Geomorphological Controls on the Distribution of Liquefaction in Blenheim, New Zealand, during the 2016 M_w7.8 Kaikōura Earthquake

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ABSTRACT

The moment magnitude (M_w) 7.8 Kaikōura, New Zealand, earthquake triggered relatively few cases of liquefaction and related phenomena (e.g., lateral spreading) despite the large magnitude of the event. Cases of severe liquefaction manifestation were confined to localized areas proximal to waterways near the township of Blenheim, in the north-eastern corner of the South Island of New Zealand. The occurrence and non-occurrence of liquefaction within the wider Blenheim area is shown to closely correspond with fluvial geomorphology and associated depositional setting of the sediments. Herein, the distribution of liquefaction within the region is detailed in the context of the geomorphological influences and sedimentologic controls. This work highlights the influence of geomorphic variability on the occurrence of liquefaction, with the aim of improving the assessment of liquefaction hazards for future events worldwide.

INTRODUCTION

Earthquake-induced liquefaction poses a significant hazard to the built environment, as observed following many recent and historical events. Detailed mapping of the distributions of liquefaction manifestations following recent events provides insights the geomorphologic settings and soil profiles in areas where liquefaction typically does and does not manifest. This paper provides an overview of the distributions of liquefaction manifestations within the lower Wairau Plains following the 2016 Kaikōura earthquake as derived from post-event reconnaissance. The influences of geomorphic and sedimentologic variability on the distribution of liquefaction-induced damage is discussed, with the aim of highlighting the importance of incorporating local geomorphic variability into liquefaction hazard maps and land-use planning decisions for local and regional authorities.

The 2016 M_w 7.8 Kaikōura earthquake triggered localized liquefaction in the Wairau Plains, proximal to the township of Blenheim, on the South Island of New Zealand (GEER, 2017; Stringer *et al*., 2017). Initial post-event reconnaissance led by a team comprised of New Zealand-based researchers and practicing engineers and members of the Geotechnical Extreme Events Reconnaissance Association (GEER) provided an overview of the distributions of liquefaction manifestations and is outlined in GEER (2017). The impact of lateral spreading on infrastructure was generally low due to the rural nature of the area, with few buildings present in these areas (GEER, 2017). Post-event mapping indicates localized cases of lateral spreading and associated surface manifestations of liquefaction ejecta occurred in the unprotected flood plains adjacent to the Lower Wairau and Ōpaoa Rivers to the east of the Blenheim township (Figure 1; GEER, 2017; Stringer *et al*., 2017). The extent and severity of liquefaction manifestations are shown to spatially vary along the lengths of these rivers and thus indicates that variations in river morphology and associated depositional settings of the sediments may influence the observed manifestations. A peak horizontal ground acceleration (PGA) of 0.22 g was recorded at a strong motion station within the lower Wairau Plains, and subsequent modelling of the ground motions suggests little spatial variability in PGA in the area (Bradley et al., 2017). Localized cases of minor liquefaction manifestations were reported across the upper portion of the South Island of New Zealand following the 2016 Kaikōura earthquake and are summarized in GEER (2017). The localized nature of these distributions reflects a lack of susceptible sediments in regions that experienced intense shaking, and conversely, regions having deposits susceptible to liquefaction (e.g., Christchurch) having experienced less intense shaking (GEER, 2017).

Prior to 2016, liquefaction and lateral spreading had been reported proximal to rivers and streams within the Wairau Plains and surrounding Marlborough region following the 1848 M_w7.5 Marlborough and 1855 M_w8.2 Wairarapa earthquakes (Arnold 1847; Mason and Little 2006; Thompson 1859). Localized liquefaction was also reported proximal to the Ōpaoa River and Wairau Lagoon following the 2013 M_w 6.6 Lake Grassmere earthquake (van Dissen et al., 2013). The consistency in the distributions of the recent and historical cases of liquefaction indicates that areas of recent fluvial sediments are highly susceptible to liquefaction, and a basic knowledge of fluvial deposition may aid the assessment of liquefaction hazards.

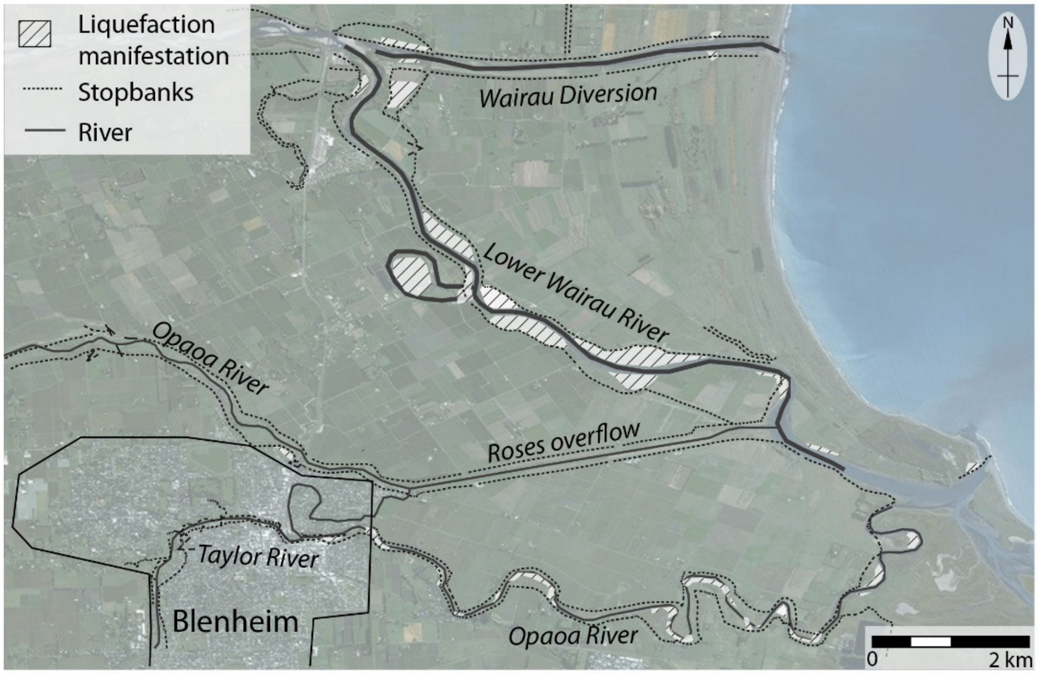


Figure 1. Overview of liquefaction damage in Blenheim and the Wairau Plains resulting from the 2016 M_W7.8 Kaikōura earthquake (modified from Bastin et al., 2017)

OVERVIEW OF THE GEOLOGIC AND GEOMORPHIC SETTING

The township of Blenheim is situated upon the Wairau Plains which comprise the alluvial outwash plain of the Wairau River and are predominantly underlain by alluvially re-worked glacial outwash gravels, sands, and silts sourced from the surrounding mountains (Basher et al., 1995). The active flood-plain has avulsed across the region over geologic time, as reflected by the many active and paleo-channels that transect the surface of the plains. The Wairau River transitions from braided, in the upper portion of the plains, to meandering approximately 7 km inland from the coast as a result of decreasing topographic gradient. The geomorphology and drainage modification of the area are summarized in detail herein for later comparison with the liquefaction distributions.

The township of Blenheim is predominantly underlain by Holocene alluvial deposits composed of poorly consolidated alluvial sand, silt, and peat swamps. Sediments were initially deposited by the Wairau River, but have subsequently been re-worked by the meandering Ōpaoa (previously named Opawa), Taylor, and Omaka Rivers which flow through the township (Figure 1; Basher et al., 1995). Low topographic relief combined with regular flooding resulted in large swamps forming in the area now comprising Blenheim. Paleo-channels and associated crevasse splay deposits are present across the lower portion of the plains and reflect channel avulsion and bank overtopping flood events prior to settlement. Alluvial sediments to the east of the township are inter-fingered with lagoonal muds and coastal sands, silts, and gravels which reflect coastline progradation and marine regression following the mid-

Holocene highstand 6,000 years before present (Basher et al., 1995). Gravel beach ridges are present from the modern coastline to 5.5 km inland, while discontinuous sand dunes are present from 5.5 to 7 km inland and reflect the position of the paleo-coastlines. The course of the meandering section of the Wairau River is diverted around the beach ridges, which are of sufficient height and erosional resistance that the river has maintained its position for at least the last 2000 years (Christensen and Doscher, 2010).

Significant river control and drainage works have been undertaken within the lower portion of the Wairau Plains in an attempt to reduce the flooding hazard. Stopbanks (or levees) were constructed along the banks of the meandering Taylor, Omaka, and Ōpaoa Rivers within central Blenheim as part of the initial drainage works (Marlborough Catchment Board, 1959; Christensen and Doscher, 2010). Stopbanks were also constructed along the Upper Wairau River in an attempt to reduce over-bank flows through Blenheim, but have resulted in the flooding hazard being transferred downstream. Remedial works, including straightening of an "S-bend," were subsequently undertaken to reduce flooding in the Lower Wairau River. Work culminated in the construction of a diversion channel that provides a direct route from the braided Upper Wairau River to the ocean (Figure 1). The unprotected floodplain surrounding the Lower Wairau and Ōpaoa Rivers is highly susceptible to flooding with over-bank floods regularly depositing loosely consolidated fine sand to silt in these areas. Flooding in the distal floodplains protected by stopbanks is limited to major events (i.e. 20 to 50 year events; Christensen and Doscher, 2010).

SEDIMENTOLOGIC AND GEOMORPHOLOGICAL INFLUENCES ON THE DISTRIBUTION OF LIQUEFACTION MANIFESTATIONS

Post-event reconnaissance mapping indicated that liquefaction manifestations were primarily confined to the un-protected flood-plains adjacent Lower Wairau and Ōpaoa Rivers. The extent and severity of liquefaction manifestations spatially varied along the lengths of these rivers and predominantly confined to the inside banks of meander bends to the east of the township (Figure 1). The observed distributions indicate that a basic understanding of fluvial geomorphology may be employed to interpret the soil properties at sites where liquefaction was and was not observed (Bastin et al. 2017). The geomorphology of the lower portion of the Wairau Plains was mapped in detail by Bastin et al. (2017) from subtle variations in topography, as observed within the pre-event DEM, supplemented with analysis of river morphologies, historical maps, and literature outlining drainage modification of the area (e.g. Cook, 1895; Basher et al., 1995). Topographic variability across the lower Wairau Plains is indicated in the pre-event DEM presented in Figure 2a, while the geomorphology mapped as part of this study is presented in Figure 2b.

(a)

(b)

Figure 2. a) DEM of the lower Wairau Plains with the distribution of liquefaction manifestations mapped following the 2016 Kaikōura earthquake indicated. b) Geomorphic map of the lower Wairau Plains. (Bastin et al. 2017)

The morphology of the meandering Lower Wairau and Ōpaoa Rivers are typical of meandering rivers which comprise a single, sinuous channel. The river channel typically migrates across the surrounding alluvial plain as a result of erosion and retreat of the outer banks, and subsequent re-deposition on the adjacent inner bank. Erosion occurs as the highest flow velocities are concentrated towards the outer banks during bank-full conditions with flow then deflected towards the adjacent inner-bank where eroded sediments are deposited, and typically comprise fine sands grading to silts, termed point-bar deposits. Point-bar deposits may be interbedded with over-bank flood deposits comprising fine to medium sand to silt (Fryirs and Brierley, 2012). The surrounding alluvial plain typically contains fine sand to silt deposited as the river over-tops its banks during flood events, while swamps may form distal to the river in areas where standing water remains following floods (Fryirs and Brierley, 2012). Meander-bends may be cut-off from the main channel due to rapid avulsion of the channel. The resultant abandoned river channel, termed paleo-channel, are preserved in the landscape as topographic depressions and are typically infilled with fine to medium sands, overlain by silts deposited as flow-rates waned (Fryirs and Brierley, 2012). The geologically young, unconsolidated, and saturated nature of point-bar and paleo-channel deposits make them highly susceptible to liquefaction, as shown following recent events in Canterbury, New Zealand, and Japan (e.g., Wotherspoon et al., 2012; Wakamatsu, 2012). The limited deposition on the outer-bank and predominance of silts in the distal flood plain results in lower liquefaction susceptibilities of the underlying sediments.

The observed extents of liquefaction manifestation along the Lower Wairau and Ōpaoa Rivers are shown to predominantly correspond with areas of low-elevation (<1.5 m asl) and underlain by point-bar deposits within the proximal unprotected flood plain (Figure 1). Additional areas of observed liquefaction manifestation correspond with the positions of paleo-channels of the Wairau and Ōpaoa Rivers as determined from historical maps (i.e. Cook 1895). For example, liquefaction manifestations observed at the Blenheim Rowing Club corresponds with an area of low topographic relief (0.5-1 m) which is indicated in historical maps as comprising the former "S-bend" of the Wairau River prior to straightening (Figure 3). The affected area is confined to the boundaries of the paleo-channel, and thus is likely to be underlain by young, unconsolidated, and saturated fine to medium sands. In addition, liquefaction manifestations at the Marlborough Equestrian Park are shown to correspond with the position of point-bar and paleo-channel deposits associated with the former meander bend of the Lower Wairau River which was cut-off during construction of the Wairau Diversion Channel (Figure 4). Localized stopbank failures along the adjacent section of the Wairau Diversion additionally correspond with the position of the paleo-channel (Figure 4a).

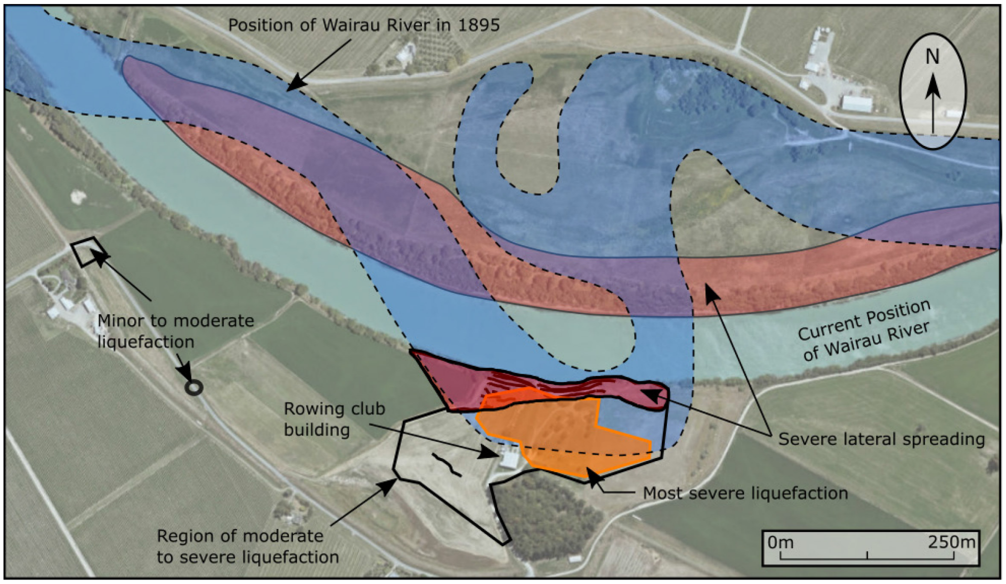
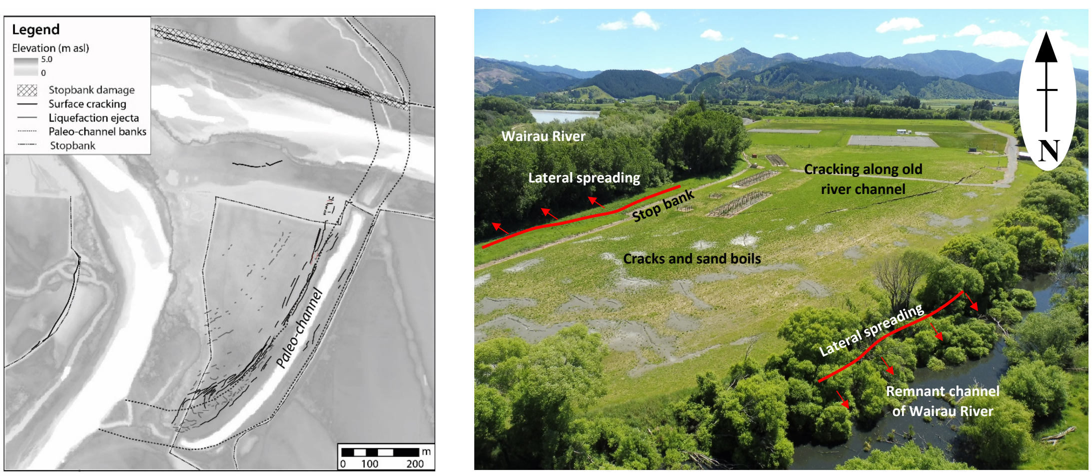


Figure 3. Summary of observations at Blenheim Rowing Club. (Basemap: Marlborough District Council 2017; Stringer et al. 2017)



(a) (b)

Figure 4. Liquefaction induced damage is shown to correspond with the position of paleo-channels of the lower Wairau River at the Marlborough Equestrian Park. Stopbank failures are also shown to correspond with the location of paleo-channels and point-bar deposits. (Bastin et al. 2017; Stringer et al. 2017)

Liquefaction manifestations observed at the Wairau Rowing Club and surrounding Grovetown Lagoon also correspond with the position of paleo-channel deposits associated with a former meander bend of the Wairau River (Figure 5). The meander bend was cut-off from the river during a flood-event prior to European settlement of the area, subsequently forming Grovetown Lagoon.

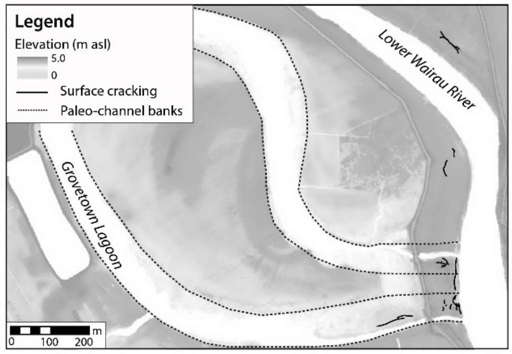


Figure 5. Liquefaction induced damage is shown to correspond with the position of paleo-channels of the lower Wairau River at the Wairau Rowing Club. (Bastin et al. 2017)

No liquefaction manifestations were observed in the alluvial plains protected by the stopbank network in the lower portion of the Wairau Plains. Localized liquefaction was observed in paleo-channels within these areas following the 2013 Lake Grassmere earthquake (van Dissen et al., 2013), thus it is possible that localized liquefaction did occur but went unreported because the reconnaissance trips did not target the farmland in which the paleo-channels are located. Liquefaction manifestations were additionally not observed to the west of the township which is predominantly underlain by alluvial outwash gravels that have been re-worked and redeposited by the Upper Wairau River and rivers fed from the mountain ranges to the south. The area exhibits a higher elevation than the lower portion of the plains, resulting in a greater depth to the ground water table (>30 m), which combined with the predominance of gravels results in a lower liquefaction hazard.

SUMMARY AND CONCLUSIONS

The spatial extents and distributions of liquefaction manifestations resulting from the 2016 M_W7.8 Kaikōura earthquake are shown to spatially vary across the Wairau Plains. Areas of liquefaction manifestation are concentrated around meandering rivers and streams within the lower portion of the Wairau Plains and correspond with the position of point-bar and paleo-channel deposits, areas of low elevation (0.5-1 m asl). Active point-bar deposits are typically recognizable from the morphology of meandering rivers, while paleo-channels may be recognized from local topography and/or historical maps.

Post-event modelling indicates that the PGA did not significantly vary across the Wairau Plains (Bradley et al., 2017). Spatial variability in shaking intensities therefore did not contribute to the observed spatial variability in the occurrence and non-occurrence of liquefaction manifestations across the Wairau Plains. Geotechnical characterization of the sediments in areas affected by liquefaction and in areas exhibiting no manifestations moving away from the is the subject of ongoing research. This work is anticipated to further characterize sedimentologic characteristics resulting in surficial liquefaction manifestations.

The detailed comparisons of liquefaction manifestations and geomorphic variability across the Wairau Plains will potentially assist in identifying sediments susceptible to liquefaction and assessing the liquefaction hazard of the region. Furthermore, the direct correlation between liquefaction and fluvial geomorphology within the Wairau Plains highlights the potential applications of geomorphic mapping and depth to the ground water table, in addition to the traditional approach of geotechnical testing, in identifying areas susceptible to liquefaction. It is anticipated that this improved understanding of the influences of geomorphic and sedimentologic variability on the distribution of liquefaction will assist in improved assessments of liquefaction hazard in future events worldwide.

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