Seismically induced displacement of land affecting multiple residential properties in the Port Hills, Christchurch, New Zealand, following the 2010/2011 earthquake sequence

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ABSTRACT

This paper presents a summary of land damage observed in the Port Hills of Christchurch, New Zealand, following the earthquake sequence of 4 September 2010, in particular the land damage associated with a period of high seismic activity which commenced in February 2011. The earthquakes that occurred in this period have been collectively termed the Canterbury Earthquake Sequence (CES), consisting of four main earthquakes causing land damage in the Port Hills and some 20 significant aftershocks.

In New Zealand, the Earthquake Commission (EQC) administers and assesses claims made under the Earthquake Commission Act 1993 for residential land damage from earthquakes, (and other events included in the Act).

During the initial steps in property land damage mapping and assessment in the Port Hills for the EQC, it became apparent that in some areas, land deformation and movement observed on individual properties may have been the result of a mechanism that extended across many adjoining properties. Ultimately 22 such areas were identified to EQC and the observations made in those 22 areas form the basis of this paper.

1 INTRODUCTION

The Canterbury Earthquake Sequence (CES) that commenced on 4 September 2010 resulted in significant land deformation to the Port Hills in Christchurch. The strong intensities of shaking resulted in the yielding of soils on slopes, rocks from cliff faces, and retaining walls. The New Zealand Earthquake Commission (EQC) insures specific residential land damaged as a result of certain natural disasters. Assessment of the damage to assist insurance claim settlement is required. The authors firm has managed assessment of land damage on properties on the Port Hills for EQC since September 2010. The mapping assessment and quantification of damage are discussed in Wallace (2013). During the initial stages of land damage mapping and assessment, it became apparent that many individual properties had land damage that was the result of a mechanism which extended across numerous properties. In total, 22 such areas were identified. These were labelled ‘Area Wide Assessment Areas’ (AWAA), which required a more detailed assessment and understanding of their failure mechanism to be developed. Investigations included walk over surveys, test pitting, rotary drilling with core recovery, cone penetration tests, piezometer and inclinometer installations and monitoring. This paper summaries observations and possible mechanisms of failure leading to deformation, made during these area wide investigations.

2 PORT HILLS GEOLOGY AND GEOMORPHOLOGY

The Port Hills (Forsyth et al, 2008) are comprised of a non-homogeneous sequence of strong basaltic lava flows which are interclasted with weaker scoria and pyroclastics, formed by main two volcanic centres (and other smaller volcanic centres) originating in the Miocene. While lavas have well developed cooling joints, breccias and ash are typically massive with only occasional joints. These volcanics are capped by loess, a windblown glacial silt, typically 1 to 20m thick. The lower slopes typically comprise loess colluvium, or reworked loess that has been eroded from the upper loess slopes and redeposited in the lower slopes, to form a wedge of soil at a lower slope angle than the in-situ loess slopes above. Loess and loess colluvium can be up to 50m thick at the base of the hills. Ridges and peaks on the hills have a thin cap of loess, with sporadic protruding volcanic rock. The flat land at the toe of slopes is typically comprised of alluvial silts, sands and deeper gravels, interbedded with marine deposits, such as beach sands.

A series of ridges and valleys trend out from the hill peaks, formed by volcanic lava flows and the incision from intermittent stream flows. Near vertical coastal cliffs have formed by marine erosion and seismic events, with cliff heights exceeding 100m in many places.

3 FAILURE MECHANISMS

There were four main failure mechanisms observed on the Port Hills that caused deformation of land to multiple adjoining properties, as a result of the CES. These range from the more severe cliff collapse, which cannot be remediated, to repairable slope displacements that caused cracked and compressed land, to the yielding of retaining walls. This section will discuss observations made during area wide assessments, summarising land deformation typical for each type of failure mechanism.

3.1 Cliff collapse

Land displacement initially occurred in the M6.2 Christchurch Earthquake of 22nd February 2011, with toppling of the rock mass being the main driver of tension cracks within loess, and the opening and formation of joints and fractures within the volcanic basalt, breccia and ash layers. This land deformation resulted in the evacuation of land (and in some cases, parts of residential structures) at the top of cliffs, and inundation of land by the settling debris at the base of cliffs. This type of land damage is mostly confined to the coastal suburbs of Sumner and Redcliffs.

Ground deformation is characterised by persistent tension cracks that trace generally parallel to cliff edges (Figure 1), and the formation of head scarps. These tension cracks opened further in subsequent aftershocks, particularly in the M6.4 earthquake on 13th June 2011, where some tension cracks that formed as a result of the 22nd February earthquake, became the location of the new cliff edge. Factors that have affected the individual site response include topographic amplification, seismic wave directionality, and the locali geology.

Figure 1: Tension crack traverses parallel to cliff edge along Whitewash Head showing the opening of the fractured volcanic lava and the overlying soil

It is thought that the toppling and sliding would have occurred on largely pre-existing fractures in the rock mass, with the likelihood that additional tension cracks also opened up back from the cliff as the rock mass dilated when shaken. There is evidence that amplification of seismic acceleration, of the order of 2 to 4 times that recorded locally, occurred on ridge crests. The relatively weathered state of the volcanic units on the outer cliff faces, where zones of cavernous weathering and marine undercutting were apparent, is likely to have facilitated tension crack development and subsequent failure under seismic loading. Figure 2 shows schematic sketches of typical cliff profiles, geology and possible cliff collapse mechanisms.

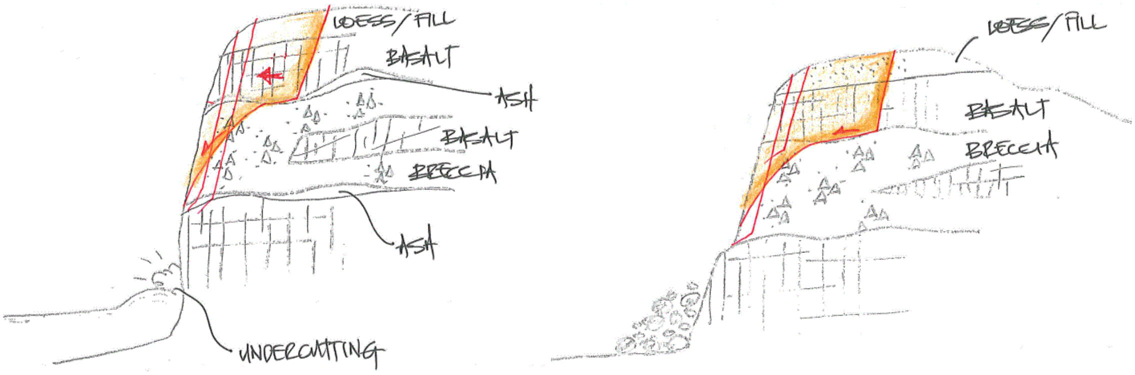

Figure 2: Schematic diagrams to show the failure mechanisms of cliff collapse

Cliff collapse has affected a number of residential properties, public, private and commercial land, with the loss of land at the top of the cliff, and deposition of fallen rock and soil debris at the base (Figure 3). Some structures have been affected as the retreating cliff edge has caused the dwelling foundations to be undermined, resulting in the partial collapse and loss of building structures over the edge of the cliff face (Figure 4), and the evacuation of private accessways, as shown in Figure 5. At the bottom of cliff faces, some buildings have also been damaged as a result of the fallen rock and soil material (Figure 6).

Figure 3: Cliff collapse at Redcliffs showing the large amount of rockfall material at the base of the cliff

Figure 4: A property above Peacocks Gallop (Main Road, Sumner) that has lost land and foundation support as a result of cliff collapse

Figure 5 (left): Cliff collapse resulting in the loss of access way to a dwelling on Whitewash Head

Figure 6 (right): Dwellings at the bottom of a failed cliff that were damaged by fallen rock debris

While some cliffs have experienced no or only a small volume of rock ejection from the cliff face and no regression of the cliff edge, others have had several meters of cliff edge regression, such as Whitewash Head which lost up to 30m of land. The lateral extent of tension cracking upslope of the cliffs is dependent on factors such as the topography, geology and distance from the epicentre, and can extend up to 550m in a semi continuous length. Tension cracks can extend up to 50m back from the cliff edge, with crack widths generally decreasing in offset with distance back from the cliff top.

3.2 Colluvial wedge deformation

Land displacement initially occurred in the M6.2 earthquake event of 22nd February 2011. Ground deformation observed is characterised by semi-continuous, stepped and en-echelon tension cracks (Figure 7 and Figure 8), either narrowly focussed or in a broader zone. These features are generally present at elevations ranging between relative level (RL) 10 m and RL 25 m and slope angles between 4 and 24° at the toe of the Port Hills. Down slope displacements from all seismic events were up to 670 mm, with lateral extents extending up to 850 m in any one area. Some AWAA's also exhibit compression features aligned in the same orientation as the tension cracks and located at the edge of the valley floor. A schematic sketch of the geology and potential failure surface is shown in Figure 9.

As a majority of the Port Hills is characterised by colluvial wedge like geology at the toe of slopes, this type of land deformation is widely observed, with generally decreasing displacements away from the 22nd February and 13th June earthquake epicentres. For the many dwellings that straddled the cracks in the land, stretching of foundations and structures has occurred, while dwellings above and below the cracks have sustained significantly less structural damage, most of which can be predominantly attributed to the strong seismic accelerations. Some structures in the zones of compression have experienced foundation and structural damage as a result of these compressive forces (Figure 10).

A liquefaction analysis based on Cone Penetration Tests (CPTs) in valley floors, identified layers of soil that have the potential to liquefy in earthquake events. The driving mechanism for these colluvial wedge failures may be partially driven by a softening of liquefiable layers in the toe region of these slopes, resulting in a reduction in the resisting force, allowing the slope to be more easily displaced during seismic accelerations. Newmark slope stability modelling showed that the high seismic acceleration, especially the vertical acceleration, was the most sensitive parameter imposed on the slope to exceed the cohesive and frictional resistance resulting in slope displacement.


Figure 7 (left): Tension cracking across a driveway on Vernon Terrace

Figure 8 (right): Typical tension crack in the lower colluvial wedge slope area near Ramahana Road

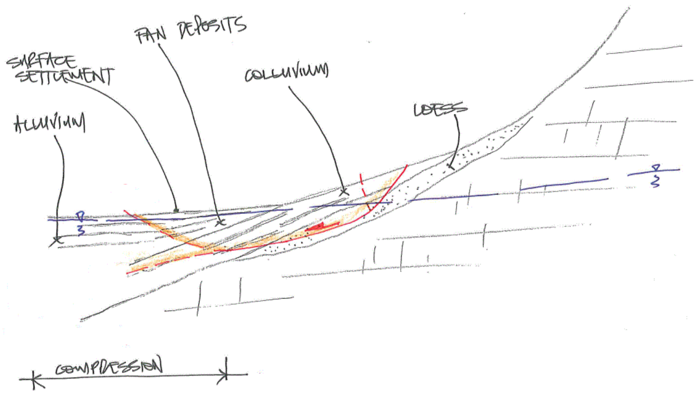

Figure 9: Schematic diagram to show the possible colluvial wedge failure mechanism.

Figure 10: Compression expressed in the fence and driveway of a property on Vernon Terrace.

3.3 Slope mantle deformation

Land displacement in the slope mantle (loess and loess colluvium on mid to upper Port Hill slopes) initially occurred in the M6.2 Christchurch Earthquake of 22nd February 2011. Ground deformation is characterised by persistent tension cracks and formation of a head scarp (Figure 12) with some lateral scarp shear displacement. This damage was also characterised by a minimal visible compression zone or toe breakout of the slope displacement. As a result, dwellings straddling land cracks have been stretched, making some unsafe and/or not practicable to occupy.

Slope displacements resulted from the high vertical and horizontal accelerations originally during the 22nd February earthquake, and again during the 13th June earthquake. There is also evidence that smaller, harder to measure displacements have occurred as a result of other significant seismic events. Failure mechanisms may be attributed to separation and shearing near the loess-rock interface, combined with some internal deformation within the loess. As this paper is prepared, it is not yet clear whether any of this deformation can be attributed to dilation within the underlying rock mass. Seismic amplification, seismic wave directionality and contrasting seismic wave velocities between the bedrock and loess may have had a significant role in initiating this mechanism. Figure 11 shows a schematic cross section showing the typical slope profile and geology, illustrating the possible deformation mechanisms.

Total down slope displacements accumulated across multiple seismic events typically range from 50mm to 200mm, with the exception being Kinsey Terrace which has experienced up to 1100mm of displacement (Figure 13 and Figure 14).

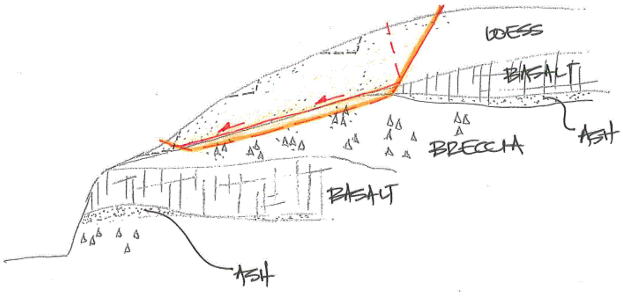

Figure 11: Schematic diagram to show a possible slope mantle deformation failure mechanism.

Figure 12: Head scarp region of a slope mantle displacement – direction of movement towards right side of page.

Figure 13: Head scarp crack tracking through a dwelling, pulling it apart.

3.4 Retaining wall deformation

High vertical and horizontal accelerations resulting from earthquake events have caused a seismic loading on retaining walls that have exceeded their capacity, resulting in deformation generally visible as rotation, bulging and sliding or, in some cases, total collapse. This deformation has resulted in displacement of soils behind the walls manifesting as land cracks and settlement of soil and/or fill.

There are thousands of damaged retaining walls across the Port Hills, many of which are un-engineered rock facings that have a purpose more closely aligned to erosion protection. However, there are also many examples of yielded engineered timber pole walls, timber and concrete crib walls, concrete in-situ walls and concrete block walls that have also experienced some damage as a result of the earthquakes. In some locations, generally along road cuts, there are laterally continuous sections of retaining structures that have all experienced some deformation. As a result, retained soils have also deformed and caused cracking at the land surface across multiple properties. An example of this is shown in Figure 14, where a concrete crib retaining wall extending over a 500m length deformed and resulted in the relaxation and settlement of the retained fill, which manifested in cracks that extend for the length of the retaining structure. As a result, the footpath and road have been compromised, with foot and road traffic being diverted.

Figure 14: Deformation behind a concrete crib retaining wall, affecting approximately 500m of footpath and roadway along Mt. Pleasant Road.

4 CONCLUSIONS

As a result of the earthquake occurring on 22nd February 2011 and the subsequent seismic events that followed, 22 areas were identified on the Port Hills in Christchurch where laterally continuous land damage had occurred, affecting multiple residential properties. Area wide investigations were carried out to determine likely failure mechanisms occurring at each site, which can generally be summarised into cliff collapse, colluvial wedge deformation, slope mantle deformation and retaining wall deformations. The resulting damage to land includes cracking, settlement of the ground, compression of the ground, the loss of land down cliff faces and the inundation of land from falling soil and rock debris.

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