REPORT

Geotechnical information on horizontal land movement due to the Canterbury Earthquake Sequence

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Table of contents

Executive summary

Background

Land Information New Zealand (LINZ) has recognised that the ground movements that have occurred as a result of the Canterbury Earthquake Sequence (CES) may have implications for cadastral survey work. LINZ have requested that T&T collate this report to provide background geotechnical information about these ground movements.

The purpose of this report is to provide an overview of the various mechanisms of ground movement that have occurred across Canterbury as a result of the CES, focussing on horizontal ground movements of most relevance for cadastral surveyors. The report explains the key geological mechanisms, and outlines the data that is available on the Canterbury Geotechnical Database (CGD) that relates to these mechanisms. It also seeks to summarise the key features and limitations of this information that need to be considered when using the data.

This report does not attempt to delineate areas where ground movements may have an impact on cadastral surveys, or propose any solutions for these issues. It simply provides background information to assist the surveying profession as it works to resolve this complex situation.

Horizontal ground movement mechanisms

Horizontal ground movements can result in four different types of physical effects at the ground surface that are relevant to cadastral surveyors. As discussed in Section 3.1, these effects are uniform translation, rotation, extension and contraction.

The geological mechanisms that caused horizontal ground movement in the Canterbury Earthquake Sequence (CES) can be grouped into two fundamental types: deep-seated and shallow ground movement mechanisms. In most locations across Christchurch, deep-seated movement can be considered effectively uniform across the extent of a typical-scale cadastral survey. Shallow ground movements relate to the topography of the land and the response of near-surface soils. Generally most of this deformation occurs between the surface and a depth of about 10 to 20 metres. Shallow movement can cause significant extension and contraction of the ground.

A range of geological mechanisms caused horizontal ground movements in the CES:

- ***Deep-seated ground movement mechanisms*** *(Section 3.2):*
  - Slow (interseismic) movement related to plate tectonic deformation
  - Rapid (co-seismic) movement due to fault rupture
  - Permanent deformation of the deep sediments
- ***Shallow ground movement mechanisms on the Port Hills*** *(Section 3.3):*
  - Small-scale rockfall, ground movement and retaining wall movement
  - Large-scale earthquake-induced landslides (mass movement), including cliff collapse, ridge and crest slope failure, and toe slumping
- ***Shallow ground movement mechanisms on the flat-land*** *(Section 3.4):*
  - Lateral spreading, including large-scale spreading of gently sloping land, small-scale spreading of steeply-sloping land, and downslope sliding of land
  - Liquefaction-induced ground oscillation
  - Area-wide ground stretching

Available geotechnical information

There is a wealth of technical information available that can assist in understanding the ground movements that have occurred as a result of the CES. But when using this information it is important to understand the key features and limitations of the data, as outlined in Chapters 4 and 5 of this report. In most cases it will be necessary to weigh up information from a number of data sources and a range of scales. Some mechanisms of ground movement are localised in nature and might be easily identified on site, while other mechanisms are more subtle and might only be identified from an area-wide assessment.

Chapter 5 summarises the existing information that is freely available for use by technical professionals via the Canterbury Geotechnical Database (CGD). Surveyors are encouraged to register for access at https://canterburygeotechnicaldatabase.projectorbit.com

The key data sources on the CGD to assist in the assessment of horizontal ground surface movements are:

- ***Information on ground surface movements in general*** *(Section 5.1):*
  - NZGD2000 deformation model
  - LiDAR and digital elevation models
  - Vertical ground movements inferred from LiDAR
- ***Information on shallow ground movement on the Port Hills*** *(Section 5.2):*
  - Port Hills mass movements and surface deformations
- ***Information on shallow ground movement on the flat land*** *(Section 5.3):*
  - EQC liquefaction and lateral spreading observations
  - MBIE residential foundation technical categories
  - MBIE guidance areas of lateral ground movement
  - EQC observed ground crack locations
  - Rivers and catchments
  - Horizontal movement vectors inferred from LiDAR

Chapter 6 provides an estimate of the number of residential properties affected by the various forms of ground movement that have been observed. This information is intended to help convey the relative extent of the different mechanisms and severity of ground movement.

Technical collaboration

The ground movements caused by the CES can be very complex, and it is likely that a degree of residual uncertainty will remain in many cases. In some cases, there may be a need for surveyors and geotechnical engineers to work together to better understand the ground movements and the implications for cadastral survey.

1 Introduction

During the 2010/2011 Canterbury Earthquake Sequence (CES), many properties across Canterbury were affected by various types of permanent ground movements. Land Information New Zealand (LINZ) already maintain the local accuracy of their coordinate system to account for deep-seated movements. This accounts for both the continuous movement of the land surface as it follows the underlying tectonic plates, and more localised deformations during significant earthquakes. These movements are defined by a time-dependent NZGD2000 Deformation Model, which is updated periodically and after significant earthquakes (LINZ, 2013).

During the CES, a range of different geological mechanisms caused shallow ground movements, on both the Canterbury Plains and Port Hills. LINZ recognised that these shallow ground movements potentially have more complex implications for cadastral survey than deep-seated movements. An important first step towards understanding these implications is to understand the geological processes leading to the ground movements, as well as their scale and extent.

This report therefore provides an overview of the geological processes that lead to shallow ground movements. This report is based on data that is freely available through the Canterbury Geotechnical Database (CGD). While the maps in Appendix A of this report provide an overview of this data, survey professionals are encouraged to register for access to the detailed database, at https://canterburygeotechnicaldatabase.projectorbit.com.

The CGD provides a collation of data from various sources, in particular the Earthquake Commission (EQC), Ministry of Business, Innovation and Employment (MBIE), Christchurch City Council (CCC), Tonkin & Taylor Ltd (T&T), and GNS Science (GNS). This information plays an important role in the Canterbury recovery and ongoing scientific research, so the data and the way it was collected has been carefully reviewed by a range of experts.

The factual data available on the CGD that is most relevant to cadastral surveyors is summarised in this report, along with an explanation of the geological mechanisms involved, and the key features and limitations of the data. The collated information helps to build an understanding of the scale and extent of the ground movements that have occurred. The limitations inherent in the available data and the complexity of the ground response means that this information is most appropriate for understanding earthquake-induced movements at a neighbourhood-wide scale, rather than individual-property scale.

The ground deformations that have occurred as a result of the CES can be very complex, and in some cases are best understood using a combination of surveying and geotechnical knowledge. Therefore this report also aims to develop consistent terminology for survey and geotechnical professionals to use for describing the types of ground movement that have occurred, and facilitate collaboration between the professions.

2 Geological setting

2.1 The Port Hills and Canterbury Plains

The Port Hills and Canterbury Plains provide two distinctly different geological settings that responded differently during the CES.

The Port Hills and Banks Peninsula to the south of Christchurch City are part of a volcanic complex that became extinct approximately 6 million years ago and have been overlain since then by loess soil deposits (a fine wind-blown silt).

The Canterbury Plains (often referred to as the "flat-land") were progressively formed by braided rivers flowing eastward from the foothills of the uplifting Southern Alps. In the Christchurch City area, outwash fans deposited over 400 m of interlayered gravels, sands and silts on top of the basement rock over the last half million years. There are fine-grained marine/estuarine sediments up to 15 km west of the present-day shoreline (Suggate, 1958; Brown & Weeber, 1992; Forsyth et al., 2008).

The present-day flat-land surface features reflect a generally westward moving shore line, ranging from the now dry braided river beds to the west and north of Christchurch City to the undulating sand dunes in the estuarine areas and shoreline to the east. The present-day Avon and Heathcote Rivers are constrained by development and border the central city to the north and south. These surface features are well illustrated by the ground elevation map in Appendix A (Map 1).

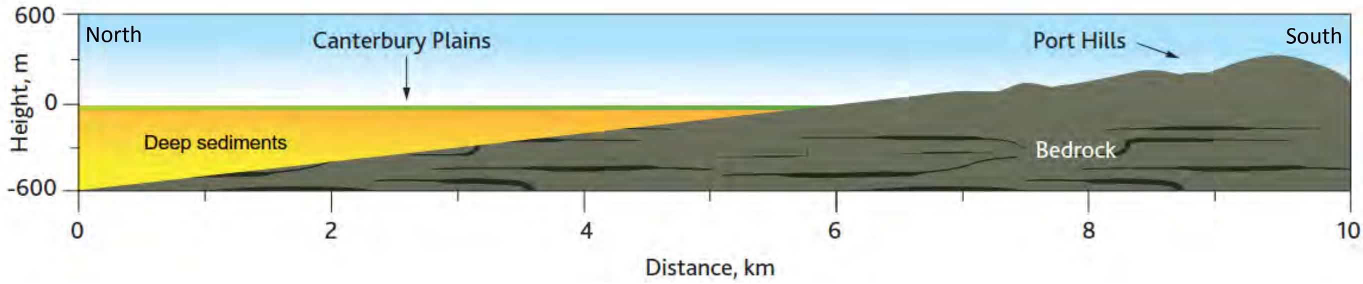

Figure 2.1: Simplified cross section across the Port Hills and Canterbury Plains

2.2 The Canterbury Earthquake Sequence (CES)

Table 2.1 below outlines the four main earthquakes in the Canterbury Earthquake Sequence (CES) that resulted in observed land damage and had potential to generate significant ground movement. Many smaller aftershocks occurred after each of these main earthquakes, but these aftershocks are unlikely to have resulted in significant ground movement in residential green zone areas. Deep-seated movements due to these four earthquakes are incorporated within the 20130801 version of the NZGD2000 Deformation Model (LINZ, 2013).

Table 2.1: The main earthquakes in the Canterbury Earthquake Sequence (CES)

Date	Magnitude	Location
4 September 2010	M_w 7.1	38 km west of Christchurch CBD
22 February 2011	M_w 6.2	6 km south of Christchurch CBD
13 June 2011	M_w 6.0	9 km southeast of Christchurch CBD
23 December 2011	M_w 5.9	9 km east of Christchurch CBD

3 Horizontal ground movement mechanisms

This chapter outlines the various forms of horizontal ground movement observed as a result of the CES. The CES also caused vertical ground movements, but these are less important for cadastral surveying (because in isolation they do not affect the plan area or shape of a property) so are not described in detail in this report. Some general concepts and terminology are first introduced to describe the physical effects of ground movement as observed at the surface, and the underlying geological mechanisms that have caused this ground movement. The observed ground surface movements are then separated into their deep-seated and shallow movement components, and the associated geological mechanisms are examined in more detail.

3.1 Background

3.1.1 Physical effects of horizontal ground movements

Horizontal ground movements can be grouped into four basic types relevant for cadastral surveyors:

- ***Uniform translation of the ground surface*** – e.g. all the survey pegs, and everything else on the land, have moved approximately the same distance and direction (if not exactly the same, then at least close enough to be effectively uniform for surveying purposes)
- ***Rotation of the ground surface –*** *e.g. the distance between survey pegs stays the same, but the bearing changes*
- ***Extension of the ground surface*** – e.g. the distance between survey pegs increases enough for the change to be significant for surveying purposes
- ***Contraction of the ground surface*** – e.g. the distance between survey pegs decreases enough for the change to be significant for surveying purposes

A useful measure to assess the significance of extension and contraction of the ground surface is the amount of strain that has occurred. Strain is a dimensionless value, which is defined as the change in the distance between two points, divided by the initial distance between those points.

The surveying significance of extension and contraction of the ground surface will depend on the amount of strain that has occurred, the distance over which the strain accumulates, and the scale of the survey being undertaken. A small strain may be of little significance for a small-scale survey (e.g. 0.05% strain results in just 0.01 m change between boundary pegs 20m apart). But the same amount of strain could become more significant for a larger-scale survey (e.g. 0.1 m change between survey benchmarks 200 m apart).

3.1.2 Deep-seated and shallow ground movement mechanisms

The geological mechanisms that caused horizontal ground movement in the CES can be grouped into two fundamental types: deep-seated and shallow ground movement mechanisms.

Deep-seated ground movement mechanisms

Deep-seated ground movement mechanisms relate to the deformation of the underlying bedrock, and the response of the deep sediment deposit that sits above the rock (the deep sediments can be over 400 m thick in parts of Christchurch, as shown in Figure 2.1).

Deep-seated ground movement usually only deforms the ground surface very gradually over large distances (i.e. very low strain). Therefore in most locations across Christchurch, this type of movement can be considered as being effectively uniform across the extent of a typical neighbourhood-scale cadastral survey. The exception to this is areas which are close to the fault rupture, where there are significant strains and dislocations due to the deep-seated movement, which may be significant for larger-scale cadastral surveying.

Shallow ground movement mechanisms

Shallow ground movement mechanisms relate to the topography of the land and the seismic response of the near-surface soils. This includes both landslide-induced movement on the Port Hills and liquefaction-induced movement on the flat-land. There is not an exact definition of “shallow” depth, but generally most of the significant deformation from these mechanisms is associated with the soil between the surface and a depth of about 10 to 20 metres.

The topography of the land and response of near-surface soils can be highly variable across the plan extent of a typical neighbourhood-scale cadastral survey. Therefore in some cases there can be significant differences in the distance and direction of shallow ground movement over short distances, resulting in significant extension and contraction of the ground.

3.1.3 Overview of the geological mechanisms causing ground movement

There are a range of geological mechanisms that can cause horizontal movements at the ground surface. These are summarised below, and examined in more detail in the following sections.

- ***Deep-seated ground movement mechanisms*** *(Section 3.2):*
  - Slow (interseismic) movement related to plate tectonic deformation
    Millimetres to centimetres of movement per year
  - Rapid (co-seismic) movement due to fault rupture
    Centimetres to metres of movement during a single earthquake
  - Permanent deformation of the deep sediments
    Millimetres to centimetres of movement due to earthquakes or other subsurface processes

- ***Shallow ground movement mechanisms on the Port Hills*** *(Section 3.3):*
  - Small-scale rockfall, ground movement and retaining wall movement
  - Large-scale earthquake-induced landslides (mass movement)

- ***Shallow ground movement mechanisms on the flat-land*** *(Section 3.4):*
  - Lateral spreading
  - Liquefaction-induced ground oscillation
  - Area-wide ground stretching

3.2 Deep-seated ground movement mechanisms

3.2.1 Slow (interseismic) movement related to plate tectonic deformation

Due to New Zealand’s position at the boundary between the Australian and Pacific tectonic plates, different parts of the country move in different directions at rates of several centimetres per year. This slow, interseismic (between earthquakes) movement is driven by plate tectonic movements and recorded by continuous and campaign GPS measurements. Surveyors must account for interseismic movements because the reference frame for the New Zealand cadastre is constantly moving.

Parts of New Zealand on the Pacific Plate (e.g. Christchurch) move up to 30 to 40 mm per year southwest relative to parts of New Zealand on the Australian Plate (e.g. Auckland). But over smaller distances (tens to hundreds of kilometres) and away from the main plate boundary zone, this relative interseismic movement is typically very small. For example, Christchurch moves only a few millimetres per year closer to the Southern Alps.

The measurement of relative movement over a given area is typically calculated as strain. The gradual accumulation of strain increases the stress applied on active faults in these areas.

3.2.2 Rapid (co-seismic) movement due to fault rupture

When the stress resulting from interseismic strain has reached a level greater than the strength of active faults, the faults may break (rupture) and rapid co-seismic (during earthquake) movement may occur. If the displacement on a fault occurs rapidly, it sends out energy waves that are defined as an earthquake.

The amount of fault slip that occurs in an earthquake relates to the area of the fault rupture. Faults with enough displacement may cause a surface rupture. Earthquakes on smaller faults may cause folding or doming of the Earth's surface without causing a discrete surface rupture. Permanent ground movements of centimetres to several metres may occur at the surface due to the fault movement.

If the fault ruptures the surface, relative movements of metres can occur over the narrow width of the surface rupture. For example, several metres of relative movement occurred at sites only a few metres apart across the surface rupture of the Greendale Fault during the September 2010 Darfield earthquake (Quigley et al., 2012), as shown in Figure 3.1.

For faults that do not rupture the surface, movements are typically smaller and change more slowly over larger distances. For example, the 2011 Christchurch earthquake did not rupture the ground surface, and resulted in ground movements that varied by only tens of centimetres over several kilometres (Beavan et al., 2012). Figure 3.2 below presents a simplified example of how the fault rupture can propagate from the bedrock up through the overlying deep sediments. In this example the fault rupture does not reach the ground surface, and surface ground movements are distributed over a greater distance than the abrupt bedrock rupture.

Beavan et al. (2012) presents a model which estimates tectonic ground movements across greater Christchurch as a result of the CES (refer to Map 2b in Appendix A). This tectonic movement model formed the basis for the updates to the NZGD2000 Deformation Model following the CES (LINZ, 2013). The tectonic model was computed by including movement observations at survey marks located on rock, as well as marks that were not on rock but were assessed to be unaffected by significant shallow ground movement. Where the marks are not in bedrock, this approach provides a good estimate of the surface movement due to bedrock movement, but the measurements are still at the ground surface, so cannot capture the underlying bedrock movements perfectly. This tectonic ground movement model also draws on the analysis of interferometric synthetic aperture radar (InSAR) data.

The accumulation of tectonic ground movements over the course of the CES resulted in the area around the Avon/Heathcote estuary being uplifted by up to 400 mm, with the central and north-eastern areas of Christchurch City subsiding by up to 150 mm (in addition to settlements caused by liquefaction and shallow ground movements).

Figure 3.1: Aerial photo showing ground surface rupture of the Greendale fault from the September 2010 Darfield earthquake. Annotations indicate the direction of ground offset across the fault. Photo sourced from Environment Canterbury.

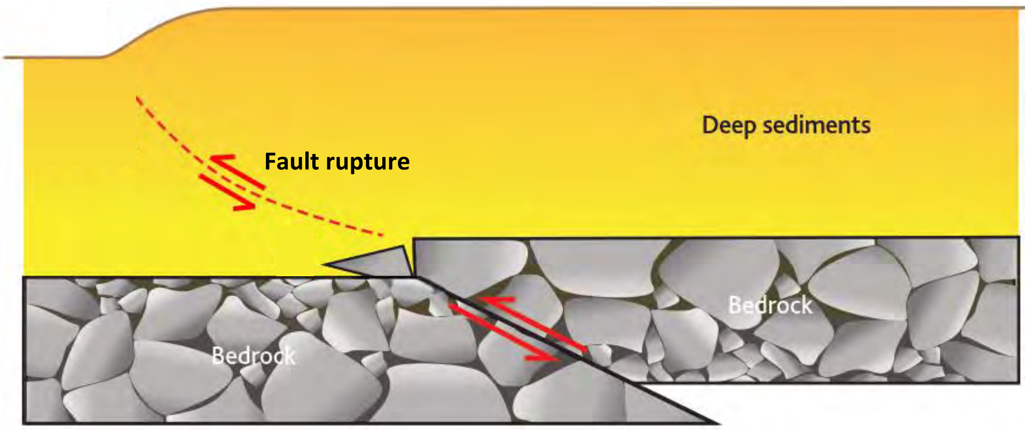

Figure 3.2: Simplified cross section illustrating the propagation of a fault from bedrock up through the deep sediments and the offset at the ground surface.

3.2.3 Permanent deformation of the deep sediments

As shown in Figure 2.1, the deep sediments overlying bedrock can be many hundreds of metres deep across the Canterbury Plains. Compaction of the deep sediments due to earthquake shaking or loading by overburden, groundwater withdrawal, and other processes may cause ground subsidence and horizontal movements.

The patterns of land deformation observed from the CES suggest that any ground surface movement that might have occurred due to these mechanisms is only very minor (in terms of both amount of movement and strain) when compared to the effects of shallow ground movement and fault rupture. It appears unlikely that these mechanisms of ground movement would need to be specifically considered for most cadastral survey work in this particular setting. Any minor deformations that may have occurred within the deep sediments are likely to have been captured by the update to the NZGD2000 deformation model following the CES (LINZ, 2013).

3.3 Shallow ground movement mechanisms on the Port Hills

A rapid reconnaissance assessment of the Port Hills following the February 2011 earthquake identified three main geological mechanisms that resulted in shallow ground movement on the Port Hills (EQC, Stage 3 Land report, 2012). These were:

- Small-scale rockfall
- Small-scale ground movement and retaining wall movement
- Large-scale earthquake-induced landslides (mass movement)

3.3.1 Small-scale rockfall, ground movement and retaining wall movement

The rockfall and small scale ground movement mechanisms are localised failures of surface features (e.g. rock bluffs and retaining walls). These can often be easily identified on individual sites, and may cause movement of the ground in one part of the property, without significant extension or contraction of the ground in other parts of the property. The following indicators may help surveyors identify such features, and plan their survey accordingly.

The key features to identify small-scale rockfall areas are:

- Exposed rock bluffs
- Rock faces that appear visually different in comparison to the rest of the exposed rock e.g. lighter colour, less weathering, and less lichen growth
- Rock debris at the base of exposed bluff (refer Figure 3.3)

The key features to indicate that localised small scale ground movement and/or retaining wall failure has occurred are:

- Visible failure of the retaining wall including, bulging, rotation or collapse
- Settlement/depression of the slope or land upslope of the retaining wall (refer Figure 3.4)
- Ground cracking upslope of the slope or retaining wall
- Buckling or compression of hard surfaces at the base of the retaining wall
- Separation of structures such as fences
- Bulging of the slope, distortion at the toe of the slope

Figure 3.3: Small-scale rockfall on a residential property in Whitewash Head. Photo sourced from Tonkin & Taylor.

Figure 3.4: Localised depression of land immediately upslope of retaining wall that has laterally displaced. Photo sourced from EERI, Christchurch Earthquake Clearinghouse. Retrieved 02/03/15

3.3.2 Large-scale earthquake-induced landslides (mass movement)

As a result of the CES, a number of large-scale earthquake-induced landslide failure mechanisms were observed in the Port Hills. These mechanisms included cliff collapse, ridge and crest slope failure, and toe slumping – these are discussed in more detail below. Areas affected by these large-scale failure mechanisms due to the February and June 2011 Christchurch earthquakes were later classified by GNS Science as areas of mass movement (GNS, 2012).

There are currently 46 areas across the Port Hills that have been identified by GNS as having experienced large scale failure mechanisms (mass movements) due to the CES. These areas have been grouped into three categories based on the risk from the known hazard: Class I, Class II and Class III (refer to Map 3 in Appendix A).

The Class I mass movement category comprises 15 areas across the residential Port Hills area. Class I mass movement areas have been identified as the highest risk with the potential to result in loss of life in the case of another large earthquake. Many of these areas identified as Class I are associated with cliff collapse failure.

The Class II category comprises 18 areas, while Class III comprises the remaining 13 areas across the residential Port Hills. Class III areas pose the lowest risk to loss of life, damage to buildings and infrastructure as they are estimated to have a smaller scale of shallow ground movement. Both Class II and Class III mass movement areas incorporate toe slumping movement mechanisms.

Landslides - Cliff collapse (GNS Class I mass movement), Ridge and crest slope failure

Cliff collapse comprises areas where at a large scale, the bedrock comprising the cliffs collapses and the material falls downslope to the base of the cliff as illustrated in Figure 3.5. A cliff can recede back tens of meters from a single earthquake event. Not only does the loss of land at the edge of the cliff occur, but tension cracks often occur parallel to the cliff face resulting in a shallow ground movement affecting individual properties situated in close proximity to the cliff.

Large-scale cliff collapse occurred as a result of the February and June 2011 earthquakes in the suburbs of Clifton and Redcliffs and resulted in up to 10 m of total regression of the cliff line in these areas (GNS, 2012). Figure 3.6 illustrates some of the observed tension cracking observed in the Port Hills as a result of cliff collapse due to the CES.

Ridges can also experience landslides of the shallow soils where the land slopes away from the ridge line, as illustrated in Figure 3.7. This topographic situation often encompasses two failure mechanisms in close proximity – cliff collapse and landslides.

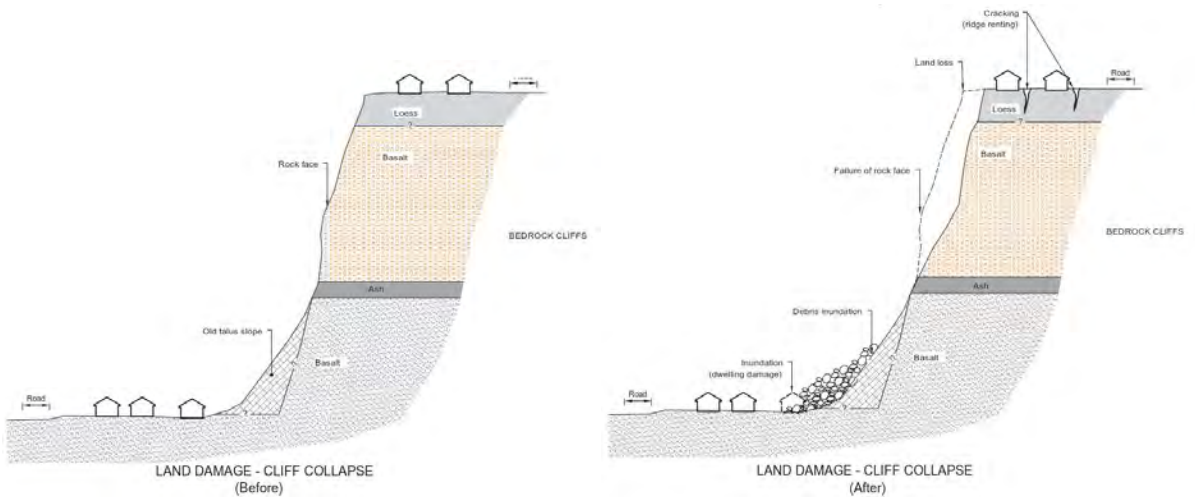

Figure 3.5: Simplified cross-section of large scale landslide – cliff collapse failure mechanism (T&T, 2012).

Figure 3.6: Tension cracking as a result of cliff collapse in the Port Hills. Photo: Tonkin & Taylor

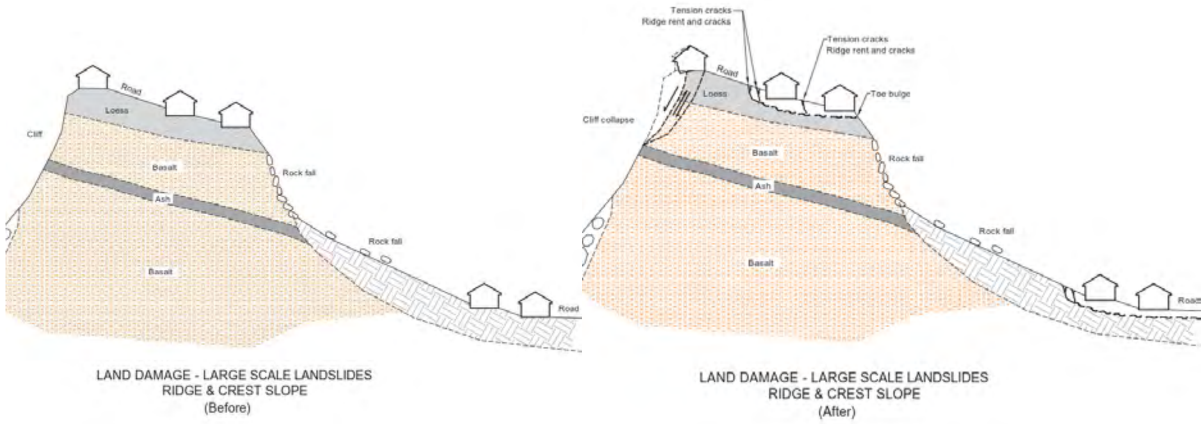

Figure 3.7: Simplified cross-section of large scale landslide - ridge and crest slope mechanism. (T&T, 2012)

Landslides - Toe slumping (GNS Class II and III)

Toe slumping is a landslide mechanism that results in downward translational movement of the shallow soils on a slope. As a result of the CES, this type of large scale horizontal movement occurred at various locations across the Port Hills. During the seismic shaking of the February and June 2011 earthquakes, the soft alluvial deposits (predominantly sands and silts) at the toe (i.e. base) of the slopes temporarily lost some of their strength. This allowed the loess soils (the soft surface sediments on the Port Hills), to slide downslope during the seismic shaking, as shown in Figure 3.8.

The horizontal movement resulted in extension, translation and contraction at different elevations. Zones of extension were typically found near the upper part of the landslide, often indicated by tension cracking of the ground surface such as illustrated in Figure 3.9. In the middle part of the landslide the ground usually experienced near-uniform downslope translation, with little or no observed ground cracking (but may still have experienced minor tension or contraction). Zones of contraction generally occurred at the toe of the slope, indicated by bulging of the ground.

Shallow horizontal ground movements of up to about 0.5 m typically occurred in the areas of toe slumping observed on the Port Hills, reaching up to 1.5 m in rare cases.

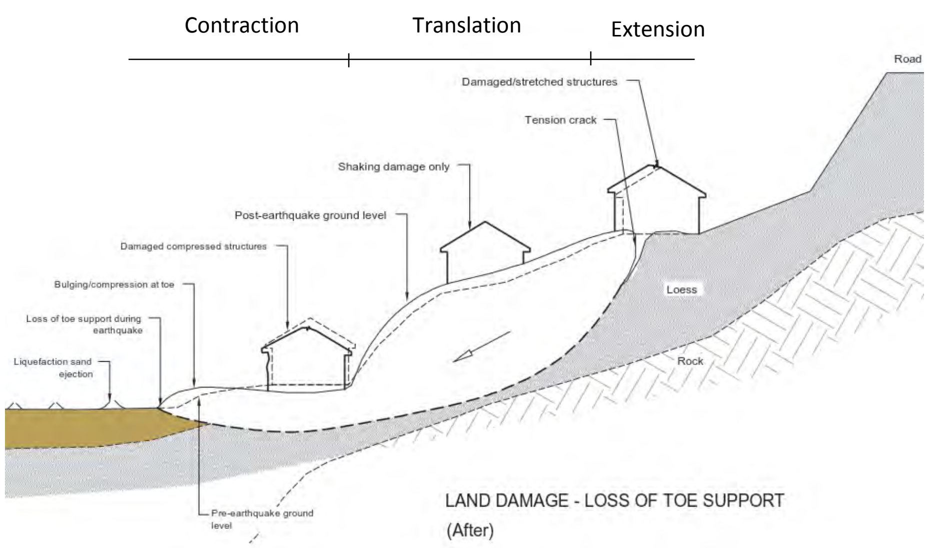

Figure 3.8: Simplified cross-section of large scale landslide - toe slumping mechanism (based on T&T, 2012)

Figure 3.9: Graben feature as observed in zone of extension as a result of toe slumping mass movement on Maurice Knowles Lane, Port Hills. Photo sourced from MBIE (2013).

3.4 Shallow ground movement mechanisms on the flat-land

Liquefaction-induced horizontal ground movements occurred across much of the greater Christchurch area as a result of the CES. The main movement mechanisms were lateral spreading, liquefaction-induced ground oscillation, and area-wide ground stretching.

3.4.1 Lateral spreading

Lateral spreading is horizontal movement of land towards a free face such as rivers, streams, channels or dips where the land is not physically constrained. Tension cracks in the land develop parallel to the free face as a result of the horizontal (and sometimes vertical) movement of the ground surface, as illustrated in refer Figure 3.10.

Lateral spreading occurs when soils liquefy under seismic shaking. When these soils liquefy, the strength of the soil is momentarily decreased and it acts more like a fluid. The soil above the groundwater table does not liquefy, and so “rafts” over the top of the liquefied soils and can slide towards the free-face. Lateral spreading is influenced by proximity to the free-face, so the likelihood and amount of ground movement from lateral spreading typically decreases with increasing distance away from the free-face.

The lateral spreading observed in the CES can be grouped into three main types based on the geometry of the ground movement mechanism, and the underlying geology:

- Large-scale lateral spreading of gently-sloping land towards a free face
- Small-scale lateral spreading of steeply-sloping land towards a free face
- Downslope sliding of land

While the geological mechanism is the same for all three types, when assessing the implications for cadastral survey it is useful to understand the differences in geometry, scale, and distribution of ground movements.

In the CES, large-scale lateral spreading of gently-sloping land was most often observed along the lower reaches of the Avon River (east of Barbadoes St) and the Kaiapoi River. Small-scale lateral spreading was most often observed along the upper reaches of the Avon River (west of Barbadoes St), the lower reaches of the Heathcote River (east of Colombo St), and the tributary streams of these rivers. This is a general observation only, and it is not suggested that there is any sudden change in the mechanism of movement or ground conditions at these indicative locations. It should also be noted that these observations relate to the specific geology and topography of the greater Christchurch area, and will not necessarily be applicable in other regions with different conditions.

Large-scale lateral spreading of gently-sloping land towards a free face

Where the land slopes towards the free face at a shallow angle, ground extension due to lateral spreading in the CES tended to extend a long way back from the free face (up to 200 m in some areas). The ground movement accumulated over many sets of parallel cracks, so the land can be conceptualised as a series of blocks moving different distances, as shown in Figure 3.11. This geometry of lateral spreading tended to include large lengths of riverbank within the one block of ground movement (typically 0.5 - 2 km length of riverbank).

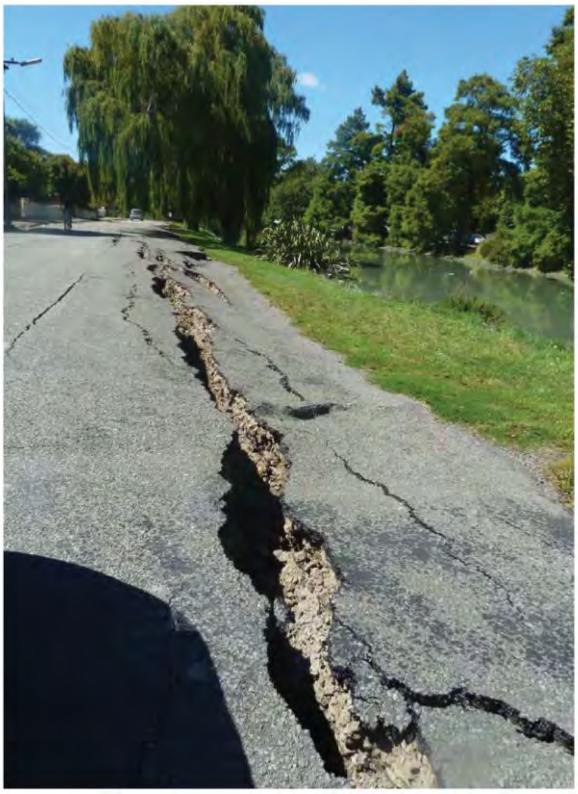

Figure 3.10: Photo showing large-sale lateral spreading of gently-sloping land towards the Avon River. Photo: Tonkin & Taylor

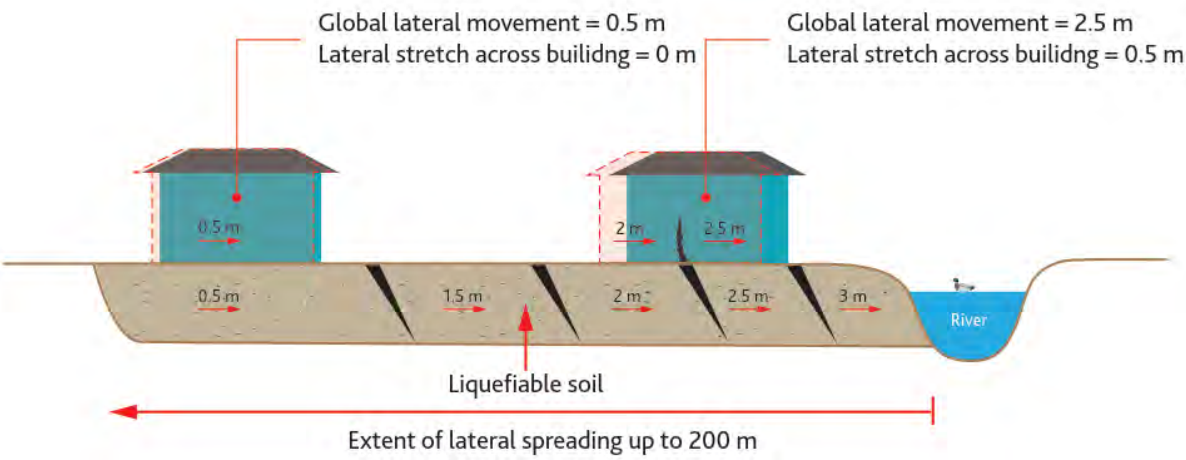

Figure 3.11: Simplified cross-section showing large-scale lateral spreading of gently-sloping land. Based on MBIE (2012).

Small-scale lateral spreading of steeply-sloping land towards a free face

Where the land slopes towards the free face at a steeper angle, ground extension tended to be limited to within a short distance from the free face (usually 50 – 100 m), as shown in Figure 3.12. The ground movement occurred primarily over one or two main sets of cracks, so the land can be conceptualised as one main block moving towards the free face, with some additional cracking due to local slope failure at the river edge. This geometry of lateral spreading tended to include shorter lengths of riverbank within the one block of land movement (typically 100 – 500 m length of riverbank).

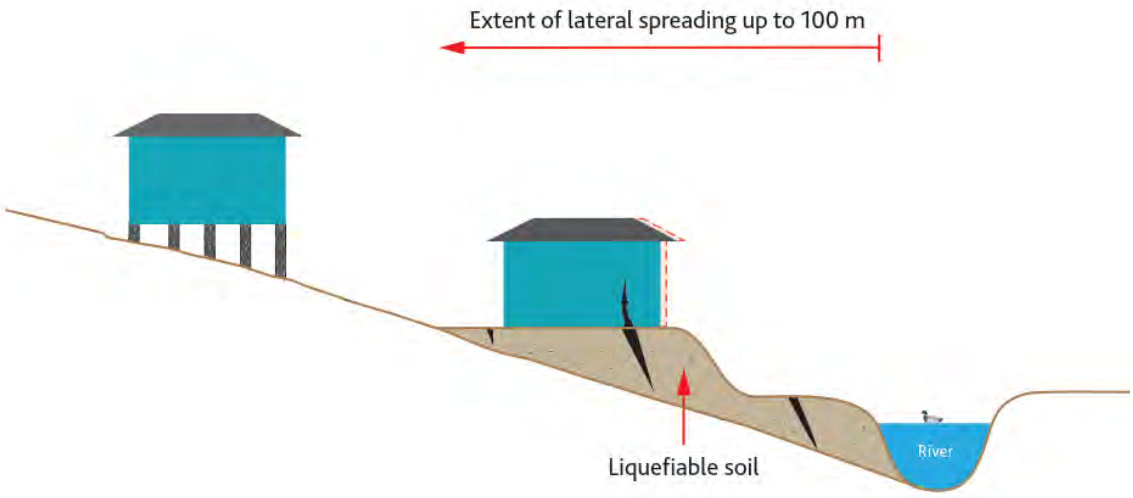

Figure 3.12: Simplified cross-section showing small-scale lateral spreading of steeply-sloping land.

Downslope sliding of land

Sliding deformation is a horizontal movement mechanism that was observed in some areas of Christchurch due to the CES, in particular within the oxbow of Horseshoe Lake. Downslope sliding is a type of large-scale lateral spreading that can occur when there are two free faces in an area, but the ground does not displace towards the nearest free-face – instead the ground mainly displaces in a downslope direction.

An example of this mechanism is illustrated in Figures 3.13 and 3.14 below. The old river channel which forms the oxbow of Horseshoe Lake provided free faces for horizontal movement to occur on three sides. However, due to an overall gentle slope of the ground, most of the ground displaced towards the eastern free-face, even if the western or northern free face was closer. Localised lateral spreading was still observed towards the closer edge however, a disproportionate mass of ground moved towards the eastern channel.

This type of deformation mechanism highlights the importance of understanding the underlying geological processes and the effect of the surrounding topography. In this case the lateral spreading movement occurred towards the nearest *downslope* free face, not just the nearest free face. If a survey assumed that movement occurred towards the nearest free face, then the assumed direction of movement could be incorrect.

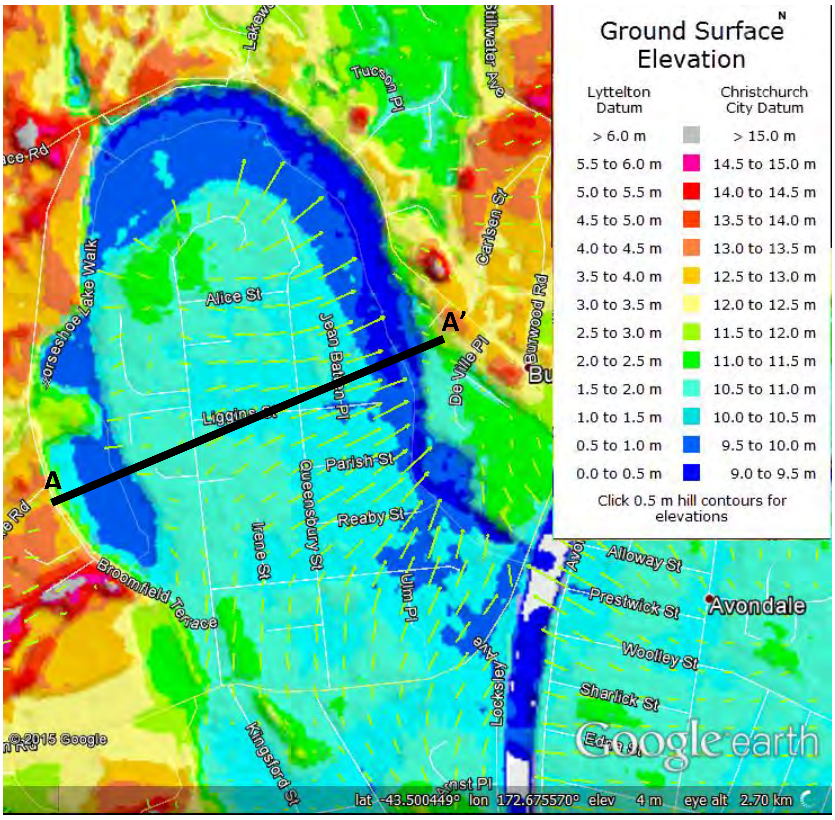

Figure 3.13: Screenshot from the CGD showing horizontal movement vectors (with deep-seated tectonic movement filtered out) plotted over ground surface elevation shading, illustrating downslope sliding mechanism in Horseshoe Lake (Source: CGD).

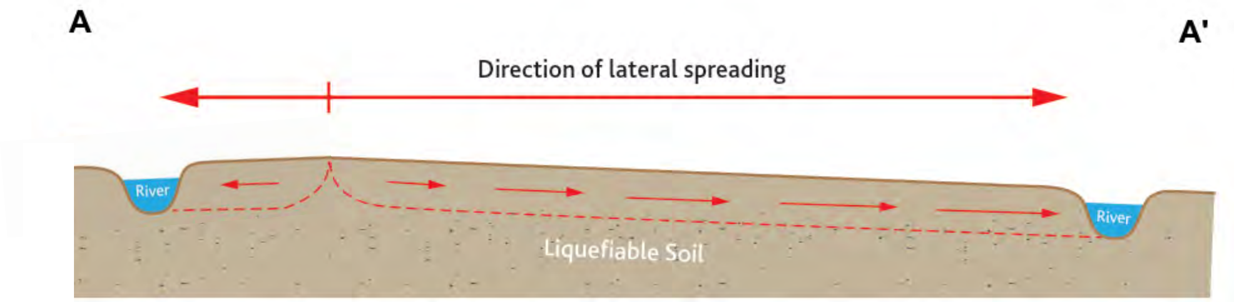

Figure 3.14: Simplified cross-section A-A' from Figure 3.13 showing downslope sliding lateral spread mechanism.

3.4.2 Liquefaction-induced ground oscillation

Liquefaction-induced ground oscillation is a localised surface deformation resulting in tension cracking or contraction of the ground surface during earthquake shaking. If liquefaction occurs in flat land away from a free-face, then there is no preferential direction of ground movement, so the ground surface just moves backwards and forwards. Cracks in the ground tend to mostly open and close with each cycle of shaking, rather than getting progressively wider. Ground cracks from this mechanism are usually narrower than 50 mm, without any obvious pattern or direction of movement. This mechanism can also result in areas of contraction, which are often indicated by bulging or buckling in hard surfaces such as driveways or kerbs, as shown in Figure 3.15.

If there is a slight local ground slope then the backwards and forwards movements might not completely cancel out. For example a driveway might slope gently down to the street - this might result in a series of tension cracks along the driveway, then an area of bulging or buckling where the driveway meets the street. This is a very localised form of ground movement, and is of a much smaller scale than the lateral spreading mechanisms discussed in Section 3.4.1.

Many of the observed oscillation cracks due to the CES were concentrated around the foundations of buildings and other structures (as seen in Figure 3.16). This appears to be related to the building foundations pushing backwards and forwards against the surrounding ground as the building is shaken during the earthquake. Ground cracks caused by oscillation in the CES often provided a pathway for ejection of liquefied material, but not always.

Ground cracking resulting from ground oscillation is often mistaken for lateral spreading – but the implications for cadastral survey are quite different. This is primarily due to the different scale and extent of ground movements – ground oscillation tends to result in only minor overall cumulative extension or contraction of the land across a property. If ground movements do not appear to be related to a nearby free face or sloping ground, then movements are more likely to be from local ground oscillation rather than large-scale lateral spreading.

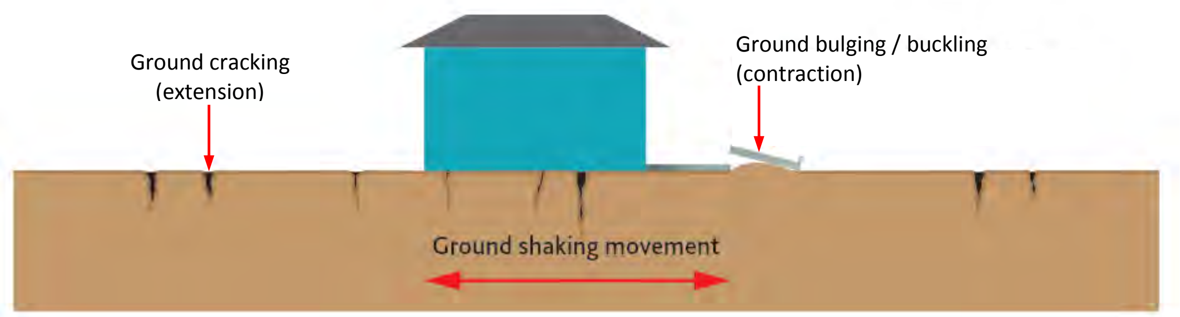

Figure 3.15: Simplified cross-section of localised ground cracking as a result of ground oscillation.

Figure 3.16: Ground crack resulting from ground oscillation during seismic shaking.

3.4.3 Area-wide ground stretching

While the Canterbury Plains may appear to be flat, as the shoreline and rivers have progressed from west to east across the city over the past 6000 years the associated erosion and deposition has altered the shape of the land. This has resulted in a present-day topography that is gently undulating, with elevation changes of up to 1-2m sometimes occurring over distances of 0.5 – 1 km (as shown in Map 1 in Appendix A). This can result in minor to moderate downslope movement of the ground surface during earthquake shaking, particularly if the underlying soils liquefy.

This stretching is very subtle, and causes only very small strains – the stretch across an individual property is usually less than 20 mm over a 20 m horizontal distance (0.1% strain), so it generally causes very little ground cracking or other damage. However as this stretch can accumulate over large distances across the large-scale topographical features, it can result in significant absolute ground movements (up to 1 m in some cases).

This mechanism of ground movement was first identified on the large-scale sand dune feature in North New Brighton. Figure 3.17 shows the estimated shallow ground movements in this area (i.e. with the deep-seated tectonic component of movement filtered out). There is a general trend of observed ground movement radiating outward from the high point in the middle of the dune area (red shading). This results from a "slumping" form of movement, with the land dropping in the middle of the dune, and moving outwards towards the edges, as illustrated in Figure 3.19.

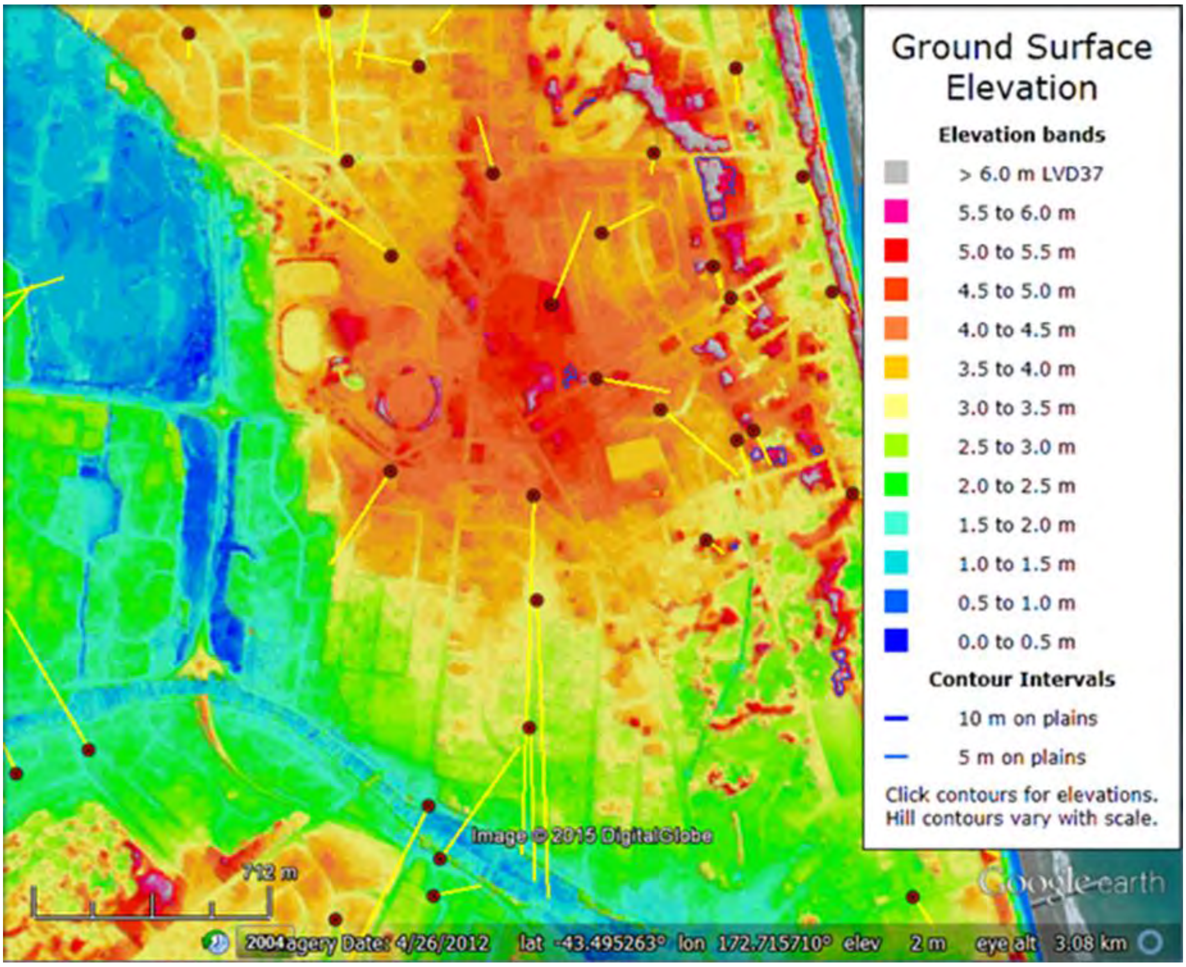

Figure 3.17: Screenshot from the CGD showing horizontal movement vectors (with deep-seated tectonic movement filtered out) plotted over ground surface elevation shading, illustrating area wide ground stretching in North New Brighton, radially away from the local high spot. (Source: CGD).

Area-wide ground stretching can either occur in the form of radial movement away from a local high spot (such as the example in Figure 3.17), or as a more general downslope movement. This general downslope movement can occur in response to the overall slope of the ground from west to east across Christchurch, or the subtle ridge features associated with sand dunes and riverbank levees. This second scenario is illustrated in Figure 3.18 for the Spreydon/Sydenham area, where the horizontal ground movements are generally perpendicular to the elevation contours.

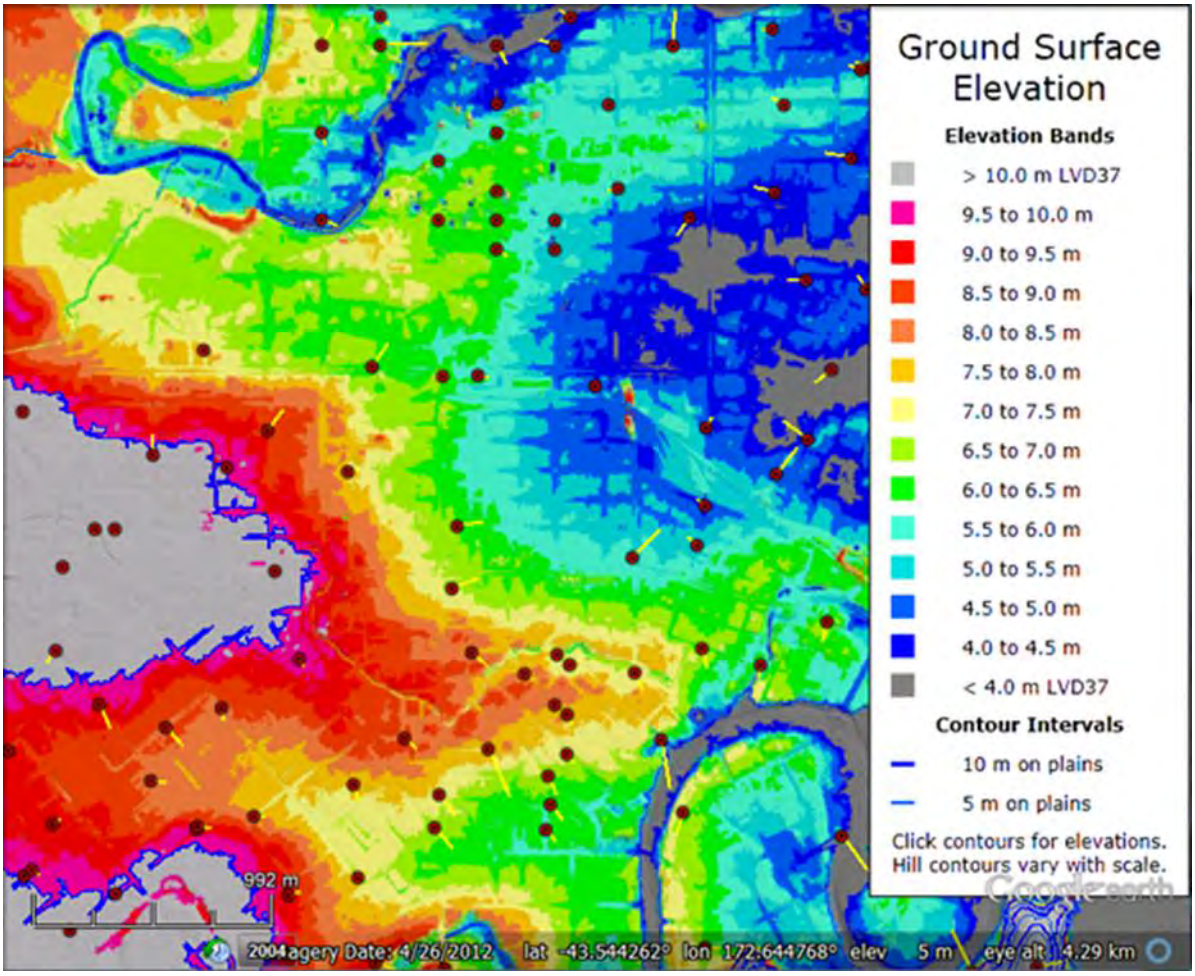

Figure 3.18: Screenshot from the CGD showing horizontal movement vectors (with deep-seated tectonic movement filtered out) plotted over ground surface elevation shading, illustrating area-wide ground stretching in Spreydon/Sydenham, with movements in a general downslope direction. (Source: CGD).

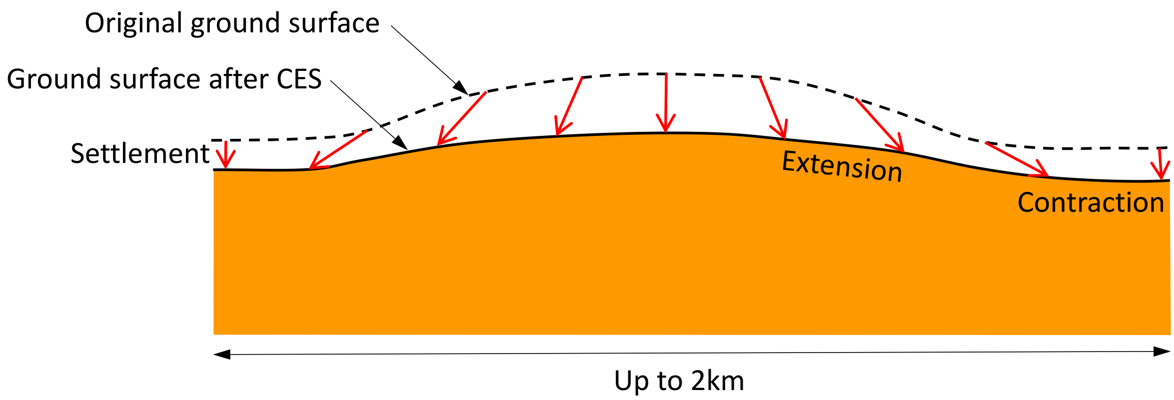

Figure 3.19: Simplified cross-section of surface deformation from area-wide stretching (in conjunction with area-wide settlement due to liquefaction and tectonic movements). Exaggerated vertical scale.

4 Understanding the limitations of the available information

There is a wealth of technical information available that can assist in understanding the ground movements that have occurred in Canterbury as a result of the CES. The data sources of most relevance for cadastral survey are outlined in Section 5. Before examining this data in detail, it is important to understand the limitations and uncertainty associated with this information. Each data source should not be examined in isolation – in most cases it will be necessary to weigh up information from a number of data sources and a range of scales to develop an understanding of the ground movements that have occurred.

4.1 Data limitations and uncertainties

The key limitations and uncertainties associated with the available data include:

- **Incomplete:** much of the data is concentrated in residential areas of known significant land damage, and not all areas were examined in detail after each main earthquake
- **Variable:** the subsurface profile and the resulting seismic performance of the river-deposited soils across Christchurch can be highly variable over short distances
- **Noise:** some of the available data is subject to significant measurement noise or errors (e.g. LiDAR elevation survey data and correlation analysis)
- **Different purpose:** much of the geotechnical data was collected on behalf of EQC for the specific purpose of assessing residential insurance claims – other purposes may have different information requirements

These limitations and uncertainties can be managed by evaluating data from a range of sources, along with an understanding of the underlying geological processes, to build up a broader picture of the performance of the ground. However, there is still likely to be a degree of residual uncertainty in the results of any assessment of shallow ground movements.

Due to the variability of ground performance and the deformation mechanisms involved, within even a small area there may be many properties that have experienced significant ground extension or contraction, but also many properties which have experienced little or none. Similarly, while the available data will likely encompass the majority of land in Canterbury with significant extension or contraction, it is likely that not all such land has been identified. It is therefore important that cadastral surveyors are able to manage these situations as they arise.

This report is intended to assist surveyors understand geotechnical information about ground movements resulting from the CES. It provides an overview of the geotechnical information currently available, and outlines how this data can be used to develop a general understanding of the ground movements that have occurred. In some cases, where the ground movements are complex or the data is inconclusive, there may be a need for surveyors and geotechnical engineers to work together to better understand the implications for cadastral survey.

4.2 Using the map layers in the Canterbury Geotechnical Database

By simultaneously overlaying layers of information in the Canterbury Geotechnical Database (CGD), the user is able to synthesise an understanding of the physical meaning of the information being displayed. This is also helpful for both identifying and quantifying the noise or error within the acquired data. All available information should be considered, at a range of scales, in order to identify outliers within the data (in particular the LiDAR data). Some data sources may be less reliable than others (as discussed further in Chapter 5), so this needs to be taken into account when weighing up the available information to develop conclusions.

The maps are intended to be used at large scales to synthesise an understanding over a significant area (i.e. within a street or suburb). Figures 3.17 and 3.18 illustrate how multiple layers can be overlaid, at an appropriate viewing scale, to help explain the movement mechanism. By overlaying the digital elevation model (Appendix A, Map 1) with movement of survey marks, it was identified that the surface movement of the survey marks was driven by the topography (area-wide ground stretching) in these instances.

4.3 Non-residential property

As much of the existing available data was collected by EQC for insurance purposes, it is focussed primarily on residential property within the main urban areas of Greater Christchurch. The data is more limited in non-residential areas, such as the Christchurch CBD, commercial/industrial areas, parks, and rural areas. In many cases the presence of large buildings, near-complete coverage of the land by buildings, and the effects of widespread demolition limits the ability to collect observations and measurements of the ground performance.

The reduced detail of geotechnical information in the Christchurch CBD is unlikely to cause significant issues for cadastral survey in most cases, because of the minor shallow horizontal ground movements that have occurred. Much of the central part of the CBD is underlain by alluvial deposits with a large proportion of gravel, which performed well in the earthquakes. The main shallow ground movement observed in the CBD was vertical subsidence through the ejection of liquefiable soils. Lateral spreading was also observed in the CBD as a result of the February 2011 earthquake, however this was constrained to a narrow corridor along the Avon River. River terraces to the north of the Avon River (near Peterborough St) were also subjected to some localised shallow ground movements. To assess the likelihood that shallow ground movement has occurred for locations in the CBD, the post-earthquake air photos available on the CGD should be inspected for the wider neighbourhood in addition to the maps of liquefaction and lateral spreading observations (Maps 4a and 4b in Appendix A).

5 Available geotechnical information

Following the CES, an extensive amount of data collection, mapping, and assessments have been undertaken by a wide range of geotechnical professionals and academic organisations both nationally and internationally. The amount of technical information now available is immense, and continuing to grow.

This chapter provides a collation of the information regarding ground movement collected following the CES, focussing on the shallow horizontal ground movement of most relevance for cadastral survey. It details the available data, how it was collected, and how each set of data relates to the various movement mechanisms described in Chapter 3. When using the data it is important to understand its limitations – this is discussed in general terms in Chapter 4, and more specifically for each data set in each section below.

The detailed data presented in this Chapter is freely available for use by surveyors and other technical professionals via the Canterbury Geotechnical Database (https://canterburygeotechnicaldatabase.projectorbit.com).

5.1 Information on ground surface movements in general

It is only practical to measure ground movements at the surface, which almost always includes a combination of deep-seated tectonic movements and shallow ground movements. While the precise proportions of the two deformation sources are unknown, the deep-seated tectonic movements are more uniform over large areas than the shallow ground movements. This allows these tectonic movements to be modelled reasonably accurately in comparison to the shallow surface movements. Shallow surface movements can then be approximated by subtracting the modelled deep-seated movements from those observed at the ground surface.

5.1.1 NZGD2000 deformation model

The GNS Science dislocation models (Beavan, 2012) that were used to update the NZGD2000 Deformation Model (LINZ, 2013) are based on a combination of inferred movements along buried faults and deformation observations for surveyed marks founded either directly on rock or marks that are not expected to be significantly influenced shallow ground movements.

Movement mechanisms reflected in this dataset

These deep-seated movements affect all of the movement mechanisms described in Section 3 because they represent the movement of the basement rock. For most situations away from the fault ruptures and their surface expressions, the tectonic ground movements could be considered effectively uniform across the extent of a typical-scale cadastral survey. Tectonic ground movements may become more significant for larger-scale surveys, or for surveys close to the fault.

Limitations

The deformations predicted by the models are inherently less accurate near the surface expressions of the faults because the surface soil strains will be more complex (and rapidly changing) than they are further away from the fault.

The observations used to derive the deep seated movements could be affected by shaking damage of rock outcrops and shallow ground movements that were not recognised when filtering the survey data.

5.1.2 LiDAR and digital elevation models

Aerial LiDAR surveys were undertaken following the September 2010, February 2011, June 2011 and December 2011 earthquakes to measure the elevation of the ground surface. LiDAR surveys had also been undertaken across the region prior to the earthquakes, between 2003 and 2008.

A broad overview of the LiDAR digital elevation model (DEM) available on the CGD is presented as Map 1 in Appendix A.

Movement mechanisms reflected in this dataset

The digital elevation data is a valuable tool to identify topographic patterns and features. In conjunction with other data sources, such as the horizontal movement vectors (Section 5.3.6), the more subtle movement mechanisms such as downslope sliding and area-wide ground stretching (sections 3.4.1 and 3.4.3) can be identified.

Furthermore, the digital elevation model can assist in identifying the location of topographic changes (which can often reflect underlying geological changes). This can be useful when assessing the potential extent of ground movements in an area.

Limitations

The extent of the LiDAR surveys varied, with the July 2003 and September 2011 surveys covering the largest extent of greater Christchurch. LiDAR surveys following the other earthquakes were focussed on the areas of most significant land damage observed in each event. Urban areas not covered by the survey undertaken after the December 2011 earthquake were generally well away from the strongest shaking and significant land damage, so are likely to have experienced only very minor changes in ground elevation. Therefore in these areas the September 2011 survey is usually adopted as the post-CES ground level.

The accuracy of the LiDAR surveys vary between providers (as outlined in Appendix A – Map 1), however typically range between ±0.07 – 0.15 m. The flight paths taken for each survey generate an amount of 'noise' in the surveys (included within the stated accuracy level), which present as linear stripe features in the LiDAR output (particularly visible on the maps of vertical ground movements, as discussed further in Section 5.1.3).

5.1.3 Vertical ground movements inferred from LiDAR

As described in Section 5.1.2 above, LiDAR ground elevation surveys were undertaken prior to the September 2010 earthquake and following the main events in the CES. The change in ground elevation caused by each major earthquake has been inferred using simple differencing between each survey. This provides a useful tool for understanding the extent and scale of the vertical ground movements from each earthquake.

Movement mechanisms reflected in this dataset

While vertical ground movements alone may not be directly relevant for cadastral survey, it provides a useful tool to help develop an understanding of how the ground in an area has responded to the earthquakes. Areas with greater shallow ground settlement are more likely to have also experienced a degree of horizontal shallow ground movement.

Maps 2a, 2b and 2c in Appendix A illustrate the vertical ground movements across Canterbury, and the contribution of each mechanism of ground movement:

- Map 2a presents the total change in ground elevation caused by the CES.
- Map 2b shows the estimated portion of the change in ground elevation caused by deep-seated ground movement over the course of the CES. This is based on the GNS model for tectonic deformations (Beavan, 2012), which shows the area around the Avon/Heathcote estuary being uplifted by up to 400 mm, with the central and north-eastern areas of Christchurch City subsiding by up to 150 mm.
- Map 2c shows the portion of the change in ground elevation inferred to have been caused by shallow ground movements (calculated as the difference between the total change and the deep-seated change). These shallow ground movements are sometimes referred to as the “local” component of the observed ground surface movement. These movements generally take the form of ground subsidence, and are usually related to liquefaction.

Limitations

Not all of the LiDAR surveys cover the full extent of Christchurch, so in some areas it is difficult to separate the effects of each individual earthquake. As discussed in Section 5.1.2, for areas outside the coverage of the survey undertaken following the December 2011 earthquake, the September 2011 survey is usually assumed to adequately represent the post-CES ground level.

The accuracy of the LiDAR surveys vary between providers, however typically range between ±0.07 – 0.15 m. Because the LiDAR survey is undertaken as a series of strips there is potential for errors between one strip and the next (this error is included within the stated accuracy). This is visible as south-west to north-east trending stripes in Map 2c, but can also be seen as north to south trending stripes in some of the other surveys, depending on the flight paths used.

Comparing ground elevations from one survey to another results in some degree of accumulation of the uncertainties in each. In particular, the LiDAR surveys undertaken before the CES had a lower accuracy than subsequent surveys, which increases the uncertainty when estimating changes in ground elevation over the entire CES. Similarly, the total tectonic ground movement over the CES is estimated by summing the modelled movements from each of the four main events, potentially also accumulating greater uncertainty.

For steeply-sloping ground such as hills and riverbanks, a horizontal change in position (e.g. from tectonic ground movement) may be misinterpreted as a change in ground elevation. The LiDAR vertical ground movement data information should be interpreted with particular care in these circumstances.

Examination of the inferred shallow ground movements (Map 2c) shows that the areas of most significant shallow ground subsidence (more than 0.5m) generally correlate well with the observed areas of most significant liquefaction and lateral spreading. However, at the lower end of the movement scale the trends are less clear. For example, Map 2c suggests that much of northwestern Christchurch experienced 0.1 – 0.2m of shallow ground subsidence (yellow shading on the map), but this is not consistent with the gravelly ground conditions and the absence of observed liquefaction effects. Possible explanations for this inconsistency could include a systematic error in one or more LiDAR surveys, an under-prediction of tectonic ground movements, or settlement occurring within the deep sediments (which if it occurred would be likely to cause relatively uniform ground movements).

5.2 Information on shallow ground movement on the Port Hills

5.2.1 Port Hills mass movements and surface deformations

The mass movement areas identify land on the Port Hills that has experienced large-scale ground deformations as a result of the CES. GNS originally published the mass movement areas in their Stage 1 report (GNS, 2012) for the CCC, and these areas were based on field investigations and assessments carried out by geotechnical professionals who mapped the observed surface deformations, including tension cracks and contraction features such as bulging of the land and buckling of hard surfaces.

The GNS mass movement study considered the conditions required to trigger a mass movement, the scale of movement, and location of where the land was likely to move. GNS categorised the relative hazard and risk to people and their property from the various mass movement mechanisms observed.

The Port Hills mass movement map contained within this report (Appendix A, Map 3) has been directly sourced from the CGD.

Movement mechanisms reflected in this dataset

The mass movement areas are shallow ground movements identified as large-scale landslides (Section 3.3.2). There are many forms of mass movement – the main types are cliff collapse, toe slumping, and ridge and crest slope failure. Each mass movement type was observed in multiple areas of the Port Hills due to the CES, and affected multiple properties at each location.

The most common shallow ground movement mechanisms observed within the mass movement areas were:

- Class I
  - Cliff collapse
- Class II and Class III
  - Ridge and crest slope failure
  - Toe slumping

The characteristics and explanation of the process of these failure mechanisms have been described further in Section 3.3.2 and also describe the shallow ground movements experienced.

Limitations

Not all mass movement areas have been identified. The majority of the data collected and assessed was focussed on residential areas. There may be some areas that are not currently residential which experienced such movement, or have the potential for movement in a future earthquake.

5.3 Information on flat land shallow ground movement

The following sections discuss data sources that specifically relate to shallow ground movement on the flat land. The LiDAR ground elevation survey also provides useful information for assessing shallow ground movements, as discussed further in Sections 5.1.2 and 5.1.3.

5.3.1 EQC liquefaction and lateral spreading observations

Rapid property-by-property mapping of liquefaction and lateral spreading observations was undertaken on the residential flat-land areas of greater Christchurch after each of the main earthquakes in the CES.

The mapping undertaken following the September 2010 and February 2011 earthquakes was undertaken on foot in the immediate weeks following each earthquake, and assigned observations to each individual property. The mapping covered the majority of urban residential land in greater Christchurch where the effects of liquefaction were observed from each event.

Rapid mapping was again undertaken following the June and December 2011 earthquakes, however this focussed on street-scale observations rather than property-scale, and was less extensive in coverage area. In general, areas that experienced liquefaction in the June and December 2011 earthquakes had already experienced similar liquefaction in the February 2011 earthquake. If it is necessary to determine whether or not liquefaction occurred in an area during the June or December 2011 earthquakes, it is advisable to inspect the post-earthquake air photos available on the CGD in addition to the road-level liquefaction mapping available for June.

The mapping was undertaken by geotechnical professionals on behalf of EQC, and was focussed on rapid reconnaissance rather than detailed inspections. Liquefaction and lateral spreading observations were categorised into different levels of severity, and mapped using a colour scale.

The categories used to assess land damage severity varied slightly between the September 2010 and the subsequent earthquakes. Following the September 2010 earthquake, a severity scale consisting of five land damage categories was used as outlined in Table 5.1. The severity scale used for land damage observation mapping following the February and June 2011 earthquakes consisted of six land damage categories as outlined in Table 5.2. The additional category (dark orange) was used to better distinguish the more severe liquefaction observed from these earthquakes.

The liquefaction and lateral spreading observation maps contained within this report (Appendix A, Maps 4a, 4b and 4c) have been directly sourced from the CGD (2014) and help to provide an overview of the liquefaction and lateral spreading that occurred across greater Christchurch. Although these maps do not provide complete coverage of all areas after each earthquake, they do provide a comparison of the scale and pattern of liquefaction effects experienced across the region as a result of each earthquake.

Table 5.1: Liquefaction and lateral spreading categories used for rapid mapping following September 2010 earthquake

Land Observation Category	Criteria / Description
Blue	• No observed cracks, undulations / deformations at the ground surface, and, • No signs of ejected liquefied material at the ground surface, and, • No apparent lateral movement.
Green	• Shaking-induced damage resulting from cyclic deformation and surface-waves causing ground surface damage. Ground surface damage likely limited to minor cracking (tension) and buckling (contraction) and/or minor undulations at the ground surface, and, • No signs of ejected liquefied material at the ground surface, and, • No apparent lateral movement.
Light Orange	• Minor to moderate quantities of ejected liquefied material on ground surface (generally <25% of site covered with ejected material), and/or, • Small cracks from ground oscillations (<0.05 m) may be present, but little to no vertical displacement across cracks, and, • No apparent lateral movement.
Red	Either • Large quantities of ejected liquefied material on ground surface (generally >25% of the site covered with ejected material), and/or, • Severe observed ground surface subsidence, and/or; • Small cracks from ground oscillations (<0.05 m) may be present, but little to no vertical displacement across cracks, and, • Limited evidence of lateral movement. or • Moderate to major lateral spreading (<1 m cumulative), and/or, • Large cracks extending across the ground surface, with horizontal and/or vertical displacement (>0.05 m, but generally <0.2 m). • Ejection of liquefied material at the ground surface may also be observed
Dark Red	• Extensive lateral spreading (=1 m cumulative), and/or, • Large open cracks extending through the ground surface, with very severe horizontal and/or vertical displacements (=0.2 m), and, • Ejection of liquefied material at the ground surface may also be observed.

Table 5.2: Liquefaction and lateral spreading categories used for rapid mapping following February 2011 and June 2011 earthquakes

Land Observation Category	Criteria / Description
Blue	• No observed cracks, undulations / deformations at the ground surface, and, • No signs of ejected liquefied material at the ground surface, and, • No apparent lateral movement.
Green	• Shaking-induced damage resulting from cyclic deformation and surface-waves causing ground surface damage. Ground surface damage likely limited to minor cracking (tension) and buckling (contraction) and/or minor undulations at the ground surface, and, • No signs of ejected liquefied material at the ground surface, and, • No apparent lateral movement.
Light Orange	• Minor to moderate quantities of ejected liquefied material on ground surface (generally <25% of site covered with ejected material), and/or, • Small cracks from ground oscillations (<0.05 m) may be present, but little to no vertical displacement across cracks, and, • No apparent lateral movement.
Dark Orange	• Large quantities of ejected liquefied material on ground surface (generally >25% of the site covered with ejected material), and/or, • Severe observed ground surface subsidence, and/or; • Small cracks from ground oscillations (<0.05 m) may be present, but little to no vertical displacement across cracks, and, • Limited evidence of lateral movement.
Red	• Moderate to major lateral spreading (<1 m cumulative), and/or, • Large cracks extending across the ground surface, with horizontal and/or vertical displacement (>0.05 m, but generally <0.2 m). • Ejection of liquefied material at the ground surface may also be observed
Dark Red	• Extensive lateral spreading (=1 m cumulative), and/or, • Large open cracks extending through the ground surface, with very severe horizontal and/or vertical displacements (=0.2 m), and, • Ejection of liquefied material at the ground surface may also be observed.

Movement mechanisms reflected in this dataset

For the purposes of identifying areas that may have experienced shallow ground movement, the land damage observation maps are a good tool to help identify areas of lateral spreading and the severity of that horizontal movement. These land damage observation maps should be used in conjunction with the MBIE Guidance areas of lateral movement (Section 5.3.3) and EQC observed ground crack locations (Section 4.3.4) when assessing whether land is likely to have been affected by lateral spreading.

From the land damage categories described earlier, properties observed to be affected by significant lateral spreading were mapped as red and dark red (note that these mapping colours are different to the CERA Residential Red Zone). Properties mapped as red were observed to have experienced moderate to major lateral spreading due to the respective earthquakes. These properties likely experienced up to 1 m of shallow ground movement, with individual ground cracks up to 0.2 m. Properties which were mapped as dark red generally experienced severe shallow ground movement of 1 m or more, with individual ground cracks exceeding 0.2 m. Most properties that experienced severe lateral spreading were later included in the CERA Residential Red Zone.

Properties mapped as green, orange or dark orange may have had observable land cracking. These ground cracks are considered to be predominantly due to liquefaction-induced ground oscillation (refer Section 3.4.2), rather than lateral spreading. However, in some cases there may still be a minor degree of ground extension in these areas due to ground relaxation in response to adjacent lateral spreading land. Properties affected by the ejection of liquefied material were mapped as orange or higher on the severity scale. Although much of the greater Christchurch experienced varying amounts of ejection of liquefied soil, this usually resulted in mostly vertical ground movement (liquefaction-induced settlement) with only a minor degree of horizontal movement (lateral spreading or ground stretching).

Limitations

The mapping was undertaken as a broad scale, rapid visual assessment of the land damage in various residential flat land areas of greater Christchurch. The visual assessments were often undertaken from the street only. These maps should not be used as a definitive assessment of land performance for a property, and should only be used in conjunction with other available information as part of a broader assessment.

As a result of the region experiencing multiple large earthquakes causing extensive land damage to many properties in a short timeframe, the land damage mapping incorporates an element of accumulated land damage. Areas most significantly affected by major lateral spreading in February 2011, were again likely to have experienced further lateral spreading due to the June 2011 earthquake although likely not as severe as previously experienced. As the land damage was usually not repaired between the various earthquakes, interpretation the damage caused by each individual earthquake was difficult and may be skewed towards the most severe level of damage previously experienced at each property.

The full extent of liquefaction in greater Christchurch was not mapped following each of the main earthquakes – mapping was primarily focussed in areas where liquefaction was known to have occurred. The widest mapping coverage was following the February 2011 earthquake. As the mapping was undertaken on behalf of EQC, it is primarily focussed on the main urban residential areas of greater Christchurch, although some commercial areas are also included.

5.3.2 MBIE residential foundation technical categories

Following the September 2010 earthquake it was recognised by the Ministry of Business, Innovation and Employment (MBIE) that general engineering guidance was required to speed up the residential recovery. This requirement increased further following the February 2011 earthquake, as the scale and extent of damage vastly increased.

As part of the MBIE engineering guidance (MBIE, 2012) the urban residential land across greater Christchurch was categorised to reflect the varying need for geotechnical investigations and specific engineering input into foundation design. These categories were primarily based on the liquefaction and lateral spreading observations collected following the September 2010 and February 2011 earthquakes (Section 5.3.1). Three MBIE residential foundation categories were identified; Technical Category 1 (TC 1), Technical Category 2 (TC 2), and Technical Category 3 (TC 3).

The MBIE Technical Categories map contained within this report (Appendix A, Map 5) was directly sourced from the CGD.

Movement mechanisms reflected in this dataset

The MBIE Technical Categories is a good initial screening tool to help understand the types and extent of land deformations that may have occurred in an area:

- **TC 1:** For almost all TC1 properties there was no observed liquefaction or lateral spreading in the CES. These properties are unlikely to have been affected by significant shallow land movements as a result of the CES, but may still have experienced some degree of deep-seated movement.
- **TC 2:** For many properties in TC2 there was a minor to moderate severity of liquefaction observed in the CES. For the remaining properties, while there was no evidence of liquefaction observed at the ground surface, it is possible that liquefaction may have occurred at depth without any obvious evidence being observed. Liquefaction-induced ground oscillation is the most likely form of shallow horizontal ground movement to have occurred in TC2 areas.
- **TC 3:** For most properties in TC3 there was a minor to major severity of liquefaction or lateral spreading observed in the CES. Much of the land in TC3 may have experienced some degree of liquefaction-induced ground oscillation, lateral spreading, or area-wide ground stretching.
- **CERA Residential Red Zone:** The CERA Residential Red zone encompasses the areas of most severe land damage caused by the CES. Most land within the residential Red zone has experienced large shallow horizontal ground movements.

Limitations

The MBIE Residential Foundation Technical Categories were defined on an area-wide basis, including other technical considerations in addition to the observed land performance. They provide a starting point for the engineering assessment process, rather than an absolute description of the land performance during the CES. There can be significant variability in the performance of land within an area – some properties might have experienced less ground deformation than implied by the technical category, while others might have experienced more.

5.3.3 MBIE guidance areas of lateral ground movement

As part of the MBIE guidance (MBIE, 2012), advice was provided to engineers to assist in the assessment of whether a site was likely to have experienced a major degree of lateral ground movement or ground stretching in the CES.

Section 12.2 of the MBIE guidance provides a preliminary assessment tool for two different horizontal movement mechanisms:

- **Lateral spreading adjacent to rivers**: The guidance defines setback distances from the main rivers and waterways across greater Christchurch. A larger offset is adopted for the lower reaches of the Avon and Heathcote Rivers as a result of the scale of lateral spreading observed due to the CES, as discussed in Section 3.4.1.
- **Area-wide ground stretching**: The guidance defines two geographical areas within New Brighton and Wainoni, where evidence of area-wide ground stretching was observed due to the CES.

The areas identified in Section 12.2 of the MBIE guidance were defined primarily using the liquefaction and lateral spreading observations (Section 5.3.1) and ground crack mapping (Section 5.3.4).

For properties beyond these defined areas, the guidance indicates that only "Minor to Moderate" lateral spreading is likely to have occurred during the CES, unless there is evidence to the contrary. "Minor to Moderate" is defined in the guidance as global lateral movement less than 300mm, and lateral stretch of the ground across a building footprint of less than 200mm.

The MBIE guidance does not suggest that all properties within the defined area have experienced major lateral spreading or ground stretching – indeed some will have experienced none at all. The guidance simply requires that engineers designing new foundations within this area undertake a more detailed assessment to consider the potential for lateral ground movements in future.

The map of these areas contained within this report (Appendix A, Map 6) was produced by T&T and draws directly from the MBIE guidance.

Movement mechanisms reflected in this dataset

The light purple shading on the map indicates areas that may have experienced more significant lateral spreading towards the main rivers and smaller waterways (refer to Section 3.4.1).

The dark purple shading on the map indicates areas that may have experienced area-wide ground stretching (refer to Section 3.4.3). There is one area identified in New Brighton and one in Wainoni, however it is possible that this mechanism has occurred elsewhere but has not yet been identified.

Limitations

This map is based on broad scale observations gathered during the rapid reconnaissance mapping phase (Section 5.3.1) and a generalised application has been adopted. This is a generally conservative screening approach and many properties outlined in the purple area might not have been subjected to lateral spreading as a result of the CES. However, some properties that lie outside this identified area may have experienced some degree of lateral spreading.

The areas outlined in the MBIE guidance should only be used as an indicative guide to areas potentially affected by lateral ground movement, and assessed in conjunction with other information sources.

This map only covers the main waterways – there are other smaller waterways and steep changes in ground level not identified on this map which should also be considered when assessing the potential for lateral ground movements to occur.

5.3.4 EQC observed ground crack locations – flat-land

Following the September 2010 and February 2011 earthquakes, property-by-property land inspections were undertaken by geotechnical professionals on behalf of EQC. The location and width of each ground crack was recorded on aerial photographs. The aerials were later scanned and manually digitised to record their coordinates and offsets.

Following the September 2010 earthquake, the principle objective of the ground crack mapping was insurance claim settlements for each individual property. An area-wide assessment was not carried out. The extent of the mapping was limited to the areas of most significant known land damage, and not all properties affected by ground cracking were mapped prior to the February 2011 earthquake.

Following the February 2011 earthquake, the information collection process altered slightly. An initial stage of area-wide rapid mapping focusing on identifying the extent of lateral spreading cracks was undertaken over the two week period following the earthquake. This mapping was at a scale of 1:5000 to 1:10000, and individual crack widths were not recorded during this process. Following this initial mapping, additional crack mapping was undertaken for all areas of known land damage as part of the EQC property-by-property land inspections.

The map contained within this report (Appendix A, Map 7) has been directly sourced from the CGD and helps to provide an overview of the ground cracking across the urban residential parts of greater Christchurch most affected by liquefaction during the CES.

Movement mechanisms reflected in this dataset

The crack mapping identifies areas affected by ground extension due to lateral spreading and to some extent, ground oscillation. Ground cracks associated with lateral spreading generally indicated a consistent movement direction, usually towards a river channel or other identified free-face. Ground cracks due to liquefaction-induced ground oscillation were interpreted as cracks less than 0.05 m without a consistent direction of movement. Often the oscillation cracking and bulging were expressed in hard surfaces such as driveways and paths ways as discussed in Section 3.4.2.

Limitations

The observed ground crack mapping is a very useful tool in identifying areas affected by horizontal ground movements, but there are some limitations to this data that should be recognised.

Due to the changing main objectives and the process in collecting the data, there are some inconsistencies within the dataset. Following the September 2010 earthquake, the main objective was for individual property assessment. Many lateral spreading cracks were not traced or assessed beyond the individual property boundary, and non-residential land (e.g. parks and roads) was not mapped. In the mapping in the immediate weeks following the February 2011 earthquake, lateral spreading cracks were traced through multiple properties, however the width of these cracks was not recorded. It was not until March 2011 when an area-wide approach was fully adopted that the location, scale and extent of the lateral spreading cracks was recorded. By this time some of the cracks had been repaired, limiting the available information.

Furthermore, mapping of ground cracks that resulted from the 4 September 2010 earthquake was incomplete when 22 February 2011 earthquake struck. The crack mapping remains incomplete. The focus of EQC's assessment has been in the CERA Residential Green Zone, so comprehensive crack mapping has not been completed in many parts of the Residential Red zone (although several areas have been studied in detail by researchers).

As a result of the above factors, it must be recognised that this dataset is not absolute. While it records much of the most significant ground cracking across the region, it does not record all the ground cracking that occurred. The absence of mapped cracks on a property does not provide conclusive evidence that horizontal ground movement has not occurred.

5.3.5 Rivers and catchments

The Rivers and Catchments map (included as part of Map 6 in Appendix A) identifies present-day rivers, streams, drainage culverts and feeders.

The rivers and catchments map draws on information held by the Christchurch City Council (CCC). This map helps to provide an overview of the extent of watercourses across Christchurch.

Movement mechanisms reflected in this dataset

This map helps to identify the present day rivers/streams which provide free-faces for horizontal movement to occur as a result of lateral spreading (Section 3.4.1).

Limitations

It is likely that many of the properties surrounding the rivers/streams identified in this map will not have experienced any shallow ground movement due to the CES. This map should be used in conjunction with the observed land damage, MBIE lateral ground movement, and EQC observed ground crack locations (Appendix A – Maps 4a, 4b, 4c, 6, 7) to better identify the areas affected by shallow ground movement during the CES.

This map only illustrates the present day location and presence of rivers/streams. Relic river channels are not shown, and these geological settings may be prone to liquefaction and shallow ground movement resulting from liquefaction-induced ground oscillation and lateral spreading.

The map also identifies man-made drainage channels and culverts that may have been constructed with stiffer materials and appropriately compacted. Retaining structures may be present and these have not been identified within this map, which again will minimise the likelihood of shallow ground movement having occurred in these areas.

5.3.6 Horizontal movement vectors inferred from LiDAR

Horizontal ground surface movements during the CES were estimated using a sub-pixel correlation method developed by Imagin' Labs Corp. and the California Institute of Technology to compare the LiDAR point cloud acquired in July 2003 with those acquired in September 2011 and February 2012.

North-south and east-west horizontal movements were calculated on a 4m grid for both pairs of point clouds. These were averaged to accommodate the noise in each pair of LiDAR sets and supplied as movements within a 56m grid. The grid points were omitted for significant waterways, coastal marine areas and most other non-residential land where the movements were poorly correlated and produced less accurate horizontal movement estimates.

The GNS dislocation models (Beavan, 2012) provide estimates of the horizontal deep-seated ground movements during each of the four main earthquakes. These movements were summed for consecutive earthquakes and used to estimate the shallow ground movements by subtracting them from the total calculated ground surface movements.

The horizontal vectors maps contained within this report (Appendix A, Map 8a, 8b, 8c) were directly sourced from the CGD and helps to provide an overview of the shallow ground movement directions across Christchurch caused by the four main earthquakes of the CES.

Movement mechanisms reflected in this dataset

The horizontal movement vectors are useful to identify, in principle, the patterns of surface ground movements due to the CES. Although the direction and extent of the movements are not a reliable dataset in isolation, they are a useful tool for further analysis in conjunction with the digital elevation model and lateral spreading observations.

Limitations

These horizontal movement vectors only provide an approximation of the true ground surface movements. The equipment used to acquire the LiDAR has lower horizontal accuracy (±0.4m) than vertical, and the reports accompanying the supplied movements note that vertical elevation artefacts (termed ‘jitter’) in the point cloud data (particularly for the July 2003 survey) artificially increased the estimated movements.

Comparison of the horizontal movements inferred from the LiDAR with the measured movement of survey marks suggests that the LiDAR analysis is unable to reliably resolve ground movements less than about 0.3 to 0.4 m. In some locations the inferred movements appear to be influenced by localised changes such as new or demolished buildings, vegetation and earthworks for subdivisions.

As explained in Section 5.1.3, the flight paths taken for each LiDAR survey generate an amount of ‘noise’ in the surveys that present as linear stripe features in the LiDAR output. This translates into the data and the understanding of this noise is crucial when using the data to interpret changes in elevation.

As a result of these limitations, this dataset is generally only useful in areas where large horizontal ground movements have occurred (more than about 0.4 m), or for interpolation of ground movements between widely-spaced survey marks. In these situations this data can provide a useful indication of the pattern and extent of ground movement.

It should be noted that the comparison with LINZ mark movements is not entirely comparing like with like. The inferred horizontal movements present an averaged movement over a large area, which is less likely to be influenced by the localized ground movements from surface shaking that can influence individual marks. If the marks were undisturbed by shaking, the movements inferred from the LiDAR may be able to be adapted to interpolate between marks. However, high resolution aerial photography may provide this more conveniently.

In areas where only small horizontal ground movements have occurred, the pattern and extent of ground movement inferred from the LiDAR survey does not appear to correlate with surface observations of ground deformations. In these situations this data can provide a misleading picture, suggesting that significant ground movements have occurred. It is therefore essential that this dataset is used in conjunction with other sources of information to understand the behaviour of the land, and this dataset should be discounted when it conflicts with more reliable information.

5.4 Additional information available on the CGD

There is some additional information that is available on the CGD that has not been incorporated within this report, because of its more specialist geotechnical nature. Additional information includes geological maps, historic maps, geotechnical data, and analysis of the subsoil conditions.

The geological maps of Christchurch (Brown, 1992) help to identify at a broad scale the location and extent of the various soil deposits across Christchurch.

The historical “Black Maps” of Christchurch are another source of information that provides an indication of the geology and ecology of the land prior to the development of Christchurch city.

There have been extensive geotechnical investigations carried out across Canterbury that have informed detailed analysis of the subsurface soils. Analysis of the soil properties further aids in developing a higher level of understanding of the soils in Canterbury and their seismic performance.

In some cases, where the ground movements are complex or the data is inconclusive, there may be a need for surveyors and geotechnical engineers to work together and explore all available information, to better understand the implications for cadastral survey.

6 Estimated numbers of properties

Table 6.1 below provides an estimate of the number of residential properties affected by the various forms of ground movement that have been observed. This information is intended to help convey the relative extent of the different mechanisms and severity of ground movement.

Table 6.1: Estimated number of residential properties

Dataset	Estimated number of residential properties included in each category
Large scale landslides – GNS mass movement areas:	
• Class I	190
• Class II	645
• Class III	305
GNS mapped ground cracking in the Port Hills	1104
Observed liquefaction and lateral spreading caused by the February 2011 earthquake:	
• Blue – No observed ground cracking or ejected liquefied material	48,657
• Green – Minor ground cracking but no observed ejected liquefied material	3,177
• Orange – No lateral spreading but minor to moderate quantities of ejected material	38,909
• Dark orange – Limited evidence of lateral movement but large quantities of ejected material	4,267
• Red – Moderate to major lateral spreading; ejected material often observed	5,549
• Dark red – Severe lateral spreading; ejected material often observed.	736
MBIE Technical Categories and CERA Residential Red zone:	
• TC 1	23,278
• TC 2	81,404
• TC 3	28,218
• Residential Red zone	7,859
MBIE guidance areas of lateral ground movement:	
• Within potential lateral spreading setback distance	16,318
• Area-wide ground stretching	3,242
EQC mapped ground cracking on the flat-land:	
• Only cracks less than 50 mm wide on property	2,819
• Only cracks 50 mm wide or greater on property	3,621

7 References

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8 Glossary

Term	Engineering Description
Area wide ground stretching	A mechanism of shallow ground movement, driven by an area of higher ground elevation or sloping ground. Refer to Section 3.4.3.
CES	2010/2011 Canterbury Earthquake Sequence (CES). This sequence of earthquakes includes the main earthquakes of: Darfield 4 September 2010, Christchurch earthquakes 22 February 2011, 13 June 2011 and 23 December 2011.
Contraction	Differential shortening of the ground surface, often visibly depicted by buckling of ground or hard surfaces. Refer to Section 3.1.1.
Deep-seated ground movement	Deformations occurring deep underground (typically from tens to hundreds of metres depth) that result in movement of the ground surface. Primarily due to movement of the bedrock due to fault rupture. Refer to Sections 3.1.2 and 3.2.
Extension	Differential elongation of the ground surface, often visibly depicted by tension cracking of the ground. Refer to Section 3.1.1.
Free-face	A location where the ground is not horizontally restrained, e.g. a riverbank or terrace edge. Often associated with lateral spreading mechanisms. Refer to Section 3.4.1.
Neighbourhood - wide scale	Term used to illustrate the level of accuracy of the data described within this report. Due to the highly variable soils in Canterbury, the available information is best assessed at a suburb-wide scale, rather than at individual-property scale.
Lateral spreading	Horizontal ground movement towards a free face, caused by liquefaction of the underlying ground. This can result in cracking and subsidence of the ground. Refer to Section 3.4.1.
Liquefaction	A process where loose soils below the groundwater level substantially lose strength and stiffness in response to earthquake shaking, causing the soil to behave like a pressurised liquid. In some cases this soil/water mixture is ejected to the ground surface.
Loess	A fine windblown silt, which forms a thin surface soil covering the volcanic rock over much of the Port Hills. Refer to Section 3.3.
Mass movement area	A form of large-scale landsliding observed on the Port Hills in the CES, which can include cliff collapse, toe slumping, ridge and crest slope failure. Refer to Section 3.3.2.
Shallow ground movement	Ground surface movement related to the topography of the land and the seismic response of near-surface soils (from the ground surface down to a depth of about 10 to 20 metres). Refer to Sections 3.1.2, 3.3 and 3.4.
Liquefaction-induced ground oscillation	In areas where liquefaction occurs away from a free-face, large permanent horizontal movements are unable to occur. However, due to the underlying liquefied material, the ground surface is able to move backwards and forwards (oscillate) during earthquake shaking. This may cause ground cracking at the surface. Refer to Section 3.4.2.
Strain	A dimensionless value, defined as the change in the distance between two points divided by the initial distance between those points. Strain can be used as a measure of the degree of extension or contraction of the ground surface. Refer to Section 3.1.1.
Tension crack	An open crack in the ground, often due to ground extension. Refer to Section 3.1.1.
Toe slumping	A form of large-scale landslide identified as one of the mass movement mechanisms observed on the Port Hills in the CES. Refer to Section 3.3.2.
Topography	The physical shape of the ground surface. While the Canterbury plains might be considered generally flat, there can be significant but subtle undulations in ground elevation, which can influence some kinds of ground movements. Refer to Section 3.4.3.

9 Applicability

This report has been prepared for the benefit of Land Information New Zealand (LINZ) with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose without our prior review and agreement.

Canterbury Geotechnical Database: Important notice

The maps presented in this report are created from maps and/or data extracted from the Canterbury Geotechnical Database (https://canterburygeotechnicaldatabase.projectorbit.com), which were prepared and/or compiled for the Earthquake Commission (EQC) to assist in assessing insurance claims made under the Earthquake Commission Act 1993 and/or for the Canterbury Geotechnical Database on behalf of the Canterbury Recovery Authority (CERA). The source maps and data were not intended for any other purpose. EQC, CERA, their data suppliers and their engineers, Tonkin & Taylor, have no liability for any use of the maps and data or for the consequences of any person relying on them in any way. This "Important notice" must be reproduced wherever these maps or any derivatives are reproduced.

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