4 Observed Liquefaction and Response Spectra in CBD during the 2010 and 2011 Christchurch Earthquakes

4.1 Soil Liquefaction During the 22 February 2011 Earthquake

The series of earthquakes that hit Christchurch in the period between 4 September 2010 and 13 June 2011 caused repeated liquefaction through its suburbs and the CBD itself. The 22 February earthquake was the most damaging, inducing widespread liquefaction and lateral spreading in the eastern suburbs and within parts of the CBD. The liquefaction in the CBD adversely affected the performance of many buildings resulting in differential settlements, lateral movement of foundations, tilt of buildings, and some bearing failures.

Figure 9 shows the extent of liquefaction caused by the 22 February 2011 earthquake in wider Christchurch documented through a drive-through reconnaissance that was conducted in the period from 23 February to 1 March by the University of Canterbury (Cubrinovski and Taylor, 2011). The drive-through survey aimed at capturing surface evidence of liquefaction as quickly as possible and quantifying its severity in a consistent and systematic manner. Four areas of different liquefaction severity are indicated in the map: (a) moderate to severe liquefaction (red zone, with very large areas covered by sand ejecta, mud and water, large distortion (undulations) of ground and pavement surfaces, large cracks and fissures in the ground, and significant liquefaction-induced impacts on buildings), (b) low to moderate liquefaction (yellow zone, with generally similar features as for the severe liquefaction, but of lesser intensity and extent), (c) liquefaction predominantly on roads with some on properties (magenta zone, where heavy effects of liquefaction were seen predominantly on roads, with large sinkholes and 'vents' for pore pressure dissipation, and limited damage to properties/houses), and (d) traces of liquefaction (red circular symbols, with clear signs of liquefaction, but limited in extent and deemed not too damaging for structures). The suburbs to the east of CBD along Avon River (Avonside, Dallington, Avondale, Burwood and Bexley) were most severely affected by liquefaction, which coincides with the area where about 5000 residential properties will be abandoned (New Zealand Government, 2011).

Ten days after the earthquake, after the urban search and rescue efforts had largely finished, a comprehensive ground survey within the CBD was initiated to document liquefaction effects in this area. Figure 10 shows the resulting liquefaction documentation map for the CBD. The principal zone of liquefaction stretches west to east through the CBD, from Hagley Park to the west, along the Avon River to the northeast boundary of the CBD at the Fitzgerald Bridge. This zone is of particular interest because many high-rise buildings on shallow foundations and deep foundations were affected by the liquefaction in different ways. Note that this zone consists mostly of sandy soils and it largely coincides with the path of the Avon River and the network of old streams shown in the 1850s survey maps (Figure 4). Another zone of moderate to severe liquefaction was found in the south-east part of the CBD, though its effects were less significant in relative terms.

Even though the map shown in Figure 10 distinguishes the zone along Avon River as the most significantly affected by liquefaction, the severity of liquefaction within this zone was not uniform. In this zone, the manifestation of liquefaction was primarily of moderate intensity with relatively extensive areas and volumes of sand/silt ejecta. There were also areas of low manifestation or only traces of liquefaction, but also pockets of

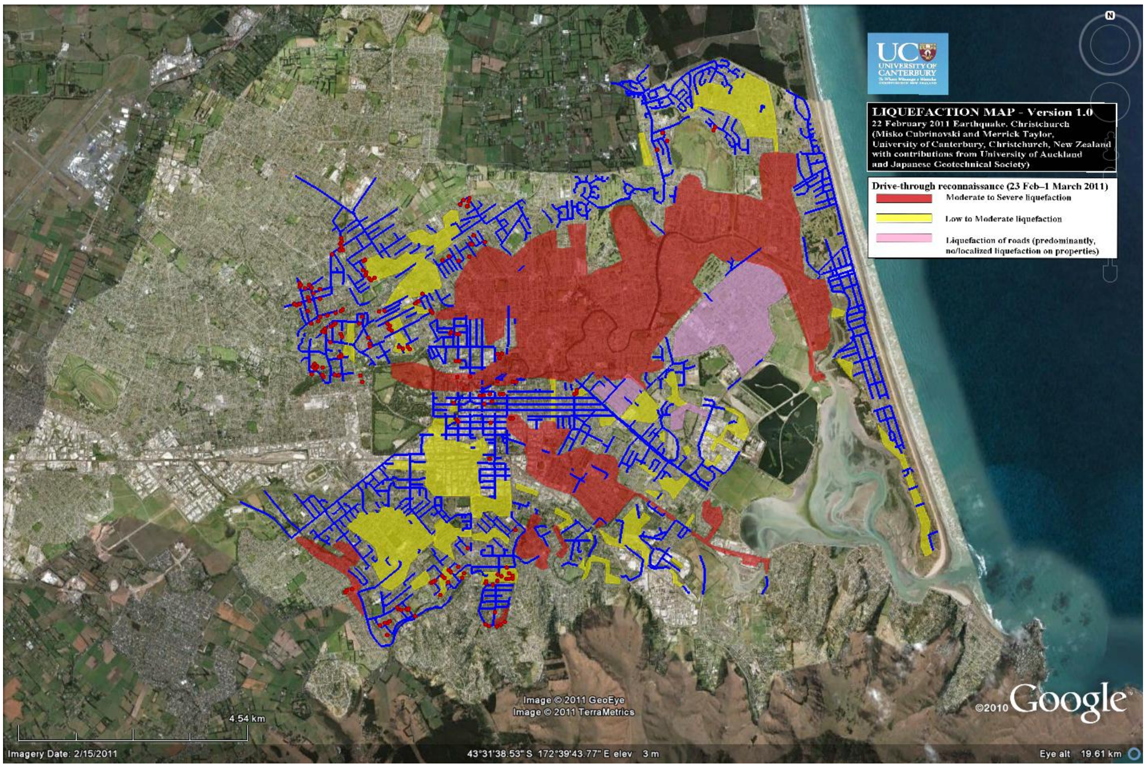

Figure 9. Preliminary liquefaction map of Christchurch from drive-through reconnaissance (Cubrinovski and Taylor, 2011); the map is not complete and shows only general overlay of areas (it cannot be used on property basis)

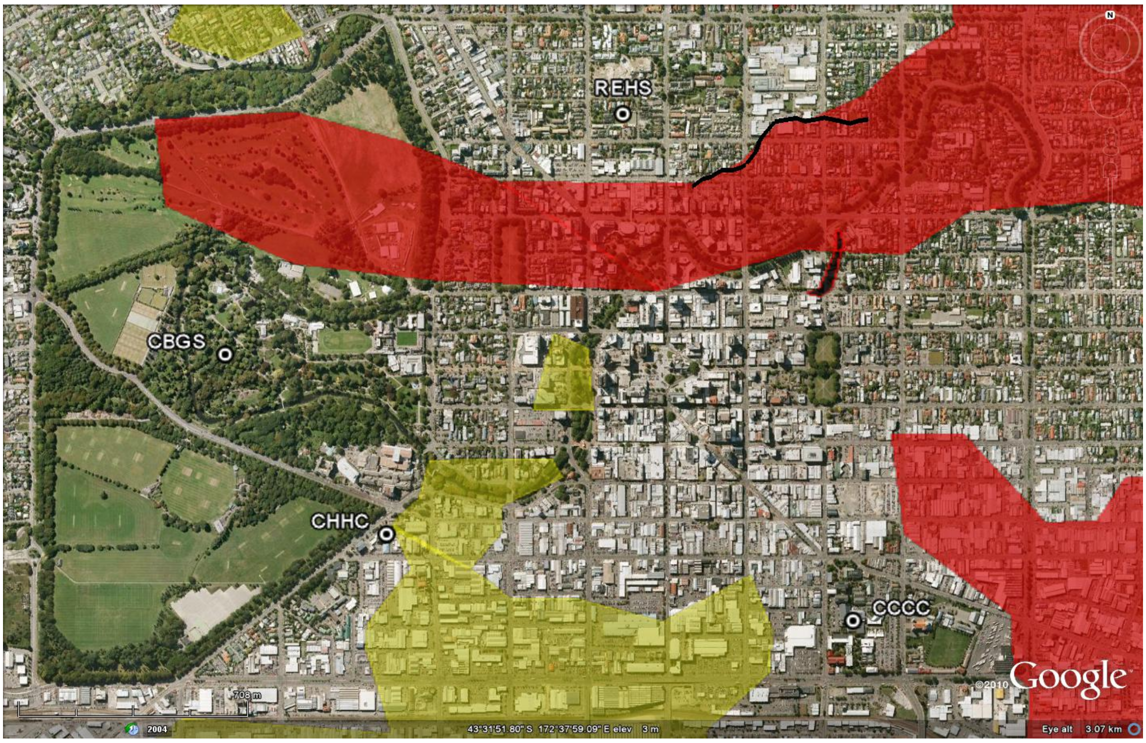

Figure 10. Preliminary liquefaction map indicating areas within the CBD affected by liquefaction in the 22 February earthquake

severe liquefaction with very pronounced ground distortion, fissures, large settlements and substantial lateral ground movements. The zones of more pronounced liquefaction do appear somewhat to "line up" with the old stream channels, which sheds some light on the reasons for variability in liquefaction manifestation. One should not expect though that all liquefaction features and zones of pronounced ground weakness could be explained with reference to the stream channels dating back to 1850s, because the earlier depositional history and re-working of surficial soils is also very relevant for their liquefaction susceptibility.

The north extent of the zone, which is shown by the thick black line in Figure 10, is a clearly defined geomorphic boundary (easily detectable change in the ground surface due to features of underlying soils) running east to west. This feature was marked by a slight change in elevation of about 1 m to 1.5 m over approximately 2 m to 10 m wide zone, and was characterized by ground fissures and distortion associated with gentle slumping of the ground surface and localized spreading towards the down-slope side. Ground cracks, fissures and a distorted pavement surface marked this feature, which runs continuously through properties and affected a number of buildings causing cracks in both the foundations and their structures. Liquefaction and associated ground deformation were pronounced and extensive on the down-slope side between the identified geomorphic feature and the Avon River, but noticeably absent on the slightly higher elevation to the north (upslope side away from the river). This feature is thought to delineate the extent of a geologically recent river meander loop characterized by deposition of loose sand deposits under low velocity conditions. A similar geomorphic feature was observed delineating the boundary between liquefaction damage and unaffected ground within a current meander loop of the river to the east of this area (Oxford Terrace between Barbados Street and Fitzgerald Avenue).

Liquefaction-induced lateral spreading occurred along the Avon River in the liquefied zone within the CBD, and the horizontal stretching of the ground adversely affected several buildings. Ground surveying measurements conducted at about ten transects on Avon River within the CBD after the 22 February earthquake indicated that at several locations, the banks of Avon River moved laterally about 50-70 cm towards the river, whereas at most of the other locations the spreading displacements were on the order of 10 cm to 20 cm. The zone affected by spreading was relatively narrow usually within 50 m from the Avon River, though at a few locations the spreading extended up to 100 m to 150 m from the banks. There were many smaller buildings suffering serious damage to the foundations due to spreading as well as clear signs of effects of spreading on some larger buildings both at the foundations and through the superstructure. Structures and foundations within the spreading zone are greatly impacted by the horizontal ground strains causing stretching of the ground, foundations and then the building itself.

4.2 Repeated Liquefaction within CBD during the 2010-2011 Earthquakes

Soil liquefaction repeatedly occurred at the same sites during the earthquakes producing strong ground shaking in Christchurch, and in particular during the 4 September 2010, 22 February 2011, and 13 June 2011 earthquakes. Figure 11 comparatively shows liquefied areas of Christchurch in these three events, as documented by field inspections. Note that only parts of Christchurch have been surveyed (coloured areas) and that the aim of the surveys was to capture general features and areas affected by liquefaction as observed from the roads, hence, the zoning is not applicable to specific properties.

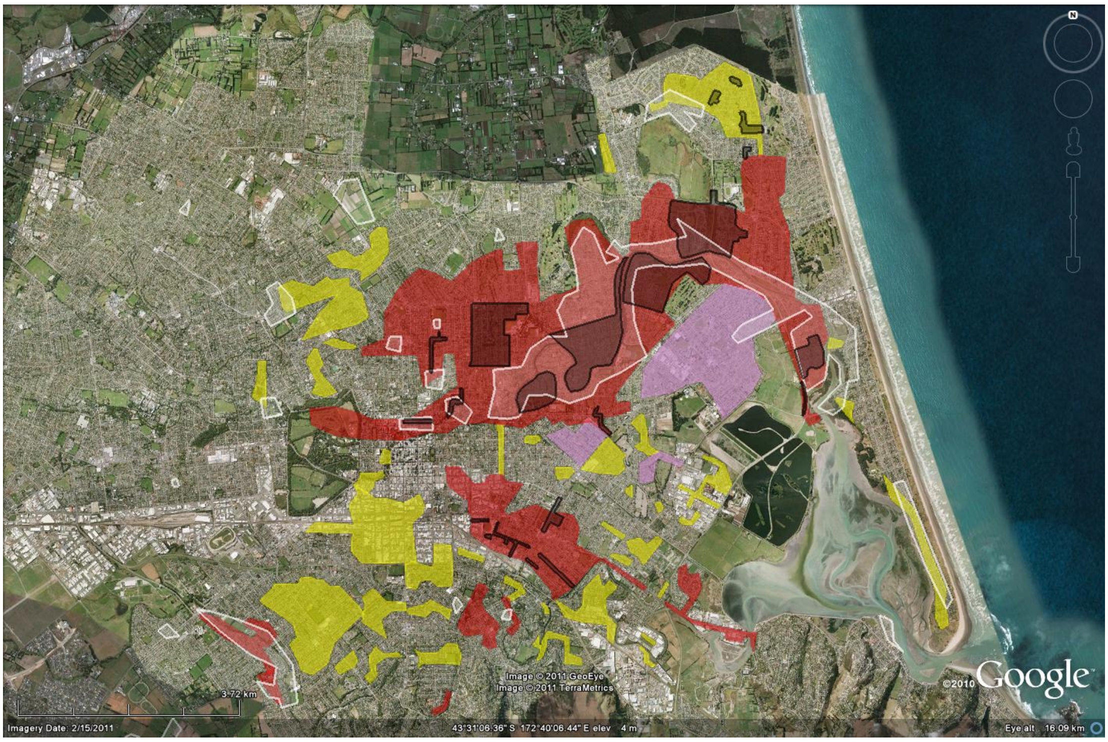

Figure 11. **Preliminary liquefaction maps documenting areas of observed liquefaction in the 4 September 2010 (white contours), 22 February 2011 (red, yellow, magenta areas), and 13 June 2011 (black contours) earthquakes; note that only parts of Christchurch were surveyed (coloured areas), and that the aim of the surveys was to capture general features and areas affected by liquefaction as observed from the roads, hence, the zoning is not applicable to specific properties**

The repeated occurrence of liquefaction at a given site during an earthquake is not surprising because liquefaction generally does not increase the liquefaction resistance nor prevents the occurrence of liquefaction of the site in subsequent earthquakes. The sequence of events in Christchurch has certainly proven this notion.

The repeated liquefaction was often quite severe and many residents reported that in some cases the severity increased in subsequent events. In addition to the inherent level of liquefaction resistance of soils (a specific strength property), whether liquefaction will occur or not, and what will be its severity, should it occur, depends on the severity of ground shaking caused by the earthquake. In this context, each of these earthquakes produced different ground shaking within the CBD. Table 1 summarises the peak ground accelerations (PGA) recorded at four strong motion stations within/close to the CBD (CBGS, CCCC, CHHC, REHS; locations listed in the footnote of Table 1) during five earthquakes producing damaging levels of ground shaking.

The simplified procedure for liquefaction evaluation enables us to combine two key features of ground shaking (i.e. its amplitude and duration) into a single parameter (CSR), and hence comparatively examine the severity of ground shaking or seismic demand on soils imposed by different earthquake events. More details around this procedure are given in Section 6, while here the results of the simplified analysis are briefly discussed. Table 1, in addition to the PGAs, also summarises the calculated