Engineering Geology 237 (2018) 181–197

Contents lists available at ScienceDirect

Engineering Geology

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

Associations between sediment architecture and liquefaction susceptibility in fluvial settings: The 2010–2011 Canterbury Earthquake Sequence, New Zealand

Giona Bucci M.[a,*], Villamor P.[b], Almond P.[a], Tuttle M.[c], Stringer M.[d], Ries W.[b], Smith C.[a], Hodge M.[e], Watson M.[f]

[a] Lincoln University, Soil Science Department, P O Box 85084, Lincoln, New Zealand
[b] GNS Science, Active Landscapes Department, PO Box 30368, Lower Hutt, New Zealand
[c] M. Tuttle & Associates, PO Box 345, Georgetown, ME 04548, USA
[d] University of Canterbury, PO Box 4800, Christchurch 8140, New Zealand
[e] U.N. Statistical Institute for Asia and Pacific, USA
[f] ScanTec, Geophysical Consultants, Ltd, PO Box 999, Whangarei, New Zealand

ARTICLE INFO

Keywords:
Liquefaction susceptibility
Fluvial geomorphology
Liquefaction source layer
Paleoseismology
Cone-penetration test
Ground-penetrating radar
Paleoseismic trenches
LIDAR remote sensing
Earthquake hazard

ABSTRACT

This study focuses on the sedimentary architecture of sites in the Halswell floodplain (Christchurch, New Zealand) that experienced liquefaction during the 2010–2011 Canterbury Earthquake Sequence. We investigated landforms where ejecta were and were not observed, and define their 3D geometry and sediment characteristics. The first site straddles an abandoned channel of the Halswell River that is overlain by a crevasse splay deposit. The second site is located on the inside bend of an active meander of the river. Both sites were severely affected by liquefaction during the Darfield and Christchurch earthquakes. A suite of techniques was used in the characterization of both sites: detailed geomorphic and liquefaction mapping with DEMs derived from LIDAR; Ground-Penetrating Radar (GPR); paleoseismic trenches; hand-piston cores, radiocarbon dating, grain-size analysis, and cone-penetration tests. Potentially liquefiable sands, based on their grain characteristics and water saturation, were found in many environments within the alluvial setting studied (river channel, point bar deposits and flood plain). The surficial geology of the two study sites is mapped as crevasse splay and point bar deposits. However, the layers that liquefied were at depth within buried abandoned channel and point bar deposits at the Hardwick site, and within buried point bar deposits at the Marchand site. The location of the surface manifestation of liquefaction was characterized by specific geometry of the sedimentary architecture of the alluvial floodplain that facilitated or hindered flow of the slurry of water and entrained sediment towards the surface. On the one hand, the inclined contacts of paleochannel and point bar deposits created pathways for the liquefied material to travel to the surface. On the other hand, in the floodplain, with no ejecta, sand and silty sand layers interfingered with clay lenses, lack the specific geometry that facilitates the ejecta at the surface. The CPT analysis showed that liquefaction ejecta occurred above a thick homogeneous layer of sand, whereas liquefaction ejecta did not occur (or sand blows did not form) where clay lenses were interfingered with sand. At both sites the surface manifestation of liquefaction was mainly located on slightly higher topographic areas, suggesting the topography is an additional controlling factor on the surface distribution of liquefaction ejecta. In summary, the surface manifestation of liquefaction is a result of a specific sediment type that was saturated, sedimentary setting that facilitated flow of fluidized sediment to the surface, and topographic relief prone to cracking.

1. Introduction

Liquefaction, as a consequence of strong ground shaking, has been responsible for severe damage and large economic losses in alluvial settings worldwide. For example, the 2010–2011 Canterbury Earthquake Sequence resulted in NZ$40 billion (~30 US$) of economic loss (equivalent ~20% of New Zealand GDP; New Zealand Treasury, 2013) of which a large part was due to liquefaction (Cubrinovski et al.,

* Corresponding author.
E-mail address: monicagionabucci@gmail.com (M. Giona Bucci).

https://doi.org/10.1016/j.enggeo.2018.01.013
Received 3 July 2017; Received in revised form 12 November 2017; Accepted 19 January 2018
Available online 21 March 2018

2011a). However, liquefaction was not distributed evenly across the Canterbury Plains alluvial setting (Townsend et al., 2016; Tuttle et al., 2017). The association between earthquake induced liquefaction ejecta and the alluvial setting has been investigated around the world, including in Italy (e.g. Alessio et al., 2013), Japan (e.g. Iwasaki et al., 1978) and the USA (e.g. Boulanger et al., 1997). Previous research has documented the association of liquefaction ejecta with specific parts of the fluvial environment, and the susceptibility of specific geomorphic features such as fluvial channels (Tuttle and Barstow, 1996) and point-bar deposits (Holzer et al., 2010; Tuttle, 2001). These findings not only suggest where surface manifestation of liquefaction (sand blows, blisters and dikes) may occur but also where ground failures may occur that could impact engineered structures such as bridges and pipelines (Tuttle and Barstow, 1996).

Recent research on liquefaction in the Canterbury Plains provided further information about the spatial association of alluvial geomorphic features and surface expression of liquefaction (Almond et al., 2012; Townsend et al., 2016), the PGA (Peak Ground Acceleration) threshold of liquefaction (Bastin et al., 2015; Quigley et al., 2013; Villamor et al., 2014, 2016), and the land damage caused by liquefaction (Bray et al., 2014; Cubrinovski et al., 2010, 2011a,b; Monk et al., 2016; Orense et al., 2011; van Ballegooy et al., 2014). However, none of these Canterbury studies investigated *why* surface manifestation of liquefaction occurs in specific elements of the alluvial system (specific geomorphic settings) and what role their subsurface sedimentary architecture plays in determining surface ejecta patterns.

The scope of this paper is to assess the influence of the sedimentary architecture of the alluvial environment in controlling the surface manifestation of liquefaction during the Canterbury Earthquake Sequence (CES), and thus evaluate the susceptibility of different sedimentary elements within the alluvial setting. We exploit the rich dataset of liquefaction features provided by the CES events and integrate several techniques such as geomorphic mapping, analysis of exploratory excavations and hand piston cores, detailed grain size analysis, and ground penetrating radar (GPR) and seismic cone penetration test (CPT) surveys. We build 3D models by combining stratigraphic cross sections developed from trench and core logs and geomorphic maps that show the morphology (sedimentary unit shape) and the sedimentary characteristics (grain size, sorting, density) of subsurface layers. We also identified the source layer that liquefied, using a new statistical grain size analysis to assess provenance of liquefaction ejecta. This approach involves resolving and comparing grain size sub-populations for both samples of the ejected and subsurface sands. Grain size results are integrated with results from seismic CPTs and visual core inspections to further assess the liquefaction source. We finally discuss the alluvial elements that are more prone to liquefaction and that facilitate ground failure and sand ejection. Results from this study will contribute to a better understanding of the susceptibility to liquefaction of the alluvial settings and can be used for better siting of paleoliquefaction and geotechnical studies. Also, in conjunction with traditional geotechnical exploratory techniques, the results presented here will contribute to better land use planning, appropriate design of engineered structures, and mitigation of liquefaction-prone sites.

1.1. The Canterbury Plains and previous studies on liquefaction in the Canterbury region

The Canterbury Plains comprise landforms and deposits of Late Pleistocene and Holocene age (Brown and Weeber, 1992). The Plains are formed by a series of coalescing alluvial fans built by the Canterbury rivers coming from the Southern Alps and their foothills (Brown et al., 1988 and Fig. 1). The Waimakariri River is the major player in the study area. Some of the currently abandoned channels can be traced through the wider area of Christchurch and were probably active within the last 500 years (Basher et al., 1988). Some of these channels were particularly prone to liquefaction during the CES (Almond et al., 2010a; Bastin et al., 2015; Nobes et al., 2013; Villamor et al., 2014, 2016; Wotherspoon et al., 2012).

Prior to the CES, liquefaction hazard was well-known in the area (Brown and Weeber, 1992; Clough, 2005; Elder et al., 1991; Stirling et al., 1999), although it was not a priority for geoscientists and NZ government (for a review see Brackley et al., 2012). However, none of these predictions envisaged the level of liquefaction damage that occurred during the CES events.

1.2. The Canterbury Earthquake Sequence

The 2010–2011 CES began with the Mw 7.1 Darfield earthquake on 4 September 2010 (Bannister and Gledhill, 2012). This event was caused by an unknown, blind fault (the Greendale Fault) near Darfield, with a hypocentre located at a depth of 10 km (Fig. 1) (Quigley et al., 2012). Liquefaction affected residential houses or neighbourhoods near waterways or streams, wetlands throughout the city of Christchurch and the town of Kaiapoi, as well as rural areas near streams and former channels of the Waimakariri River (Almond et al., 2012; Brackley et al., 2012; CGD0200, 2013; Orense et al., 2011; Townsend et al., 2016; Tuttle et al., 2017; Villamor et al., 2016).

The sequence continued in a series of aftershocks through 2010 and early 2011 (Bannister and Gledhill, 2012). The most devastating aftershock, the Mw 6.2 Christchurch earthquake of 22 February 2011, caused 185 fatalities, damaging landslides and rock falls in the hills, and extensive liquefaction throughout the city (Brackley et al., 2012; Kaiser et al., 2012; Townsend et al., 2016). A significant event with Mw 6.3 occurred on 13 June 2011 causing liquefaction and damage in the eastern hill suburbs, followed by additional events of Mw 5.8 and Mw 5.9 offshore from Christchurch in December 2011, which caused local liquefaction (e.g., Quigley et al., 2013). A relatively recent event, the Mw 14 February 2017 earthquake offshore of Christchurch, also produced liquefaction along the coastal fringe (Giona Bucci et al., 2017).

2. Methods

A multidisciplinary approach has been used to assess the influence of the sedimentary architecture of a floodplain in controlling the surface manifestation of liquefaction during the Canterbury Earthquake Sequence (CES). To address this, our research i) documents the spatial correlation between surface manifestation of liquefaction and geomorphic elements of the Halswell River (detailed geomorphic mapping); ii) defines the specific elements of the subsurface sedimentary architecture that influence the surface manifestation of liquefaction (visual inspection of trenches and cores, GPR and seismic CPT), including potentially identifying the subsurface layers that liquefied during the CES (grain size analysis and seismic CPT); and iii) develops a conceptual model of the relationships between alluvial sedimentation, floodplain architecture, and surface manifestation of liquefaction.

Two study sites were selected on the floodplain of the Halswell River (Fig. 2) because they are located in a greenfield area where minimal surface modification allowed landform elements to be mapped accurately. The Hardwick and Marchand properties experienced at least three liquefaction events, during September 2010, February 2011, and June 2011 earthquakes, and were documented by aerial photos and local reports (Tuttle et al., 2017; Villamor et al., 2014, 2016).

2.1. Lidar data interpretation and detailed geomorphic map of the Halswell river

A detailed geomorphic map was produced to show the spatial association of surface manifestation of liquefaction with landforms of the alluvial system (e.g. point bars, abandoned river channels, etc.). Landforms were mapped using aerial photos from 2010 and a 1 m DEM (digital elevation model) derived from LIDAR (acquired by Selwyn District Council in 2008; Fig. 2). These datasets were previously used by