

## Correlations between liquefaction induced damage and former river channels in Kaiapoi

L M Wotherspoon, M J Pender, R P Orense  
Civil & Environmental Engineering, The University of Auckland, NZ.  
[l.wotherspoon@auckland.ac.nz](mailto:l.wotherspoon@auckland.ac.nz) (Corresponding author)

Keywords: Liquefaction, river modification, Canterbury earthquakes

### ABSTRACT

The town of Kaiapoi, 17 km north of the city of Christchurch, suffered significant liquefaction induced damage during the Canterbury earthquake sequence. Severe lateral spreading and large volumes of ejecta were present throughout the town and surrounding region after multiple earthquakes in this sequence. This region has also seen significant changes to the paths of rivers since European settlement in the 1850's, and as a result there are many areas within the town and surrounding area that were, until recently, channels of the Waimakariri River. Using historical data, the reclaimed channels were identified, which were shown to have a strong correlation with the areas of severe liquefaction damage following these earthquakes. Examples of damage in these areas are presented and related to the relatively recent changes to the river channels in the region. The significant damage to the infrastructure in these old channels highlights the importance of having a clear understanding of the historical changes to river paths in seismically active regions.

### 1 INTRODUCTION

Kaiapoi is situated 17 km north of central Christchurch at the north eastern end of the Canterbury Plains. The plains were formed by the overlapping alluvial fans of rivers flowing from the Southern Alps mountain range (Brown & Weeber, 1992). Surficial deposits in the coastal regions east of Kaiapoi consist of Christchurch formation dune and coastal swamp deposits, with Springston formation silty sand and gravels in the region behind this (Brown & Weeber, 1992). The ground water table is shallow and varies between 1 and 2 m below the ground surface. Floods from the Waimakariri River have caused significant damage to Kaiapoi since European settlement, with flooding also impacting Christchurch on many occasions (Logan, 2008). Substantial man-made and natural changes to the river have occurred during this time, with diversions and stopbanks constraining the river to its current position. This has resulted in many areas of land reclamation and abandoned river channels.

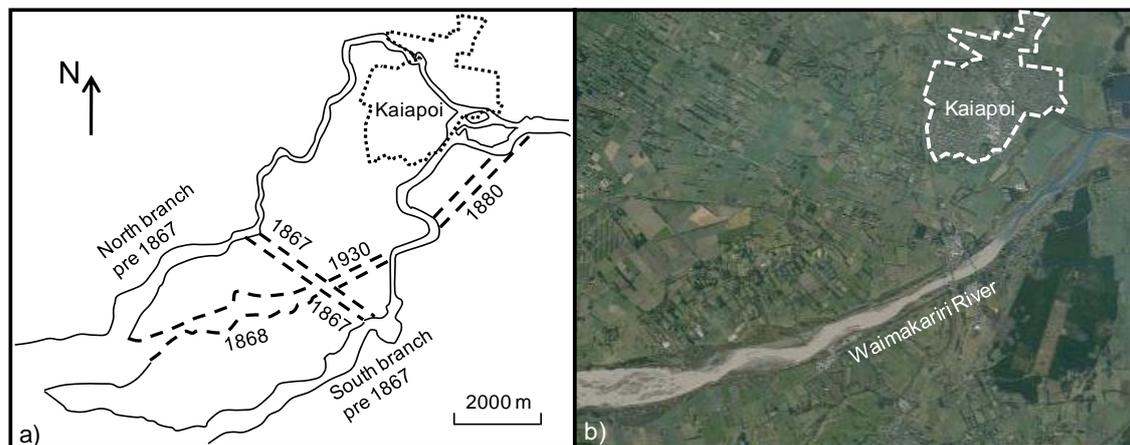
The area in and around Kaiapoi suffered severe liquefaction during the 4th September 2010 (local time)  $M_w 7.0$  Darfield earthquake, resulting in significant damage to housing, roading and services. Less severe but still significant liquefaction induced damage was evident following the 22nd February 2011  $M_w 6.2$  Christchurch earthquake and other major events in the Canterbury earthquake sequence. This paper outlines the modification to river channels in and around Kaiapoi since European settlement, and compares these regions with the surface manifestations of liquefaction identified following the major earthquake events of 2010 and 2011.

### 2 HISTORICAL RIVER MODIFICATION

At the time of the settlement of the town of Kaiapoi in 1850's the Waimakariri River had a north and a south branch that split west of Kaiapoi and rejoined to the east (Figure 1a), with the north branch running through the centre of the town (which would later be renamed the Kaiapoi River). These two branches created what was termed Kaiapoi Island, with swampy areas in the north and south, and a sandy north-eastern region (Wood, 1993). Initially, the southern part of

the town was built in the swampy areas of Kaiapoi Island, while the northern part of the town was built on sand hills on the other side of the river (Hawkins, 1957).

The dates of the major natural and man-made changes to the Waimakariri River that have occurred since the settlement of the town are shown in Figure 1 (Wood, 1993, Logan, 1998). Throughout the 1860's the main flow of the river was along the north branch and through the centre of the town. As a result, the town suffered many serious floods in its early years, with only very rudimentary flood protection works were in place. In 1867 and 1868 the local residents constructed new channels that choked off the north branch of the Waimakariri and shifted the entire flow of the river along this new path. In 1880 a new channel was formed that shifted the main flow of the river away from the town, reducing the old main channel down to a small stream that still exists today. In response to floods in the 1920's a major river improvement scheme known the Hays No. 2 scheme was implemented, completing the straightening of the river to its present course and the construction of stopbanks. This system of stopbanks has been further improved in response to flooding to the scheme as it exists today. The present day Waimakariri River has only one branch, following the path of the 1868, 1930, and 1880 river modifications shown in Figure 1a and b, with a system of stopbanks constraining the flow along this path. A more detailed account of the river modifications is given in Wotherspoon et al. (2012).



**Figure 1: Kaiapoi and its surrounds a) historical river modifications; b) present day river characteristics**

### 3 LIQUEFACTION DAMAGE AND LOCATION OF OLD CHANNELS

#### 3.1 Past Liquefaction

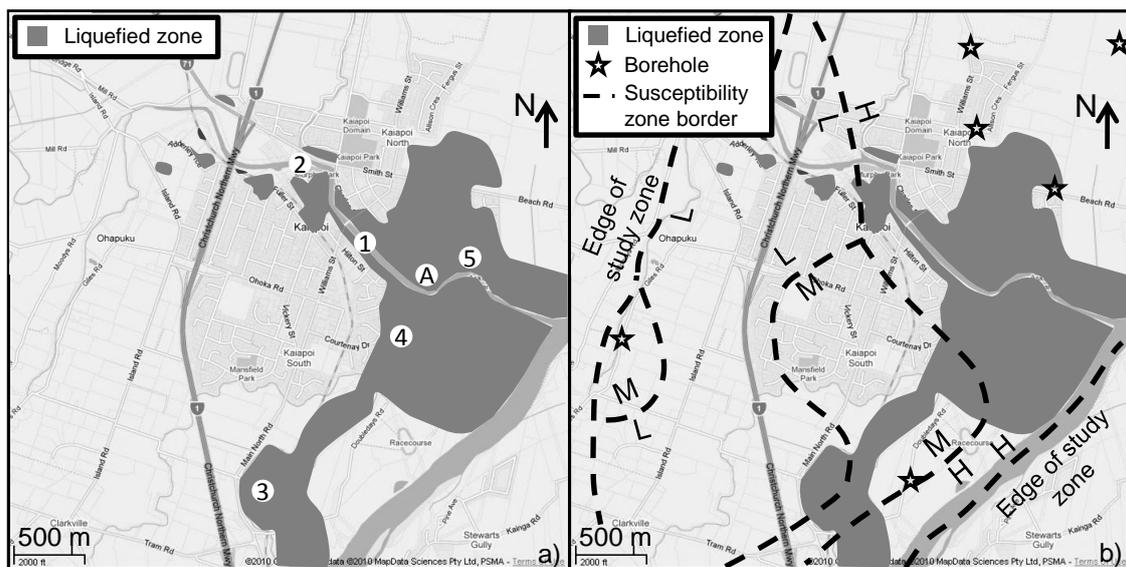
Well documented evidence of liquefaction in Kaiapoi during the 1901 Cheviot earthquake can be found in newspaper reports following the event. These detail ejection of sand, lateral spreading and ground settlement features in an area at the eastern edge of Kaiapoi on both sides of the Kaiapoi River (then the North branch of the Waimakariri River). Through discussion with local residents, Berrill et al. (1994) showed that these areas were two properties at location A in Figure 2a). Fissures also opened on the other side of the river up to 60 cm wide, while smaller cracks were filled with ejecta.

In 2001 a study of the liquefaction potential of the eastern Waimakariri District was carried out that included the area in and around Kaiapoi (Christensen, 2001). Existing soil information was supplemented with data from 26 boreholes to define the distribution of soil profile characteristics in the region. The location of these test sites near Kaiapoi are represented in Figure 2b by star symbols. A map of liquefaction susceptibility was developed for the region, with the section of this map from the Kaiapoi area shown in this figure. Three regions of high (H), medium (M) and low (L) liquefaction susceptibility are separated by dashed lines, with areas to the west of town and south of the Waimakariri River outside the study area.

### 3.2 Canterbury Earthquake Sequence

In this section we focus on specific areas in and around Kaiapoi and the correlation between damage as a result of the Darfield event and the position of old river channels. Further discussion of this relationship is provided in Wotherspoon et al. (2012). This region is reasonably flat, with the largest slopes in the area resulting from stopbank construction and land reclamation along the Kaiapoi and Waimakariri Rivers. Using data from aerial photographs (NZAM, 2010) and ground reconnaissance, the areas that experienced liquefaction in this area following the 4<sup>th</sup> September 2010 Darfield earthquake are shown shaded in Figure 2. Looking at the areas near the town, the most extensive liquefaction damage occurred on the north side and at the eastern edge. Less severe but still significant liquefaction induced damage was evident following the 22<sup>nd</sup> February 2011 Christchurch earthquake, the 13<sup>th</sup> June 2011 events, and the 23 December 2011 earthquake. A reduced area within the shaded zones in Figure 2 was affected by each of these events, and locations that suffered from repeated significant liquefaction damage are outlined in the following sections. The majority of this affected area has been deemed uneconomical to repair due to the poor soil conditions and classified as red zone, with much of this region formed of old and reclaimed river channels.

Comparison between the liquefied zones and liquefaction susceptibility zones from the 2001 study (Christensen, 2001) in Figure 2b indicates that much of the area that experienced liquefaction had been mapped as highly susceptible zones. The only regions that are mismatched is the area of extensive liquefaction south east of town that cuts through medium and low susceptibility zones, which is described in further detail in Section 3.2.2.



**Figure 2: Kaiapoi a) liquefied zone following the Darfield earthquake and locations of interest; b) site investigation and 2001 liquefaction susceptibility zones**

Kaiapoi River, at position 1 in Figure 2a, originally spanned the distance between the roads on both sides of the river when it was the north branch of the Waimakariri River. This width has been halved as a result of progressive land reclamation that began in 1907 with dredging of the river, as highlighted in Figure 3, where the red dashed lines indicate the location of the river banks prior to reclamation (Wood, 1993). These areas are now parks, with stopbanks built up along both sides. This area suffered extensive liquefaction and large lateral spread fissuring parallel to the riverbanks. Up to 3 m of total permanent lateral displacement was recorded in this area following the Darfield earthquake (Robinson et al., 2011), damaging stopbanks, bridges and structures along the river banks (Figure 3a). Some of these fissures were up to a metre wide, and two metres deep. Behind this area, further from the river, large volumes of ejecta were evident, resulting in settlement of structures and damage to roading and services.

Further spreading movements were identified in this reclaimed area following the Christchurch earthquake.

In the area of position 2 in Figure 2 there have been many shifts in the river, both natural and manmade. When the main flow of the Waimakariri River followed this branch the river had multiple channels, shifting naturally in the area. When the main flow of the Waimakariri shifted away from this branch the channel size reduced. Since 1941 the renamed Kaiapoi River, and the Cam River (flowing from the north down to position 2) have been realigned to allow for motorway construction (Wood, 1993). Following the Darfield earthquake Wyllie and Murphy parks, on opposite sides of the river had large volumes of ejecta along these reclaimed river channels. Houses and roads in this region were affected, with moderate lateral spreading. The severity of liquefaction damage in this area was less following the 22 February 2011 Christchurch earthquake, with damage confined to the area south of the river.

Prior to 1880, Figure 1a shows that the south branch of the river was positioned at the edge of the present day town. With the shift of the flow away from the town after a diversion of the river in 1880, the old channel was filled, and only a small creek remained. The path of this old river channel correlates well with the region of liquefaction in Figure 2, following the path from the bottom centre of the figure (position 3), up along the edge of the town and passing beneath the houses in the area, before shifting towards the east. The damage in this area will be discussed in the following sections.



**Figure 3: Liquefaction damage along the Kaiapoi River following the Darfield earthquake and location of old river banks.**



**Figure 4: Liquefaction damage following the Darfield earthquake a) lateral spreading along the Kaiapoi River; b) widespread ejecta in eastern Kaiapoi.**

### 3.2.1 Eastern Kaiapoi

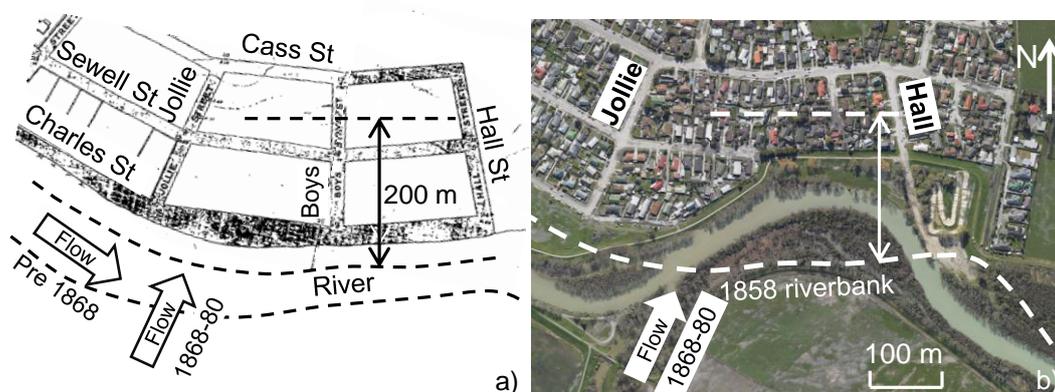
At the time of settlement of the town in the 1850's, the bend of the river at position 5 in Figure 2a did not exist, with the river instead travelling straight between the start and end of the bend.

The 1858 street plan for Kaiapoi shows this, with Charles St and Sewell St both continuing east to Hall St, while in-between Jollie St and Hall St was Boys St.

When the main flow of the Waimakariri River shifted from the north branch to the south branch in 1868, the increased flow of the river was directed perpendicular to the river banks, progressively eroding the north bank and creating the bend at position 5 in Figure 2a. The river bend had progressed further north at the time, with witness accounts indicating that the river had encroached by 200 m in the soft sandy soil in the area (Wood 1993). The progression of this erosion ceased when the main channel of the Waimakariri shifted away from the town in 1880 as detailed in Section 2.

To provide a conservative estimate of the erosion, the river banks at mean water level from 1858 were used as the origin of the 200 m offset to show the extent of erosion in 1878. This erosion would have removed much of the planned positions of Charles, Sewell and Boys St shown in Figure 5a. It is also clear from Figure 5b that the present day river banks are much closer to the 1858 position, indicating that much of the eroded area was either aggraded due to the accumulation of loose sediments as a result of the reduced flow of the river or reclaimed by other means.

This region experienced some of the most severe liquefaction damage, with ejecta up to 400 mm thick and settlement of houses in the area following the Darfield earthquake (Figure 4b). Services and roadways were damaged due to ground movement throughout. Adjacent to the river lateral spreading was evident, with large ejecta volumes in the low lying areas. Severe liquefaction damage was again evident following the Christchurch earthquake, with minor-moderate damage apparent after both the June and December events.

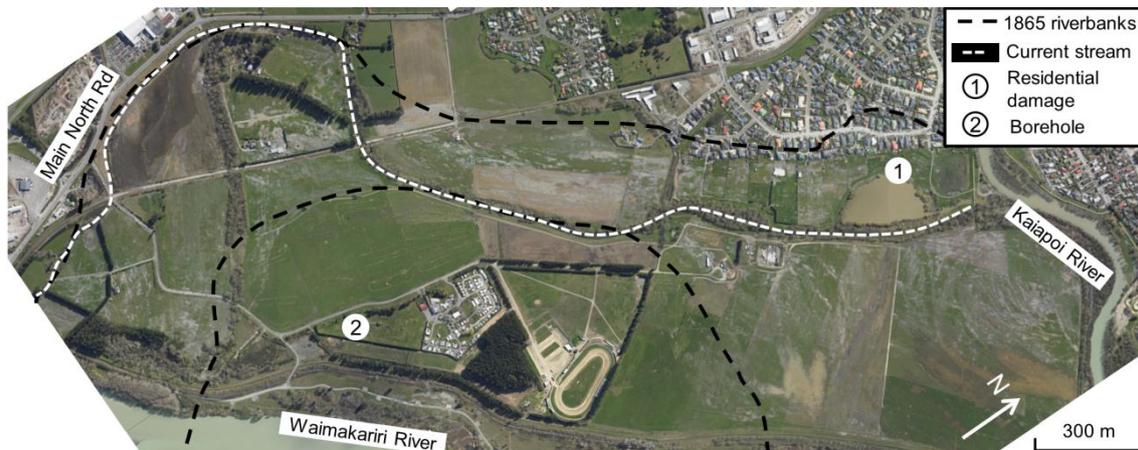


**Figure 5: Eastern Kaiapoi a) 1858 street plan and river characteristics; b) present day river location**

### 3.2.2 South-Eastern Kaiapoi

An aerial view of the eastern edge of Kaiapoi south of the Kaiapoi River following the Darfield earthquake is presented in Figure 6, with the boundary of the old southern channel of the Waimakariri River between the years 1865-1880 shown by the dashed black line (Ward & Reeves, 1865, Cass, 1864, Logan, 1998). What is immediately obvious is that the regions of liquefaction damage demonstrate a close correlation to the position of the old river channel. Large volumes of ejected sand and ground cracking are evident in the fields east of Kaiapoi, while heading south, the liquefaction damage follows a more confined path along the former river channel. One of the exploratory boreholes from the 2001 liquefaction study was at position 2 in Figure 6 and in Figure 2b, clearly outside the path of the old river channel and in an area where no liquefaction was evident at the surface. Knowledge of the location of the old river channel would likely have influenced the definition of the various liquefaction susceptibility zones outlined in Figure 2b. Five distinct episodes of liquefaction were evident in the structure

of a sand boil that was trenched in this region, clearly exhibiting the high liquefaction susceptibility of these loose deposits (Green et al. 2012).



**Figure 6: Liquefaction damage following the Darfield earthquake and location of old river channel in South-Eastern Kaiapoi**

On the eastern side of Kaiapoi, the old channel passes underneath the present day Courtenay Drive area shown by position 1 in Figure 6, the site of widespread damage to residential properties as a result of liquefaction and extensive lateral spreading following the Darfield earthquake. This was evident along the eastern side of Courtenay Drive for a distance of approximately 700 m. Up to 500 mm of ejected sand covered much of the roads and properties in this area following the event. Large lateral spread fissures between 0.5 and 1.5 m wide ran through residential areas parallel to the banks of the old river channel, with many of these filled with ejecta. This spreading resulted in permanent displacements of the ground of between 1.3 and 2.8 m towards Courtenay Stream, the present day small water course that follows the approximate path of the old river channel. The characteristics of the lateral spreading in this area were different to those observed elsewhere in Kaiapoi, with the majority of large fissures developing 120 – 200 m from the banks of Courtenay Stream in a block-like movement, instead of the larger cracks close to the free face (Robinson et al., 2011). At the free face there were only a few small cracks evident. The residential one and two storey structures in this area, especially on the eastern side of Courtenay Drive, were severely damaged due to these large movements as indicated in Figure 7. Structural damage was a result of tilting, differential settlement, loss of foundation support, and cracking of foundation slabs (Allen et al., 2010). Further lateral spreading occurred in this area during the Christchurch and December earthquakes.



**Figure 7: Lateral spreading induced damage in South-Eastern Kaiapoi following the Darfield earthquake**

## 4 CONCLUSIONS

Liquefaction damage in and around the town of Kaiapoi has occurred following multiple earthquakes in recorded history, with much of this area identified as having a high susceptibility to liquefaction. Areas with the most significant damage have been shown to be river channels than have either been reclaimed or had flow diverted away. The extensive modification of the Waimakariri River in the past meant that some parts of the town have since been extended into these old channels. These old channels were shown to have a strong correlation with the areas of severe liquefaction damage following these earthquakes, and within the town these old channel areas were ultimately deemed uneconomical to repair. Observations from the damage at Kaiapoi highlight the highly susceptible nature of former river channels and abandoned meanders to liquefaction, reinforcing the importance of having a detailed knowledge of the fluvial history of a region when undertaking liquefaction assessments.

## 5 ACKNOWLEDGEMENTS

The authors thank the Earthquake Commission for funding Dr. Wotherspoon's position at the University of Auckland, and the NZ-GEER reconnaissance team for gathering liquefaction damage data following the Darfield and Christchurch earthquakes. The authors also acknowledge the data contained in the Canterbury Geotechnical database.

## REFERENCES

- Allen, J., Ashford, S., Bowman, E., Bradley, B., Cox, B., Cubrinovski, M., Green, R.A., Hutchinson, T., Kavazanjian, E., Orense, R., Pender, M., Quigley, M., Wotherspoon, L. (2010) Geotechnical reconnaissance of the 2010 Darfield (New Zealand) Earthquake. *Bulletin of the NZSEE*. 43(4), 243-321.
- Berrill, J.B., Mulqueen, P.C. & Ooi, E.T.C. (1994) Liquefaction at Kaiapoi in the 1901 Cheviot, New Zealand Earthquake. *Bulletin of the NZSEE*. 27(3), 178-189.
- Brown, L.J. and Weeber, J. H. (1992) *Geology of the Christchurch urban area*. Institute of Geological and Nuclear Sciences, Lower Hutt.
- Cass, T. (1864) *Mandeville and Rangiora Road District. (map)*. 1:31,680.
- Christensen, S.A. (2001) Regional liquefaction study for Waimakariri District. *Proceedings NZSEE Conference*.
- Green R.A., Maurer B.W., Wotherspoon L.M., Cubrinovski M., Quigley M., Bastin S. (2013) Use of Liquefaction Observations in New Zealand for Interpreting Paleoliquefaction Features in the NMSZ, *Seismological Research Letters* 84(1),153.
- Hawkins, D.N. (1957) *Beyond the Waimakariri*. Whitcombe & Tombs, Christchurch.
- Logan, R. (2008) *Waimakariri An illustrated history*. Phillips & King, Christchurch.
- NZ Aerial Mapping (2010) *Kaiapoi. (air photo)*. Wellington, NZ. NZ Aerial Mapping.
- Robinson, K., Cubrinovski, M., Kailey, P., Orense, R.P. (2011) Field measurements of lateral spreading following the 2010 Darfield earthquake. *Proceedings 9th Pacific Conference on Earthquake Engineering*, Auckland, New Zealand.
- Ward and Reeves (1865) *Plan of portion of the plains of Canterbury. (map)*. 1:126,720. Ward & Reeves, Christchurch, Image from Christchurch City Libraries.

**Wotherspoon, L.M., Pender, M.J. & Orense, R.P. (2013).**  
Correlations between liquefaction induced damage and former river channels in Kaiapoi

Wood, P. (1993) *Kaiapoi A search for identity*. Waimakariri District Council, Rangiora.

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*. *Engineering Geology*. 125: 45-55.