LANDSLIDES CAUSED BY THE 22 FEBRUARY 2011 CHRISTCHURCH EARTHQUAKE AND MANAGEMENT OF LANDSLIDE RISK IN THE IMMEDIATE AFTERMATH

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ABSTRACT

At 12.51 pm (NZST) on 22 February 2011 a shallow, magnitude M_W 6.2 earthquake with an epicentre located just south of Christchurch, New Zealand, caused widespread devastation including building collapse, liquefaction and landslides. Throughout the Port Hills of Banks Peninsula on the southern fringes of Christchurch landslide and ground damage caused by the earthquake included rock-fall (both cliff collapse and boulder roll), incipient loess landslides, and retaining wall and fill failures. Four deaths from rock-fall occurred during the mainshock and one during an aftershock later in the afternoon of the 22nd. Hundreds of houses were damaged by rock-falls and landslide-induced ground cracking.

Four distinct landslide or ground failure types have been recognised. Firstly, rocks fell from lava outcrops on the Port Hills and rolled and bounced over hundreds of metres damaging houses located on lower slopes and on valley floors. Secondly, over-steepened present-day and former sea-cliffs collapsed catastrophically. Houses were damaged by tension cracks on the slopes above the cliff faces and by debris inundation at the toe of the slopes. Thirdly, incipient movement of landslides in loess, ranging from a few millimetres up to 0.35 metres, occurred at several locations. Again houses were damaged by extension fissuring at the head of these features and compressional movement at the toe. The fourth mode of failure observed was retaining wall and fill failures, including shaking-induced settlement and fill displacement. These failures commonly affected both houses and roads.

In the days and weeks immediately following the earthquake a major concern was how to manage the risks from another large aftershock or a long return period rainstorm, in the areas worst affected by landslides, should one occur. Each of the four identified landslide types required a different risk management strategy. The rock-fall and boulder roll hazard was managed by identifying buildings at risk and enforcing mandatory evacuation. In the days immediately following the earthquake this process was based on expert opinion. In the weeks after the earthquake this process was rapidly enhanced with empirical data to confirm the risk. The rock-falls associated with cliff collapse were managed by evacuating properties damaged by extensional ground cracking at the top of the cliffs, adjacent properties, and properties damaged by debris inundation at the toe of the cliffs. The incipient landslide hazard was managed by rapidly deploying movement monitoring technologies to determine if these features were still moving and to monitor their response to on-going aftershock activity. The fill and retaining wall failures were managed by encouraging public reporting of areas of concern for rapid assessment by a geotechnical professional.

The success of the landslide risk management strategy was demonstrated by the magnitude M_W 6.0 earthquake of 13 June when rock-falls and boulder roll damaged evacuated buildings and ground cracking and debris inundation further damaged evacuated areas. Some incipient landslides reactivated, producing similar movement patterns to the 22 February 2011 earthquake. Several retaining walls identified as dangerous and cordoned off also collapsed. No lives were lost and no serious injuries were reported from landslides in the 13 June 2011 earthquake.

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INTRODUCTION

A shallow M_w 6.2 earthquake severely shook Christchurch, New Zealand, at 12:51 pm on 22 February, 2011 (NZ Standard Time). This earthquake, now called the Christchurch earthquake, has a hypocentral location beneath the Heathcote valley in the Port Hills on the southern fringe of Christchurch (Fig 1) (e.g. Kaiser et al. in press), and is the largest aftershock, to date, of the Canterbury earthquake sequence which began on 4 September, 2010, with the M_w 7.1 Darfield earthquake (e.g. Gledhill et al. 2010, 2011, Quigley et al. 2010a). Unlike the larger, but more distant, September, 2010, Darfield earthquake, the 22 February, 2011, Christchurch earthquake caused widespread landslides in the Port Hills (e.g. Hancox et al. 2010). For the purposes of this paper the Port Hills is defined as the area between the suburbs of Cashmere and Governors Bay, and Godley Head on the northern side of Lyttelton Harbour (Fig 2). Although landslides (mostly rock-fall) were reported elsewhere in Banks Peninsula during the February earthquake they are not discussed further as they caused only minor damage to roads and were generally small in size. By far the most intense landslide damage was in the Port Hills area and it is this damage that is the focus of this paper.

In the hours following the 22 February 2011 Christchurch earthquake it became apparent that landslides were the source of widespread damage in the Port Hills. Landslide response efforts were initiated by three separate groups including Urban Search and Rescue (USAR) geotechnical specialists, the Port Hills Geotechnical Group (PHGG - comprising representatives from all the major geotechnical consultants based in Christchurch and the geology and engineering departments of the University of Canterbury), and the GNS Science Landslide Response Team. Initial efforts focussed on determining the types of slope instability that had occurred through a combination of aerial and ground reconnaissance. Within two-three days of the earthquake co-ordination was established between the three groups. USAR geotechnical specialists took the lead on victim recovery and public safety (as they operate under New Zealand Fire Service legislation). The PHGG assigned sectors to each of the contributing geotechnical consultancies to assist with public enquiries received via the Christchurch City Council and any other site specific issues that arose, along with systematic mapping of rock-falls, incipient landslides and other ground failures. The GNS Science Landslide Response Team (funded by the Earthquake Commission through the Geonet Project) undertook general reconnaissance, provided technical support and equipment for landslide monitoring and processed remotely sensed data to make it available to the wider group.

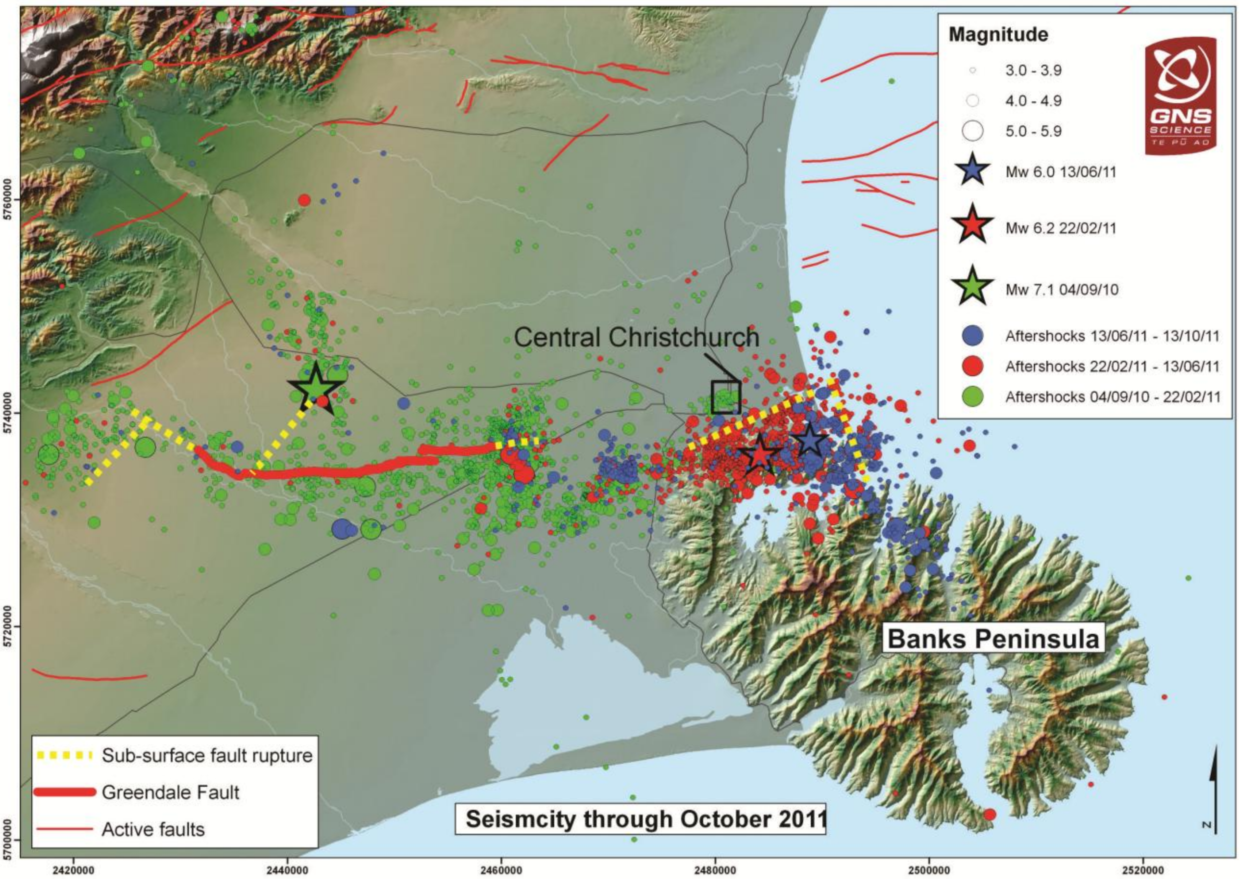

Figure 1: The Canterbury earthquake sequence from 4 September, 2010, through to mid-October 2011 (epicentre locations from GeoNet, www.geonet.org.nz). Red star denotes the epicenter of the M_w 6.2 Christchurch earthquake (e.g. Kaiser et al. in press), the largest aftershock, to date, of the sequence. Green star shows the location of the 4 September, 2010, Darfield earthquake (e.g. Gledhill et al. 2010, 2011), the main shock of the sequence, which generated about 30 km of surface rupture on the Greendale Fault (bold red line) (Quigley et al. 2010b, 2012, Barrell et al. 2011). Surface projection of buried ruptures associated with the Darfield earthquake (Beavan et al. 2010, Holden et al. 2011), the Christchurch earthquake (Beavan et al. 2011) and the preliminary result for the M_w 6.0 June aftershock (Beavan, pers. com.) are shown as yellow dashed lines. The Port Hills of Bank Peninsula are obscured by the cloud of aftershocks generated by the M_w 6.2 Christchurch earthquake and the M_w 6.0 June event (red and blue dots, respectively). Surface traces of other on-land active faults (thin red lines) are from Forsyth et al. (2008) and GNS Active Faults Database: http://data.gns.cri.nz/af/). Coordinates are New Zealand Map Grid (m).

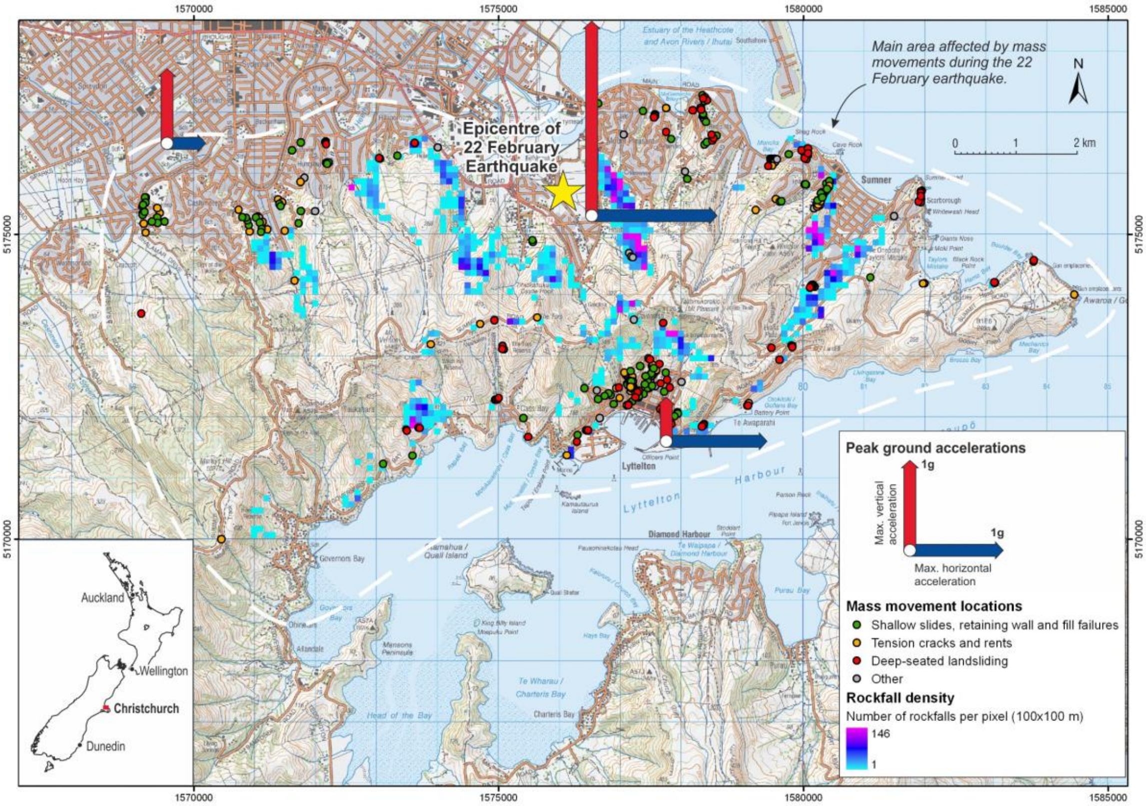

Figure 2: ***Rock-fall (boulder roll) density in the Port Hills of Christchurch following the 22 February 2011 earthquake.***

A variety of different landslide types were observed during and after the earthquake. This paper describes the four main types of landslide failure that occurred as a result of the earthquake, namely rock-fall associated with long-distance boulder roll, rock-fall associated with cliff collapse, incipient landslides in loess deposits, and retaining wall and fill failures. Initial efforts to manage the risks arising from the range of landslide hazards are described. The Christchurch earthquake generated very strong to extreme levels of ground shaking in the Port Hills (Fig. 2). Recorded peak ground accelerations at the four strong motion recorder sites in, or immediately adjacent to, the Port Hills ranged from 0.3g-1.4g (horizontal), and 0.4g-2.2g (vertical) (e.g. Bradley and Cubrinovski 2011, Kaiser *et al.* in press). Initial work on shaking intensities suggests that the intense landslide damage is associated with a peak ground acceleration (pga) of greater than 0.4g and a Modified Mercalli (MM) shaking intensity of MM8 to MM9 (Hancox *et al*, 2011; Bradley and Cubrinovski, 2011).

ROCK-FALL (BOULDER ROLL)

The rock-falls caused by the 22 February earthquake had two very distinct failure modes. The first mode is where individual joint-controlled lava blocks were dislodged from lava flow outcrops often high up on the slopes of valleys and bluffs in the Port Hills (Figs 2-6). Once dislodged these blocks could in some cases roll, bounce and slide hundreds of metres before coming to rest, either as the slopes flattened out, or at the bottom of valleys. Individual boulders ranged in size from less than 0.1 m^3 to more than 10 m^3. Blocks dislodged from lava flows with joint spacing greater than one metre tended to be slightly more rounded (Fig 3, Fig 5b) than blocks dislodged from more closely jointed outcrops (Fig 6).

Unfortunately for the residents of the Port Hills, many homes are located on lower slopes or on valley floors adjacent to the valley walls and were damaged or destroyed by displaced boulders (Fig 3, Fig 5a). No-one was killed by these rock-falls, probably because the earthquake occurred shortly after midday when many of the homes were unoccupied as residents were at their place of work or school.

Figure 3: ***Boulder damage to a house in Morgans Valley, Christchurch following the 22 February 2011 earthquake.***

Figure 4: ***The source area for the boulders that fell and rolled in the upper part of the Heathcote Valley (Morgans Valley) (Figure 3) is the lava outcrops immediately below the skyline crest. Note the large distances to the houses, some hit by boulders, on the valley floor.***

(a)

(b)

Figure 5: ***(a) Rolling boulder damage to a house in Rapaki. The house was struck by four separate boulders, one of which smashed right through the house. Note the boulder bounce impact crater in front of the house. (b) The final resting place of the large boulder (~15 m^3) that smashed right through the house in (a) above. The source area for the boulders was the bluffs near the summit of the peak visible above the house.***

Areas worst affected by this mode of rock-fall included the Avoca Valley, Bowenvale Valley, Horotane Valley, Heathcote and Morgans Valleys, Sumner, Summit Road below Mt Cavendish, Sumner Road, Lyttelton, Rapaki and Governors Bay Road between Rapaki and Governors Bay (Fig. 2).

In the immediate aftermath of the 22 February earthquake, one of the potential hazards that was identified and that needed prompt mitigation was the risk of more boulders falling as the result of an aftershock. USAR geotechnical specialists, the PHGG and the GNS Science Landslide Response Team worked to identify hazardous areas so that at risk properties could be evacuated. Initially this identification was based on expert knowledge. Subsequently, the hazard evaluation process for rock-fall and boulder roll has become more empirically based and constrained by extensive data sets collected after the event.

The prudence of this effort was demonstrated in the 13 June 2011 aftershock which dislodged hundreds more boulders in the Port Hills, particularly in the Sumner area. These boulders either further damaged already damaged houses or caused damage to houses that were undamaged after the February earthquake but which had been evacuated because of the perceived risk. As a result no-one was killed or injured by rock-fall in the 13 June 2011 earthquake.

ROCK-FALL (CLIFF COLLAPSE)

The second mode of rock-fall failure in the 22 February earthquake was cliff collapse. This occurred at coastal cliffs, former (Holocene) coastal cliffs, former quarry faces and steep bluffs further inland. The cliff collapses were characterised by large volumes of debris (thousands of cubic metres). The hazards associated with these cliff collapses included incipient cracking, often with differential vertical displacement and minor extension behind the top of the failed cliff faces, as well as a debris inundation hazard at the base of the cliff face.

Five people were killed by cliff collapse. Two of the deaths were individuals outdoors in the debris accumulation zone at the time of the earthquake, while a third victim was killed in a house destroyed by falling debris. Two further deaths occurred in the Lyttelton area to individuals who were outside in open spaces when rock bluffs collapsed. One of the Lyttelton fatalities occurred as the result of a rock-fall some four hours after the mainshock, presumably precipitated by an aftershock.

Urban areas affected by the cliff collapses include the cliff face at Peacocks Gallop between Sumner and Moncks Bay (Fig 7), the cliff behind the Sumner Returned Services Association (RSA) (the collapse extended a few tens of metres either side of the RSA building), the cliff at Whitewash Head in Scarborough (Fig 8) and the cliff face behind Redcliffs which extended several hundred metres (Figs 9 and 10). The steep bluffs and escarpments behind Lyttelton also collapsed in several places, with debris accumulating at the toe of the bluffs.

Figure 6: Rock-falls from the steep bluffs below Mt Cavendish blocked the Summit Road. The Summit Road and Armco barrier acted as a partial catch-bench for rock-fall debris. The size distribution and angularity of the rocks on the Summit Road reflects the more closely jointed nature of the source area compared to the lava flow above the Heathcote Valley (Figs 3 and 4).

Figure 7a: Cliff collapse at Peacocks Gallop between Sumner and Moncks Bay. This photo shows the extent of the fresh debris on the talus apron after cliff collapse at this site following the 22 February 2011 earthquake.

Figure 7b: Additional cliff collapse at Peacocks Gallop following the 13 June 2011 earthquake. The debris accumulation at the western end of the cliff was much greater following the 13 June event which resulted in at least 15 metres of cliff-top retreat, undermining at least one house. Risk mitigation measures put in place after the 22 February earthquake (house evacuations for the properties at the top of the cliff and the rock-fall barrier of ballasted containers at the toe of the cliff) meant there was little disruption to recovery activities because of the additional collapse at this site on 13 June.

Houses that were damaged by incipient cracking at the head of the cliff collapse areas and those that were damaged by debris inundation at the foot of the cliffs were evacuated. Temporary barriers against rock-fall, consisting of initially a single height row of ballasted containers, were installed, for example, below Peacocks Gallop (Fig 7) and along Wakefield Avenue in Sumner to provide greater route security (in June the containers were raised to a double height row). Again these measures prevented further loss of life and provided protection to key transport routes from the additional cliff collapse rock-falls caused by the 13 June aftershock. In addition all public walking tracks in the Port Hills area administered by the Christchurch City Council Parks Department or the Department of Conservation were closed to the public.

As part of the recovery process the long-term viability of properties above and below the cliff collapse rock-fall sites are being assessed on a life-safety basis to ensure that the hazard is appropriately mitigated. It is worth noting that rock-fall barriers (catch-fences) installed prior to the earthquakes at the base of cliffs in Redcliffs and Heathcote Valley were overwhelmed by the quantity of debris coming off the cliff face.

The use of light detecting and ranging (LIDAR) topographic data both from aerial and terrestrial based acquisition systems has allowed the accurate determination of the volumes of material coming off the cliff faces in response to specific aftershocks. This has allowed areas of movement and loose material to be identified for treatment to reduce the hazard.

INCIPIENT LARGE LANDSLIDES

The third type of landslide observed after the major Christchurch earthquake of 22 February 2011 was incipient landslide failure. These landslides were characterised by tension cracks with small amounts of vertical displacement in the head-scarp area and compressional features near the toe areas. Incipient landslides have been identified in both loess overlying volcanic materials (Fig 11) and in deep surficial loess inter-bedded with marginal marine sediments adjacent to former sea cliffs. The initial horizontal and vertical displacements across the tension cracks in the head-scarp regions were less than one metre (Figs 11 to 16). Similar amounts of movement were seen across compressional features at the toe of these landslides (Figs 17 and 18). Several of these landslides moved in later aftershocks, such as 13 June 2011, but the cumulative displacements across the tension cracks still rarely exceed one metre. None of these incipient large landslides have yet failed catastrophically during aftershocks.

No-one was killed or injured by these landslides. Their primary impact was to irreparably damage large numbers of houses. Houses straddling the tension cracks at the head of the landslides were pulled apart by the deformation (Fig 15), while those in the toe area shortened due to compressional damage (Figs 17 and 18). Houses located within the landslide (i.e. between the head-scarp and the toe) were undamaged or suffered minor tilting and distortion (twisting). The large area involved in some of these landslides resulted in tens of houses being affected at some sites.

Examples of incipient landslides include Kinsey Terrace (Clifton), Bridle Path Road (Heathcote), Vernon Terrace (Hillsborough), Egnot Heights and Defender Lane (Redcliffs), Ramahana Road (Huntsbury) and Maffeys Road (McCormacks Bay). Each landslide appears unique and the result of different geological conditions. For example, the Maffeys Road landslide has occurred in an area where slope stability problems have previously occurred during heavy rainfall events. The Bridle Path Road landslide extends for hundreds of metres with the head-scarp above the road, either

Figure 8a: ***Ground cracking on the cliff top at Whitewash Head, Scarborough after the 22 February 2011 earthquake. This crack is visible in front of the blue-roofed house in the upper left of Figure 8b.***

Figure 8b: ***Cliff-top homes at Whitewash Head, Scarborough are buffered from the cliff edge by the Sumner-Taylors Mistake walkway. After the 22 February 2011 earthquake incipient cracking developed in the walkway zone. As a result residents evacuated homes bordering the walkway reserve.***

Figure 8c: ***The cliff-top at Whitewash Head, Scarborough following the 13 June 2011 earthquake. The cliff top has collapsed along the line of the incipient crack visible in Figure 8b above.***

behind or through the row of houses immediately adjacent to the road and the toe area apparent on the downhill side of the road. This landslide is analogous to the Vernon Terrace landslide and other toe-slope failures with liquefaction (or almost liquefaction) inferred at the toe, followed by cracking and movement in the head area. Damage from movement of the Vernon Terrace landslide was first observed after the Darfield Earthquake of 4 September 2010. It subsequently reactivated after the Christchurch earthquake of 22 February 2011. One postulated explanation for this is that the toe of the Vernon Terrace landslide was 'buttressed' by saturated marginal marine sediments that may have liquefied during the 22 February 2011 earthquake, and because the strength recovery in these sediments occurred over a period of days, if not weeks, this allowed the landslide to continue moving. This inferred loss of strength in the toe buttress materials may also explain the landslide movement observed at Vernon Terrace after the 4 September 2010 Darfield earthquake.

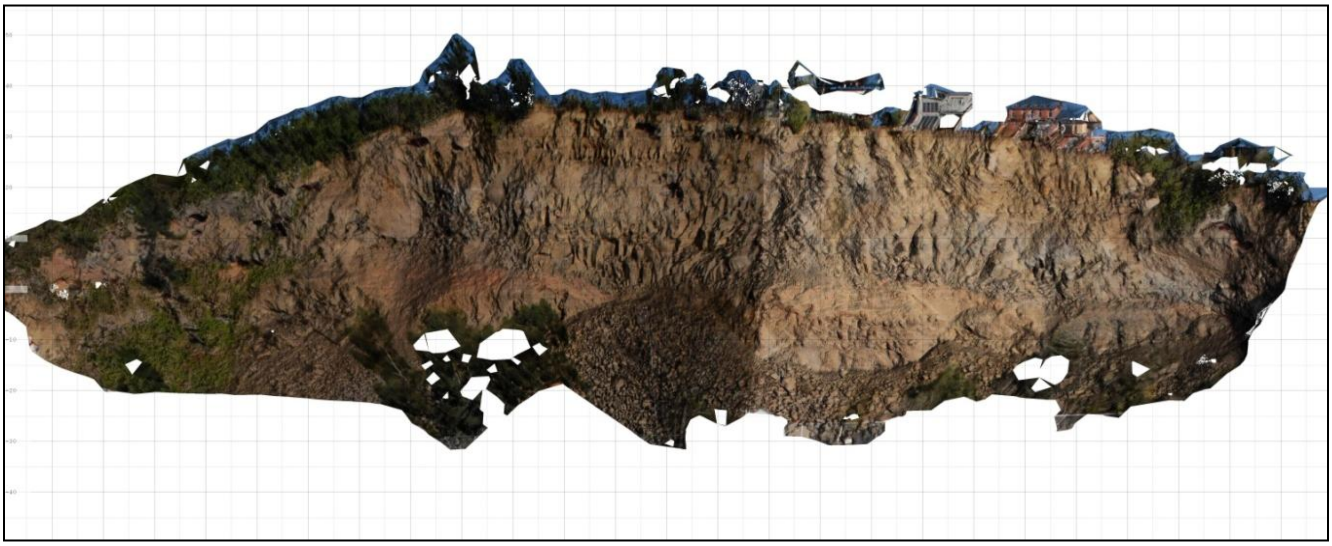

Figure 9a: ***A true colour image of the cliff behind Redcliffs captured using a terrestrial laser scanner. This image was taken after the 13 June 2011 earthquake.***

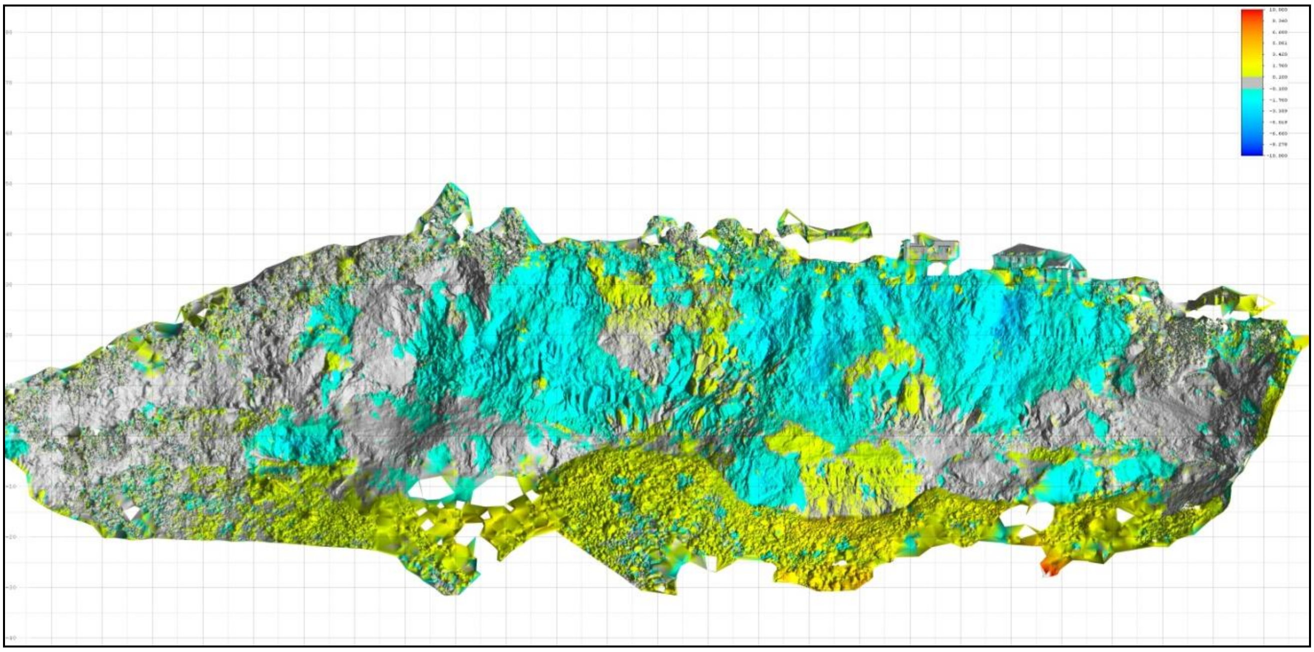

Figure 9b: ***A differencing image of the cliff behind Redcliffs created by comparing terrestrial LIDAR images from before and after the 13 June 2011 earthquake. Blue represents areas where material has fallen from the cliff face, while yellow and red show areas where material has accumulated.***

Figure 10: ***The cliff behind Redcliffs taken shortly after the 22 February 2011 earthquake. In the bottom centre is the cul-de-sac at the end of Raekura Place. Two of the five rock-fall fatalities occurred here.***

Tonkin and Taylor on behalf of the Earthquake Commission are carrying out ground investigations at these landslides to characterise the engineering geological models so their likely long-term behaviour can be fed into risk models to determine the appropriate mitigation at these sites for recovery purposes.

In the weeks immediately following the 22 February 2011 earthquake the key task in response to these landslides was setting up monitoring regimes appropriate to the risks posed by the individual landslides. This involved a combination of ground survey networks, continuous GPS (cGPS) installations, and strong motion instruments. The sophistication of the installed monitoring also increased over time with simple string lines being used in the days immediately after the earthquake (Fig 12) while more advanced resources were sourced for deployment to critical sites (Figs 13 and 14). The monitoring results indicated a variety of movement patterns with some landslides only moving in response to strong shaking (e.g. Kinsey Terrace) while others appeared to creep for some time after the 22 February earthquake (e.g. Bridle Path Road).

An interesting observation made in relation to tension cracks in the head-scarp area of these landslides was that they widened in the days after the earthquake. Two different causes were observed for this, a) continuing creep movement (e.g. Vernon Terrace and Bridle Path Road where tension cracks in the head-scarp area of the landslide continued to widen in the days and weeks after 22 February 2011) or b) collapse of graben walls into the graben cavity thus widening ground cracks as vertical ‘graben’ walls adjust to a more stable angle (e.g. Kinsey Terrace). Evidence for the continuing creep movement was provided by the increasing deformation of buildings straddling the tension cracks. In contrast, cGPS monitoring showed no creep at Kinsey terrace.

Figure 11: ***An aerial view of the Kinsey Terrace landslide on Clifton Hill. A large tension crack is visible across Kinsey Terrace in the foreground. The crack extends towards the left hand side of the orange tile-roofed house on the northern side of the road and towards the red roof just visible in the lower right of the photo.***

Figure 12: ***The tension crack of the Kinsey Terrace landslide crossing Kinsey Terrace. Note the initial crack monitoring consisting of two 10 mm diameter steel pins and builder's string installed 36 hours after the earthquake.***

Figure 13: ***Tension crack and temporary continuous-GPS installation on the Kinsey Terrace landslide.***

Figure 14: ***Permanent continuous-GPS installation on the Kinsey Terrace landslide at the same site as the temporary continuous-GPS in Figure 13.***

Figure 15: ***Foundation damage to the red-roofed house partially visible in Fig 11 (lower right) was caused by tension cracks.***

Figure 16: ***Tension crack at the head of the Vernon Terrace landslide in Hillsborough on possible pre-historic head-scarp.***

Figure 17: ***Compressional ridge of the toe of the Vernon Terrace landslide in Hillsborough.***

Figure 18: ***Compressional cracking of curb and channel at the toe of the Vernon Terrace landslide in Hillsborough.***

Figure 19: ***Gabion and geogrid retaining wall failure in the Redcliffs area.***

Figure 20: ***Concrete crib retaining wall failure, Mt Pleasant Road, Mt Pleasant. The retaining wall has not collapsed but has bulged outward allowing the fill behind the retaining wall to settle destroying the curb and channel and footpath.***

Figure 21: ***These retaining walls in Glendevere Terrace, Redcliffs showed contrasting behaviour. The anchored pole retaining wall in the foreground performed well. The bulging timber crib retaining wall next to it performed poorly in the 22 February 2011 earthquake and was cordoned off. It subsequently failed catastrophically in the 13 June 2011 aftershock.***

FILL AND RETAINING WALL FAILURES

The fourth type of ground failure observed after the 22 February 2011 earthquake was widespread but minor failures of retaining walls and the settlement of poorly compacted fills. These failures were usually small (< 100 m^3) but ranged from incipient cracking of a few millimetres (Fig 19) to extensive deformation of retaining walls (Figs 20 and 21) through to catastrophic collapse of retaining walls (Fig 22).

These failures were widespread throughout the Port Hills area but were particularly noticeable in the Mt Pleasant area and through the older part of Lyttelton. Other areas affected by this type of failure included the upper part of Clifton Terrace, the slopes above the Heathcote Valley, the higher parts of Redcliffs, Hillsborough, Huntsbury and Cashmere. Minor fill failures were also observed on the rural roads of the Port Hills.

Although these failures were widespread, the damage they caused was often very limited in extent as the fills were small (< 100 m^3) and damage was confined to one or two properties or half the outside lane on the road network (Figs 19 and 20). The same applies to retaining wall and stonework failures. Older lava block stonework facings in front of loess cuts in Lyttelton suffered badly with numerous collapses. Elsewhere crib walls (both timber and concrete) performed poorly while anchored pole walls performed well (Fig 21).

The widespread distribution of these types of failures and the limited damage they caused meant they were not perceived to be a life-safety risk in the immediate aftermath of the earthquake. Where unstable areas were encountered, for example a badly deformed retaining wall in Glendevere Terrace above Redcliffs (Fig 21), they were cordoned off to manage the hazard and its consequent risks. The Port Hills Geotechnical Group relied on public enquiries to provide notification of sites where fills and retaining walls were damaged. Once notification was received the Port Hills Geotechnical Group organised for each location to be assessed by a geotechnical practitioner to assess the nature of the hazard and to make any recommendations to mitigate the immediate risk.

As the authorities moved into the recovery phase it was decided that the limited size and localised nature of these ground failures could be left to the insurance companies and road network operators to remedy as they posed no ongoing wide-spread threat to property or public safety, unlike the three landslide types described earlier.

Figure 22: ***Collapse of concrete crib retaining wall in Soleares Ave., Mt Pleasant.***

DISCUSSION

It quickly became apparent that the rock-fall and boulder roll hazard posed a major risk should a large aftershock occur. The extent of the cliff collapse rock-fall hazard and the ground cracking associated with incipient landslides were both able to be areally limited by direct observation and mapping. In contrast, the rock-fall boulder roll hazard was considered a risk to life-safety as it threatened houses and lifelines (roads) that were undamaged after the 22 February 2011 earthquake and often tens to hundreds of metres from the rock-fall source areas. Consequently effort was put into evacuating residents from high-risk properties, initially on the basis of expert opinion, and setting up the bureaucratic mechanisms to allow the evacuated residents to access insurance resources even though in most cases their houses were undamaged by rock-fall and structurally sound. As time went on the process for evaluating the rock-fall and boulder roll hazard and the consequent risk to life and property became more empirical and was based on data collected on potential boulder source areas and likely travel paths and distances. The initial assessments made by the geotechnical practitioners have in most cases proved accurate. Roads were protected by the placement of ballasted containers such as at the northern entrance to the Lyttelton tunnel below Castle Rock. The rock-fall and boulder roll that occurred during the earthquake of 13 June 2011 demonstrated the necessity for the evacuation of properties and other mitigation measures.

The risk management for the cliff collapse rock-fall involved evacuating any houses affected by tension cracking in the head-scarp areas at the top of the cliffs, evacuating properties at the toe of the cliffs where they had been impacted by rock-fall debris in the February earthquake, and providing a buffer of at least one property. The cliff collapse hazard below the cliff at Peacocks Gallop saw the construction of a bund of ballasted containers to provide route security in the event of another aftershock. A similar ballasted container bund was also put in place along Wakefield Avenue in Sumner to provide route security.

The risk management of the incipient landslides was a two-pronged approach with the evacuation of residents from structurally compromised houses, either from tensional damage (being pulled apart) or compressional damage (being squeezed together). In addition monitoring of the landslides was commenced as soon as these landslides were recognised. Initially the monitoring consisted of simple pins connected across tension cracks by string, but this quickly evolved as resources became available. The installation of continuous-GPS receivers to provide continuous monitoring was initially on a temporary basis but within six weeks semi-permanent installations had been built.

The short-term risk management of more localised fill failures and retaining wall collapses was based on the results of reconnaissance work identifying that these were small failures, but widely dispersed throughout the Port Hills. The risk management strategy that developed was to respond to requests from the public to the Christchurch City Council for a geotechnical assessment if a property owner or occupier was concerned about ground damage to a property. This ground failure hazard was assessed as presenting the lowest on-going risk and the management strategy for this hazard has proven appropriate to date.

As part of the recovery process the long-term viability of properties in the Port Hills is being assessed using a risk-based methodology to calculate risk to life-safety on an annual basis. The results of this methodology will provide a measure that will allow the life-safety risk to be assessed as acceptable, tolerable or unacceptable. The annual life-safety risk values to be used as boundaries between the three risk-categories will be set by the Christchurch community taking into account internationally accepted values.

Mitigation could range from withdrawal from a site through to the installation of appropriately designed and rated physical barriers to reduce the risk to an acceptable level or, if the risk is deemed low enough, do nothing. This work is currently in progress.

SUMMARY

At 12.51 pm (NZST) on 22 February 2011 a shallow magnitude M_W 6.2 earthquake with an epicentre located on the southern fringe of Christchurch, New Zealand, caused widespread devastation. The damage caused by the earthquake included two distant types of rock-falls, incipient landslides, and retaining wall and fill failures throughout the Port Hills of Banks Peninsula on the southern fringes of Christchurch. Four deaths from rock-fall occurred in the main-shock and one in an aftershock later in the afternoon of the 22nd. Hundreds of houses were damaged by rock-falls and landslide-induced ground cracking.

Three groups, USAR geotechnical specialists, the Port Hills Geotechnical Group and the GNS Landslide Response team, rapidly developed a co-ordinated approach to identifying the landslide hazards and potential risks as a result of the 22 February 2011 earthquake.

This co-ordinated effort resulted in the evacuation (in many cases voluntarily) of several hundred properties in the Port Hills because of on-going landslide risks. The necessity and effectiveness of the landslide risk management was demonstrated on 13 June 2011 when another shallow, magnitude M_W 6.0 earthquake with an epicentre near Moncks Bay area caused widespread landsliding in the Port Hills, particularly in Redcliffs and Sumner. No-one was killed or injured by landslide activity in the Port Hills during this aftershock but evacuated buildings were destroyed or damaged.

ACKNOWLEDGEMENTS

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