Characterisation of modern and paleoliquefaction features in eastern Christchurch, NZ following the 2010-2011 Canterbury earthquake sequence

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ABSTRACT
Liquefaction during the 2010 Mw 7.1 Darfield earthquake and subsequent aftershocks (Canterbury earthquake sequence, CES) caused severe damage to land and infrastructure in Christchurch, New Zealand. As many as ten liquefaction episodes occurred in parts of eastern Christchurch, which manifested at the surface as sand blows, fissures and differential settlement. Trenching to water-table depths (~1-2 m below surface) across aligned sand blow vents and fissures revealed the subsurface geometry of the feeder dike system. In addition to the multiple CES dike generations, subsurface evidence for paleo liquefaction was found at two study sites in Avonside, eastern Christchurch. The tendency for reactivation of the liquefaction source conduit indicates that the locations of modern liquefaction are likely to contain geologic evidence for paleo liquefaction. We outline strategies that combine geomorphic, geological and geotechnical approaches for investigating paleoliquefaction elsewhere at sites that may or may not have historical evidence of liquefaction.

INTRODUCTION
Liquefaction occurs where earthquake-induced cyclic shearing of loose, saturated sediments results in the collapse of the soil skeleton and the commensurate transfer of the overburden stress to the pore fluid and transition to a liquefied state (Seed & Idriss, 1982; Idriss & Boulanger, 2008). Such soil deformation may cause severe land and infrastructure damage (e.g., Cubrinovski & Green, 2010). Understanding the liquefaction susceptibility of geologic deposits is therefore an important component of increasing resilience to earthquakes. The susceptibility of soils to liquefaction can be assessed by historical records, in situ geotechnical testing such as Cone penetrometer tests (CPT), Standard Penetration Tests (SPT), Swedish Weight Sounding (SWS), and Dynamic Cone Penetration Tests (DCPT), physical criteria such as grain-size distribution, particle shape, and plasticity characteristics, and the geologic characteristics such as depositional setting and groundwater depth (see Kramer, 1996 for review; Green et al., 2005; Green et al., 2011). Information on the location and magnitude of both historic and/or pre-historic earthquakes can be obtained by detailed studies of liquefaction-induced features such as sand blows and their ‘feeder dikes’ (Tuttle, 2001, Green et al., 2005).

The 2010-2012 Canterbury earthquake sequence (CES) caused at least ten distinct liquefaction episodes in parts of eastern Christchurch (Quigley et al., 2013), resulting in significant land and infrastructure damage (Cubrinovski et al. 2012). The most severe liquefaction was associated with the September 2010 Mw7.1 Darfield event, and the February 2011 Mw 6.2, June 2011 Mw6.0, and December Mw 5.9 events (Quigley et al., 2013). Surface manifestations of CES-induced liquefaction included sand blow (Figure 2) and blister formation, lateral spreading induced fissuring (Figure 1), and other surface deformations including differential settlement. The high liquefaction potential of the sediments underlying eastern Christchurch had long been recognized based on geotechnical, compositional, and geological characteristics (Elder, et al., 1991). There are no reports or evidence of historical or paleoliquefaction in eastern or central Christchurch prior to the CES, although liquefaction was reported in the township of Kaiapoi to the north of Christchurch and in the northern suburb of Belfast following the 1901 Cheviot earthquake (Berrill et.al., 1994; Downes & Yetton, 2012). Given that the sand blow vents were repeatedly reactivated during the CES, we sought to investigate these features in the subsurface to see whether any evidence for paleoliquefaction could be found. In this paper we document the subsurface expression of liquefaction caused by the CES at two study sites in eastern Christchurch. We provide evidence for paleoliquefaction at these sites and outline strategies for investigating liquefaction histories in areas that may or may not have evidence for modern liquefaction.

Figure 1: Study area showing distribution of surface liquefaction features and investigation sites. Liquefaction features aligned with the closest down-slope free face, being either the Avon River or the paleocut bank.

STUDY AREA

Figure 1 above shows the study area. Christchurch is primarily built on alluvial silt and sand deposits, drained peat swamps and estuaries, sand of fixed to semi-fixed 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 up to ~3km inland of the central city at 6.5 ka (Brown & Weeber, 1992). The combination of loose, fine-grained sands and silts, with high water tables (typically 1-2 m depth), and localized artesian water pressures that minimize soil cementation and 'ageing' effects, were known to pose a significant liquefaction hazard for much of Christchurch (Elder et al., 1991).

The study area of Avonside, eastern Christchurch is located within an inside meander bend of the Avon River (Figure 1), which undergoes tidal current reversals. Near-surface deposits beneath the top soil and anthropogenic material consist of alluvial silts and sands, with some gravel units in abandoned channels. Two study sites are investigated in this paper (Figure 1). The study site at 11 Bracken St experienced liquefaction and formation of sand blows (Figure 2) in at least ten CES earthquakes with local PGA ≥ 0.1g (Quigley et al., 2013). The Sullivan Park study site experienced significant liquefaction in the largest CES earthquakes and formed large lateral spreading cracks up to 0.5 m in width during the February 2011 Mw 6.2 event.

Figure 2: Photographs taken in the backyard of the Bracken St site following the September 2010 Mw7.1 event (a), and the February 2011 Mw 6.2 (b), June 2011 Mw 6.0 (c), and December Mw 5.9 (d) events, with the alignment and re-activation of the sand blow vents evident.

INVESTIGATION METHODS