Case History

2010 Darfield (New Zealand) Earthquake: Impacts of liquefaction and lateral spreading

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Introduction

On 4 September 2010, a magnitude M_w 7.1 earthquake struck the Canterbury region on the South Island of New Zealand. The epicentre of the earthquake was located in the Darfield area about 40 km west of the city of Christchurch. Extensive damage was inflicted to lifelines and residential houses due to widespread liquefaction and lateral spreading in areas close to major streams, rivers and wetlands throughout the city of Christchurch and the town of Kaiapoi. Unreinforced masonry buildings also suffered extensive damage throughout the region. Despite the severe damage to infrastructure and residential houses, fortunately, no deaths occurred and only two serious injuries were reported in this earthquake. From an engineering viewpoint, one may argue that the most significant aspects of the 2010 Darfield Earthquake were geotechnical in nature, with liquefaction and lateral spreading being the principal culprits for the inflicted damage. Following the earthquake, an intensive geotechnical reconnaissance was conducted to capture evidence and perishable data from this event. The team included the following members: Misko Cubrinovski (University of Canterbury, NZ, Team Leader), Russell Green (Virginia Tech, USA, GEER Team Leader), Mitsu Okamura (Ehime University, Japan, JGS Team Leader), John Allen (TRI Environmental, Inc, TX, USA), Scott Ashford (Oregon State University, USA), Elisabeth Bowman (University of Canterbury, NZ), Brendon Bradley (University of Canterbury, NZ), Brady Cox (University of Arkansas, USA), Tara Hutchinson (University of California, San Diego, USA), Edward Kavazanjian (Arizona State University, USA), Takashi Kiyota (IIS, University of Tokyo, Japan), Rolando Orense (University of Auckland, NZ), Michael Pender (University of Auckland, NZ), Hirofumi Toyota (Nagaoka University of Technology, Japan) and Liam Wotherspoon (University of Auckland, NZ). This article summarizes some observations and preliminary findings from this early reconnaissance work.

The 2010 Darfield (Canterbury) Earthquake

The earthquake occurred at 4.35 am local time, on 4 September 2010. It was caused by a rupture of a previously unrecognized strike-slip fault, now well-known as the Greendale fault. The earthquake resulted in a surface rupture approximately 29 km long in the east-west direction (Figure 1). The length of the fault rupture at depth is estimated to be on the order of about 40 km. Aerial photos of the surface rupture expression taken from a helicopter flyover on 10 September is shown in Figure 2. It is interesting to note that the faulting resulted in a narrow rupture zone at the surface despite hundreds of metres of thick gravel deposits at the ground surface.

Figure 1. Aerial image of Christchurch area indicating the surface fault rupture and the epicentre of the Darfield earthquake. The city of Christchurch is located east of the Greendale Fault, while the town of Kaiapoi is north of Christchurch. (Image courtesy of Mark Quigley; Google Inc. 2010)

Figure 2. Surface fault rupture on farm land. The right lateral offset was approximately 4 m at the tree line (top of the photo)

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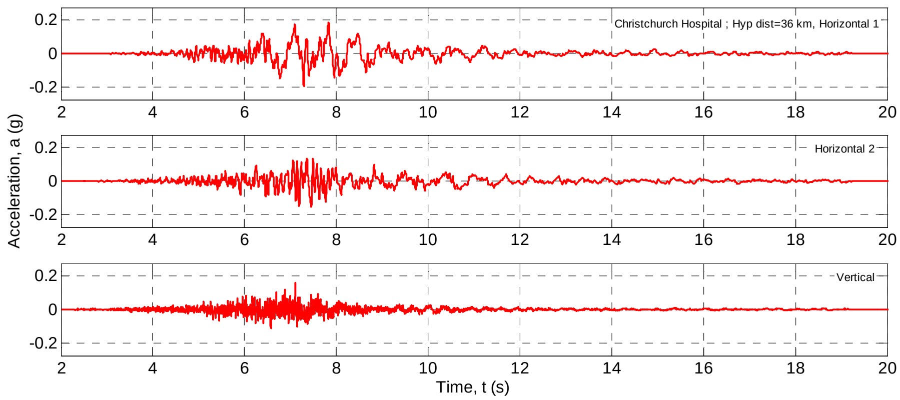

Figure 3. Acceleration records of the 2010 Darfield Earthquake at the Christchurch Hospital

The ground motion produced by the main shock of the Darfield earthquake was recorded at nearly 40 strong motion stations within the epicentral region. In the city of Christchurch and the town of Kaiapoi, peak horizontal ground accelerations on the order of 0.15-0.35 g were recorded indicating moderate-to-strong ground shaking in the urban areas. Acceleration time histories recorded at the Christchurch Hospital are shown in Figure 3. The response spectra of the recorded ground motions showed high spectral accelerations at 2-3 seconds vibration periods reflecting the effects of deep gravelly deposits that underlie the shallow surface soils in the Canterbury plains.

Regional geomorphology

The city of Christchurch has a population of about 350,000 (the second largest city in New Zealand) and an urban area that covers approximately 450 km^2. It is sparsely developed with approximately 150,000 dwellings (predominantly single-storey houses with a smaller number of two-storey houses) spread across a large area with many parks, natural reserves and recreation grounds. The Central Business District (CBD) is more densely developed with multi-storey buildings and a relatively large number of historic buildings. The epicentre of the 2010 Darfield Earthquake was located approximately 40 km west of the Christchurch CBD (Figure 1).

Christchurch is located on Holocene deposits of the Canterbury Plains, except for its southern edge, which is located on the slopes of the Port Hills of Banks Peninsula. The river floodplain and the loess sediments of the Port Hills are the dominant geomorphic features of the Christchurch urban area.

The Canterbury Plains are complex fans deposited by eastward-flowing rivers from the Southern Alps to the Pegasus Bay coast. The fan surfaces cover an area 50-km wide by 160-km long. At Christchurch, surface postglacial sediments have a thickness between 15 and 40 m and overlie 300-400 m thick inter-layered gravelly formations (Brown and Webber, 1992). The surface sediments are either fluvial gravels, sands and silts (Springston formation, with a maximum thickness of 20 m to the west of Christchurch) or estuarine, lagoon, beach, and coastal swamp deposits of sand, silt, clay and peat (Christchurch formation, with a maximum thickness of 40 m at New Brighton coast, east of CBD). The soil deposits at relatively shallow depths of up to 15-20 m vary significantly within short distances, both horizontally and vertically.

As described by Brown and Webber (1992), the original site of Christchurch was *"mainly swamp lying behind beach dune sand, estuaries and lagoons, and gravel, sand and silt of river channel and flood deposits of the coastal Waimakariri River flood plain. Since European settlement in the 1850s, extensive drainage and infilling of swamps has been undertaken."*

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Canterbury has an abundant water supply through open-channels (rivers, streams) and very rich aquifers. The dominant features of present day Christchurch are the Avon and Heathcote rivers that originate from springs in western Christchurch, meander through the city, and feed the estuary at the southeast end of the city. The ground water table is deepest at the west end of the city (at about 5 m depth), gradually increases towards east, and approaches the ground surface near the coastline. The water table is within 1.0-1.5 m of the ground surface for most of the city east of the CBD.

Effects of liquefaction

The earthquake caused widespread liquefaction in the suburbs of Christchurch along the Avon River, particularly to the east and north-east of the CBD. Widespread liquefaction also occurred in Halswell, at the southwest end of the city. Pockets of limited or partial liquefaction were observed in other parts of Christchurch, though these were much fewer to the west of CBD. Figure 4 shows areas of observed liquefaction in the urban area of Christchurch based on surface manifestation of liquefaction visible in aerial photographs and initial observations from ground surveying.

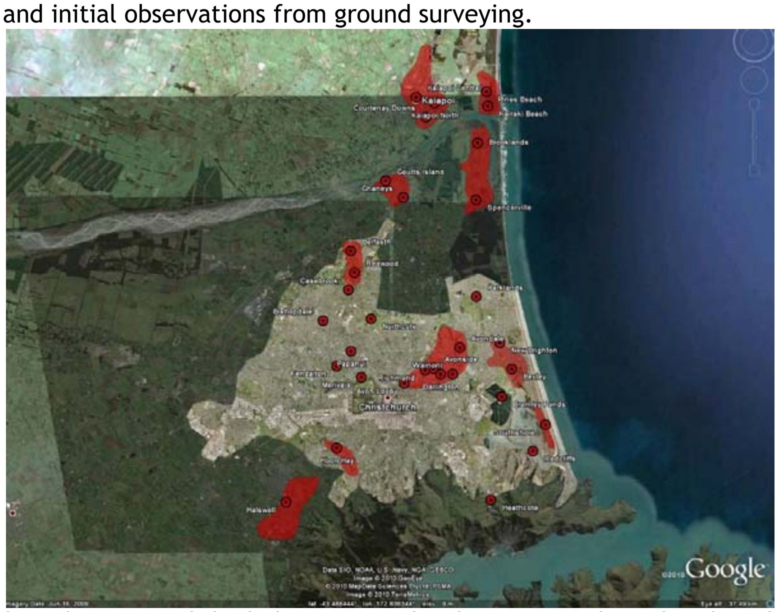

Figure 4. Areas of liquefaction (red shaded regions and red points) in Christchurch and Kaiapoi caused by the 2010 Darfield Earthquake

The areas most severely affected by liquefaction and lateral spreading were close to waterways (rivers, streams, swamps). Figure 5 shows an aerial photo of the Porritt Park, in Wainoni, Christchurch, taken from a helicopter flyover on 10 September. The park is enclosed by the Avon River and a diverted stream around its perimeter. Large sand boils with significant volume of sand ejecta covered substantial areas of the park. Parallel cracks spaced regularly along drainage lines were indicative of slumping and spreading towards the north and south branches of the stream. A couple of hockey fields located in the park were severely damaged by the liquefaction, resulting in a very uneven, bumpy surface of the fields.

Typical manifestation of liquefaction in the backyard of a residential property is shown in Figure 6. Sand boil ejecta covered most of the lawn and was about 20 cm thick in places. There was evidence of massive liquefaction and large surface distortion in the neighbouring streets. The potable water and sewer systems were out of service at the time of the inspections. Despite significant amounts of liquefaction ejecta and broken utilities throughout the neighbourhood, the house shown in the pictures suffered relatively minor damage in terms of differential settlement and cracking.

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In the Darfield earthquake, widespread liquefaction occurred north of the Kaiapoi River affecting a large number of residential houses in the town of Kaiapoi (population ~10,000; area ~5 km^2). The houses in this area are typically single or two-storey brick/stone block masonry or timber structures on spread footings. Kaiapoi is situated about 17 km north of Christchurch, near the north-eastern end of the Canterbury Plains (Figure 1). At Kaiapoi, recent Holocene sediments, approximately 100 m thick, overlie 300-400 m of late Pleistocene sands and gravels, which in turn rest on rock and a greywacke basement rock. Present day Kaiapoi is divided into North Kaiapoi and South Kaiapoi by the Kaiapoi River. The Waimakariri River and its abandoned channels significantly influenced liquefaction susceptibility of Kaiapoi. Several old meander loops of pre-1868 Waimakariri River have deposited loose silty sands both north and south of the present Kaiapoi River. In this area, the ground water table is generally shallow within 1-2 m of the ground surface.

Figure 5. Evidence of extensive liquefaction (large sand boils) in Porritt Park, Christchurch. Using the vehicles (bottom of photo) or the hockey field (top of photo) for scale gives a good indication of the significant volume of sand ejecta.

Figure 6. Evidence of extensive liquefaction (large sand boils) in residential areas of Avonside. Notice the chair embedded in 20 cm thick sand ejecta in the backyard of the property.

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In the worst hit area, the silty sand ejecta was about 400 mm thick (Figure 7). Some residents reported geysers appearing in the backyard following the earthquake, often forming a small pond near the house that remained for several days after the event. The severe liquefaction often led to large settlement of houses, including differential settlement that resulted in structural and foundation damage. The large ground distortion, cracks and fissures in the ground also caused significant damage to buried lifelines. This area of Kaiapoi also liquefied during the 1901 Cheviot earthquake (Berrill et al., 1994).

(a) ~40 cm thick layer of silt-sand-water mixture covering a residential property affected by very severe liquefaction; (b) same-angle view, but after the clean up of sand ejecta

(c) View from the street (before clean up); (d) liquefied silt-sand-water mixture covering a rug inside the house and the ground outside the house (seen through a window from inside the house)

Figure 7. Manifestation of very severe liquefaction in residential area of North Kaiapoi

Impacts of lateral spreading

In the areas close to waterways, the liquefaction was accompanied by a lateral spreading which resulted in permanent lateral ground displacements from several tens of centimetres to several metres. The spreading progressed inland as far as 200-300 m from the waterway, often significantly affecting residential properties and houses. Typical manifestation of lateral spreading and its impacts on houses is shown in Figure 8.

Residential houses in this area were severely affected both by liquefaction and lateral spreading. A large number of houses settled, tilted and suffered structural/foundation damage. Large size sand ejecta, spread across the area between the stopbank (levee) and street, are seen in Figure 8. The huge piles of cleaned up sand indicated as position S clearly illustrate the massive liquefaction that occurred in the area. The liquefaction was accompanied by a significant lateral spreading towards the Kaiapoi River that affected a number of houses along the street.

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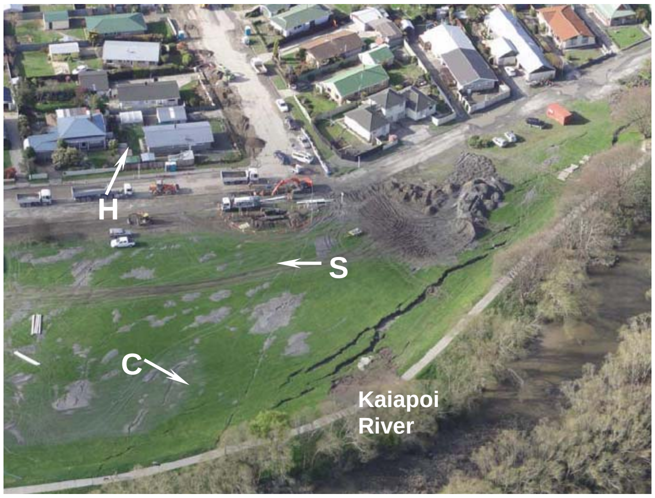

(a) Aerial view of North Kaiapoi (from a helicopter flyover on 10 September)

(b) Lateral spreading crack running through a residential property; (c) Lateral spread and slumping of the north stopbank of the Kaiapoi River; note the huge piles of cleaned up sand obstructing the view of the houses

Figure 8. Liquefaction and lateral spreading in North Kaiapoi

In South Kaiapoi, the most dominant ground failure feature was the liquefaction and massive lateral spreading that affected the eastern branch of Courtenay Drive. The area affected by lateral spreading, shown in Figure 9, was approximately 1-km long in the north-south direction and extended between 200 m and 300 m inland from the Courtenay Stream and Courtenay Lake. The lake was artificially created during the construction of the northern end of Courtenay Dr. Borrow material was removed from the area where the lake is presently located and used as hydraulic fill (about 1 m thick) for the northern branch of Courtenay Dr.

The area where massive lateral spreading occurred coincides with the old Waimakariri River channel from 1865. On the eastern side of South Kaiapoi, the old channel passes underneath the present day Courtenay Dr area shown as position 1 in Figure 9, where severe damage to residential properties occurred due to lateral spreading.

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Lateral spreading resulted in large permanent lateral displacements on the order of 1.0-3.5 m with large ground cracks of about 0.5-1.5 m wide running through residential properties/houses. In this area, single storey and two storey houses suffered very severe damage due to large lateral ground movements including substantial tilt, loss of foundation support, tension cracks in foundations and slabs (Figure 10). It was significant that despite the extreme lateral movement of the immediate foundation soils and the foundations themselves, all houses showed large ductile deformation capacity and continued to carry gravity loads, despite literally being ripped in half in some cases. Detailed inspections revealed that in some parts of the affected area the lateral movement continued to increase well after the main event (Figure 11). Two consecutive measurements of the width of a large ground crack carried out on 11 and 15 September showed an increase in the width of 20 cm over this period (from 1.4 m to 1.6 m). The neighbouring residents also reported new cracks appearing in their house over the same time period. It is believed that this continued deformation was the result of a combination of creep due to static shear stresses, significantly softened soils and effects of aftershocks on a structure marginally stable under gravity loads.

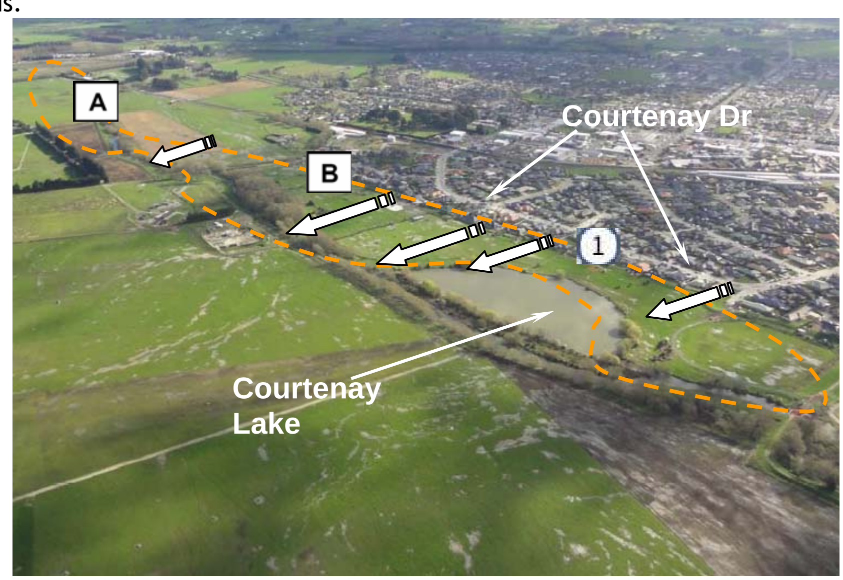

Figure 9. Massive lateral spreading at South Kaiapoi; sand ejecta and area affected by lateral spreading around Courtenay Lake

Figure 10. Severe damage to residential houses/properties due to lateral spreading in South Kaiapoi; (a) Lateral spreading crack running through residential property; (b) Severe damage to timber dwelling on slab foundation affected by lateral spreading displacements of about 1.5 m across the footprint of the house. In areas severely affected by lateral spreading, damage to spread footings and foundation slabs was common, and often significant.

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Figure 11. Severe damage to residential houses/properties due to lateral spreading in South Kaiapoi; (a) Excessive tilt and uplift of foundations due to lateral spreading; (b) The width of this crack increased from 1.4m to 1.6m in the period between 11 and 15 September (7-11 days after the mainshock).

Characteristics of liquefied soils

The ejecta from sand boils in areas affected by liquefaction were generally very similar and had several distinctive features. They were non-plastic fine sands and silty sands with an easily recognizable grey/blue colour.

Grain-size distribution curves of ejecta samples taken from areas of Christchurch and Kaiapoi (courtesy of Prof. Michael Pender; Cubrinovski et al., 2010a;) and previous detailed laboratory studies on the Christchurch soils (Cubrinovski et al., 2010b) clearly put these soils in the group of soils highly-susceptible to liquefaction. This feature together with the high saturation, very intense groundwater regime, relatively recent and loose state of deposition contributed to the extensive liquefaction and lateral spreading during the 2010 Darfield earthquake.

After the earthquake, Swedish Weight Sounding (SWS) tests were performed at numerous locations affected by liquefaction and lateral spreading. So far, about 150 SWS tests have been conducted in the areas of Christchurch and Kaiapoi. SWS is a simple manually operated penetration test under a dead-load of 100 kg in which the number of half-rotations required for a 25 cm penetration of a rod (screw point) is recorded (JIS, 1995). One of the advantages of the SWS test which was heavily utilized in this investigation is the ability to perform the test within a confined space in backyards of residential properties. Typical results of SWS tests conducted at two locations in Dallington and Avonside, expressed in terms of the number of half-rotations per metre, N_{SW}, are shown in Figure 12.

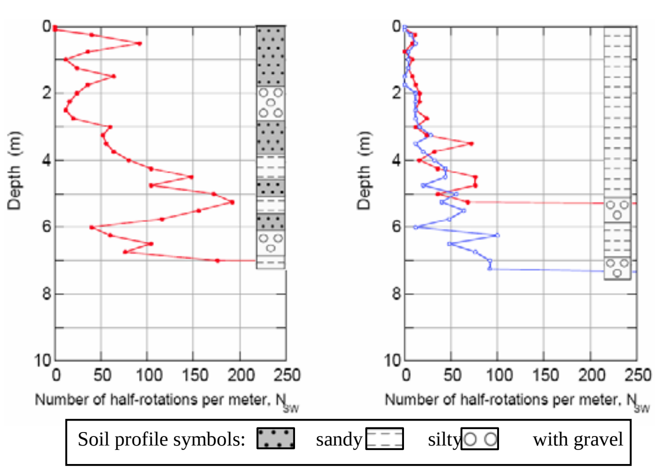

Figure 12. Post-event penetration resistance in Dallington and Avonside measured in SWS tests

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Re-liquefaction caused by a M_W 5.0 aftershock

On 19 October 2010, a M_W 5.0 aftershock struck the region, with an epicentre about 10 km southwest of the CBD. The aftershock caused re-liquefaction in the area of Hoon Hay, a suburb located at an epicentral distance of about 8 km. Figure 13 shows large amount of sand ejecta on a residential property and in a park due to the re-liquefaction during this aftershock. Many residents in the area reported that houses suffered additional damage during the aftershock including widening of the cracks in walls and foundations due to lateral movement of foundation soils. This area of Hoon Hay heavily liquefied during the mainshock of the Darfield earthquake.

Figure 13. Sand ejecta at the perimeter of house foundations and in a park in Hoon Hay due to re-liquefaction during a M_W 5 aftershock; the aftershock occurred 45 days after the mainshock.

Summary remarks

The magnitude M_W 7.1 Darfield earthquake caused widespread liquefaction and lateral spreading in areas close to rivers and wetlands throughout Christchurch and Kaiapoi. Relatively loose sandy soils with 0-30 % non-plastic silts heavily liquefied causing damage to residential houses and lifeline systems. Particularly severe damage was inflicted to houses affected by lateral spreading. Significant volume of sand ejecta, ground distortion, settlement, slumping and large lateral ground movement were evident in the areas affected by liquefaction and lateral spreading. In the liquefied areas, a large number of residential houses suffered global and differential settlements, and some structural/foundation damage. In areas severely affected by lateral spreading, large ground cracks about 0.5-1.5m wide run through residential properties/houses causing very severe structural and foundation damage, and nearly collapse in some cases. Preliminary estimates indicate an economic loss associated with the earthquake of about 5 billion NZ dollars. At least half of this cost is directly related to ground damage and its impacts on residential areas and lifeline systems. Despite the severe damage to infrastructure and residential houses, fortunately, no deaths occurred and only two serious injuries were reported in this earthquake. The city of Christchurch is now embarking on a large reconstruction project in which ground remediation, foundation engineering and restoration of lifelines will be the principal activities in rebuilding the city.

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APPENDIX

Witness Report of a Geotechnical Engineer

Lis Bowman

Friday 3rd September 2010 marked the end of the third term for the university year and Saturday would be the beginning of the mid semester break. A number of colleagues, Misko Cubrinovski included, had set out in the preceding days for an international earthquake conference to be held in Macedonia. That evening, in my house in Dallington, situated to the eastern side of the city and near the River Avon, I prepared a list of things I would need to deal with over the two week break, before heading to bed and a dreamless sleep. However, as one man once put it: "life is what happens to you while you're busy making other plans"…

I was fortunate or unfortunate enough to be awoken at 4.25am by the 4th September 2010 7.1 magnitude earthquake, as an insistent rocking of the bed ("What the....?"), followed by a series of violent jolts ("Oh!"). The thought of leaping up to stand in a doorway crossed my mind; however, I discovered it was all I could do to simply hold on (noting hopefully as I did, that any potential roof beams would fall to the left or right of where I lay, should it come to that). The noise from the earthquake was deafening and seemed to be made up of the sounds of falling furniture, smashing glass and something more low pitched. After a jerky crescendo, the rocking died away to a gentle sway and finally subsided. I tried the light switch (dead, as expected really), then checked the clock (4.30am: light in 2 hours). By the moonlight, the house appeared to be intact at least, if now, as I was soon to realise, at a slight lean. I made my way downstairs to find a torch, clambering over broken and fallen objects as I did so.

I opened the front door and went outside, slap – straight into a puddle of… soil?? Up to my ankles! I shone the torch around, to find large mounds of liquefied soil and water covering the driveway and gardens. "Wow! This is liquefaction! These are sand boils!" My bemused neighbours soon appeared and wondered if the water mains had broken and forced the soil up. The sounds of rushing water underground still came from 10cm fissures that had opened up between and, in some places, through the houses. In some excitement I found myself explaining to them that this is what could happen in an earthquake – at least when the soil was loose silty sand and the water table was high. This was straight out of a textbook. For a moment, I couldn't believe my luck – to actually witness liquefaction as it pretty much had occurred was surely a geotechnical engineer's dream? Poor Misko, I thought. He will be spitting.

One neighbour had not yet appeared, and was found to be trapped in her house – with all her doors stuck shut. We passed a torch to her through an open window and somebody eventually forced one of the doors. We wondered about how the earthquake had affected others elsewhere, although the general feeling locally seemed to be one of astonishment rather than fear. It was not until listening to the radio that we found that, at least in terms of fatalities, Canterbury had been incredibly lucky and Dallington was actually one of the worst affected areas in terms of damage.

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Over the next several days, cut-off as we initially were by largely impassable roads, the neighbourhood organised itself to clean up the “silt” as it was universally dubbed (the soil was actually fine sand with approximately 10-20% silt – and it would readily reliquefy upon disturbance with a shovel) and to then protect houses from rising floods as the burst water mains were repaired in other parts of the city, causing the mains pressure to increase locally. Electricity was briefly restored for several hours during Saturday, only to be lost again until Tuesday evening. Running water, lost since the earthquake, was restored on Wednesday evening, although it still needed to be boiled for drinking. Some neighbours, with severe house damage or young families, moved out as soon as they were able. Those that remained checked on each other daily to ensure everyone had what they needed – water, torches, portable radios, cooking and heating supplies. Those who did not were invited for dinner, taken for showers to other parts of the city or accommodated elsewhere by those who did. The community spirit truly was remarkable. Meanwhile, from 6.30am that morning and over the next 4 days I took a series of trips on foot and by mountain bike to record the effects in the local area. For these early trips, three elements stood out: liquefied soil and water everywhere; fissures, buckled roads and pavements, particularly towards the river; and fallen masonry, mainly from brick chimneys. Some of the photos are given here.

Photo 1: First light - liquefaction street scape in the neighbourhood

Photo 2: First light - a view of my driveway with liquefied soil and water

Photo 3: First light: typical chimney debris of a house in adjacent street