Regions Of Liquefaction Damage In Kaiapoi Following The Canterbury Earthquakes And Their Correlation With Former River Channels

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SUMMARY:
The town of Kaiapoi, 17 km north of the city of Christchurch in the Canterbury region of New Zealand, suffered significant damage as a result of liquefaction and lateral spreading during the 2010-2011 Canterbury earthquake sequence. Severe lateral spreading and large volumes of ejecta were present throughout the town and surrounding region. Shifts in the path of the rivers in the region have been extensive since the beginnings of European settlement in the 1850s, and as a result there are multiple areas within the town and surrounding area that were, until recently, channels of the river. Using historical data, areas that had been reclaimed were identified, and when compared with the areas of severe liquefaction damage following these earthquakes, the strong correlation between the two was revealed. The significant damage to buildings, infrastructure and services in these regions highlights the importance of having a clear understanding of historical river modifications in seismically active regions.

Keywords: Liquefaction, lateral spreading, Canterbury earthquakes, river modification

1. INTRODUCTION

Kaiapoi is a small town approximately 17 km north of the city of Christchurch in the Canterbury region of New Zealand (See Figure 1 and 3a). On 4 September 2010, the M_w7.1 Darfield earthquake occurred 42 km to the south west of Kaiapoi. This earthquake resulted in severe liquefaction-induced damage in both Christchurch and Kaiapoi, with Kaiapoi experiencing some of the most severe damage from the resulting lateral spreading, settlement and ejected material. In Kaiapoi, the peak ground acceleration (PGA) of the ground motion was 0.32g, and a 20 second bracketed duration (GNS 2011). Figure 3 summarises the areas in Kaiapoi with surface manifestations of liquefaction following this earthquake.

Kaiapoi suffered further liquefaction-induced damage following the 22 February 2011 M_w6.2 Christchurch earthquake, with an epicentre approximately 20 km to the south. However the effects of this event were less severe than that experienced following the Darfield earthquake in Kaiapoi, with the most severe damage occurring in Christchurch due to its proximity to the fault rupture. The ground motion in Kaiapoi had a PGA of 0.20g (GNS 2011). Further minor liquefaction induced damage was evident in Kaiapoi following the 13 June 2011 M_w6.0 earthquake to the east of Christchurch. The location of the epicentres of these events is summarised in Figure 1b. As a result of the damage that occurred during these events, 860 residential properties in Kaiapoi were designated red zoned, meaning the area was deemed uneconomic to repair (CERA 2011). Figure 3a shows the location of the red zoned areas, containing approximately one fifth of the residential properties in the town.

This paper uses observations following the 2010 and 2011 earthquakes to determine the relationship between the liquefaction-induced damage in and around Kaiapoi and the locations of old reclaimed channels of the surrounding rivers. An overview of the development of Kaiapoi and the changes in the characteristics of the surrounding rivers is first presented, along with details of historic liquefaction in the area. This is followed by an overview of the liquefaction induced damage during 2010 and 2011 and how this relates to the locations of old river channels for a selection of regions in and around the town.

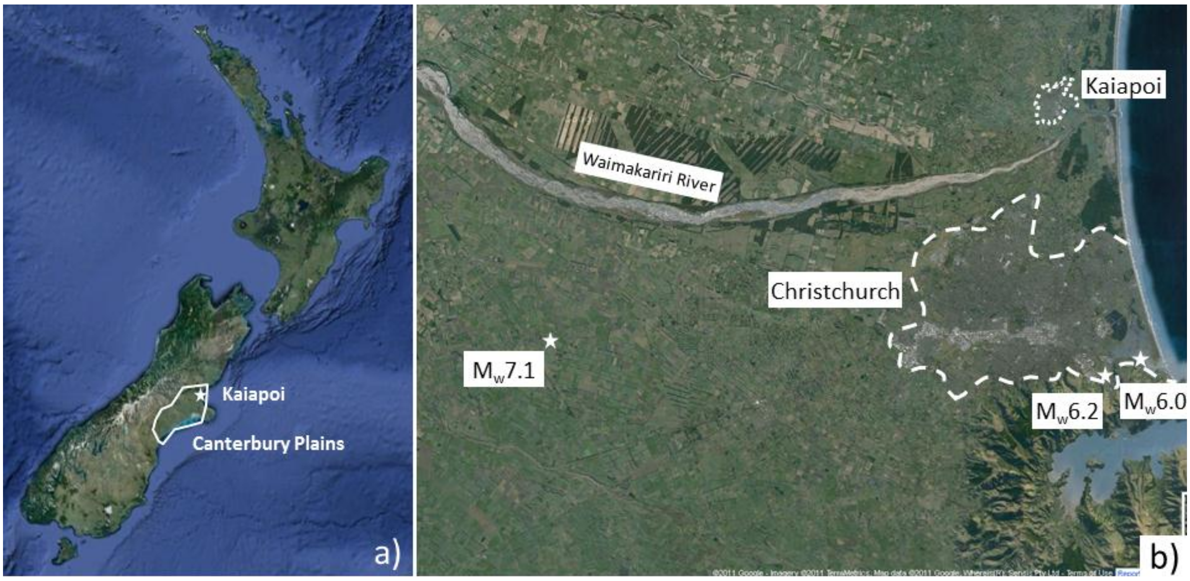

Figure 1. a) New Zealand and the location of Kaiapoi and the Canterbury Plains; b) Kaiapoi and Christchurch, indicating locations of the major earthquakes of the Canterbury earthquake sequence

2. BACKGROUND

Kaiapoi, founded in the 1850's, is located in the north eastern end of the Canterbury Plains, an approximately 160 km long by 50 km wide region in the South Island of New Zealand (Figure 1a). The Canterbury Plains were formed by the overlapping alluvial fans of multiple rivers flowing east from the Southern Alps that run along the western edge of the South Island. In the area around Kaiapoi, 300-400 m of late Pleistocene sands and gravel sit below approximately 100 m of interbedded marine and terrestrial sediments. Surface layers consist of dune and coastal swamp deposits close to the coast, with silty sands and gravels in the region behind, and a shallow water table 1-2 m deep (Brown & Weeber 1992). The Kaiapoi River cuts through the centre of Kaiapoi, and is a tributary of the Waimakariri River, a large braided gravel bed river that passes to the south of the town.

2.1. River modification

The Waimakariri River has experienced significant changes to its path since the times of first European settlement as a result of both natural and man-made processes. This section provides a summary of these changes, with a more comprehensive overview given in Wotherspoon et al. (2012).

At the time of the first settlement of Kaiapoi, the Waimakariri River had two branches shown by the solid lines indicating the pre 1867 river channels in Figure 2. The north branch (which would later be renamed the Kaiapoi River) ran through the centre of the town (the dotted line in Figure 2 indicates the outline of present day Kaiapoi), while the south branch passed to the south and along the eastern edge of the town. The two branches split to the south west of Kaiapoi, and rejoined to the east of the town, forming Kaiapoi Island where the southern part of town was located. Throughout the 1860s, the main flow of the river passed along the north branch and through the middle of Kaiapoi (Ward & Reeves 1865, Wood 1993).

The initial man-made change to the river was the construction of a canal between the north and south branch in 1867 shown in Figure 2. Soon after this, to combat the flooding of the town and island, local residents carved out a new channel in 1868 from the north branch to the 1867 channel as indicated in Figure 2. This choked off the north branch and shifted the flow of the river to this new channel and the south branch (Logan 2008). Downstream, the entire flow of the Waimakariri was carried by the remaining south branch channel.

In 1897-1880, the course of the river shifted away from the eastern edge of Kaiapoi along the channel shown in Figure 2. This meant that the entire flow of the Waimakariri was no longer passing along the edge of the town, and this reduced down to a small stream. The network of channels to the east of the town reduced down to a single channel further east of the town, with the now minor flow from the north branch connecting up to this main channel in this area.

By 1923 the north branch has been totally blocked off from the Waimakariri by stopbanks and only drained the surrounding swampland. At this time the vast majority of the flow was through the channel created in 1867 and 1868 up to its point of confluence with the south branch. In response to flooding, a major river improvement scheme was implemented to improve the channel and stopbank system (Logan 2008). The cut in 1930 shown in Figure 2 was excavated, straightening the river to its current course (following channels indicated by 1868, 1930 and 1880). Further improvements to the stopbank network were made in the 1960's, with the capacity of the system increasing in a stepwise manner up to the present.

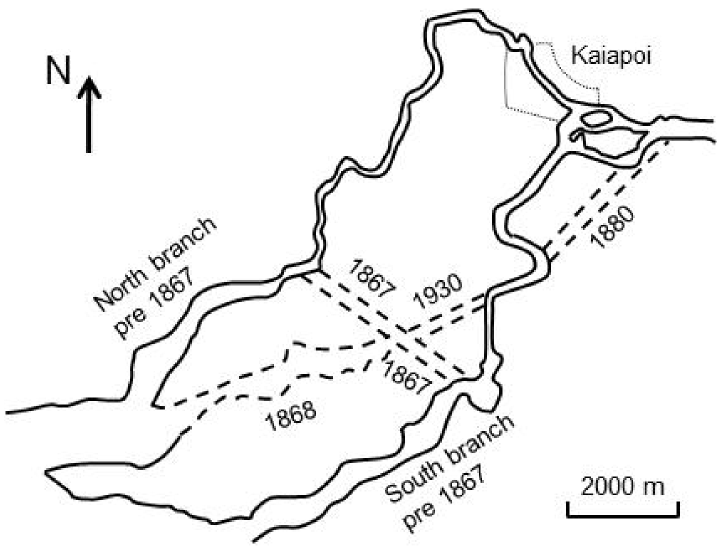

Figure 2. Waimakariri River modifications since European settlement

2.2. Historic liquefaction and previous studies

Liquefaction in Kaiapoi had previously been identified following the 1901 Cheviot earthquake, an estimated M_L6-7.5 event located approximately 80 km north-east of the town (Berrill et al. 1994). Newspaper reports following the event detail evidence of lateral spreading, settlement and ejected sand on the eastern edge of the town. Site investigations in the 1980's indicated significant liquefaction risk in the areas of Kaiapoi north of the Kaiapoi River, with the highest risk those locations closest to the river. This is detailed further in Berrill et al. (1994).

The Kaiapoi area was included as part of a liquefaction potential study of the eastern Waimakariri District in the early 2000's (Christensen 2001). The map of liquefaction susceptibility developed in this study for the area around Kaiapoi is summarised in Figure 3, with regions of high (H), medium (M), and low (L) susceptibility indicated. Liquefaction assessment used two earthquake scenarios, a M7.2 Southern Alps foothills earthquake with an epicentral distance of 50 km, and a M8 Alpine Fault earthquake with an epicentral distance of 150 km.

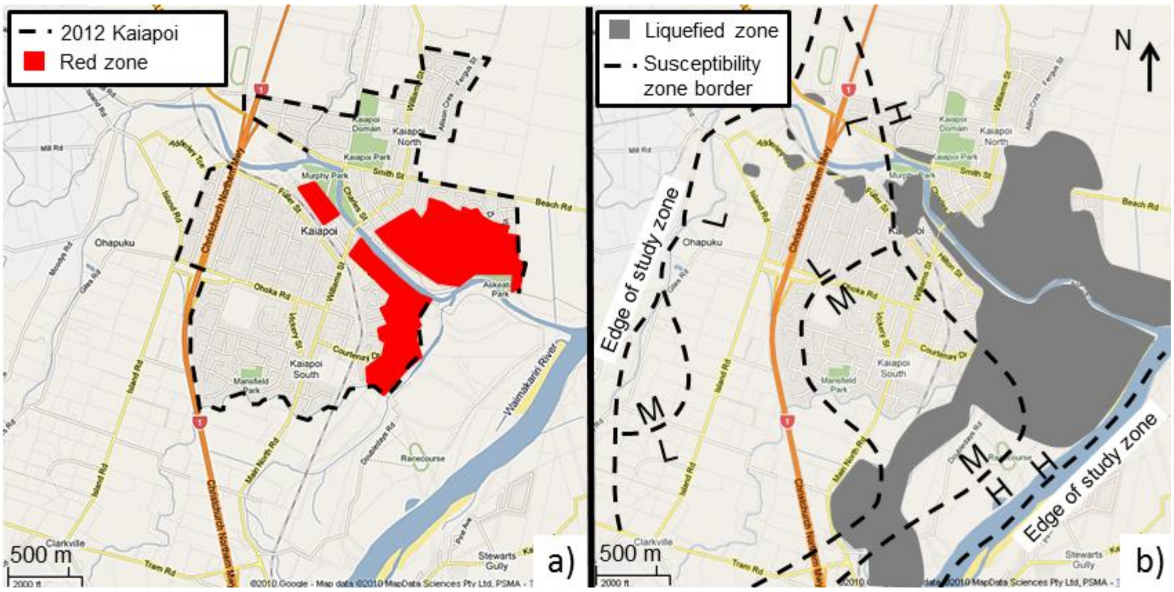

Figure 3. a) Kaiapoi town extents in 2012 and the red zoned residential areas b) Liquefaction susceptibility regions in Kaiapoi after Christensen (2001) and regions of liquefaction damage following the Darfield earthquake

3. LIQUEFACTION-INDUCED DAMAGE DURING THE CANTERBURY EARTHQUAKE SEQUENCE

As outlined previously, the town of Kaiapoi suffered liquefaction-induced damage as a result of the M_w7.1 Darfield earthquake, the M_w6.2 Christchurch earthquake and the 13 June 2011 M_w6.0 earthquake. The most severe damage was a result of the Darfield earthquake, with the severity of damage reducing in each successive event. This section outlines the damage to a selection of key areas around Kaiapoi (locations shown in Figure 4) as a result of the Darfield event in detail, and gives a brief overview of the damage in the other earthquakes. In general, the severity of the liquefaction reduced moving away from the existing river and the old river channels, as the elevation of the land and the water table depth increased.

The main focus is the correlation between liquefaction-induced damage and those areas of Kaiapoi that were built on old river channels. A more complete overview of these correlations can be found in Wotherspoon et al. (2012). This relationship between old river channels and the occurrence of liquefaction has been observed in previous earthquakes. One example, Dagupan City, was damaged as a result of the 1990 Luzon earthquake (M7.8) in the Philippines. Dagupan City is traversed by the Pantal River, whose meandering nature led to natural lateral shifting in its course and resulted in channel abandonment in some areas (Orense et al. 1991). The liquefaction-induced damage in the city correlated well with the location of these old channels.

3.1. Central Kaiapoi

As described previously, prior to 1868 the majority of the flow of the Waimakariri River was carried by the north branch that went through the centre of Kaiapoi along what is now called the Kaiapoi River. During this time the high water levels for the river were in the locations shown by the dashed red lines in Figure 5a and c, indicating that the width of the river was more than twice that of the present day. In the early 20th century the river channel was dredged and all the area between the northern bank as it exists today and the road to the north was reclaimed. Stopbanks were constructed adjacent to the new narrowed river, with the elevated land sloping gently down towards the road level in Figure 5a. In Figure 5c the stopbanks were of a similar height, however they had a steeper slope on the land side, and the area behind the stopbanks was relatively flat.

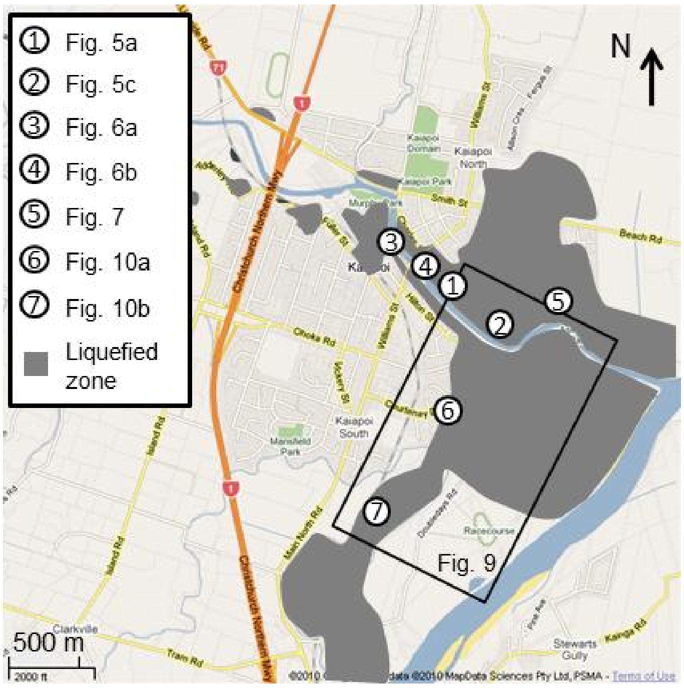

Figure 4. Location of key areas of liquefaction-induced damage outlined in following figures

Figure 5. a) Aerial view of lateral spreading along Kaiapoi River indicating lateral spreading fissures (NZAM 2010); b) ground level view of dashed area in a); c) Aerial view of lateral spreading along Kaiapoi River indicating lateral spreading and large ejecta volumes (NZAM 2010); d) ground level view of dashed area in c)

These two areas and the rest of the land along the north banks of the Kaiapoi River were damaged by severe lateral spreading, impacting multiple structures situated adjacent to the river banks. Large fissures developed along this area of reclaimed land, indicated by the aerial view in Figure 5a. The circled area in Figure 5a is shown at ground level in Figure 5b. This was the most severe lateral spreading fissure identified, with a width up to 1 m wide and a depth up to 2 m. These large fissures close to the river were free of ejecta, most likely due to their elevation in comparison to the water table. Cracks that opened up further back from the river were often filled with ejecta as these were at a lower elevation. Total lateral displacements of up to 3 m were recorded along this area (Robinson et al. 2011).

Large lateral spreading fissures were also evident in the region shown in Figure 5c, with a ground level view shown in Figure 5d. However, a much larger volume of ejecta, indicated by the grey areas in Figure 5c, was seen at the surface in this location. The most likely reason for this is the flat and low-lying characteristics in this area, meaning that the water table was closer to the ground surface in the grassed reserve area.

Figure 6. a) Damage to Mandeville footbridge; b) Back-rotation of the Kaiapoi Visitors Centre

Examples of the damage to structures along this area of reclaimed land are presented in Figure 6, the locations of which are indicated in Figure 4. The Mandeville footbridge, a wooden bridge spanning the Kaiapoi River built in 1874 and abutting an old reclaimed rubbish dump area, suffered severe buckling damage as a result of the compressive forces from lateral spreading of both riverbanks. The Kaiapoi Visitors centre, directly adjacent to the north bank of the Kaiapoi River, back-rotated approximately 5° away from the river as a result of lateral spreading.

There was further lateral spreading and ejected sands in these areas following the 2011 Christchurch earthquake. The severity of both of these was less than the Darfield earthquake, but the damage was still significant. All the properties directly behind this reclaimed area were designated as red zoned in 2011, as outlined in Figure 3a.

3.1. North-eastern Kaiapoi

Figure 7 provides an aerial view of the north-eastern region of Kaiapoi following the Darfield earthquake, with an overlay of the historic locations of the river. Prior to 1868, the main flow of the Waimakariri River was carried by the north branch, shown by the arrow in Figure 7, with the path of the river at this time shown by the location of the north bank in 1858. Following the diversion of the north branch in 1868, the main flow of the Waimakariri shifted to the southern branch and the direction of the main river flow in this area shifted to that indicated by the 1868-80 flow arrow. This forced the main flow of the river to be directed perpendicular to the existing river banks and initiated rapid erosion of the areas above the 1858 north banks. Accounts from the time indicated that the river had encroached by 10 chains (200 m) in the soft sandy soil in the area (Wood 1993).

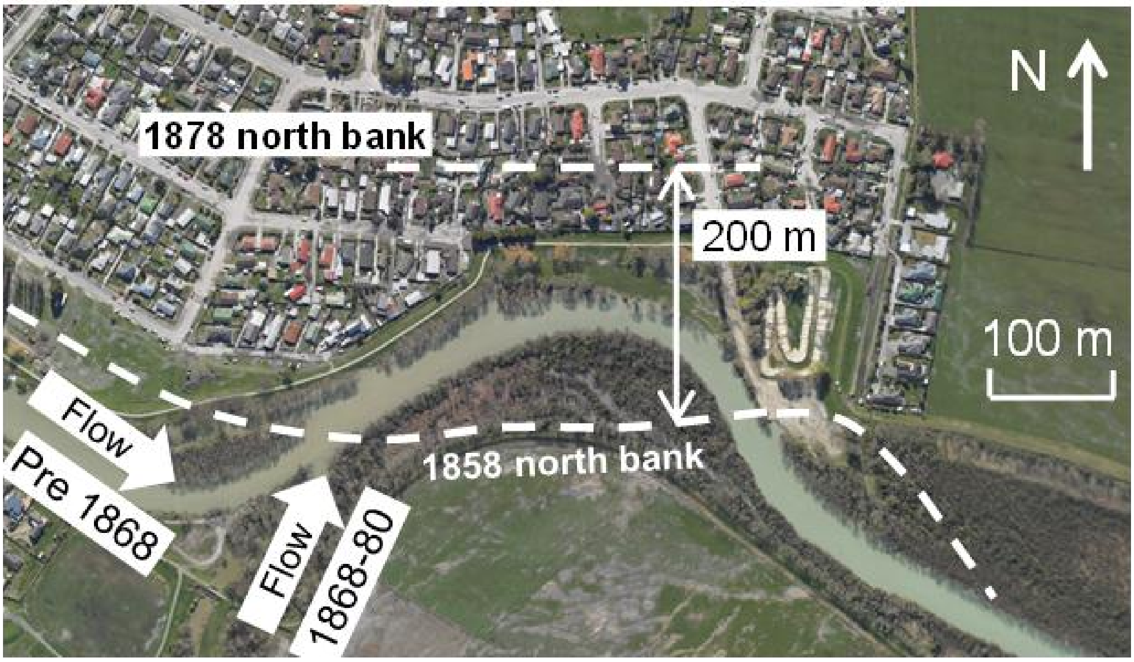

Figure 7. Aerial view of land damage in north-eastern Kaiapoi and the location of current and historic river channels (NZAM 2010)

A conservative indication of this extent of erosion is provided in Figure 7, using the location of the northern river banks from 1858 as the origin for the 200 m of river encroachment to the north due to the erosion processes. Surveyed plans for the streets in this area from 1858 show road locations cutting across the area that was eroded away during the 1868-1880 period (Wood 1993). Plans were developed to construct stopbanks to prevent further erosion north of this position. However, the main flow of the river shifted away from this location with the movement of the main channel of the Waimakariri further east of town in 1880, preventing any further erosion in this area. In fact, comparison between the 1878 and the current river banks shows that much of the eroded area was aggraded river sediments due to the reduced flow round the bend of the river.

All of the area shown in Figure 7 was affected by liquefaction, with the worst damage in the area between the current and 1878 river banks to the north of the current river bend. Significant lateral spreading fissures developed running parallel to the north banks of the river, impacting the area between the riverbank and the stopbanks set back from the river in this location. An aerial view of damage to a BMX park adjacent to the river bend is given in Figure 8a, with large lateral spreading fissures, surface ejecta and flooding. The residential buildings in this area were set back far enough from the river for lateral spreading to have little impact, however these were instead severely damaged as a result of settlement and large ejecta volumes. A close up aerial view of the cul-de-sac just to the north of the river bend in Figure 8b indicates that severe liquefaction in the resulted in extensive volumes of ejecta indicated by the dark grey areas. This was up to 400 mm thick in places, with a similar extent of settlement to some structures. This settlement also severely impacted the buried services and roadways.

Further settlement occurred in this area following both the 2011 Christchurch and 13 June 2011 earthquakes, with the severity of this and the ejected sands lessening for each event. This settlement resulted in flooding of the area just to the north of river bend following some high tide events. Many houses in this area were abandoned soon after the 2010 Darfield earthquake, with the all the residential area north of the river in Figure 6 designated as red zoned in 2011 (red zone location shown in Figure 3a).

Figure 8. a) Aerial view indicating lateral spreading fissures and ejecta; b) aerial view of significant ejecta volumes north of river bend in Figure 6 (NZAM 2010)

3.2. South-eastern Kaiapoi

To the south-east of Kaiapoi, the surface manifestations of liquefaction following the Darfield earthquake were well bounded by the location of the southern branch of the Waimakariri River as it existed prior to 1880, also shown by the solid lines representing the confluence of the north and south branches in Figure 2. An aerial view of this south-eastern area after the Darfield earthquake is shown in Figure 9, with the black dashed lines showing the location of the river banks in 1865 (Ward & Reeves 1865, Cass 1864) and the grey areas within this evidence of ejecta and the surface. Outside these lines, there is little evidence of ejected material, and this was confirmed by ground based reconnaissance following the Darfield earthquake (Green et al. 2010). The white dashed line in this figure shows the location of a small stream, which is all that remains of the old southern branch following the river diversion in 1880.

The upper black dashed line in Figure 9 can be seen to pass through a residential area in south-eastern Kaiapoi. All of this area bounded by the old channel, part of a relatively new subdivision, suffered significant damage due to lateral spreading, settlement, and large volumes of ejected material. Large lateral spreading fissures up to 1.5 m in width ran through these residential properties and structures. Overall permanent displacements of up to 2.8 m were measured following the Darfield event as the land moved towards the present day stream shown in Figure 9 (Robinson et al. 2011). Ejecta up to half a metre deep was measured in the residential properties and roads in this region. This land damage caused a range of building damage including spreading, settlement, tilting, and foundation cracking. In many houses this cracking propagated up from the foundation slab into the structure and through the roofline. An example of the damage to residential buildings is shown in Figure 10a, where lateral spreading caused significant rotation of the structure and gaps between the house and the surrounds of over a metre.

Train tracks suffered damage as they passed through the old channel in the top left corner of Figure 9. A close up aerial view of the damage is provided in Figure 10b, with significant volumes of ejecta and large lateral spreading fissures passing through the track location. The white rectangle at the top of the figure to the right of the tracks is a truck, which provides a good indication of the scale of this lateral spreading. The horizontal movements and settlement in the area meant significant remediation of the tracks was required soon after the earthquake. The race track and structures at the bottom left corner of Figure 9 were unaffected by liquefaction as they were located outside the old river channel.

These areas were further impacted following the 2011 Christchurch earthquake. There were again ejected sands evident throughout this area, and further lateral spreading affecting the residential buildings along the edge of the old channel. However, by this time many residents had already left their homes in the area due to the severity of the damage caused by the Darfield event. The severity of damage was again less following the 13 June 2011 earthquake, with some slight increases in lateral spreading, and smaller volumes of ejected sands. All the area within the banks of the old river channel was designated as red zoned in 2011.

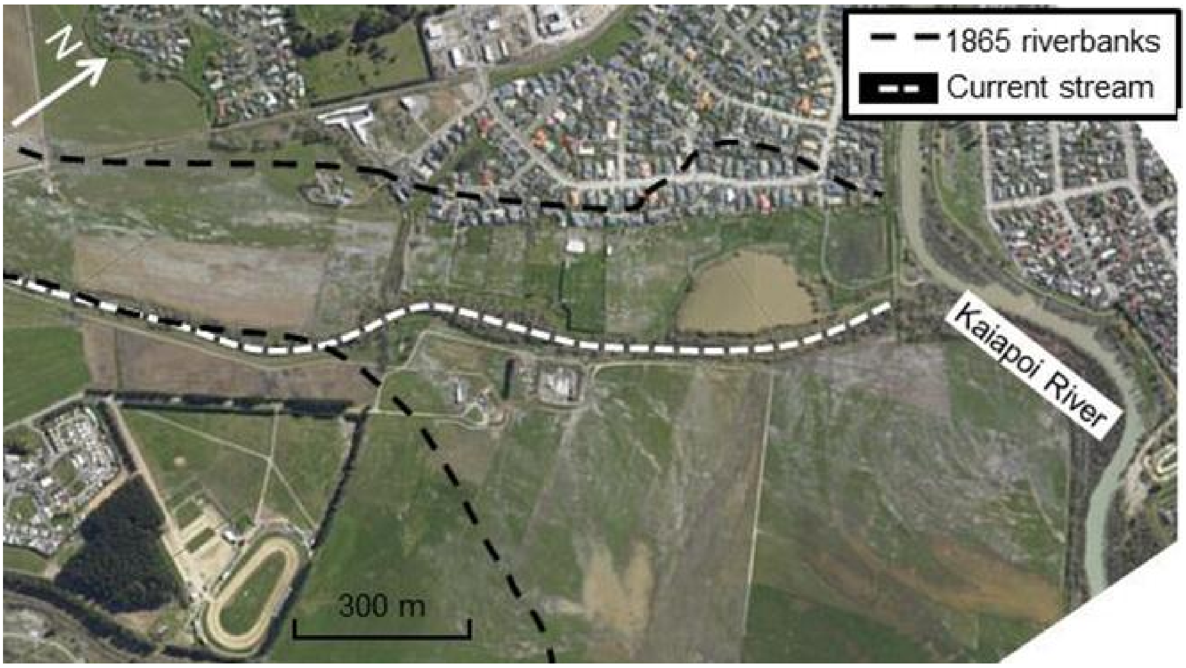

Figure 9. Aerial view of the surface manifestations of liquefaction in the south eastern region of Kaiapoi and the location of the old Waimakariri river channel (NZAM 2010)

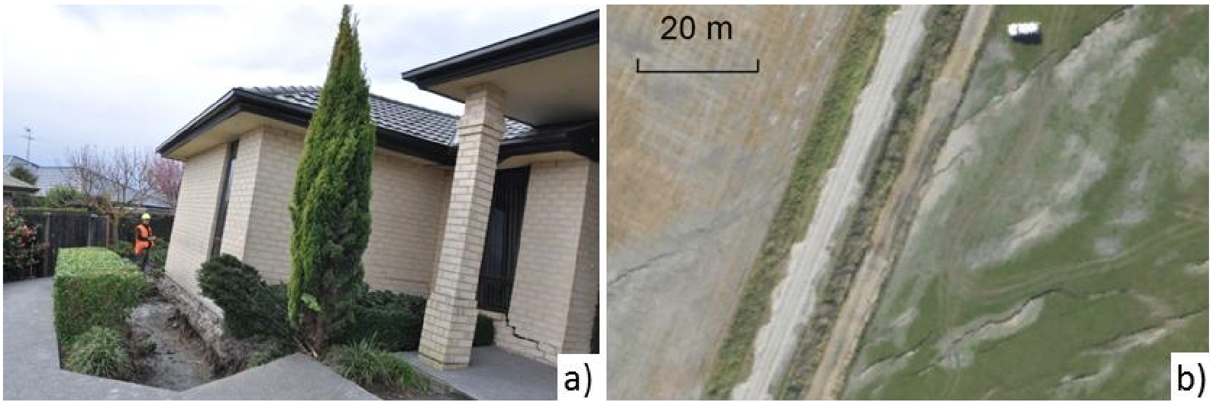

Figure 10. a) Lateral movement and tilting of house in residential area overlapping the old river channel in Figure 6; b) lateral spreading and ejecta across rail tracks (NZAM 2010)

5. CONCLUSIONS

The 2010-2011 Canterbury earthquake sequence led to widespread liquefaction-induced damage throughout the Canterbury region. Some of the most severe damage following the Darfield earthquake occurred in and around the town of Kaiapoi, an area that was also significantly affected following the 2011 Christchurch earthquake. Damage characteristics presented in this paper has shown that some of the most significant damage in Kaiapoi was in regions where old river channels had been reclaimed or flow diverted away since European settlement in the 1850's. As the town grew, some of these old channels areas had been developed, resulting in significant damage to the built environment. All of the old channel areas experienced some liquefaction induced damage. The damage observed highlights the significant liquefaction susceptibility of the loose deposits in relatively recently abandoned and reclaimed river channels, and emphasises the importance of having an understanding of the river movements and reclamation.

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