Macro and micro scale assessment and quantification of Ground damage following the Canterbury 2010/2011 Earthquake sequence

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SUMMARY:
Recent earthquakes in September 2010, and February and June 2011 caused significant damage to land in and around the city of Christchurch, New Zealand. Land damage included liquefaction, lateral spreading and sloping ground failures. Identification and quantification of the ground damage on a macro scale began soon after the initial September 4, 2010, M7.1 earthquake. As subsequent significant earthquakes occurred the 'on ground' team were able to deploy immediately and map 'real time' information of additional land damage, often as it occurred.
This paper provides an overview of the macro scale land damage mapping and micro scale land damage assessments undertaken on behalf of the Earthquake Commission by a group of geotechnical professionals that became known as the Land Damage Assessment Team (LDAT). The paper concludes with a discussion of lessons learned, and provides suggestions for procedures to follow for similar situations in future events.

Keywords: Earthquake, liquefaction, lateral spreading, mapping

1. INTRODUCTION

The city of Christchurch, in Canterbury, New Zealand, and the surrounding area, has been subject to ongoing significant close proximity seismic activity, semi-continuously since a M7.1 earthquake struck on 4 September 2010. Subsequent significant earthquakes include a M6.2 earthquake on 22 February 2011, a M6.0 earthquake on 13 June 2011 and, most recently, a M5.9 earthquake on 23 December 2011. These earthquakes are collectively known as the Canterbury Earthquake Sequence.

Christchurch city is located on the present coastal margin of an alluvial plain, next to Banks Peninsula, an extinct volcanic complex. The seismic shaking caused by the recent earthquake events has resulted in extensive ground damage; generally comprising liquefaction and lateral spreading of the predominantly flat alluvial ground, and; significant deformation of sloping ground, particularly on the northern slopes of Banks Peninsula, the Port Hills, which are closest to the city. Residential, commercial and industrial properties, horizontal infrastructure and transportation networks have been badly damaged as a result.

In New Zealand the Earthquake Commission (EQC) is the primary insurer of residential land and property for damage that is the direct result of a natural disaster.

Immediately after the first earthquake and following many of the subsequent earthquakes, macro scale mapping of the observed ground damage was undertaken by geotechnical professionals, working on behalf of the EQC. The EQC Land Damage Assessment Team (LDAT) was formed, coordinated by T&T, to assist in the micro scale quantification of the ground damage on each affected residential property.

This paper outlines the methodology used to characterise the observed ground damage and capture the data at a variety of scales, providing some commentary on the observations made, and lessons learned and presents 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 physical processes and mechanisms that result in the different types of ground damage that were observed are not discussed in this paper.

2. GEOLOGY AND GEOMORPHOLOGY

2.1. Geology

Christchurch city (excluding the Port Hills) and the 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 Riccarton Gravel lies beneath these deposits, 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 the Banks Peninsula Volcanic complex penetrates through the sediments, to rise above the Plains, and form Banks Peninsula.

The Port Hills suburbs are underlain by a variable thickness of loess (windblown silt) and colluvium derived from loess, which overlies the basaltic bedrock of the Lyttelton Volcanic group, a non-homogenous unit of basalt lava flows, with intercalcated scoria and pyroclastics (ash). Bedrock outcrops are located sporadically throughout the hill suburbs, in particular near the crest of spurs and ridges, and close to the present day coast, where historic sea cliffs, up to 80 m high, are located.

The groundwater table (unconfined/semi-confined) on the alluvial plains in Christchurch 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. A series of artesian aquifers lie in permeable gravels layers at increasing depths in the subsurface profile.

2.2. Geomorphology

An appreciation of the depositional nature that has led to the alluvial geological profile is key to understanding the extent and variability of the ground damage that has been observed in many of the flat areas in and around Christchurch as a result of the earthquakes experienced.

On a broad scale, the deposits underlying the Canterbury Plains comprise inter-fingering layers of alluvial sand and gravel deposited in periods of high flow throughout history by large, high energy rivers. The natural 'braided river channel' environment is reflected in the horizontal and vertical variability of these deposits across the Plains. Near to the present day coast, this material is overlain by lower energy deposits, placed during sequences of coastal intrusion and regression, and more recently, by lower energy flooding of meandering rivers, such as the Avon and Heathcote, which both pass through the city of Christchurch. Periodic flooding, and subsequent erosion and deposition has caused the 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.

On the Port Hills, the ground surface is generally sub-parallel to the irregular upper surface of the underlying lava (bedrock). Multiple eruptive episodes have resulted in a pattern of ridges and valleys, radiating outwards and sloping gently downwards from the former volcanic vent, located within the present day Lyttelton Harbour. Many of the valleys and the lower slopes of the ridges have been developed into residential and commercial properties. Natural processes (erosion) and human development has altered the landscape, in particular where historically, significant quarrying has been undertaken to enable extraction of both bedrock and loess, and on a more local scale, where earthworks have been undertaken to facilitate development.

3. ASSESSMENT OF GROUND/LAND DAMAGE

3.1. Background

As the primary insurer of residential land in New Zealand, the EQC, acting in response to the Earthquake Commission Act 1993, requires that every residential property that has suffered significant ground (land) damage as a result of a natural disaster be subject to a site specific land damage assessment, as part of the insurance claim settlement process.

Observations made by Engineers and Geologists from T&T immediately after the 4 September 2010 earthquake indicated that land damage had predominantly been confined to flat land, in discrete areas, generally where elevations were lowest, close to the coast (eastern Christchurch suburbs) and around existing/former water courses. While this is an observation that continued with subsequent significant earthquakes, the migration of the epicentres of these earthquakes closer to the Christchurch urban area, and the increase in felt shaking intensities/ground accelerations, despite the lower magnitudes experienced, meant that additional damage was precipitated. Most notably this resulted in the effects of liquefaction of the subsurface being noted in areas previously not affected, with a significant westwards migration of liquefaction. Significant damage to hill suburbs, previously only slightly affected, was observed following the 22 February and 13 June 2011 earthquakes. These two subsequent earthquakes resulted in the most widespread and catastrophic land damage.

Identifying the areas that have been subject to single or multiple occurrences of land damage, as well as identifying the different scales of damage in these areas, as a result of each subsequent significant earthquake is important to understanding the mechanisms that led to the damage, and in facilitating recovery/response from an insurance perspective. Identifying the worst affected areas quickly, resulted in resources being most appropriately distributed across the relatively large affected area to enable timely collation of information.

As the magnitude of the damage was appreciated, initially following the 4 September 2010 earthquake and then on a scale that was suddenly orders of magnitude greater following the February and June earthquakes, the need for collaboration and pooling of resources was recognised. In response to the EQC's direct needs T&T set up and managed the LDAT, which ultimately comprised over 400 geotechnical professionals from 39 consultancies from across New Zealand. This pool of staff was rotated on a weekly basis, with a minimum of one week and maximum of three weeks commitment per staff member in any one 'rotation'. All staff were inducted and trained in what they would be experiencing and observing 'in the field' and how to undertake assessments fit for the EQC's purpose. Staff were also supported in the development of professional skills to deal with distressed members of the public, often as a first responder.

As well as this 'field' response, a large team of office based support staff and processes were set up to facilitate the timely production of information. There were no existing templates or systems in place, and those created were constantly modified as the workscope, processes, direction and focus changed, and as subsequent earthquakes occurred.

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. Macro Scale Land Damage Mapping Methodology

3.2.1. 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 each significant earthquake occurring. Because of the logistics involved, vehicular mapping was only undertaken on flat land, where ground damage was easily observed from the property boundaries.

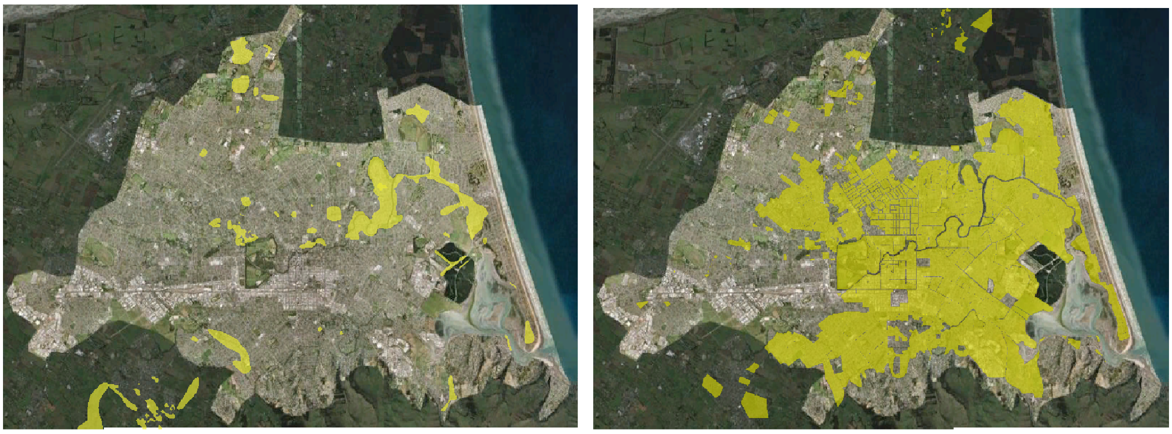

Figure 1. Macro scale 'Regional' mapping undertaken from aerial survey identifying areas where sand was observed at the surface following the 4 September 2010 (left image) and 22 February 2011 (right image) earthquakes

Maps of the areas where land damage was observed 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. This information was collated and digitised continuously, typically within 24 to 48 hours of capture, and then distributed to appropriate organisations allowing central and local government agencies to prioritise their response. 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.

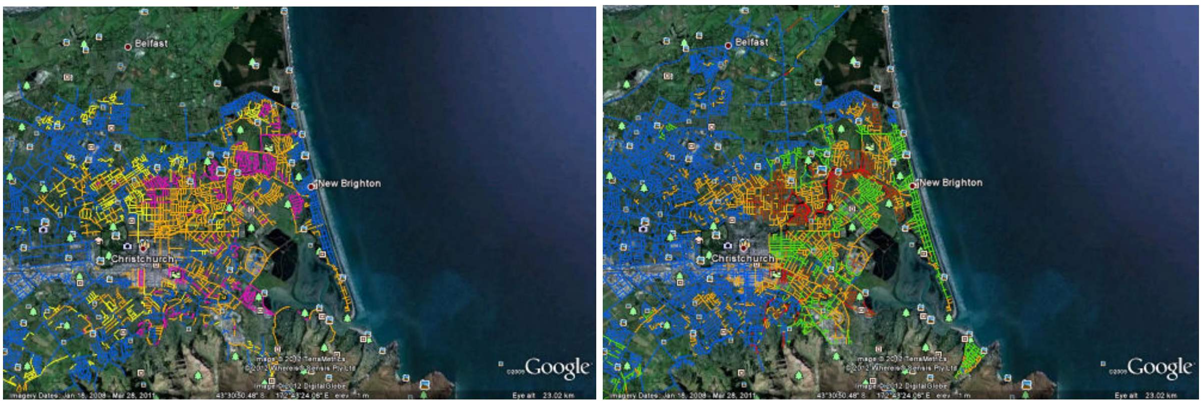

Figure 2. Macro scale 'Vehicular' road based mapping undertaken to identify severity of land damage following the 22 February 2011 (left image) and 13 June 2011 (right image) earthquakes (Refer to Table 1 for legend description)

As the city was declared to be in a 'State of emergency' immediately after the significant earthquakes, the regional scale mapping was generally undertaken by key LDAT staff, to lessen the impact of, and exposure to, additional 'out of town' staff. As the emergency situation was replaced with a response phase, additional staff were able to be brought in to enable a greater area of land to be covered in a shorter amount of time. Staff were initially tasked with completing the local scale 'macro' mapping, and then, concurrently, began the 'micro' scale mapping and assessment process. As multiple events overlapped, the different phases/processes overlapped and complemented one another.

3.2.2. Local scale mapping

Local scale mapping was undertaken as a 'foot based' road level assessment in the field utilising large scale 1:3000 plans which included aerial photos and cadastral boundaries. The type of damage on each property was noted by colour coded hatching, using a common legend to represent the five different 'damage' categories on flat land (Refer Table 1), and seven different categories on sloping land (Refer Table 2).

Table 1. Local Scale Land Damage Mapping Categories (Flat Land)

Land Damage Category	**Mapped Colour**	**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(1)		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(2)		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

The local scale field mapping on flat land generally commenced in the worst affected areas, and radiated outwards, however, as the areas and types of damage increased with subsequent earthquakes, a city wide sweep at this level was initiated. This occurred in flat land areas soon after the 22 February 2011 earthquake, and in hillside suburbs soon after the 13 June 2011 earthquake.

Table 2. Local Scale Land Damage Mapping Categories (Sloping Land)

Land Damage Category	Mapped Colour	Description
Rockfall		Large scale 'collapse' of bedrock cliffs resulting in inundation of properties (land/structures/assets) at the base of the cliff.
Minor land movement		Cracking and deformation of land resulting in lateral and vertical displacement. Future displacement unlikely. Individual cracks less than 50mm wide, or less than 100mm cumulative crack widths over a typical 30 m section.
Major to severe land movement		Cracking and deformation of land with downslope component and/or cracking may result in future downslope lateral or vertical displacement. Individual cracks greater than 50mm wide, or more than 100mm cumulative crack widths over a typical 30m section.
Inundation		Inundation from failed slopes (retained or unretained)
Minor retaining walls		Retaining walls less than 1.5 m high damaged
Major retaining walls		Retaining walls more than 1.5 m high, or less than 1.5 m high and supporting the dwelling accessway damaged
None[1]		No apparent observed land damage or signs of land cracking visible at the surface.

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

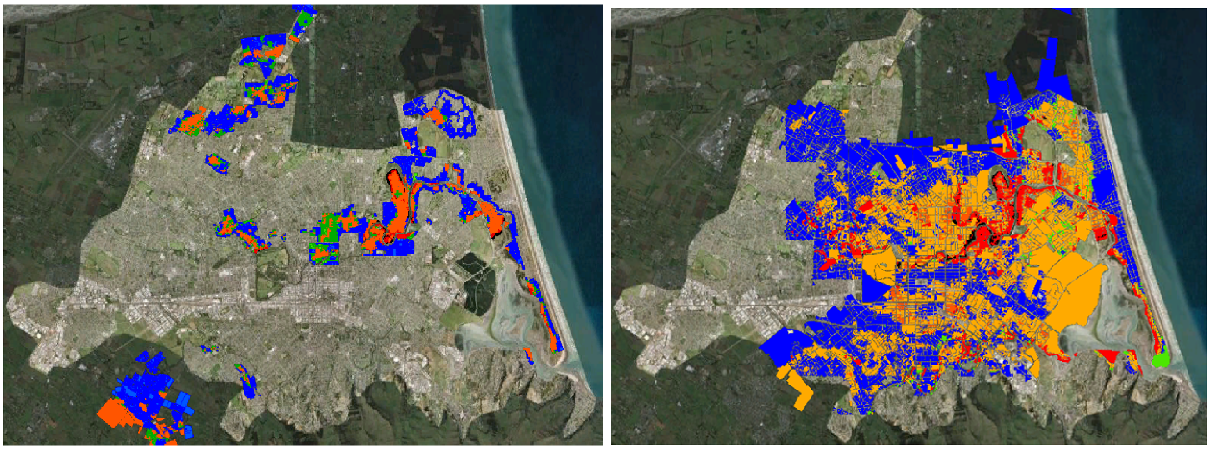

Figure 3. Macro scale 'Local' mapping undertaken as a foot based road level assessment identifying the severity of the land damage observed on flat land following the 4 September 2010 (left image) and 22 February 2011 (right image) earthquakes

Analysis of high resolution, 10GSM (10 cm ground measurement/pixel) aerial photos obtained within days of each earthquake event was undertaken within areas of damage on the flat land, to confirm the foot based mapping, particularly in areas visited weeks after the events, as the evidence of sand on the ground surface had often been removed/concealed by the time the mapping was completed.

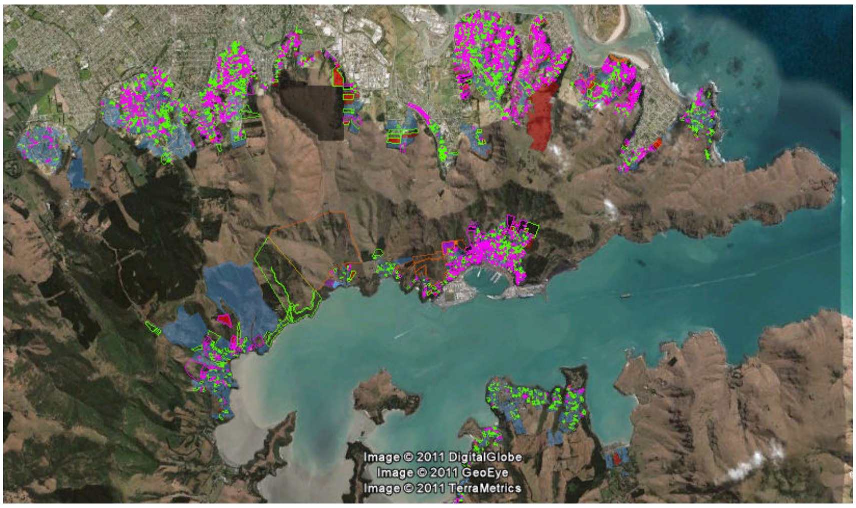

Figure 4. Macro scale 'Local' mapping undertaken as a foot based road level assessment identifying the severity of the ground damage observed on sloping land following the 13 June 2011 earthquake

Local scale mapping was generally completed within a few weeks of each earthquake, with the process becoming more efficient following every significant earthquake. Local mapping took ten weeks following the 4 September 2010 earthquake, at which time 39,000 properties had been mapped, while in the four weeks following the 22 February 2011 earthquake, a total of 100,000 properties were mapped.

3.3. Micro Scale Land Damage Assessment Methodology

In areas that were noted to have suffered land damage a site specific inspection and assessment of each residential property was completed for the purposes of EQC insurance claim settlement. Assessments were undertaken by teams of geotechnical professionals, working in pairs. A detailed post fieldwork office process ensured that each assessment report was reviewed and the relevant data captured to facilitate recovery.

The LDAT assessments focussed solely on damage to the land only. Separate assessments of the damage to structures were undertaken by other divisions of EQC. Typical damage noted in flat land included; evidence of cracks in soil, evidence of sand ejecta, evidence of undulations/changes in ground levels/ponding, formation of new springs, Typical damage noted in sloping ground included; rockfall (inundation), cracks, land movement, and failure of retaining walls. These types of damage are covered by EQC as part of the land exposure for each claim. The property assessments noted damage that was attributable to each separate earthquake event, where possible, or in an aggregated (cumulative) format where more than one significant (ie. damage causing) earthquake had occurred before the inspection is undertaken.

Between 4 September 2010 and 21 February 2011 approximately 14,000 individual detailed property assessments were completed by the EQC LDAT with each assessment generally taking between 30 minutes and an hour. Between 22 February 2011 and 17 December 2011, approximately 60,000 individual property assessments were completed by the LDAT engineers in suburbs on the flat land across Christchurch, and in surrounding towns in the Waimakariri and Selwyn Districts, and an additional 5000 properties were assessed in suburbs on the Port Hills.

The information held by EQC relating to specific damage on individual properties is privileged and as such, maps showing the damage at this 'micro' scale have not been reproduced publicly.

4. LAND DAMAGE OBSERVATIONS

4.1. Darfield Earthquake – 4 September 2010

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, where the most recent (and typically loose) 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 ('channel'). Greater/more significant damage 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.

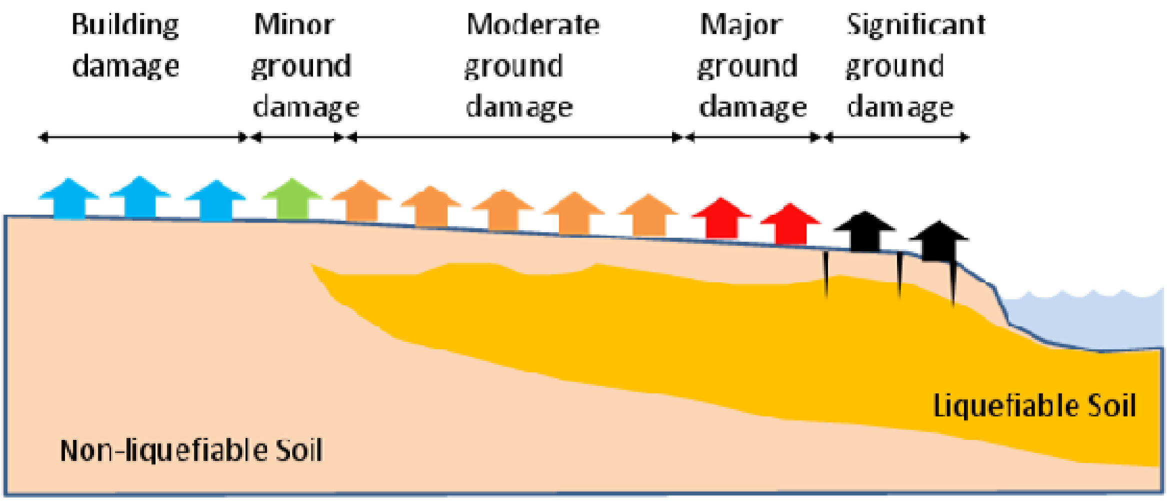

Figure 5. Typical observed pattern of severity of land damage caused by the earthquakes to land adjacent to existing and former channels

Areas of land affected were spread across the region, with parts of Halswell in the west of Christchurch, and Tai Tapu in the Selwyn District, southwest of the city having significant damage due to their close proximity to the earthquake epicentre. Other parts of eastern Christchurch, including, Burwood, Dallington, New Brighton and Bexley, as well as parts of eastern Kaiapoi, in the Waimakariri District, were also significantly affected. Note that as no significant widespread damage was noted on the sloping land as a result of the 4 September 2011 earthquake, no regional scale mapping was undertaken in this area.

4.2. Christchurch Earthquake – 22 February 2011

The pattern of observed land damage on flat land 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 city, with sand recorded on the ground surface in almost all eastern suburbs and in many western suburbs. Ejected sand was observed over approximately 12,000 Ha, or 60% of the city area. 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. Spreading often 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.

4.3. The Christchurch No. 2 Earthquake – 13 June 2011

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 significant 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.

4.4. Port Hills

In addition to the increased scale and extent of damage to flat land, the 22 February and 13 June 2011 earthquakes both resulted in significant widespread and localised damage to land and residential properties in hillside suburbs. Most notably this damage included collapse of cliffs and rockfall, as well as displacement/deformation of land, causing cracking and bulging, and failure of retaining walls.

Cliff collapse was notable, and affected properties were located at both the top and base of former seacliffs in the suburbs of Scarborough, Sumner and Redcliffs. Retreat of cliff tops by up to 5 m was recorded in the February event and up to 15 m in the June event. This resulted in significant inundation of land, including residential properties and dwellings, at the base of cliffs. This type of damage was significant in the February earthquake and severe in the June earthquake, where greater horizontal ground accelerations appeared to have caused more damage.

Rockfall most notably occurred as a result of the 22 February 2011 earthquake. While damage to land as a result of the rockfalls was limited to the formation of impact marks or inundation where rocks came to rest, damage to property, in particular dwellings, was significant.

Deformation (cracking and bulging) of land was widespread over the hills, particularly around changes in slopes, where ground accelerations were concentrated (topographical amplification). Notable patterns include a semi-continuous zone of cracking and some associated bulging located at the base of the Port Hills, which appears to be the result of high horizontal and vertical ground accelerations acting on the soil mass to produce large shaking forces which have caused the soil/ground material to displace downslope, and potentially due to dilation of the underlying rock mass, near to free faces (cliffs). In some areas the displacement was potentially exacerbated by a loss of toe support due to liquefaction of subsurface material at the base of the slope.

Retaining walls of different age, dimensions, and construction types, supporting cut and filled ground caused damage to ground on a more local scale, generally affecting land within a single or on neighbouring properties only. While some walls collapsed completely, others were structurally damaged but continued to serve the purpose, supporting the retaining land, and others were only damaged cosmetically. Some of the damage to these walls was associated with other damage noted above.

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 engineers 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.

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.

A positive outcome of the multiple earthquakes has been the resultant revision of the procedures followed. While each natural disaster worldwide will be different, there is much to be said for taking the time to calmly set up the processes, support and infrastructure that will be required, prior to getting caught up in the details. When doing so, an appreciation that you will almost always underscope what the work will entail, and how long it will take, is a valuable insight.

ACKNOWLEDGEMENT
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