sims, 1975; Obermeier et al., 1991; Obermeier, 1996; Tuttle, 2001; Bastin et al., 2013, 2015; Villamor et al., 2016). The trenches were excavated perpendicular to aligned sand blow vents. The trench walls were cleaned using handheld scrapers and then photographed and logged at centimeter scale to document small-scale changes in the morphology of the liquefaction features and the surrounding stratigraphy. The trench bottoms were also photographed at several locations of interest to highlight key liquefaction and sedimentary features. The liquefaction features and the surrounding unmodified anthropogenic fill and underlying natural stratigraphy were described in terms of their grain size, sorting, colour (using Munsell hue, value, and chroma), and degree of sediment mottling. Hand-auger borings were performed in Trenches 1 and 2 (A1 and A2, respectively) to depths of 1.73 and 1.20 m (from trench bottom), respectively (Figs. 4–6). Below these depths, the sediment lacked cohesion and could not be retrieved. Radiocarbon dating was performed on a single charcoal sample from in situ silty clay sediment located at the bottom of Trench 2 (Fig. 6). Due to the swampy conditions (i.e. high groundwater), we were unable to trench at Porritt Park.

3.3. Ground penetrating radar (GPR)

We used Ground Penetrating Radar (GPR) to help characterize subsurface features at the study sites. GPR transmitter antennae radiate high-frequency electromagnetic pulses into the subsurface that reflect off the boundaries of subsurface materials, horizons, and structures. Matching GPR receiver antennae record these reflections as a function of time to provide a cross-sectional profile of structures below the survey line. More information about GPR surveying and interpretation can be found in Jol and Bristow (2003).

Three survey lines (i.e. SL1, SL2, SL3) were conducted at Porritt Park (Fig. 9B) using a Sensors and Software pulse EKKO Pro GPR system that utilizes multiple antennae frequencies. The survey lines were positioned to cross three distinct sand blow array patterns identified during desktop mapping. Two different frequency antennae, 100 MHz and 200 MHz, were used for each survey line. Lower frequencies provide greater depth of penetration but lower resolution, while higher frequencies provide higher resolution but lower penetration depth (Jol and Bristow, 2003). The 100 MHz survey lines recorded radar readings every 0.25 m with the antennae 1.00 m apart, while 200 MHz survey lines recorded readings every 0.10 m with the antennae 0.50 m apart.

GPR was conducted at Avondale Park to resolve the nature (e.g. thickness, continuity) of individual fill layers and any underlying naturally deposited sediments. The data was collected using a GSSI-SIR-3000 system. A total of 14 GPR transects were oriented perpendicular to the western-northwestern park boundary at Avondale Park (Figs. S.2, S.3, https://doi.org/10.5061/dryad. z612jm67z). An additional two lines were performed parallel with the target feature. Two-hundred (200) and 400 MHz frequencies were performed on each transect.

3.4. Geotechnical testing

A single SCPTu (seismic cone penetration test with pore pressure [piezocone] measurement) was conducted between the



Fig. 4. Trench logs for Northeast (A) and Southeast (B) walls of T1. [Further information on Fig. 4 is provided in supplementary item ST.1, https://doi.org/10.5061/dryad. z612jm67z].



Fig. 5. Photos of CES liquefaction features in T1. (A) At least two distinct episodes of CES-induced liquefaction are evident in the southwestern wall of Trench 1. (B) LD1 crosscuts the large sill (S1) present at the bottom of F1a. (C) The orientation of CES liquefaction dikes is typically irregular through the gravel-rich fill layers F2 and F3 and preexisting liquefaction features. (D) CES liquefaction dike crosscutting natural sediment (NS). (E) Liquefied sand injecta in F2-F3. (F) Liquefaction injecta within F2-F3, primarily within the silty-clay host fill sediment. (G) Termination of CES liquefaction dike into existing perforated subdrain pipe. [Further information on Fig. 5 is provided in supplementary item ST.1, https://doi.org/10.5061/dryad.z612jm67z].

two Avondale Park trenches (Fig. 3C; Fig. S.4, https://doi.org/ 10.5061/dryad.z612jm67z) to determine (i) engineering properties of anthropogenic and natural sediments and (ii) aid in quantifying the site's susceptibility to liquefaction. The SCPT penetrated to a total depth of 15.25 m. The liquefaction potential of the subsurface strata was evaluated from the SCPTu using the Idriss and Boulanger (2008) method as modified by van Ballegooy et al. (2015a,b) (Fig. S.4, https://doi.org/10.5061/dryad.z612jm67z). This method establishes the liquefaction potential by comparing the cyclic stress ratio (CSR), which evaluates loading induced at different depths by an earthquake, with the cyclic resistance ratio (CRR), which reflects the ability of the sediment to resist liquefaction. The likelihood that a sediment will liquefy is expressed as a factor of safety against liquefaction (FS), where FS < 1 is considered potentially liquefiable.

4. Results

4.1. Avondale Park

4.1.1. Spatial distribution of liquefaction ejecta

No surface liquefaction ejecta was identified at Avondale Park during field and photographic investigations immediately following the 4 September Darfield earthquake. The most extensive sand blow development occurred during the 22 February earthquake, followed by the 13 June and 23 December earthquakes (Fig. 3C). The total area of surface ejecta at the Avondale Park study site was ~4190 m² for 22 February, ~2839 m² for 13 June, and ~946 m² for 23 December earthquakes, with June and December surface ejecta comprising ~68 % and ~23 % of the February surface ejecta area, respectively (Fig. 3C). Mapping of surface liquefaction features



Fig. 6. Trench log for Southwest wall of T2. [Further information on Fig. 6 is provided in supplementary item ST.1, https://doi.org/10.5061/dryad.z612jm67z].

(e.g. sand blows) at Avondale Park indicates recurrent liquefaction occurred at the site. At the Trench 1 location, surface sand blow features were evident only after the February and June earthquakes, while at Trench 2 surface liquefaction features were generated during each of the 2011 earthquakes (Fig. 3C).

4.1.2. Trench stratigraphy

The anthropogenic fill sequence in Trench 2 is only weakly deformed by the CES and therefore provides a stratigraphically intact sequence of fill stratigraphy (Figs. 6, 7). Four separate fill layers (F1-F4) are delineated within Trench 2 based upon a comparison of sediment colour, composition, and texture (including grain sorting) (Fig. 6). Within Trench 1, the central fill layers (i.e. F2 and F3) have been sufficiently deformed to a level where distinguishing between the two layers is difficult (Figs. 4, 5). Consequently, we collectively refer to these layers as F2-F3 when describing Trench 1 observations (Figs. 4, 5). Natural and anthropogenic fill stratigraphy is described in detail in Figs. 4 and 6. The ^{14}C age of 846 \pm 20 yr B.P. (Table S.3 and Fig. S.5, https:// doi.org/10.5061/dryad.z612jm67z) from Avondale Park represents the youngest age for *in situ* natural sediment (NS) identified at this trench site and provides a minimum age estimate for the last occurrence of liquefaction at the study site. Bastin et al. (2016) identified multiple paleo-liquefaction events since 800 B.P. at other sites in the CES area; it is likely that the Avondale Park area may have different site characteristics or geological history relative to these apparently more liquefaction-susceptible sites.

We observed a greater abundance and variety of CES liquefaction features in Trench 1 (compared with Trench 2), including development of subvertical to oblique dikes, sills, and numerous subhorizontal to irregularly oriented and shaped injection features (Figs. 4, 5). Please see Fig. 4 and Fig. 6 for sediment descriptions of CES liquefaction features. The largest liquefaction dike in Trench 1 has a maximum width of ~3 cm (see LD1 in Figs. 4, 5). We observed no distinct silt drapes at the dike wall boundaries. Oxidation along the dike boundaries is most pronounced within F4. A smaller connecting dike (LD1_a) (maximum width = \sim 1.0 cm) is observable (Fig. 4A) within the northwest trench wall (Fig. 4A). No oxidation is observed on the LD1_a wall boundaries and no obvious crosscutting relationship with LD1 is observed, suggesting the two were likely part of the same shaking episode but have experienced different post-emplacement weathering. LD2 (see Fig. 4A) extends upward vertically within the native sediment, then deflects obliquely within the fill units before terminating within a gravel filled subdrain trench (Figs. 4A and 5G). Sand (with equivalent composition/texture to that observed in LD2) has been injected into the perforated subdrain pipe and surrounding gravel backfill (Fig. 5G). Sill morphologies are observed in both Trench 1 walls (Figs. 4, 5). The largest of the sills (S1) formed at the boundary between F1 and F2 (Figs. 4, 5) and has a minimum length of \sim 4.7 m and a maximum thickness of ~28 cm. Rip-up clasts contained within S1 have diameters ranging from \sim 5 to \sim 30 centimetres, suggesting the fluidized sand had sufficient velocity to transport gravel to small pebble-sized material and also entrain large pieces of fill material. Long (\sim 3.65 m) and thin (thickness = \sim 1 – 12 cm) sills (see L1 in Fig. 5F) are developed at the F3-F4 boundary. Several oblique to horizontal sill splays with length ranging from \sim 1.0– 2.3 meters and thicknesses of $\sim 1-5$ cm are preserved in the Trench



Fig. 7. Photos of CES liquefaction features in T2. **(A)** CES liquefaction dike crosscuts natural sediment and anthropogenic fill layers. **(B)** Dike boundaries become more diffusive within fill layers F2 and F3 where gravel and randomly placed fragments of silt/clay are abundant. **(C)** Mottling from oxidation is greatest within F4. **(D)** Photo of CES liquefaction dike at trench bottom. **(E)** CES dike boundaries are distinct. [Further information on Fig. 7 is provided in supplementary item ST.1, https://doi.org/10.5061/dryad. z612jm67z].

1 walls (see S2 in Fig. 4B). A unique assemblage of horizontal to subhorizontal, elongate to irregularly shaped liquefaction injection features (Figs. 4, 5) are contained within F2-F3. Three primary 'types' of liquefaction injection features are distinguished within F2-F3 (i.e. L1, L2, L3). Sedimentary characteristics of L1-L3 are described in the Fig. 4 legend.

The modern liquefaction dikes (Fig. 6 - see LD1, LD2, LD3) in Trench 2 are oriented vertical to subvertical, have a maximum thickness of \sim 1.5 cm, and thin upwards to \sim 2–5 mm near the surface. Very thin (< 0.5 mm) silt linings were observed along the dike sidewalls. The absence of multiple crosscutting silt linings within the modern dikes makes it impossible to determine if reactivation occurred during successive CES shaking events. The modern dike walls range from distinct to highly oxidized depending on the surrounding sediment/fill and elevation relative to the water table. No significant mottling is observed along any of the dike walls. The highest degree of oxidation is observed within F4, where the dike boundaries are difficult to identify (Fig. 7C). The oxidation of liquefaction features is consistently highest within F4 in both trenches and less pronounced within the natural sediment (NS)(although minor oxidation is observable) and generally absent to minimal within F1, F2, and F3. Vertical dike orientation is most irregular (particularly for LD1) within F2 and F3 (Fig. 6), highlighting the influence that heterogeneities in anthropogenic fill (i.e. gravel and cm-scale sediment fragments) have on dike propagation and orientation. In some instances, the dike boundaries within the gravel-rich F2 and F3 layers were difficult to follow and became diffuse (Fig. 7A, B), as the higher porosity gravels allowed for local dissipation of high fluid pressures. The liquefaction dikes splay off a larger feeder dike observable at the trench bottom (Fig. 7D, E).

4.2. Porritt Park

4.2.1. Spatial distribution for surface liquefaction features

The amount of surface ejecta by percent area at Porritt Park was highest during the February and June 2011 earthquakes (Fig. 8B,C). During the February earthquake, surface ejecta covered \sim 41 % of Porritt Park. The surface patterns reveal the underlying influence of the 1970 subdrain system and meander scroll bars (Fig. 8A-D).

We mapped 1347 individual sand blow centres (692 observed, 655 inferred) for the 22 February 2011 earthquake (Fig. 9A). Locations of the 1970 subdrain lines are superimposed on the liquefaction polygons and mapped sand blow centres (Fig. 9A). Three distinct linear trends are established from the geometry/ orientation of ejecta polygons and the alignment of linear sand blow arrays (see red, green, and blue lines - Fig. 9A). Linear sand blow arrays trending E–W are attributed to the influence of the underlying 1970 subdrain lines while the sand blows trending NW-SE and SW-NE are attributed to the influence of underlying river meander scroll bars.

The red polygons show the areas where liquefaction ejecta occurred at the surface during each of the primary CES earthquakes (Fig. 9B). The total area of recurrent liquefaction was 4115 m^2 and



Fig. 8. Surface ejecta during each of the primary CES earthquakes - (A) 4 September 2010 and (B) 22 February, (C) 13 June, (D) 23 December 2011. [Further information on Fig. 8 is provided in supplementary item ST.1, https://doi.org/10.5061/dryad.z612jm67z].

represented ~11 % of the Porritt Park area. The yellow polygons depict areas of recurrent liquefaction occurring above the 1970 subdrain system. The total area of recurrent liquefaction overlying the 1970s subdrain lines was 1533 m² and comprised ~37 % of the total recurrent liquefaction area (~4 % or Porritt Park area), demonstrating the strong influence of the old subdrain lines on the surface distribution and expression of liquefaction ejecta at Porritt Park, particularly in the northern section of the site.

4.3. Ground penetrating radar

4.3.1. Porritt Park

The GPR effectively captures the locations for subdrain pipes (Fig. 10 – black and red vertical arrows) and resolves meander scroll bar and channel bottom features (Fig. 10). The 200 MHz resolution reveals subsurface pipes not apparent in the post-CES aerial photographs (see Fig. 10A, black vertical arrows). Meander scroll bar accretionary layers are evident and dip to the northeast in L1 and L2, and southeast in L3 (see Fig. 10B,C,D). Ground deformation is most severe in areas where subsurface drainpipes and distinct scroll bar reflections interact (see Fig. 10C,D), although the observed ground deformation could be partially influenced by lateral spreading closest to the Porritt Park meander boundaries. The location of mapped surface liquefaction ejecta sourced from meander scroll bars is marked on L1, L2, and L3 (see yellow stars -Fig. 10). We note the intersection of several point bar reflections with observed surface ejecta sites, suggesting that the boundaries of point bar accretionary layers (in addition to the 1970 subdrain system) act as potential conduits for liquified sediments.

4.3.2. Avondale Park

The GPR at Avondale Park is successful in determining the location for shallow subdrain and irrigation lines and imaging (to some degree) horizons within the anthropogenic fill layers (Fig. S.3, https://doi.org/10.5061/dryad.z612jm67z). However, the GPR is unable to resolve any natural depositional features presumably due to the attenuating effects of the overlying anthropogenic fill horizons, which contain appreciable amounts of silt and clay. The 200 MHz frequency data only define features at depth >2 m with very low resolution. The corresponding 400 MHz frequency loses quality below \sim 1.3 m, the depth at which naturally deposited sediments are encountered. The GPR lines suggest, in some locations, a haphazard placement of fill materials at S.3, https://doi.org/10.5061/dryad. Avondale Park (Fig. z612jm67z), though it is difficult to determine the effect that the surface subdrain and irrigation pipes have on imaging deeper fill structures.

5. Discussion

5.1. Surface liquefaction features

At Avondale Park, the spatial distribution of liquefaction ejecta points to the potential influence of subsurface infrastructure, with several linear sand blow arrays aligned with the park subdrain and irrigation lines (Fig. 3D). We are uncertain what has caused surface deposition of the long linear collection of sand blows located along the northwestern side of the playing field (see 'c' in Fig. 3D). Park restrictions precluded us from trenching across the feature, and



Fig. 9. (**A**) Liquefaction ejecta (red polygons) at Porritt Park during the 22 February 2011 earthquake. (**B**) Areas of recurrent liquefaction ejecta at Porritt Park. Red polygons show the areas where liquefaction ejecta occurred at the surface during each of the primary CES earthquakes (September 2010, February, June, December 2011). [Further information on Fig. 9 is provided in supplementary item ST.1, https://doi.org/10.5061/dryad.z612jm67z].

GPR (as well as a review of historical aerial photographs) does not indicate the existence of a channel or underground service pipe beneath the feature (see Figs. S.2, S.3). It is possible that the playing field and playground had different grading histories and compaction protocols and that liquefied sediment utilized the boundary between the two to reach the surface. We also note that feature 'c' is located at the western terminus of the subdrain and irrigation lines. It was confirmed in our Trench 1 (Fig. 4) that liquefied sand was being conducted (and presumably transported) in the subdrain pipes and surrounding gravel backfill. It is therefore possible that during the earthquakes, the volume of silt/sand overwhelmed the subdrain lines and was forced upward near the western ends of the subdrain pipes to release fluid pressure. If so, feature 'c' may have resulted from the amalgamation of sand blows erupted at the ends of the subdrain lines.

At Porritt Park, surface ejecta is more widespread and a corresponding higher degree of deformation at the surface (and in the subsurface) is evident. The total area of measured ejecta during each of the main CES earthquakes is consistent with the recorded ground shaking intensities (i.e. 22 February recorded the strongest ground shaking intensities and created the most surface ejecta by percent area) (Fig. 9C). We note that the reduction in % area of surface ejecta at Avondale Park (see Fig. 9C) could be a result of the anthropogenic fills 'capturing' liquefied sediment in the subsurface; however, we are cautious to attribute this effect solely to the engineered fills due to inter-site geological differences and the generally higher peak ground accelerations experienced at Porritt Park during the CES.

The influences of the collapsed 1970 subdrain system and underlying accretion bars are evident during each of the CES events; however, we propose the mechanism and timing of delivery may be different. The point bars represented a proximal and direct sand and silt source for surface sand blow formation and the inclined accretion boundaries may have also conducted fluidized sediment from deeper source layers (see Giona Bucci et al., 2018a, b). In contrast, the subdrain lines would have served as repositories then conduits for the transmission of fluidized sand/silt. Our discussions with city officials indicate that a series of parallel fissures were initially developed above the subdrain lines during the 4 September main shock (Fig. S.6, https://doi.org/10.5061/dryad.z612jm67z) and provided surface pathways for sand/silt ejecta. It is difficult to determine the influence of lateral spreading on the surface distribution of sand blows at Porritt Park. Significant lateral spreading cracks were created adjacent to the main Avon channel. However, the role of spreading cracks at Porritt Park is less clear. It is possible that the linear sand blow arrays (see blue lines – Fig. 9A) along the eastern side of the meander bend were erupted along smaller lateral spreading cracks, but GPR SL3 shows reflections consistent with scroll bar deposition and does not show a reduction in ground elevation (Fig. 9B), which should be evident if lateral spreading occurred.

It is clear from our results that the 1970 subdrain lines imparted a strong influence on the spatial distribution of sand blow centres at Porritt Park. The estimated total area of the park with subdrain lines is \sim 574 m² (estimated length and width of the drainage lines =1915.7 m and 0.3 m, respectively). Drainage lines occupy approximately 1.5 % of the Porritt Park field area. If the sand blows (n = 1347) were located randomly at Porritt Park then we would expect \sim 20 sand blows (that is, 0.015*1347) to be located above the subdrain pipes. However, we identify 302 sand blow centres (observed+inferred) overlying the subdrain pipes which comprises approximately 22 % of the total number of sand blows and indicates a non-random distribution. An examination of recurrent liquefaction at Porritt Park further confirms our assertion that the subdrain lines are a primary factor in controlling the spatial distribution of liquefaction ejecta. The total area of recurrent liquefaction overlying the 1970s subdrain lines comprises \sim 37 % of the total recurrent liquefaction area at Porritt Park. We note that highest degree of recurrence occurs furthest to the north where lateral spreading may have stretched and opened the subdrain trenches (Fig. 9B). GPR L2 confirms an increase in ground deformation and a reduction in ground elevation, consistent with the expected effects of lateral spreading.



Fig. 10. Ground penetrating radar (GPR) lines L1-L3 **(A–D)** at Porritt Park, eastern Christchurch. Subsurface pipes have a characteristic upward pointing parabola shape. Meander scroll bar accretions are evident and dip to the North and East. Yellow stars depict locations where surface liquefaction ejecta are influenced by scroll bars; note the intersection of several bar reflections with the observed ejecta sites. [Further information on Fig. 10 is provided in supplementary item ST.1, https://doi.org/10.5061/dryad. z612jm67z].

5.2. Subsurface liquefaction features

Trenching at Avondale Park reveals a variety of subsurface CES liquefaction features directly affected by the placement of anthropogenic fill material and installation of subdrain systems in the shallow subsurface. The injection of sill morphologies at fill layer boundaries suggests the variable sediment characteristics (i.e. porosity/permeability, cohesion, density, sorting) for the individual fill lavers created horizontal discontinuities that were exploited by the fluidized sediment. This is notable in the Trench 1 where the largest observed sill morphology (S1) is injected between the gravel-rich F2-F3 and F1 layers. F1 was found to be the most well-compacted fill layer and therefore it is not surprising that it provided a strong cap layer and constrained the deposition of S1. We are uncertain why there was no CES sill development observed at the boundary between NS and the oldest fill layer (F4). This could suggest that the bond at the NS-F4 boundary is stronger than other fill layer boundaries and/or F4 is more compacted (and therefore has less porosity) than the F2 and F3 layers.

The F2-F3 fill layers were a preferred destination for the release of fluid pressures as evidenced by deposition of injections of liquefied sediment. The observed increase in void space within F2 and F3 (compared with F1 and F4) is attributed to increased heterogeneity (chaotic mixture of sand, gravel, and silt-clay fragments) and possibly poor compaction during its original placement. It is possible that the higher amount of void space within F2 and F3 could have already existed prior to the CES, but the poorly sorted nature of the F2-F3 layers would have also left the layers vulnerable to dilation (and enhanced porosity/permeability) during CES shaking and associated deformation. We propose that most (if not all) gravel contained within F2-F3 was part of the original fill because SCPT-1 (Fig. S.4, https://doi.org/10.5061/dryad. z612jm67z) indicates no potential gravelly source layers at depth. Our trench observations suggest anthropogenic fills, particularly those that are poorly sorted and compositionally variable, have a high capacity to absorb sediment and dissipate fluid pressures.

5.3. GPR

The GPR at Porritt Park is successful in imaging anthropogenic and natural depositional features in the shallow subsurface. The 200 MHz frequency is most effective in imaging the location of drainpipes and reveals several drainpipe locations that are difficult to resolve with the 100 MHz frequency (Fig. 10). However, the 100 MHz frequency is more successful in capturing natural depositional features including meander scroll bar features and potential channel boundaries. The GPR suggests that minimal to no fill was placed beneath the area studied at Porritt Park, as several of the scroll bar horizons can be observed intersecting the ground surface (Fig. 10C). This implies that the subdrain system was excavated directly into the natural ground surface and is consistent with liquefaction ejecta strongly mimicking the meaner scroll bars at the surface. If anthropogenic fill of sufficient thickness (similar to Avondale Park) was placed on the site, we wouldn't expect the pattern of the underlying accretion bars to be so clearly expressed at the surface. In some locations, the scroll bar boundaries intersect at the surface with linear sand blow arrays (see Fig. 10C - yellow stars), suggesting that liquefied sediment is migrating upward along the boundaries between individuals point bars or being directly sourced by the point bar deposits. Giona Bucci et al. (2018a, b) describe the guiding of fluidized sand along inclined sediment body boundaries (e.g. within point bar deposits and buried channel margins) to the ground surface and present a conceptual framework for evaluating the implications of this process on transporting fluidized sediment and influencing surface liquefaction patterns. Our GPR analysis supports this model and provides the first subsurface imaging of these potential ejecta pathways. Importantly, the results indicate that, in some cases, GPR can be used to predict where liquified sediment (as sourced from natural depositional features) will erupt at the surface. We note that the zones of most severe ground damage and liquefaction ejecta coincide with areas containing multiple subdrain lines and meander scroll bars (Fig. 10). This highlights the complex interplay between the 1970 subdrain lines and the scroll bar features in delivering liquefaction ejecta to the surface, and in this case, increasing the amount of surface deformation.

5.4. Influence of prehistoric 'landscape memory' on liquefaction hazard

During the CES, lateral spreading was most severe in inner flood-plain meanders (see red arrows, Fig. 1E). However, at Porritt Park, diversion of the Avon River and filling of eastern bank with engineered material resulted in a high density of large lateral spreading cracks (see i, Fig. 1E) with an orientation and severity that would not have occurred if the river had not been diverted. To the west of the engineered stream channel (see ii, Fig. 1E), lateral spreading vectors point away (west) towards inherited (i.e. naturally-formed) topography, rather than towards the engineered reach of the proximal Avon River. This demonstrates the concept of 'landscape memory'; despite major anthropogenic landscape changes, the lateral spreading vectors are strongly influenced by pre-existing topography and geology. Subsidence of Lancaster stadium in Christchurch during the 22 February 2011 earthquake further highlights the concept of 'landscape memory'. Although localization of liquefaction ejecta around the edges of the stadium stands (red; Fig. 1F inset) and localized building subsidence (Fig. 1F) indicate anthropogenic effects on geological manifestations of liquefaction and subsidence, it is also clear that subsidence patterns in this highly engineered environment (red sinuous zone of subsidence) were strongly controlled by the presence of a prehistoric paleochannel that enhanced liquefaction and subsidence. We term these collective effects of prehistoric geology on liquefaction hazard characteristics in highly engineered environments as 'landscape memory' effects.

5.5. Implications for paleo-liquefaction studies and hazard assessments for anthropogenically-modified areas

Engineered fill layers provided low density, high permeability traps that captured fluidized sediment and promoted the formation of liquefaction-induced sediment intrusions with greater widths and more bulbous shapes than those preserved in proximal natural sediment (Fig. 5A). We assert that pore fluid pressure dissipation associated with these layers also inhibited liquefied sediment from reaching the surface where features such as sand blows would have otherwise been expected. Although it has been proposed that maximum widths of clastic dikes can be used to estimate earthquake magnitudes and shaking intensities (Lunina and Gladkov, 2015), our observations highlight the importance of considering the physical properties of the hosting sediment, including whether this sediment is natural or engineered, when inferring the shaking characteristics of contemporary earthquakes and / or predicting future dike thicknesses in engineered environments from prehistoric geological evidence in natural sediments. Furthermore, anthropogenic landscape modifications such as stream diversions and emplacements of subsurface infrastructure can be expected to change the spatial patterns (distributions, widths, orientations) of liquefaction injections and lateral spreading. Although prehistoric manifestations of liquefaction injections and ejecta such as sand blows provide important constraints on the hazardscape, an integrated earth systems approach including studies of historical and contemporary landscape evolution, hydrology, sedimentation, and infrastructure must be undertaken when using prehistoric geological features to predict future liquefaction hazards. Even under similar conditions of earthquake shaking, natural and human-influenced geological characteristics of liquefaction may be expected to differ significantly.

5.6. Final considerations

It is difficult to ubiquitously assess whether anthropogenic modifications in the shallow subsurface mitigated or increased liquefaction hazard because the expression of ejecta at the surface depends on a variety of other factors, including site geology, ground shaking characteristics, and ground water elevations. At Avondale Park, anthropogenic fill layers effectively captured CES liquefaction sediments and therefore reduced surface ejecta of liquefied sediment. We hypothesize that these engineered sediments also reduced the amount of total and differential surface settlement by enabling a more rapid decrease in pore fluid pressures in the underlying liquefiable layers. We note that fill layers exhibiting the lowest standard of fill placement (i.e. F2-F3) accommodated the highest amount of liquefied sediments. This does not negate the importance of adequately compacting artificial fill sediments but does point to the value in maintaining a certain level of porosity/permeability if subsurface capture of liquefied sediments is a primary objective. We observed several instances in T2 where CES liquefaction dikes diffused within the gravelly F2-F3 layers (Fig. 7A,B). The accommodation of CES liquefaction sediments at fill layer boundaries (see S1 – Figs. 4,5) is different and depends on inter-layer contrasts (i.e. density, composition, texture) rather than intra-layer porosity or textural heterogeneities. We are unable to determine if CES liquefaction sediments preferred deposition between or within the fill layers; our trench observations suggest roughly equal per-area concentrations in each.

The role of the subdrain systems in enhancing or reducing liquefaction hazard is more complex. It is probable that during the early phases of liquefaction-induced ground deformation the subdrain trenches (and perforated pipes) mitigate liquefaction hazard by accommodating fluidized sediment and limiting its ejection at the surface. However, once the volume of sediment becomes too great and/or fissures develop above the drainage lines, the sediment will erupt at the surface. This was observed to varying degrees at Porritt Park and Avondale Park. At Porritt Park, strong ground deformation (including high fluid pressures) and associated settlement created long continuous fissures directly above the 1970 drainage trenches (Fig. S.6, https://doi.org/10.5061/dryad.z612jm67z). These zones were preferentially targeted as sediment eruption sites, especially in areas where confining pressures remained high enough to facilitate sand blow deposition at the surface. At Avondale Park, similar fissures were not developed to the degree apparent at Porritt Park, but their influence on distributing liquefaction ejecta is still evident and suggests minor settlement may have occurred and/or fluid pressures were high enough (in some locations) within the subdrain trenches to create pathways to the surface, particularly along the western boundary of the subdrain system.

It is worthwhile to consider whether or not the amount of surface ejecta at Porritt Park would have been lower if the 1970 subdrain system had not been installed. Did the presence of the subdrain system provide more opportunity for the eruption of sand ejecta or would natural stratigraphic boundaries (e.g. meander scroll bars) have facilitated eruption of the same volume of ejecta during CES shaking? It is safe to assume that the subdrain lines do *not* affect the amount of available sediment at depth, but does their existence potentially create a stronger linkage and connectivity between distinct sources (i.e. point bar morphologies) and provide easier pathways for sediment eruption over CES shaking durations? We are inclined to think so. In light of this, future research needs to consider the impact that large cityscale infrastructure systems have on liquefaction processes and its surface distribution. Given the pervasiveness of engineered structures (including underground service utilities) and sediments in cities, their influence is undoubtedly significant.

6. Conclusions

The results of our study clearly demonstrate the significant influence of anthropogenic landscape modifications and infrastructure on the geological characteristics of liquefaction. We conclude that (i) anthropogenic fill layers provided low density, high permeability traps that captured fluidized sediment and promoted the formation of a unique assemblage of liquefactioninduced sediment intrusions that differ from those preserved in proximal natural sediment; (ii) pre-existing subsurface drainage systems served as conduits for liquefied sediment and imparted significant influence on the location, size, and orientation of liquefaction ejecta features; and (iii) sediments adjacent to engineered stream channels experienced large lateral strains that are unlikely to have occurred in the absence of channel modifications.

Our study also suggests that spatial variations in naturallyformed topography and liquefaction-susceptible sediments exert strong influences on the characteristics of liquefaction hazards, even in highly anthropogenically-modified environments. This paper highlights important interactions between natural and human-modified environments that should be thoroughly considered when interpreting the geologic effects of contemporary earthquakes and/or using prehistoric geological records to predict future hazards.

Author contribution

J.B. performed the field work and was the primary contributor to the data interpretation and paper authorship. M.Q. contributed to the data interpretation and authorship of the manuscript. M.R. and H.J. performed the GPR data collection and processing, analyses of Porritt Park surface liquefaction ejecta, and contributed to the preparation of the manuscript. S.T. and M.B. performed logging of the exploratory trenches. S.H. and D.G. contributed to the preparation of the manuscript.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

Acknowledgements

Financial support for the project came from Frontiers Abroad and the EQC (Earthquake Commission) capability fund for South Island geohazards research. We are appreciative of the constructive feedback provided by the two anonymous reviewers, which helped improve the quality of the initial manuscript. Special thanks to Sjoerd Van Ballegooy for helping with the processing and interpretation of SCPT-1. The authors thank Peter Almond, Monica Giona Bucci, Sarah Bastin, Laura Stamp, Henry Lanman, Matt Cockcroft, Kevin Williams, Andrea Barrier, David Bell, Jarg Pettinga, Chris Massey, Sacha Baldwin, and Peter Borella. We also thank the Christchurch City Council for park access.

References

- Adalier, K., Elgamal, A., 2004. Mitigation of liquefaction and associated ground deformations by stone columns. Eng. Geol. 72, 275–291. doi:http://dx.doi.org/ 10.1016/j.enggeo.2003.11.001.
- Almond, P., Villamor, P., Tuttle, M., Langridge, R., Clark, K., Eger, A., Bastin, S., Quigley, M., Barker, P., Vandergoes, M., 2013. Liquefaction induced by the 2010–2011 Canterbury earthquake sequence and implications of recently discovered paleoliquefaction features. Geological Society of America Abstracts with Programs 414 44.
- Bartlett, S.F., Youd, T.L., 1992. Empirical Analysis of Horizontal Ground Displacement Generated by Liquefaction-Induced Lateral Spread. Tech. Rep. No. NCEER-92-0021, 1992. National Center for Earthquake Engineering Research, Buffalo, NY, USA, pp. 114.
- Bastin, S.H., Quigley, M.C., Bassett, K., Green, R.A., 2013. Characterisation of modern and paleo-liquefaction features in eastern Christchurch, NZ, following the 2010–2011 Canterbury earthquake sequence. NZ Geomechanics News 26, 38–46.
- Bastin, S.H., Quigley, M.C., Bassett, K., 2015. Paleoliquefaction in Christchurch, New Zealand. Bulletin of the Geological Society of America 127, 1348–1365. doi: http://dx.doi.org/10.1130/B31174.1.
- Bastin, S.H., Bassett, K., Quigley, M.C., Maurer, B., Green, R.A., Bradley, B., Jacobson, D., 2016. Late Holocene liquefaction at sites of contemporary liquefaction during the 2010–2011 Canterbury earthquake sequence, New Zealand. Bull. Seismol. Soc. Am. 106, 881–903. doi:http://dx.doi.org/10.1785/0120150166.
- Bird, J.F., Bommer, J.J., 2004. Earthquake losses due to ground failure. Eng. Geol. 75, 147–179.
- Borella, J.W., Quigley, M., Vick, L., 2016. Anthropocene rockfalls travel farther than prehistoric predecessors. Sci. Adv. 2, e1600969 doi:http://dx.doi.org/10.1126/ sciadv.1600969.
- Borella, J., Quigley, M., Krauss, Z., Lincoln, K., Attanayake, J., Stamp, L., Lanman, H., Levine, S., Hampton, S., Gravley, D., 2019. Geologic and geomorphic controls on rockfall hazard: how well do past rockfalls predict future distributions? Nat. Hazards Earth Syst. Sci. Discuss. 19, 2249–2280. doi:http://dx.doi.org/10.5194/ nhess-19-2249-2019.
- Bradley, B.A., Hughes, M., 2012a. Conditional Peak Ground Accelerations in the Canterbury Earthquakes for Conventional Liquefaction Assessment, Technical Report for the Ministry of Business, Innovation and Employment. April 2012., pp. 22.
- Bradley, B.A., Hughes, M., 2012b. Conditional Peak Ground Accelerations in the Canterbury Earthquakes for Conventional Liquefaction Assessment: Part 2, Technical Report for the Ministry of Business, Innovation and Employment. December 2012., pp. 19.
- Brown, L.J., Weeber, J.H., 1992. Geology of the Christchurch Urban Area: Institute of Geological and Nuclear Sciences Geological Map 1, Scale. 1:25,000, 1 sheet + 105 p.
- Cowie, C.A., 1957. Floods in New Zealand 1920–1953, With Notes on Some Earlier Floods. The Soil Conservation and Rivers Control Council, Wellington, New Zealand.
- Cox, S.C., Rutter, H.K., Sims, A., Manga, M., Weir, J.J., Ezzy, T., White, P.A., Scott, D., 2012. Hydrological effects of the M W 7.1 Darfield (Canterbury) earthquake, 4 September 2010, New Zealand. New Zealand J. Geol. Geophys. 55, 231–247. doi: http://dx.doi.org/10.1080/00288306.2012.680474.
- Cubrinovski, M., Green, R.A., 2010. Geotechnical reconnaissance of the 2010 Darfield (Canterbury) earthquake (contributing authors. In: Allen, J., Ashford, S., Bowman, E., Bradley, B., Cox, B., Cubrinovski, M., Green, R., Hutchinson, T., Kavazanjian, E., Orense, R., Pender, M., Quigley, M., Wotherspoon, L. (Eds.), Bulletin of the New Zealand Society for Earthquake Engineering, 43., pp. 243–320.
 Cubrinovski, M., Bradley, B., Wotherspoon, L., Green, R., Bray, J., Wood, C., Pender, M.,
- Cubrinovski, M., Bradley, B., Wotherspoon, L., Green, R., Bray, J., Wood, C., Pender, M., Allen, J., Bradshaw, A., Rix, G., Taylor, M., Robinson, K., Henderson, D., Giorgini, S., Ma, K., Winkley, A., Zupan, J., O'Rourke, T., DePascale, G., Wells, D., 2011a. Geotechnical aspects of the 22 February 2011 Christchurch earthquake. Bulletin of the New Zealand Society for Earthquake Engineering 44, 205–226.
- Cubrinovski, M., Bray, J.D., Taylor, M., Giorgini, S., Bradley, B.A., Wotherspoon, L., Zupan, J., 2011b. Soil liquefaction effects in the central business district during the February 2011 Christchurch Earthquake. Seismol. Res. Lett. 82, 893–904. Gianella, T.N., Stuedlein, A.W., Canivan, G.J., 2015. Densification of liquefiable soils
- Gianella, T.N., Stuedlein, A.W., Canivan, G.J., 2015. Densification of liquefiable soil using driven timber piles. 6th International Conference on Earthquake Geotechnical Engineering, Christchurch, New Zealand.
- Giona Bucci, M., Villamor, P., Almond, P., Tuttle, M., Stringer, M., Ries, W., Smith, C., Hodge, M., Watson, M., 2018a. Associations between sediment architecture and liquefaction susceptibility in fluvial settings: the 2010–2011 Canterbury Earthquake Sequence, New Zealand. Eng. Geol. 237, 181–197. doi:http://dx.doi. org/10.1016/j.enggeo.2018.01.013.
- Giona Bucci, M., Almond, P.C., Villamor, P., Tuttle, M.P., Stringer, M., Smith, C., Ries, W., Bourgeois, J., Loame, R., Howarth, J., Watson, M., 2018b. Controls on patterns of liquefaction in a coastal dune environment, Christchurch, New Zealand. Sediment. Geol. 377, 17–33. doi:http://dx.doi.org/10.1016/j.sedgeo.2018.09.005.
- Hughes, M.W., Quigley, M.C., van Ballegooy, S., Deam, B.L., Bradley, B.A., Hart, D.E., Measures, R., 2015. The sinking city: earthquakes increase flood hazard in Chaited and Content a
- Christchurch, New Zealand. GSA Today 25, 4–10. doi:http://dx.doi.org/10.1130/ GSATG221A.1. Idriss, I.M., Boulanger, R.W., 2006. Semi-empirical procedures for evaluating
- liquefaction potential during earthquakes. Soil Dyn. Earthq. Eng. 26, 115–130.

- Idriss, I.M., Boulanger, R.W., 2008. Soil Liquefaction During Earthquakes, Monograph Series. Earthquake Engineering Research Institute, Oakland, California, pp. 261.
- Jol, H.M., Bristow, C.S., 2003. GPR in Sediments: Advice on Data Collection, Basic Processing and Interpretation, a Good Practice Guide, 211. Geological Society, London, Special Publications, pp. 1–7. doi:http://dx.doi.org/10.1144/GSL. SP.2001.211.01.01.
- Juang, C.H., Yuan, H., Lee, D.H., Lin, P.S., 2003. Simplified cone penetration test-based method for evaluating liquefaction resistance of soils. J. Geotech. Geoenviron. Eng. 129, 66–80. doi:http://dx.doi.org/10.1061/(ASCE)1090-0241(2003)129:1 (66).
- Kramer, S.L., Elgamal, A., 2001. Modeling Soil Liquefaction Hazards for Performancebased Earthquake Engineering. PEER Report 2001/13. Pacific Earthquake Engineering Research Center (PEER), Berkeley, Calif.
- Lewis, S.L., Maslin, M.A., 2015. Defining the anthropocene. Nature 519, 171–180. doi: http://dx.doi.org/10.1038/nature14258.
- Lunina, Ö.V., Gladköv, A.S., 2015. Seismically induced clastic dikes as a potential approach for the estimation of the lower-bound magnitude/intensity of paleoearthquakes. Eng. Geol. 195, 206–213. doi:http://dx.doi.org/10.1016/j. enggeo.2015.06.008.
- O'Rourke, T.D., Jeon, S.-S., Toprak, S., Cubrinovski, M., Jung, J.K., 2012. Underground lifeline system performance during the Canterbury earthquake sequence. Proceedings of the 15th World Congress on Earthquake Engineering (15WCEE), Lisbon, Portugal, 24-28 Sep 2012.
- Obermeier, S.F., 1996. Use of liquefaction-induced features for paleoseismic analysis – An overview of how seismic liquefaction features can be distinguished from other features and how their regional distribution and properties of source sediment can be used to infer the location and strength of Holocene paleoearthquakes. Eng. Geol. 44, 1–76.
- Obermeier, S.F., Bleuer, N.K., Munson, C.A., Munson, P.J., Martin, W.S., McWilliams, K. M., Tabaczynski, D.A., Odum, J.K., Rubin, M., Eggart, D.L., 1991. Evidence of strong earthquake shaking in the lower Wabash Valley from prehistoric liquefaction features. Science 251, 1061–1063.
- Pirhadi, N., Tang, X., Yang, Q., Kang, F., 2019. A new equation to evaluate liquefaction triggering using the response surface method and parametric sensitivity analysis. Sustainability 11, 112. doi:http://dx.doi.org/10.3390/su11010112.
- Pradel, D., Wartman, J., Tiwari, B., 2012. Impact of anthropogenic changes on liquefaction along the Tone River during the 2011 tohoku earthquake. Nat. Hazards Rev. 15, 13–26. doi:http://dx.doi.org/10.1061/(asce)nh.1527-6996.0000097.
- Price, S.J., Ford, J.R., Cooper, A.H., Neal, C., 2011. Humans as major geological and geomorphological agents in the Anthropocene: the significance of artificial ground in great Britain. Philosophical Transactions of the Royal Society A: mathematical. Physical and Engineering Sciences 369, 1056–1084. doi:http:// dx.doi.org/10.1098/rsta.2010.0296.
- Quigley, M., 2015. Lancaster park study, university of canterbury consultancy report CN4600001360-7. submission to Christchurch City Council 70–85. http://www. drquigs.com/wp-content/uploads/2016/04/FINAL-REPORT-combined.pdf).
- Quigley, M.C., Bastin, S., Bradley, B.A., 2013. Recurrent liquefaction in Christchurch, New Zealand, during the Canterbury earthquake sequence. Geology 41, 419– 422. doi:http://dx.doi.org/10.1130/G33944.1.
- Quigley, M.C., Hughes, M.W., Bradley, B.A., van Ballegooy, S., Reid, C., Morgenroth, J., Horton, T., Duffy, B., Pettinga, J.R., 2016. The 2010-2011 Canterbury Earthquake Sequence: environmental effects, seismic triggering thresholds and geologic legacy. Tectonophysics 672–673, 228–274. doi:http://dx.doi.org/10.1016/j. tecto.2016.01.044.
- Quigley, M.C., Bennetts, L.B., Durance, P., Kuhnert, P.M., Lindsay, M.D., Pembleton, K. G., Roberts, M.E., White, C.J., 2019a. The provision and utility of earth science to decision-makers: synthesis and key findings. Environ. Syst. Decis. 39, 349–367. doi:http://dx.doi.org/10.1007/s10669-019-09737-z.
- Quigley, M.C., Bennetts, L.B., Durance, P., Kuhnert, P.M., Lindsay, M.D., Pembleton, K. G., Roberts, M.E., White, C.J., 2019b. The provision and utility of science and uncertainty to decision-makers: earth science case studies. Environ. Syst. Decis. 39, 307–348. doi:http://dx.doi.org/10.1007/s10669-019-09728-0.
- Rutter, H., 2011. Earthquake Related Springs. Aqualinc Report No. C11069, Prepared for the New Zealand Earthquake and War Damage Commission (EQC). Aqualinc Research Ltd., Christchurch, New Zealand.
- Seed, H.B., Idriss, I.M., 1971. Simplified procedure for evaluating soil liquefaction potential. J. Soil Mech. Found. Div. 97, 1249–1273.
- Silby, K., 1856. Christchurch Area Showing Waterways Swamps and Vegetation. Christchurch Drainage Board available at http://resources.ccc.govt.nz/files/ blackmap-environmentecology.pdf (accessed June 2013).
- Sims, J.D., 1975. Determining earthquake recurrence intervals from deformational structures in young lacustrine sediments. Tectonophysics 29, 141–152. doi: http://dx.doi.org/10.1016/0040-1951(75)90139-0.
- Steffen, W., Crutzen, P.J., McNeill, J.R., 2007. The Anthropocene: Are Humans Now Overwhelming the Great Forces of Nature? Ambio 36, 614–621.
- Stuedlein, A.W., Gianella, T.N., Canivan, G., 2016. Densification of granular soils using conventional and drained timber displacement piles. J. Geotech. Geoenvironmental Eng. 142, 04016075 doi:http://dx.doi.org/10.1061/(asce) gt.1943-5606.0001554.
- Townsend, D., Lee, J.M., Strong, D.T., Jongens, R., Smith Lyttle, B., Ashraf, S., Rosser, B., Perrin, N., Lyttle, K., Cubrinovski, M., Taylor, M.L., Hughes, M.W., Wilson, T., Almond, P., Jacka, M., McCahon, I., Christensen, S., 2016. Mapping surface liquefaction caused by the September 2010 and February 2011 Canterbury

earthquakes: a digital dataset. New Zealand J. Geol. Geophys. 59, 496–513. doi: http://dx.doi.org/10.1080/00288306.2016.1182929.

- Tuttle, M., 2001. The use of liquefaction features in paleoseismology: Lessons learnt in the New Madrid seismic zone, central United States. J. Seismol. 5, 361–380. doi:http://dx.doi.org/10.1023/A:1011423525258.
- Tuttle, M.P., Hartleb, R., Wolf, L., Mayne, P.W., 2019. Paleoliquefaction Studies and the Evaluation of Seismic Hazard. Geosciences 9 (7), 311. doi:http://dx.doi.org/ 10.3390/geosciences9070311.
- van Ballegooy, S., Berryman, K., Deam, B., Jacka, M., 2014av. Repeated major episodes of tectonic deformation, lateral spread and liquefaction in Christchurch during the Canterbury Earthquake Sequence of 2010–2011. Engineering Geology for Society and Territory 5, 1043–1049.
- van Ballegooy, S., Green, R., Lees, J., Wentz, R., Maurer, B., 2015a. Assessment of various CPT based liquefaction severity index frameworks relative to the Ishihara (1985) H1–H2 boundary curves. Soil Dyn. Earthq. Eng. 79, 347–364.
- van Ballegooy, S., Lacrosse, V., Simpson, J., Malan, P., 2015b. Comparison of CPT based simplified liquefaction assessment methodologies based on Canterbury
- geotechnical dataset. Proceedings of the 12th Australia New Zealand Conference on Geomechanics, NZGS & AGS, Wellington, New Zealand, pp. 618–625.
- Villamor, P., Almond, P., Tuttle, M.P., Giona-Bucci, M., Langridge, R.M., Clark, K., Ries, W., Bastin, S.H., Eger, A., Vandergoes, M., Quigley, M.C., Barker, P., Martin, F., Howarth, J., 2016. Liquefaction features produced by the 2010-2011 Canterbury earthquake sequence in southwest Christchurch, New Zealand, and preliminary assessment of Paleoliquefaction features. Bull. Seismol. Soc. Am. 106, 1747–1771. doi:http://dx.doi.org/10.1785/0120150223.
- Waters, C.N., Zalasiewicz, J., Summerhayes, C., Barnosky, A.D., Poirier, C., Gałuszka, A., Cearreta, A., Edgeworth, M., Ellis, E.C., Ellis, M., Jeandel, C., Leinfelder, R., McNeill, J.R., Richter, D.D., Steffen, W., Syvitski, J., Vidas, D., Wagreich, M.,

Williams, M., Zhisheng, A., Grinevald, J., Odada, E., Oreskes, N., Wolfe, A.P., 2016. The Anthropocene is functionally and stratigraphically distinct from the Holocene. Science 351. doi:http://dx.doi.org/10.1126/science.aad2622.

- Watkinson, I.M., Hall, R., 2019. Impact of communal irrigation on the 2018 Palu earthquake-triggered landslides. Nat. Geosci. doi:http://dx.doi.org/10.1038/ s41561-019-0448-x.
- Wotherspoon, L.M., Pender, M.J., Orense, R.P., 2012. Relationship between observed liquefaction at Kaiapoi following the 2010 Darfield earthquake and former channels of the Waimakariri River. Eng. Geol. 125, 45–55. doi:http://dx.doi.org/ 10.1016/j.enggeo.2011.11.001.
- Youd, T.L., Idriss, I.M., Andrus, R.D., Arango, I., Castro, G., Christian, J.T., Dobry, R., Finn, W.D.L., Harder Jr., L.F., Hynes, M.E., Ishihara, K., Koester, J.P., Liao, S.S.C., Marcuson III, W.F., Martin, G.R., Mitchell, J.K., Moriwaki, Y., Power, M.S., Robertson, P.K., Seed, R.B., Stokoe II, K.H., 2001. Liquefaction resistance of soils: summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils. J. Geotech. Geoenviron. Eng. 127, 817–833.
- Zalasiewicz, J., Williams, M., Haywood, A., Ellis, M., 2011. The anthropocene: a new epoch of geological time? Philosophical Transactions of the Royal Society A: mathematical. Phys. Eng. Sci. 369, 835–841. doi:http://dx.doi.org/10.1098/ rsta.2010.0339.
- Zalasiewicz, J., Waters, C.N., Williams, M., Barnosky, A.D., Cearreta, A., Crutzen, P., Ellis, E., Ellis, M.A., Fairchild, I.J., Grinevald, J., Haff, P.K., Hajdas, I., Leinfelder, R., McNeill, J., Odada, E.O., Poirier, C., Richter, D., Steffen, W., Summerhayes, C., Syvitski, J.P.M., Vidas, D., Wagreich, M., Wing, S.L., Wolfe, A.P., Zhisheng, A., Oreskes, N., 2015. When did the Anthropocene begin? A mid-twentieth century boundary level is stratigraphically optimal. Quat. Int. 383, 196–203. doi:http:// dx.doi.org/10.1016/j.quaint.2014.11.045.