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# Observation and characterisation of land damage due to liquefaction and lateral spreading

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## ABSTRACT

The 2010 and 2011 Canterbury earthquake sequence caused significant land damage in Christchurch and outlying towns. This paper summarises the approach taken to compile land damage observations and the characterisation system which was established to map the effects of liquefaction and lateral spreading in affected residential areas. Mapping of the affected areas commenced within hours of each of the main earthquakes, giving opportunity for very early observation of all scales of damage. More detailed work continued on behalf of the Earthquake Commission (EQC), with overview mapping teams and detailed geotechnical assessment teams operating continuously on the ground in Christchurch since September 2010. This gave an overall picture of the ground movement patterns, types of land damage and effects on buildings and infrastructure and the severity and extent of the damage in terms of earthquake magnitude. This information was used to guide the recovery, land remediation and public information efforts of the EQC and the New Zealand Government.

*Keywords:* Earthquake, liquefaction, lateral spreading, land damage, characterisation, mapping,

## 1 INTRODUCTION

A series of significant earthquakes occurred near to the city of Christchurch, in the South Island of New Zealand, beginning September 2010 and continuing as this paper is prepared (December 2011). The most significant events occurred on 4 September 2010 (M7.1), 22 February 2011, (M6.2), 13 June 2011 (M6.0) and, most recently, on 23 December 2011 (M5.9). These events are collectively known as the Canterbury Earthquake Sequence.

The seismic shaking caused by these major events resulted in extensive liquefaction of the ground and associated lateral spreading in much of the eastern parts of Christchurch city, and in outlying towns such as Halswell, and Tai Tapu, in the Selwyn District, and Kaiapoi, in Waimakariri District. Much of the residential housing, commercial properties, sanitary services and transportation networks in these suburbs was severely damaged due to the effects of liquefaction and lateral spreading.

This paper summarises the data capture methodology, how the observed land damage was characterised, and provides some commentary on the observations made and a summary of the maps of the damage that were compiled. These maps were used to inform the public, and to aid in the recovery of Christchurch. The work described in this paper was coordinated by Tonkin & Taylor Ltd (T&T), on behalf of the Earthquake Commission (EQC).

In addition to the flat land damage observed, significant damage to land on residential properties in sloping suburbs (the Port Hills and Lyttelton) within Christchurch was also observed, particularly in the February 2011 and June 2011 earthquakes. However, the mechanism and extent of this type of damage is not discussed in this paper. The physical processes that result in liquefaction and lateral spreading are also not discussed in this paper.

## 2 GEOLOGY & GEOMORPHOLOGY

Christchurch suburbs (excluding the Port Hills) and surrounding towns are constructed on relatively flat to gently sloping former alluvial outwash plains and swamp/back-beach/beach deposits that have been formed in recent geologic history (last 10 to 15,000 years) and which respectively form the Springston and Christchurch Formations (Brown & Weeber, 1992, and Forsyth et al. 2008). These formations inter-finger beneath the eastern part of Christchurch City, forming a complex subsurface profile made up of multiple layers of alluvial gravel, sand, silt and occasional peat, interspersed with an

increasing percentage of gravel to the west, and increasing beach sand to the east. The natural 'braided river channel' depositional environment is reflected in the horizontal and vertical variability of these deposits. Periodic flooding, and subsequent erosion and deposition has caused formation of channel and backfilled channel features at a variety of scales, at and near to the present day ground level. The existing/former channel banks are generally formed of denser material (gravels and sands) while the backfilled channels are filled with silt, silt and sand, and in some places, swampy deposits, such as peat. The silts and sands filling the now abandoned channels, where saturated, are much more susceptible to liquefaction than the surrounding gravels, denser sands, and when near to the coast, the dense, uniformly graded beach sand deposits. The Riccarton Gravel lies beneath these Formations, at a depth of between 10 and 25 m below ground level. Bedrock is generally encountered many hundreds of metres below ground level, although this depth to bedrock decreases to the south, as the volcanic material associated with Banks Peninsula Volcanoes penetrates through the sediments, to rise above the Plains, and form Banks Peninsula.

The groundwater table (unconfined/semi-confined) affecting the near surface (upper 10 to 20 m) materials is generally 2 to 3 m below ground surface level in the west and between 0 and 2 m below ground surface level in central and eastern parts of the city.

### **3 LAND DAMAGE MAPPING**

#### **3.1 Motivation**

Soon after the initial 4 September 2010 earthquake, it became apparent that most of the significant damage to the residential housing stock had been caused by ground damage as a result of liquefaction and lateral spreading. While this is an observation that continued with subsequent earthquakes, these typically precipitated additional damage to structures from shaking, due to the extreme ground accelerations experienced, particularly in the lower magnitude but nearer field 22 February and 13 June 2011 earthquakes. These two subsequent earthquakes have resulted in the most widespread and catastrophic ground damage.

Identifying the areas that have been subject to single or multiple occurrences of ground damage, as well as identifying the different scales of damage in these areas is important to understanding the mechanisms that led to the damage. In addition, this information provides insight into the likely effects of future events on different parts of the city, to allow appropriate planning for these effects, as well as providing important information for the insurers responsible for each of the separate disaster events.

The land damage mapping and classification described in this paper was primarily undertaken to assist the EQC in understanding the nature of the event, in order to prepare the appropriate insurance response. Secondary to this, the information collected was increasingly used by Local Authorities and Central Government, in addition to the private insurers and the technical community, to understand the magnitude and extent of the land damage and to plan an appropriate recovery strategy.

#### **3.2 Methodology and Characterisation - Data Capture**

Three steps of land damage mapping, or 'data capture' were typically undertaken after each significant earthquake, each at a progressively more detailed scale than the last. These include:

##### **3.2.1 Step 1 – Broad 'Regional scale' mapping**

Regional scale mapping was undertaken initially by aerial survey from a helicopter, and, following this, rapid vehicular road level reconnaissance, which was generally completed within one to five days of the event occurring. Maps of the observed land damage were able to be produced and distributed rapidly as field teams noted the presence, or otherwise, of visible evidence of liquefaction on the ground surface on large scale, commercially available road maps. Table 1 contains a detailed description of the mapped categories. This information was typically collated and digitised within 24 to 48 hours, and then distributed to appropriate organisations allowing the response agencies to mobilise assistance to the most needy. General public release of these maps was delayed until supporting information could be prepared to ensure that the maps were not taken out of context.

Table 1: Regional Scale Land Damage Mapping Categories

Regional Land Damage Category	Description
Liquefaction Observed	Evidence of liquefaction visible at the surface. This evidence included ejected sand, ground cracking, ground subsidence, flotation of services/ tanks, foundation bearing capacity failure.
No Liquefaction Observed	No evidence of liquefaction or land damage visible at the surface. Note that the lack of surface evidence of liquefaction does not preclude that liquefaction may have occurred at depth.

### 3.2.2 Step 2 – Local scale mapping

Local scale mapping was undertaken as a 'foot based' road level assessment in the field, supported by a desk top analysis of high resolution aerial photographs which had been obtained in the days following each of the major earthquakes. Local scale mapping was undertaken to categorise the type of damage that had occurred on each residential property within areas that the Regional scale mapping had identified as having observed land damage. The categories used are summarised in Table 2. The type of damage on each property was noted by colour coded hatching using a common legend to represent the five different categories. The field mapping generally commenced in the worst affected areas, and radiated outwards, however, as the areas of damage increased with subsequent earthquakes, a city wide sweep at a 'Step 2' level was initiated. Analysis of high resolution, 10GSM (10 cm ground measurement/pixel) aerial photos was undertaken to confirm the foot based mapping, particularly in areas visited last, as the evidence of sand on the ground surface had often been removed/concealed by the time the mapping was completed. This step was generally completed within a few weeks of each earthquake, with the process becoming more efficient following every significant earthquake. To put some perspective to this, ten weeks after the 4 September 2010 earthquake, 39,000 properties had been assessed, at this scale, while in the four weeks following the 22 February 2011 earthquake, a total of 100,000 properties were assessed.

Table 2: Local Scale Land Damage Mapping Categories

Land Damage Category	Description
Very Severe	Extensive lateral spreading (>1 m) and evidence of liquefaction/ejected sand covering significant part of site, large open cracks (>100mm) with very severe horizontal and vertical displacement (>200 mm). Significant structural damage to buildings including obvious lateral and vertical displacement and stretching, twisting and cracking of the structure.
Major	Extensive evidence of liquefaction/ejected sand covering large areas of site, large cracks from ground oscillations extending across the ground surface, with >50 mm horizontal and vertical displacement across cracks. Damage to structures includes major differential settlement (>100 mm settlement over 10 m horizontal distance) with obvious lateral and vertical displacements along with twisting/cracking of the structures.
Moderate <sup>(1)</sup>	Visible signs of liquefaction (ejected sand), small cracks (<50 mm) from ground oscillation in paved surfaces but limited depth into the underlying ground, no vertical displacement of cracks. Damage to structures includes moderate differential settlement (<100 mm settlement over 10 m horizontal distance) and twisting/cracking of structures.
Minor	Shaking-induced land damage resulting from cyclic ground deformation and surface-waves. Land damage likely limited to minor cracking (tension) and buckling (compression). No signs of liquefaction visible at the surface, nor of lateral/vertical displacements.
None <sup>(2)</sup>	No apparent land damage or signs of liquefaction obviously visible at the surface.

1 – Within the moderate damage area, localised areas of major land damage might exist which were not captured by local scale mapping.

2 – Although no ground damage was noted, building damage is still possible

### **3.2.3 Step 3 – Property specific assessment**

Site specific inspection and assessment of each residential property in an area that was noted to have been affected by liquefaction was completed for the purposes of EQC insurance claim settlement. Between 4 September 2010 and 21 February 2011 approximately 14,000 individual property assessments were completed by the EQC Land Damage Assessment Team (LDAT), which was co-ordinated by T&T. Between 22 February 2011 and 17 December 2011, approximately 60,000 individual property assessments were completed by the LDAT in suburbs on the flat land across Christchurch and in surrounding towns in the Waimakariri and Selwyn Districts. Assessment of individual properties is ongoing. For further information on the LDAT response and processes please refer to the separate paper by Macdonald & Wallace (2012) in these Conference proceedings.

The information held by EQC relating to specific damage on individual properties (Steps 2 and 3) is privileged and as such, maps showing the damage at this scale have not been produced publically.

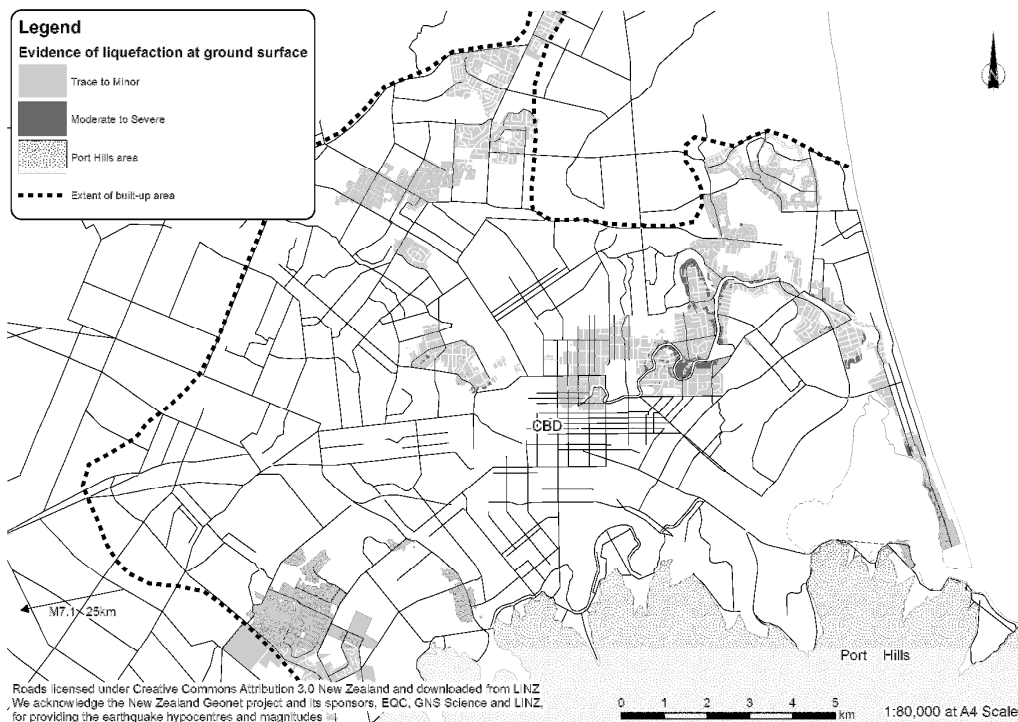
### **3.3 Limitations**

The data collected by the processes discussed in this paper has been progressively refined to suit the engineering and insurance response needs, following multiple earthquakes in Christchurch. It needs to be appreciated that damage maps produced from Steps 1 or 2 as described above are approximate only. Areas noted as having some observed land damage, indicate that, at the time of the assessment, evidence that liquefaction had occurred was observed. The land damage information discussed in this paper was predominantly collected as part of the EQC response to a series of specific earthquakes, and is not meant to be used as a tool to estimate what areas of Christchurch and surrounding towns are likely to suffer land damage in future earthquakes. It needs to be recognised that areas that have suffered land damage as a result of the Canterbury Earthquake Sequence may not be susceptible to the same damage in a different earthquake, and equally, because an area has not suffered damage in recent events, it may not be excluded from being damaged in future earthquakes. As the work was predominantly undertaken on behalf of EQC, the land damage information is limited to residential properties only.

## **4 LAND DAMAGE OBSERVATIONS**

Following the 4 September 2010 earthquake 'typical' patterns of observed land damage were noted. In general it was found that the damage was worst around existing and former river and stream channels, and adjacent to beach and estuary areas, and where the most recent (and therefore loose) alluvial deposits were located. Specific, relatively isolated streets and suburbs were severely affected by liquefaction, resulting in very deep (300 to 500 mm) layers of ejected material, and locally, what was then considered to be significant lateral spreading. Generally, the land damage category was observed to decrease in a manner that was somewhat proportional to the distance the property was from the river or beach interface. A higher category of damage (refer Table 2) was generally recorded on properties on the inside of bends and meanders in the rivers/former river channels, than was recorded on properties immediately opposite, on the outside of the river bends/meanders.

Figure 1 shows the general pattern of land damage as observed and categorised at a Regional scale, following the 4 September 2010 earthquake. Areas affected were spread across the region, with parts of Halswell in the west, and Tai Tapu in the Selwyn District, having significant damage, and other parts of eastern Christchurch, including, Burwood, Dallington and Bexley, as well as parts of eastern Kaiapoi, in the Waimakariri District, being most significantly affected.



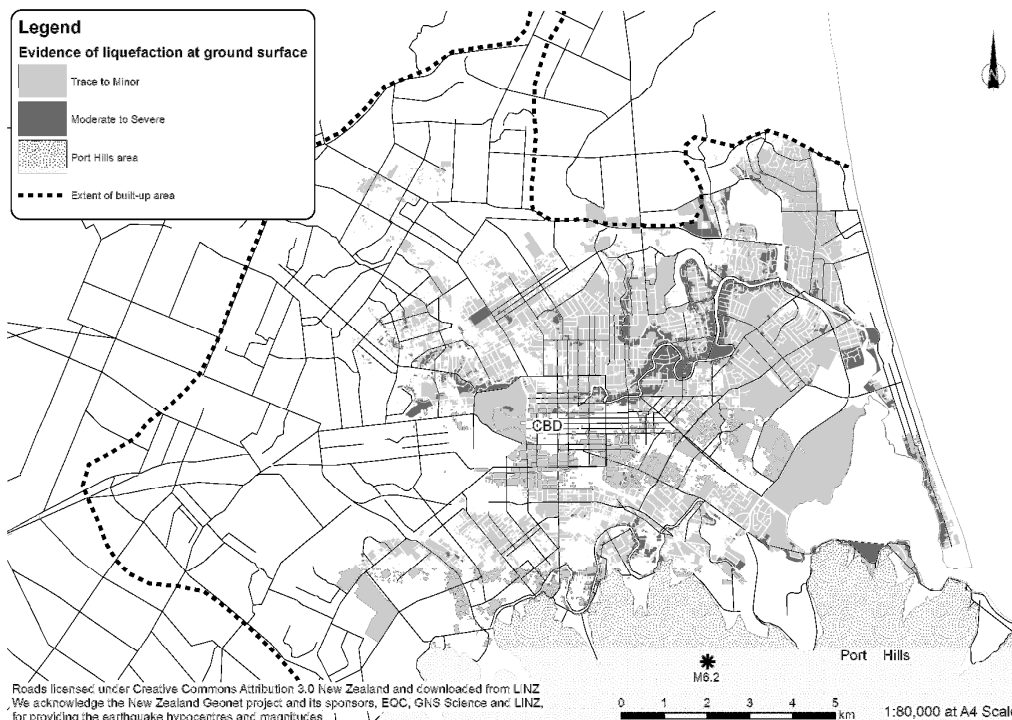
**Figure 1:** Land Damage observed in Christchurch City following the 4 September 2010 M7.1 earthquake, centred 30 km west of the CBD of Christchurch

The pattern of observed land damage increased significantly following the lower magnitude but nearer field earthquake of 22 February 2011. Evidence of liquefaction was recorded over an extensive area of Christchurch, with sand recorded on the ground surface in almost all eastern suburbs and in many western suburbs. Eastern suburbs, already badly affected by liquefaction and lateral spreading, were damaged further. Lateral spreading was observed to extend far further than previously identified, over many hundreds of meters in places, and often spreading appeared to have resulted in a net displacement away from the closest 'channel feature', due to the complex paleo-geomorphology underlying the city. Parts of Kaiapoi and Halswell/Selwyn District suffered further damage, but generally on a significantly decreased scale when compared to earlier damage.

The 13 June 2011 earthquake resulted in land damage being observed over a similar extent to the February earthquake, but to a relatively lesser degree. Following this earthquake the worst affected suburbs had been subject to three or more occurrences of liquefaction, and the cumulative effect of this on not only the land, but also the structures supported on this land was obvious. There was genuine evidence that large areas of land had suffered a significant decrease in relative levels, to the extent that flooding occurred on some inland streets adjacent to the lower reaches of the Avon River during high tides. This was confirmed by subsequent LiDAR surveys.

Figure 2 shows the general pattern of land damage as observed and categorised at a Regional scale, following, the 22 February earthquake.

At the time of preparation of this paper, maps of the extent of land damage recorded following the 13 June 2011 earthquake had not been publically released, and these have subsequently not been included in this paper.



**Figure 2:** Land Damage observed in Christchurch City, and Waimakariri and Selwyn Districts following the 22 February 2011 M6.2 earthquake, centred 5 km south of the CBD of Christchurch

## 5 CONCLUSIONS

Land damage observation and characterisation at a variety of scales has proven to be a useful tool in the aftermath of multiple natural disasters, not only in the short term response phase, but also in long term planning and recovery efforts. The work completed has emphasised the need for high quality management of data collection by experienced personnel using proven systems to ensure continuity and reliability of data collected from large areas and as a result of multiple events.

The rapid collation of 'real time' data by persons with an understanding of the processes involved, and having local knowledge is crucial to an understanding of the situation being developed by all parties, not just the engineering profession. Well managed and presented accurate data has been used to effectively plan much of the early response and recovery of Christchurch, despite being collected only hours and days after large natural disaster events.

## 6 ACKNOWLEDGEMENTS

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