Reconnaissance report on liquefaction effects and landslides caused by the M_L 6.5 Cook Strait earthquake of 21 July 2013, New Zealand

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CONTENTS

FIGURES

ABSTRACT

This report presents the results of GeoNet reconnaissance inspections of landslides and liquefaction effects caused by the M_L 6.5 Cook Strait earthquake on 21 July 2013. A field inspection and ground surveying at the CentrePort Wellington Container Storage Area, carried out on 23 July 2013, showed that the earthquake caused extensive slumping and ground cracking with minor sand ejection over a ~50,000 m^3 area of 1970s reclamation fill. The earthquake also caused a sub-aqueous sand boils in shallow water and small earth falls at Kaiwharawhara Point, minor cracking on the wharf promenade at Te Papa, and a small rock fall on old quarry slope on the western side of Lyall Bay.

The liquefaction effects that occurred during the 21 July 2013 Cook Strait earthquake are the most extensive recorded in the Wellington City area since the 1855 and June 1942 Wairarapa earthquakes. The liquefaction damage observed at the Container Storage reclamation area in Wellington Harbour is a timely reminder of the type of effects that could occur in reclaimed areas, especially during a magnitude 7.5 earthquake on the Wellington Fault, the subduction zone interface, or other active faults in the Wellington area. The damage that occurred suggests that reclamation fills are vulnerable to lateral spreading and collapse due to liquefaction of the underlying unconsolidated harbour silts and muds.

A helicopter reconnaissance flight was undertaken on 25 July 2013 to locate and photograph landslides and other ground damage caused by the earthquake. The landsliding that occurred was restricted mainly to the steep (35°) coastal cliffs within ~15 km of the epicentre, and terrace edges in the middle Awatere Valley. Only one small rock fall occurred on the south coast of Wellington 40 km northeast of the epicentre. The largest landslide that occurred was a ~100,000 m^3 rotational slide on the mudstone cliffs 1 km west of Cape Campbell. A number of debris falls occurred on White Bluffs and other similar cliffs in the area, but most were small (10-1000 m^3). A 19 m high earth dam 12 km southwest of Seddon was slightly damaged (cracking on the upstream side of crest) by the earthquake.

Most of the coseismic landslides are on the coastal cliffs on the edge of the modelled MM8 isoseismal zone, about 16 km from the epicentre. The number and size of landslides that occurred during the earthquake is at the lower end of what can be expected for a shallow M 6.5 earthquake in New Zealand. It is regarded, therefore, as a threshold event for earthquake-induced landsliding in the Wellington and Marlborough areas. The relatively limited landsliding and liquefaction damage caused by the earthquake is probably partly due to the fact that the earthquake was located offshore and about 15 to 50 km away from the affected areas. It may also reflect the fact that natural and engineered (cut) slopes in the area are less susceptible to failure for the maximum level of ground shaking that occurred (pga 0.21g at Ward). Slope angle, slope height, and material susceptibility appear to have strongly influenced the limited distribution and severity of both the landsliding and the liquefaction effects caused by the earthquake.

KEYWORDS

M_L 6.5 Cook Strait earthquake 21 July 2013, landslides and liquefaction effects, earthquake-induced landsliding, Wellington, Seddon, Ward, Cape Campbell, White Cliffs, New Zealand.

1.0 INTRODUCTION

The magnitude (M_L) 6.5 Cook Strait earthquake on Sunday, 21 July 2013 at 5:09:30 pm (NZ Standard Time) is reported by GeoNet to have been located in the southern part of Cook Strait (epicentre: 41.60°S, 174.33°E) 25 km northeast of Seddon at a focal depth of ~13 km (Figure 1) (see also Holden *et al.,* 2013). The maximum Modified Mercalli (MM) intensity modelled for the earthquake is MM 9 (using Dowrick and Rhoades 2005 attenuation model).

The strong shaking associated with that event is reported to have caused damage to buildings on both sides of Cook Strait, and minor injuries to 4 people. The Cook Strait earthquake was preceded by two moderate strength foreshocks of M_L 5.7 on Friday 19 July 2013 at 9:06:39 am (NZST) at a depth of 17 km, 30 km northeast of Seddon (41.55°S, 174.41°E), and of M_L 5.8 on Sunday July 21 2013 at 7:17:10 am located at 41.56°S, 174.40 °E, at a focal depth of 20 km.

Over the first ten days of the Cook Strait earthquake sequence there were almost 1900 earthquakes greater than magnitude 2 including: one of magnitude 6.5; 5 of magnitude 5.0–5.9; 64 of magnitude 4.0–4.9; 382 of magnitude 3.0–3.9, and 1424 of magnitude 2.0–2.9. The 10 largest events range from M_L 4.9 to 6.5 in strength at focal depths ranging from 12–20 km. The earlier earthquakes are reported to have had reverse fault focal mechanisms, but the largest (M_L6.5) earthquake and the many subsequent aftershocks have been strike slip events (see Figure 15).

Besides the reported damage to buildings in Seddon and Wellington the M_L 6.5 earthquake on Sunday 21 July 2013 caused significant liquefaction-related ground damage on reclaimed land at CentrePort's container storage area in Wellington Harbour, and an landslide was photographed on the White Bluff *(= Vernon Bluffs)* headland about 15 km northeast of Seddon. The locations of epicentres associated with the first ten days of the 2013 Cook Strait earthquake sequence and the main areas of reported ground damage due to landsliding and liquefaction (ground cracking, sand ejections, and slumping into the harbour) are shown on Figure 1, Figure 2, and Figure 3.

GeoNet responses were initiated to look for and record the landslides and liquefaction damage that was caused by the M_L 6.5 earthquake on 21 July 2013 (which has been officially named by GeoNet as the Cook Strait earthquake). This report presents the results of a ground inspection and survey of liquefaction effects at the Container storage area on Tuesday 23 July (Figure 2 and Figure 5), a helicopter landslide reconnaissance on Thursday 25 July 2013 (Figure 15). A number of photos are included to illustrate the nature of the landslides and the liquefaction damage attributed to the earthquake. These photos were taken by Graham Hancox unless stated otherwise.

<u>Note</u>: About four weeks after the Cook Strait earthquake, the M_w 6.6 Lake Grassmere earthquake occurred on 16 August, 2013. The epicentre of the Lake Grassmere earthquake is located about 20 km southwest of the epicentre of the Cook Strait event, directly under Lake Grassmere. A summary account of the source and ground motion characteristics of the Lake Grassmere earthquake can be found in Holden et al. (2013), and reconnaissance-level details regarding the ground damage effects (landsliding and liquefaction) generated by the Lake Grassmere event can be found in Van Dissen et al. (2013). The GeoNet response to the Lake Grassmere earthquake and other factors related to areas that were damaged by the Cook Strait earthquake has delayed publication of this report.

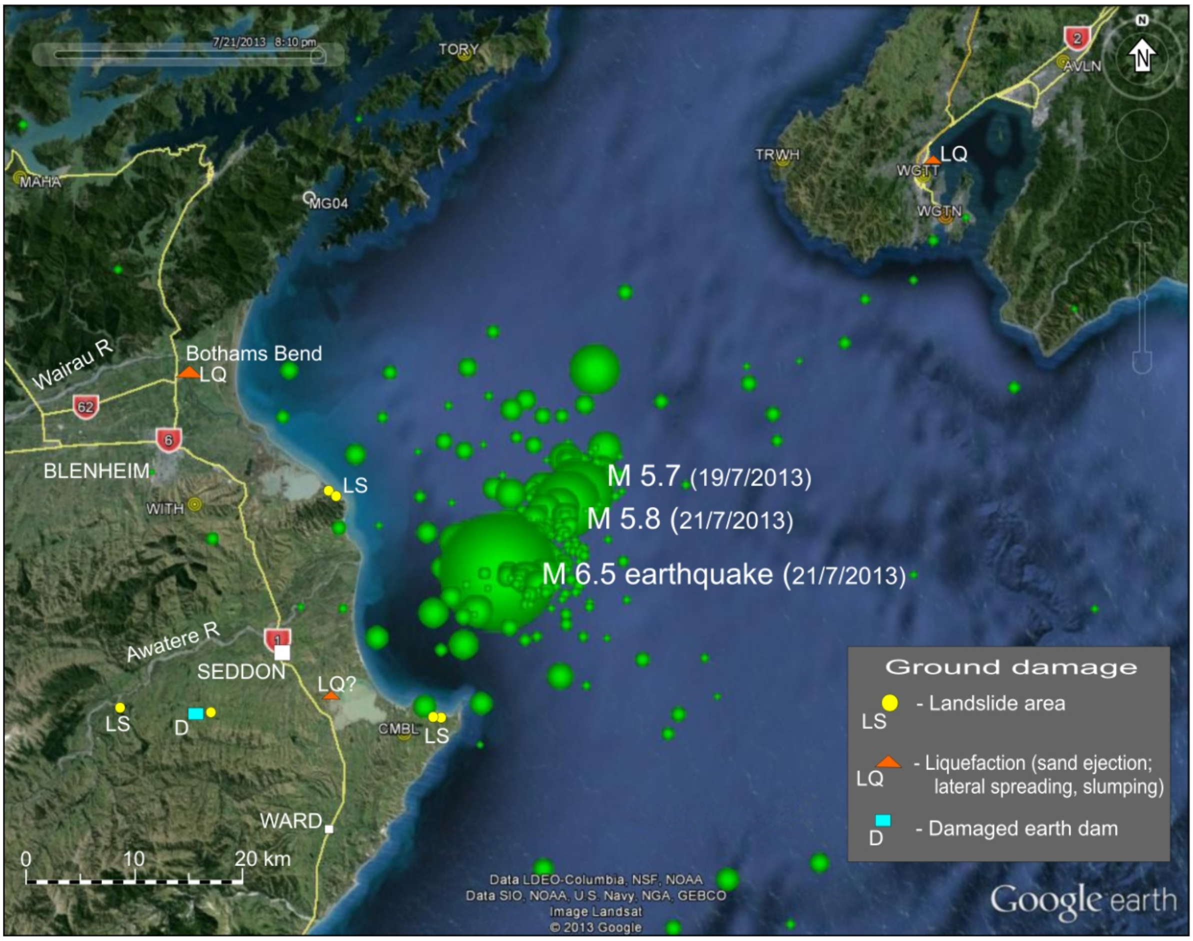

Figure 1 Annotated GoogleEarth image map showing the locations of epicentres of earthquakes that occurred during the Cook Strait earthquake swarm from 21–29 July 2013 (from GeoNet), and the main areas of landsliding and liquefaction ground damage caused by the M_L 6.5 earthquake on 21 July 2013.

Figure 2 Annotated GoogleEarth image showing the location of liquefaction damage at the container storage reclamation area, and landsliding and liquefaction at Kaiwharawhara Point in Wellington Harbour which was caused by the Cook Strait earthquake of 21 July, 2013.

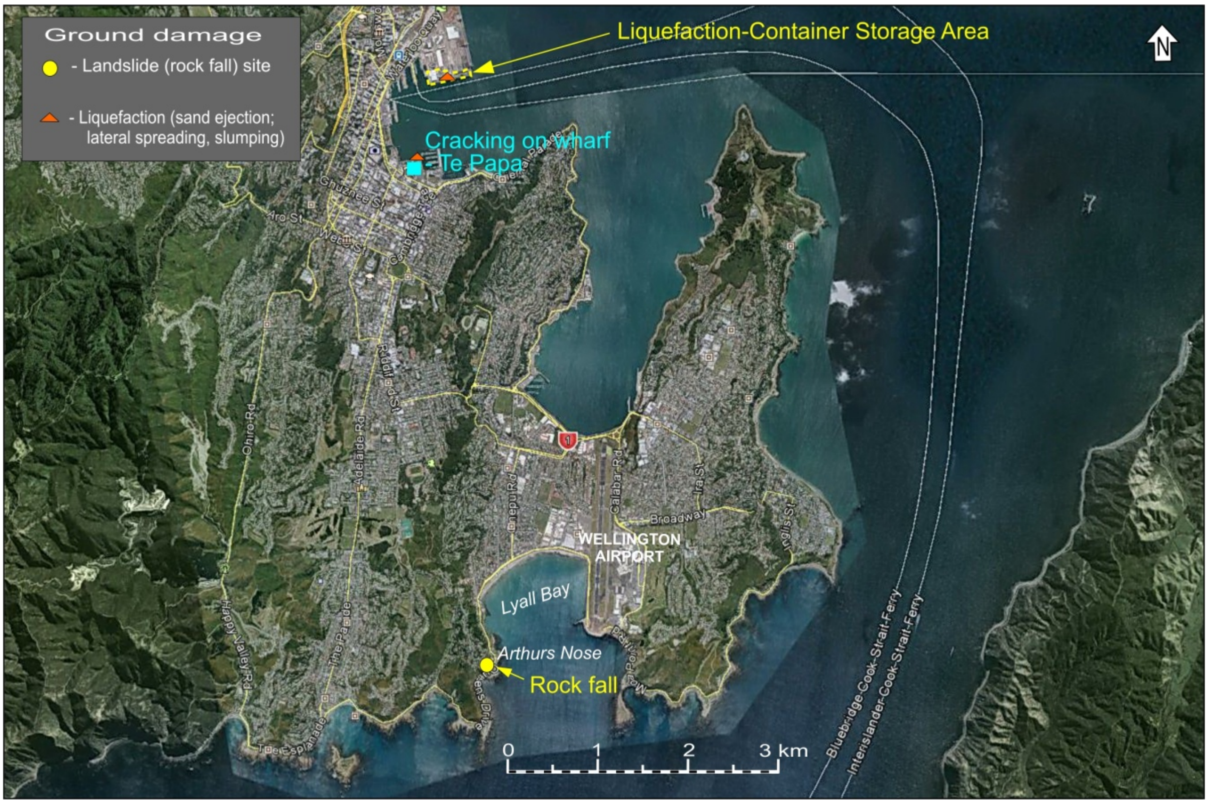

Figure 3 Annotated GoogleEarth image showing the locations of the cracking on the wharf at Te Papa and the small rock fall at Arthurs Nose on the west side of Lyall Bay about 5.5 km to the south of Te Papa, but closer to the epicentre of the Cook Strait earthquake.

Figure 4 Site of cracking *(cr)* of the wharf promenade *(wp)* at Te Papa. The arrow shows the location of the start of the cracking at the top of the steps leading to the lower deck of the wharf.

Figure 5 GoogleEarth image overlain with an RTK survey map of liquefaction-induced lateral spreading cracking, sand ejections, and slumping at the Container Storage Area reclamation fill (constructed 1960s and 1970s) into Wellington Harbour caused by the Cook Strait earthquake of 21 July, 2013. About 50,000 m^2 of the unrestrained southern edge of the reclamation area was affected by liquefaction damage.

2.0 GROUND DAMAGE IN THE WELLINGTON AREA

2.1 LIQUEFACTION EFFECTS AT CONTAINER STORAGE AREA

The ground damage to the Container Storage Area at CentrePort Wellington (Figure 2) was inspected by Graham Hancox and Garth Archibald on Tuesday 23 July 2013 following news media reports of slumping of reclaimed land and a container floating in the harbour. Garth Archibald carried out a precise RTK GPS survey of the area of slumping into the harbour and the extensive ground cracking that occurred during the M_L 6.5 Cook Strait earthquake on 21 July 2013. The inspection and surveying by GNS Science was carried out with the permission of CentrePort Wellington.

The results of the RTK survey and observations are plotted on Figure 5. Our inspection and survey shows that a large area of the unrestrained southern end of the reclaimed land used by CentrePort as a Container Storage Area was damaged by the Cook Strait earthquake. This area, located between the Thorndon Container Wharf and King's Wharf (Figure 5), is part of the Thorndon Reclamation. This gravel fill reclamation area is typically 15 m deep, and was constructed in 1972 (Murashev and Palmer, 1998) The adjoining Thorndon Container Wharf and King's Wharf provide lateral support to the fill batter slope forming the edge of the reclamation, but the southern end of the fill was unsupported.

The main damage caused by the earthquake was slumping of a 250 m long section of the western part of the southern end of the reclamation fill batter, and extending 15 to 20 m from the former reclamation shoreline to the centre of the southern perimeter roadway. Slumping and tensional cracking occurred over about ~50,000 m^2 of the Container Storage Area. A series of open lateral spreading cracks ~200–300 m long and up to ~200 mm wide were formed parallel to and up to ~140 m back from the edges of the reclamation (Figure 5, Figure 6, Figure 7, Figure 8, Figure 9 and Figure 10).

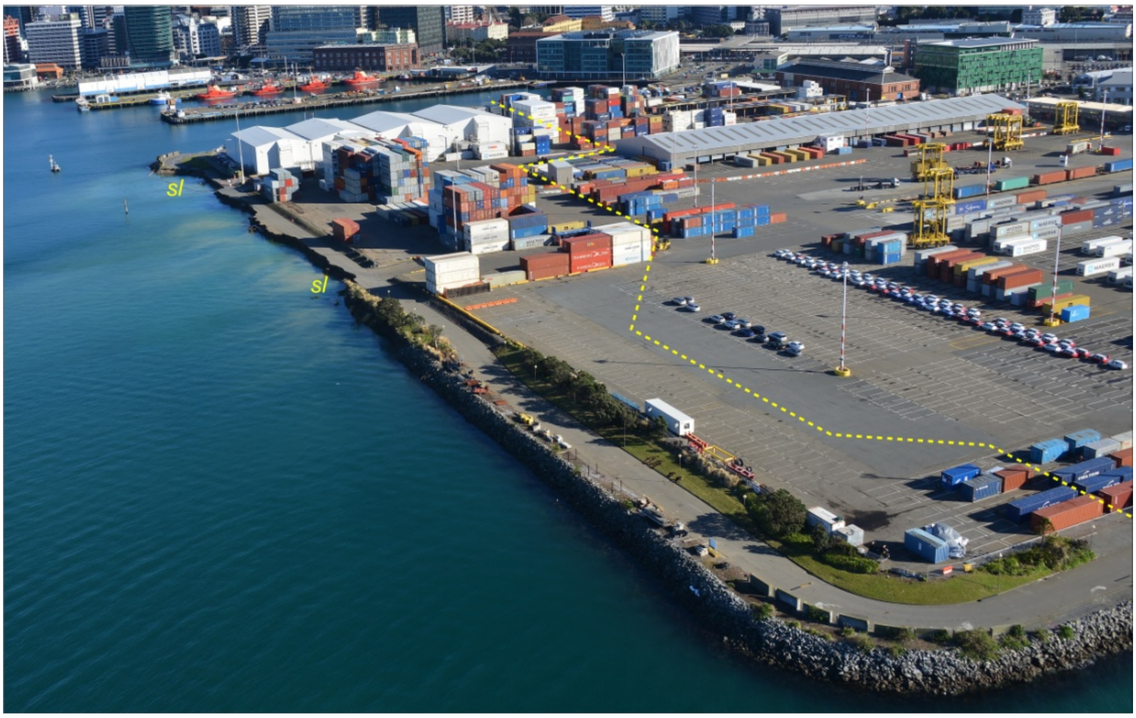

Figure 6 Aerial view of the area of slumping *(sl)* and cracking (yellow dotted line) caused by the Cook Strait earthquake of 21 July, 2013 at the Container Storage Area.

Figure 7 The most serious damage that occurred was slumping *(sl)* over a 250 m length of the roadway at the unrestrained southern end of the reclamation fill that the Container Storage Area is located on.

Figure 8 Western end of the slumping of fill into the harbour at the southern end of the reclamation. The clay-gravel fill shown here *(f)* is well compacted, but appears to have failed because the underlying weak (low density) silt and mud on the harbour bottom, on which the fill was placed, have failed.

Figure 9 Closer view of the extensive tensional cracking *(c)* and subsidence *(su)* failure area at the southwest end of the reclamation area adjacent to King's Wharf.

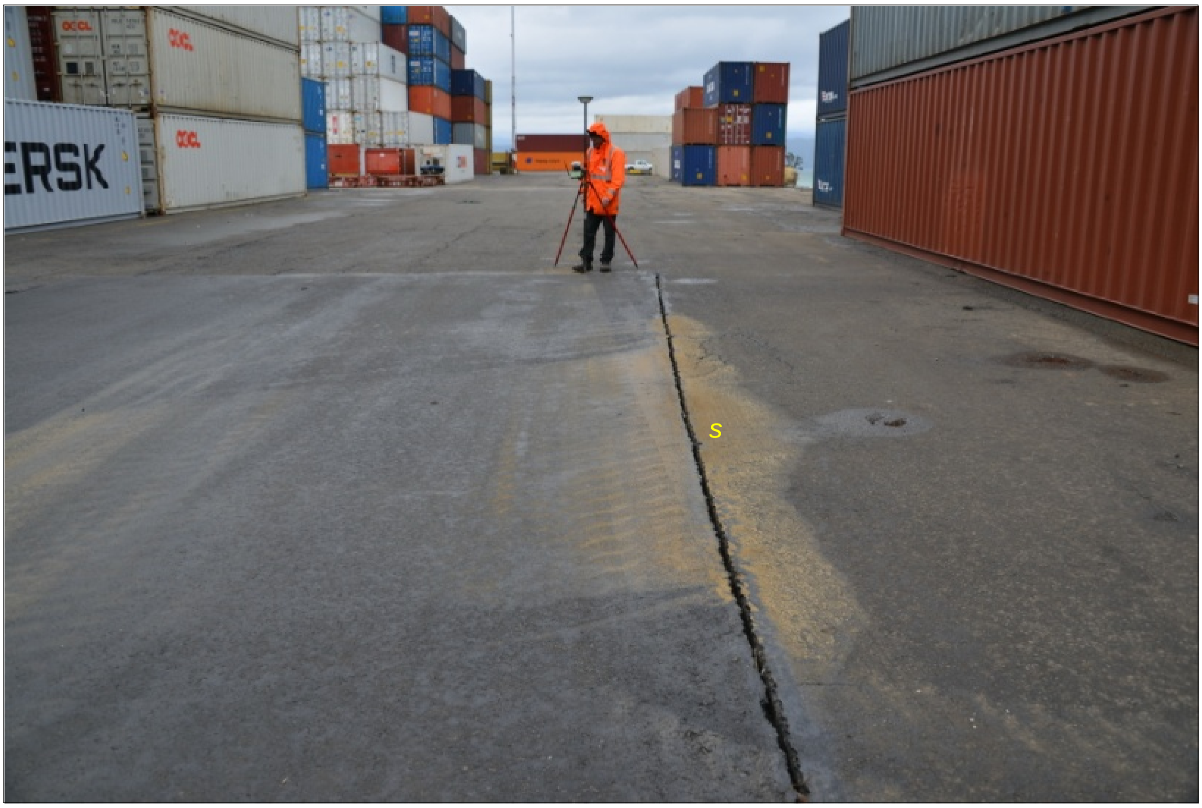

Figure 10 Open tension cracks and sand *(s)* and water ejection (liquefaction) ~30 m in from the toe of the original fill batter at the western end of the reclamation area.

Minor liquefaction-induced sand ejections were noted at two locations (Figure 5 and Figure 10). Incipient hairline cracking occurred over much of the affected area, and there was also evidence of minor subsidence in one area ~50 m south of Shed 37 (Figure 5).

The slumping, sand ejection and ground cracking in reclamation fill in the Container Storage Area at CentrePort Wellington, along with sand boils in shallow water at Kaiwharawhara Point (Figure 2) are believed to be liquefaction effects caused by the M_L 6.5 Cook Strait earthquake on 21 July 2013. Those liquefaction effects are similar to the isolated subsidences and sand boils that occurred during the M_W 7.2 Masterton earthquake of 24 June 1942 (Murashev and Palmer, 1998; Downes *et al.,* 2001). That earthquake and the 2013 Cook Strait earthquake have caused the most substantial liquefaction damage in the Wellington City area since the 1855 Wairarapa earthquake (Grapes *et al.,* 1998; Hancox *et al.,* 1997).

The nature and extent of the liquefaction effects and damage to the reclamation area in Wellington Harbour during the moderate strength earthquake on 21 July 2013 are a timely reminder of what sort of liquefaction effects and damage could occur in these areas during a much larger magnitude 7.5 earthquake on the nearby Wellington Fault, the subduction zone interface, or other active faults in the Wellington area.

The ground damage to the unrestrained southern end of the Container Storage area during the July 2013 earthquake clearly showed the vulnerability of reclamation fills that are not confined by sheet piling or a wharf. Kings Wharf and the Thorndon and Aotea Quay wharves appear to have prevented collapse and cracking of the adjacent fill.

2.2 OTHER DAMAGE

A few weeks after the Cook Strait earthquake, cracks were noted on the wharf promenade at Te Papa (Figure 3 and Figure 4). The cracks are ~5–10 mm wide with subsidence of 15–30 mm (Figure 11 and Figure 12), and are located above the edge of the underlying fill, which appears to have settled, possibly due to failure of silt and mud deposits below the fill (Figure 12).

Figure 11 Minor cracking *(cr)* and 15-30 mm subsidence in the pavement of the wharf promenade at Te Papa.

Figure 12 The cracking *(cr)* and subsidence in the pavement of the wharf promenade *(wp)* at Te Papa (a) appears to be aligned with the edge of the fill under the wharf (b). The fill appears to have settled slightly, possibly due to failure of the harbour silts and muds beneath the fill under the wharf.

Figure 13 Several small debris falls *(df)* occurred in this area of filled ground at Kaiwharawhara Point during the 21 July Cook Strait earthquake. Small liquefaction-induced sand boils *(sb)* were noted in shallow water at this location.

3.0 LANDSLIDES CAUSED BY THE COOK STRAIT EARTHQUAKE

A helicopter reconnaissance of landslides and ground damage caused by the M_L 6.5 Cook Strait earthquake was undertaken by Graham Hancox, Nick Perrin, and Santanu Misra on Thursday 25 July 2013. Our aerial inspection began in Wellington Harbour, where fresh slumping and sand boils were noted at Kaiwharawhara Point (Figure 2).

At Kaiwharawhara Point several small earth and debris falls were observed on the wave-cut end of a fill storage area. These failures are close to what appear to be sub-aqueous sand boils on the edge of the harbour (Figure 13). No other ground damage or landslides were observed in the Wellington area. The reconnaissance flight route in the South Island, and landslides and other ground damage observed in the Seddon area are shown in Figure 15.

A small rock fall also occurred on an old quarry slope at Arthurs Nose on the west side of Lyall Bay (Figure 3 and Figure 13). This failure, a reactivation of a rock fall which occurred during the 15–20 June rainstorms, was the only landslide on Wellington's southern coast that could be attributed to the Cook Strait earthquake.

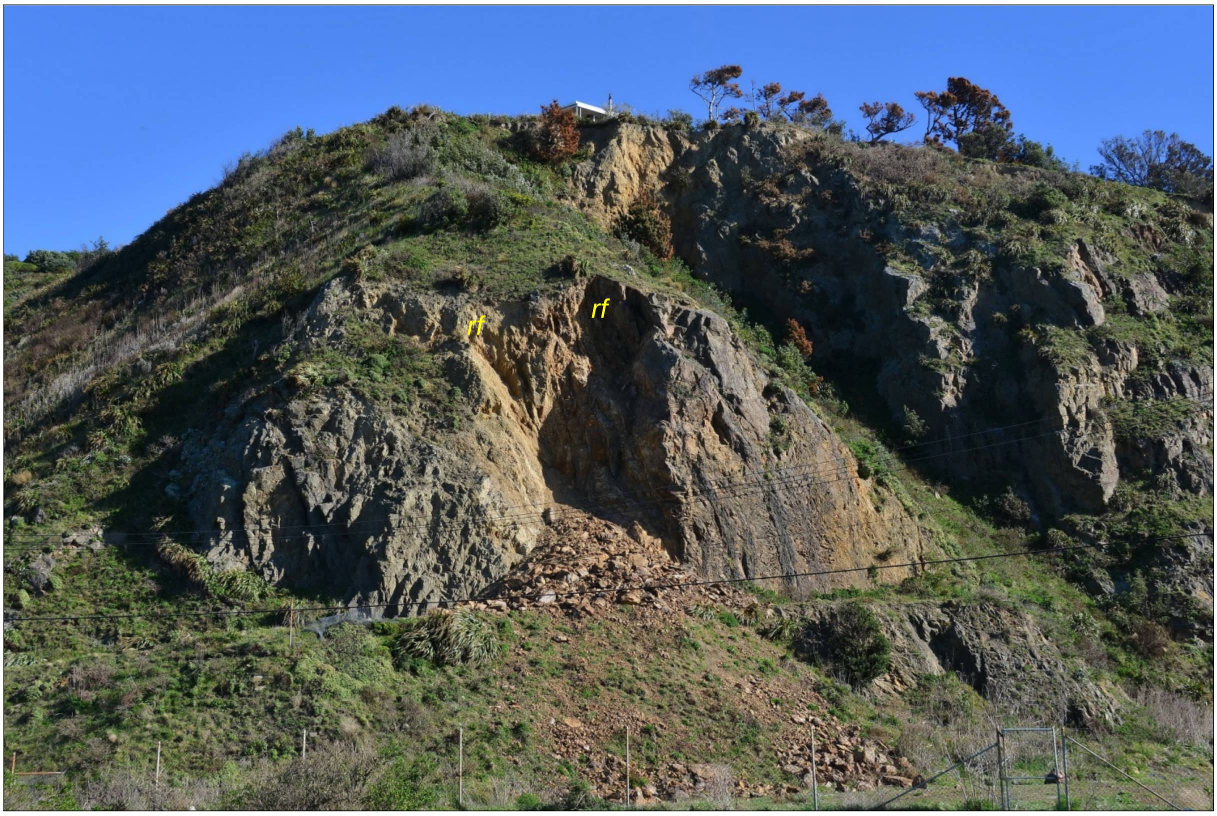

Figure 14 Rock fall *(rf)* source areas on an old quarry face at Arthurs Nose on the west side of Lyall Bay, which were reactivated by the Cook Strait earthquake of 21 July, 2013

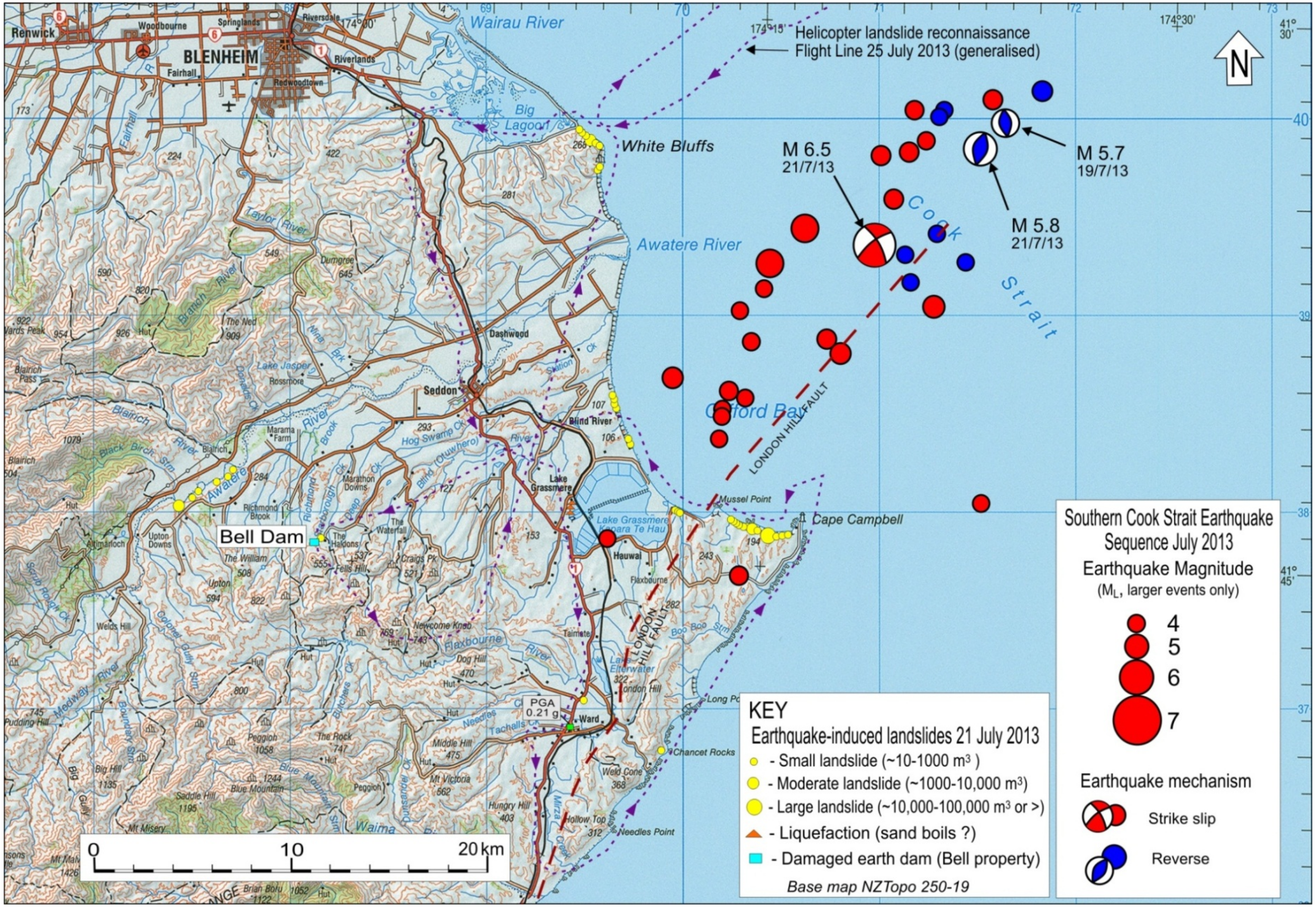

Figure 15 Map showing the route of the helicopter reconnaissance on 25 July 2013 and landslides and other ground damage attributed to the M_L 6.5 Cook Strait earthquake on 21 July 2013. The epicentre locations and mechanisms of the main earthquakes (>M 4) from 19-25 July 2013 are from the GeoNet website. The strongest PGA recorded was 0.21 g at Ward (for more detail regarding ground motions recorded during the Cook Strait event, see Holden *et al*. (2013).

The main reason for the reconnaissance flight was a photo taken by a French tourist from the Wairau Bar of a possible large landslide on White Bluffs at the time of the earthquake and featured in news media reports (Figure 16). This landslide was of interest as it provided an indication of the strength of the shaking on the headland ~15 km southeast of the earthquake epicentre (Figure 15), and was the site of earthquake-induced landslides in 1848. The dust cloud caused by the recent landslide (Figure 16) was reminiscent of the landslide(s) from White Bluffs in 1848, when the dust at the bluff was mistaken by local Maori for volcanic activity (Grapes *et al*., 1998). Although there were no other reports of landslides caused by the earthquake, it was possible that failures had occurred on other cliffs in the Seddon to Cape Campbell area. We therefore began our helicopter reconnaissance at White Bluffs (Figure 17). The results are described below.

Figure 16 Photos of White Bluff, Marlborough, taken from the Wairau Boulder Bar just before (left) and shortly after the M_L 6.5 Cook Strait earthquake on 21 July 2013 (right). The latter shows the dust cloud *(dc)* from a earthquake-triggered landslide travelling out into the sea *(Photos by Luca Zappula, 21 July 2013)*.

Figure 17 Aerial view of White Bluffs taken after the 21 July Cook Strait earthquake. This 268 m-high headland, located between the active Vernon Fault *(VF)* and the Awatere Fault *(AF)*, is formed of Tertiary age (Miocene to Pliocene) sandy siltstone and sandstone (Rattenbury *et al*. 2006). Scars of the July 2013 landslide areas are visible *(ls)* at the western (right) end of the bluffs.

3.1 HELICOPTER RECONNAISSANCE OBSERVATIONS

The general route of the helicopter flight is shown on Figure 15. After inspecting and photographing the site of the landslides on White Bluffs, we inspected the eastern end of the Wairau Boulder Bar and the southern shore of the Big Lagoon across to State Highway 1 (SH1) about 7 km southeast of Blenheim looking for landslides and liquefaction effects, but none were noted (Figure 15). The source area scars and debris from new failures on White Bluffs are quite obvious, although its appears that most of the debris that ran out into the sea had been eroded and redistributed by wave action when we inspected the site 4 days after the earthquake. The dust cloud gave the impression that a large landslide had occurred on White Bluffs, but our observations indicate that a number of small to moderate-size failures occurred at the top of the 100 m high, ~35-40° cliff face, with debris (fine siltstone and sandstone gravel) running down steep gullies onto the narrow beach and into the sea (Figure 18). Other small failures also occurred at the top of the highest part the bluff (Figure 17).

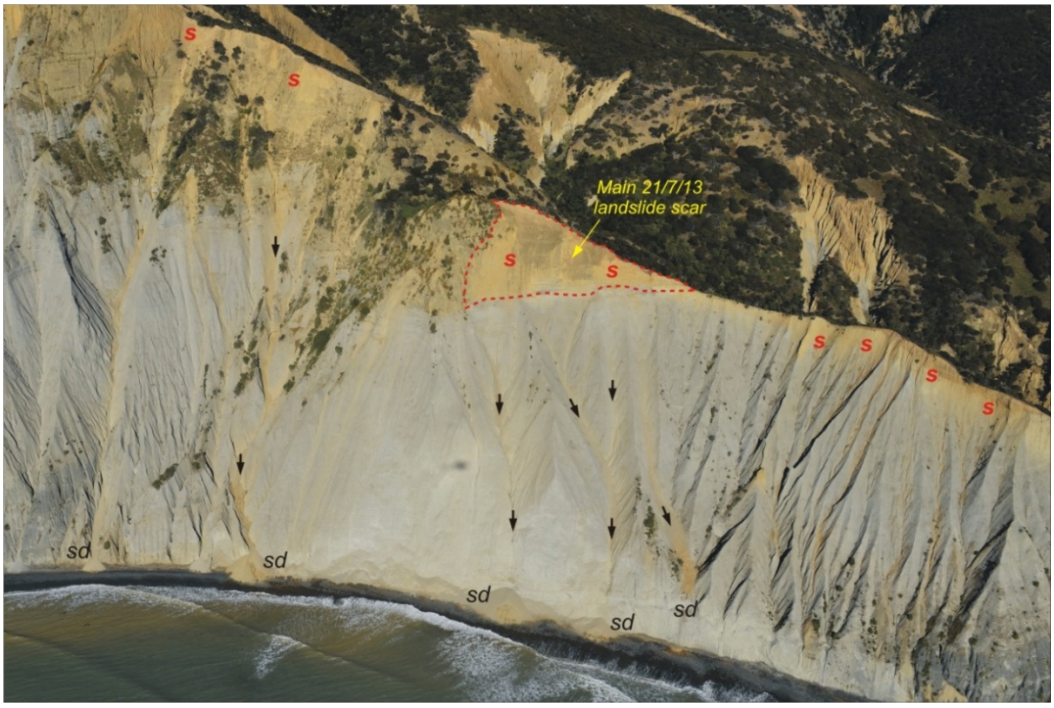

Figure 18 Aerial photo of the landslide site on White Bluffs showing the source area of the main failure on 21 July 2013, a number of smaller failure scars *(s)*, and cones of slide debris *(sd)* deposited below gullies (arrows) on the steep (~35°) cliff face. The angle of repose of the debris cones suggest that the material is relatively dry.

At SH1 we traversed south down the highway and the South Island Railway line looking for recent landslide damage. Although we were able to identify flooding damage and the scars and flows of (watery) debris from landslides that probably occurred during the 15-20 June 2013 rain storm when ~70 mm rain was recorded at Blenheim (NZ MetService), no new earthquake-induced landslides were noted within ten km north or south of Seddon.

An area of possible liquefaction effects (sand ejection) was noted in one of the evaporation ponds on the west side of Lake Grasmere. Ten km to the south one apparently new small landslide was observed in a cutting 2 km north of Ward, where the strongest ground motion (pga 0.21g) was recorded during the Cook Strait earthquake (Figure 15).

After reaching the coast ~8 km south of Ward we traversed north up the coast towards Cape Campbell, passing several large old paleolandslides on the way, none of which showed any evidence of reactivation by the earthquake.

The most substantial area of landsliding that could be attributed to 21 July 2013 earthquake is located on the steep mudstone cliffs between Cape Campbell and Mussel Point on the southern shore of Clifford Bay (Figure 15). The main landslides that occurred are shown in Figure 19, Figure 20, and Figure 21. These fresh-looking failures are not present on 30 May 2013 GoogleEarth images and they have therefore been attributed to the Cook Strait earthquake.

Figure 19 Aerial view of Cape Campbell *(c)* and recent earthquake-induced landslides *(ls)* on the moderately steep (~35°) mudstone cliffs ~1 km to the west, with the Seaward Kaikoura Mountains in the distance *(top right)*.

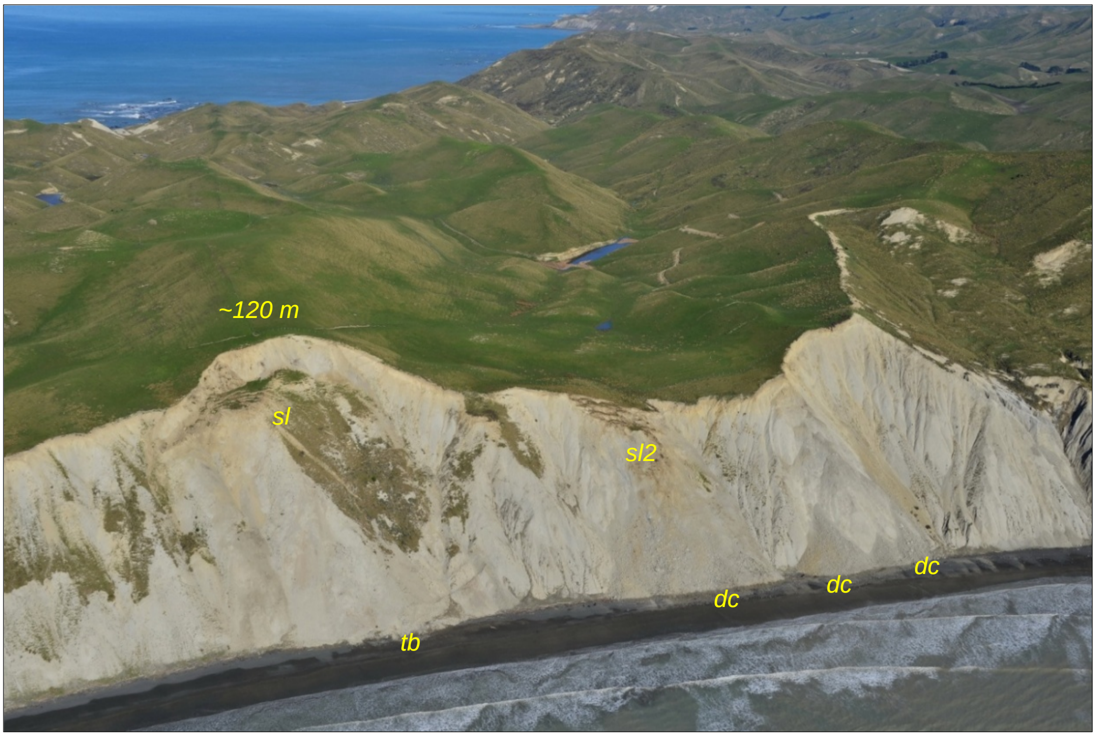

Figure 20 Slope failures triggered by the Cook Strait earthquake on 21 July 2013. The landslide to the left is a large rotational slump of about 100,000 m^3 (~70 x15 x 100 m), which has slumped about 20 m at the head *(sl).* The ~35° slope shows obvious rotational bulging at the toe on the beach *(tb)* but has not completely collapsed. Another large slumped area *(sl2)* and debris cones *(dc)* at the foot of the cliff are visible to the right.

Figure 21 Closer view of the largest landslide triggered by the Cook Strait earthquake on the cliffs 1 km west of Cape Campbell. Multiple fresh slump scarps *(s)* are visible below the ~20 m high head scarp *(hs)* at the top of this rotational landslide. Bulging at the convex toe *(t)* of the failure appears to have locally narrowed the beach.

The largest landslides triggered by the earthquake occurred on the cliff face east of Mt Tako (194 m), where the cliffs are ~100–120 m high. The extensive cracking and fresh slump scarps associated with the largest of these failures are clearly shown in Figure 21. The incomplete nature of the failure suggests that the slope was close to its natural angle of repose (30-35°) for the level of shaking that occurred during the earthquake. Further studies involving topographic, geomorphic, and geological mapping, material sampling and laboratory index and shear testing, and seismic monitoring would enable the slope failure mechanism at this site to be better defined and understood, and the extent to which geological and topographic effects (slope height, angle, and shape) influenced the strength of earthquake shaking and the failure process.

A number of small debris falls also occurred on the cliffs west of Mussel Point and north of Lake Grassmere, but no significant landslides were seen in that area. However, after returning from the flight we became aware through news media reports of landslides that occurred near Black Birch Stream in the Awatere Valley about 15 km southwest of Seddon (Figure 15). Some of these landslides were photographed during the earthquake by local resident Melinda Price, the largest of which is a rotational collapse of a ~20 m high terrace edge on the right bank of the Awatere River involving mudstone and overlying weathered gravels (Figure 22). Dust clouds from similar failures downstream are shown in Figure 23.

Figure 22 Rotational slump *(sl)* in Tertiary mudstone *(m)* and gravels *(g)* on the edge of a ~20 m high terrace on the right bank of the Awatere River *(AR),* ~15 km southwest of Seddon *(Photo M. Price, 21 July 2013)*.

Figure 23 Dust clouds from earthquake-triggered landslides *(L)* on terrace edges in the Awatere Valley southwest of Seddon *(Photo M. Price, 21 July 2013).*

3.2 DAMAGE TO IRRIGATION DAM

The reconnaissance flight also allowed us to inspect a 19 m high irrigation dam that was damaged by the 21 July earthquake. Figure 10 shows the location of the dam at the end of Haldons Road, about 11 km southwest of Seddon. Figure 19 and Figure 20 show the dam and the damage that occurred after the ~300,000 m^3 reservoir had been partly emptied because of concern about its stability and the possibility that the dam might fail during a future earthquake. Draining of the lake was stopped after engineers determined the dam to be safe.

Figure 24 Aerial view of the 19 m high earth dam which was slightly damaged during the earthquake, with a crack about 75–100 mm wide forming on the upstream side crest of the dam crest (cr). No other signs of damage to the structure were seen during the inspection, although a small earth slump (sl) on the access track on the right abutment appears to have been reactivated by the earthquake *(D. Bell pers. comm.).*

Figure 25 Closer view of the cracking *(cr)* on the upstream side of the dam crest, and a small slump *(sl)* on the edge of the right bank access track. The downstream face of the dam does not appear to be damaged.

4.0 EARTHQUAKE SHAKING AND GROUND DAMAGE DISTRIBUTION

The overall distribution of landslide and liquefaction damage caused by the M_L 6.5 Cook Strait earthquake are plotted on a Modified Mercalli (MM) shaking intensity map derived using the attenuation model of Dowrick and Rhoades (2005) attenuation model, along with the highest peak ground accelerations (pga) recorded during the earthquake.

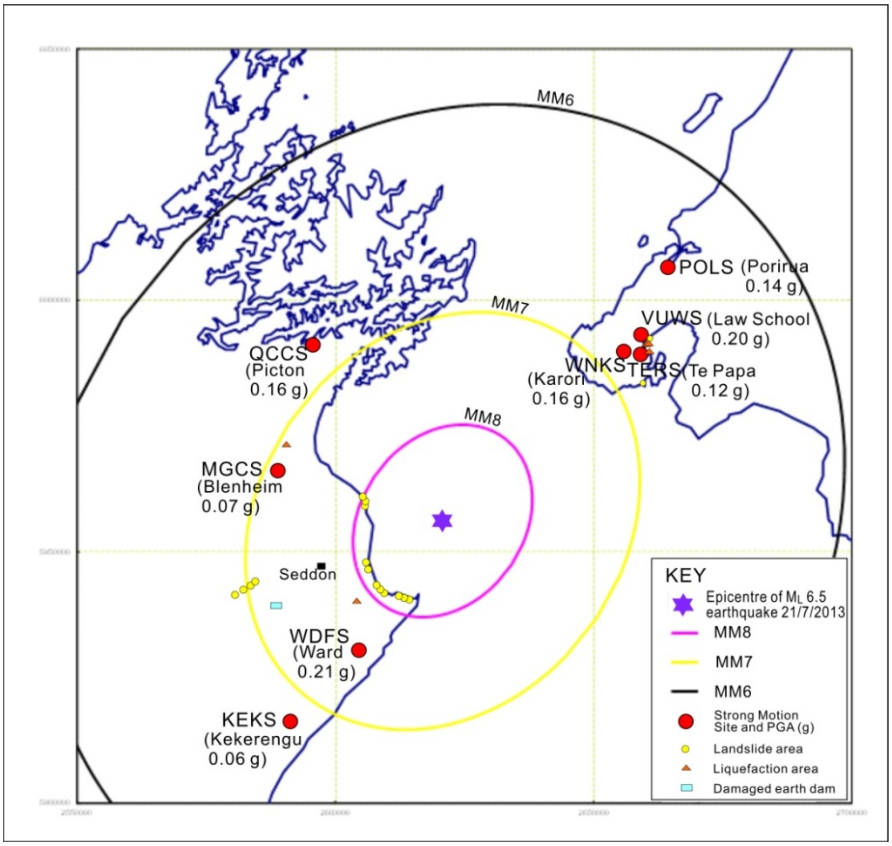

Figure 26 Maximum recorded peak ground accelerations (pga) and modelled Modified Mercalli (MM) shaking intensity map for the M_L 6.5 Cook Strait earthquake on 21 July 2013 based on the Dowrick and Rhoades (2005) attenuation function. The approximate locations of the main landslide and liquefaction areas and the damaged earth dam discussed in this report are also shown.

Figure 26 shows that most of the landslides and liquefaction effects occurred within the modelled MM8 and MM7 isoseismals, although some damage, such as in Wellington Harbour, the west side of Lyall Bay, and the middle Awatere Valley, occurred at MM6.5 to MM7, about 35 to 55 km from the epicentre. The most numerous and largest landslides which occurred on the coastal cliffs from Cape Campbell to White Cliffs, are on the edge of the MM8 isoseismal zone, about 16 km from the epicentre.

In general, the number and size of landslides triggered by the earthquake is at the lower end of what can normally be expected, i.e., it is threshold event, for a shallow magnitude 6.5 earthquake based on studies of co-seismic landsliding in New Zealand (Hancox *et al*., 1997, 2002; Dowrick *et al*., 2008). This may be partly due to the fact that the earthquake was 15 km off shore and ~13 km deep (some GeoNet reports state 18 km), but it may also reflect the fact that slopes in the area are less susceptible to failure for the level of shaking that occurred. The maximum pga recorded during the earthquake was 0.21 g at Ward but only one small slope failure was observed in that area (Figure 15 and Figure 26). This suggests that slope angle and height, and material susceptibility influenced the limited distribution and severity of the landsliding and liquefaction effects caused by the earthquake.

5.0 CONCLUSIONS

1. Field inspection and surveying carried out on 23 July 2013 showed that the M_L 6.5 Cook Strait earthquake on 21 July 2013 caused extensive slumping and ground cracking with minor sand ejection over a ~50,000 m^3 area of 1970s reclamation fill at the CentrePort Wellington Container Storage Area. The earthquake also caused sand boils in shallow water and small earth falls at Kaiwharawhara Point, minor cracking on the wharf promenade at Te Papa, and a small rock fall on old quarry slope on the western side of Lyall Bay.

2. The liquefaction effects that occurred during the 21 July 2013 Cook Strait earthquake are the most extensive recorded in the Wellington City area since the 1855 and June 1942 Wairarapa earthquakes. The liquefaction damage observed at the Container Storage reclamation area in Wellington Harbour is a timely reminder of the type of effects that could occur in reclaimed areas, especially during a magnitude 7.5 earthquake on the Wellington Fault, the subduction zone interface, or other active faults in the Wellington area. The damage that occurred suggests that reclamation fills are vulnerable to lateral spreading and collapse due to liquefaction of the underlying unconsolidated harbour silts and muds.

3. A helicopter reconnaissance flight was undertaken on 25 July 2013 to locate and photograph landslides and other ground damage caused by the earthquake. The landsliding that occurred was restricted mainly to the steep (35°) coastal cliffs within ~15 km of the epicentre, and terrace edges in the middle Awatere Valley. Only one small rock fall occurred on the south coast of Wellington 40 km northeast of the epicentre.

4. The largest landslide that occurred was a ~100,000 m^3 rotational slide on the mudstone cliffs 1 km west of Cape Campbell. A number of debris falls occurred on White Bluffs and other similar cliffs, but most of these were relatively small (10-1000 m^3) failures. A 19 m high earth dam 12 km southwest of Seddon was slightly damaged (cracking on the upstream side of the dam crest) by the earthquake.

5. Most of the coseismic landslides are on the coastal cliffs on the edge of the MM8 isoseismal zone, about 16 km from the epicentre. The number and size of landslides that occurred during the earthquake is at the lower end of what can be expected for a shallow magnitude 6.5 earthquake in New Zealand. It is regarded, therefore, as a threshold event for earthquake-induced landsliding in the Wellington and Marlborough areas.

6. The relatively limited landsliding and liquefaction damage caused by the earthquake is probably partly due to the fact that the earthquake was ~15 to 50 km from the affected areas, and at least 13 km deep (some GeoNet reports give a depth of 18 km). It may also reflect the fact that slopes in the area are less susceptible to failure for the maximum level of ground shaking that occurred (pga 0.21g at Ward). Slope angle, slope height, and material susceptibility appear to have strongly influenced the limited distribution and severity of both the landsliding and the liquefaction effects caused by the earthquake.

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