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Earthquake-Induced Ground Fissuring and Spring Formation in Foot-Slope Positions and Valley Floor of the Hillsborough Valley, Christchurch, New Zealand

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ABSTRACT

In the Hillsborough Valley of Christchurch, New Zealand, extensive loess soil fissuring and spring formation occurred following a series of local earthquakes in 2010 and 2011. Fissures were up to 800 m in length, contour-parallel and accompanied by lateral compression and spring formation in the valley floor. Soil compression likely led to the development of permeable pathways, allowing the upward migration of water resulting in springs. The spring water originates from volcanic bedrock, and has distinct rainwater contribution. The term "quasi-toppling failure" can describe the soil movement related to the fissuring, while the mechanism is a combination of the "trampoline effect", the fault movement and bedrock fracturing, and "lateral spreading" which was exacerbated by intra-loess water coursing and tunnel gullying. Infiltration of water into the fissures has potential to cause further ground movement, and as such it is important that the all fissures are infilled to prevent water ingress.

Introduction

The city of Christchurch, on the east coast of the South Island of New Zealand, is bordered to the south by the Port Hills of Banks Peninsula. Beginning on 4 September 2010 with the Mw 7.1 Darfield Earthquake the Christchurch area experienced a series of earthquakes. On 22 February 2011, a fault rupture centred beneath the Port Hills generated an Mw 6.2 earthquake – the Christchurch Earthquake. This paper details the ground fissuring and coincident spring formation that was observed in the Hillsborough Valley, Christchurch.

The Christchurch Earthquake was caused by movement on a hitherto unknown blind oblique thrust fault which dips to the southeast beneath the Port Hills (Smyrou et al. 2011; Kaiser et al. 2012). The hypocentre of the earthquake was located in the basement Torlesse Composite Terrane (Browne et al. 2012; Kaiser et al. 2012). In the Heathcote Valley, near the earthquake's epicentre, 2.21 g peak vertical ground acceleration was recorded (Bradley & Cubrinovski 2011). The rupture induced a broad warping of the surrounding ground resulting in sections of the Port Hills being uplifted relative to down-thrown regions within Christchurch City (Browne et al. 2012).

Following the Christchurch Earthquake, semi-continuous fissures were observed along the loess and loess-colluvium soils of foot-slope positions in north-facing valleys of the Port Hills. The fissuring occurred at low altitudes, showed contour-parallel orientation, and was accompanied by lateral compression features in the valley floors. Extensive valley floor

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spring formation was observed following both the Darfield and Christchurch earthquakes, and the location of the springs has strong correlation to the location of ground deformation and fissuring. Figure 1 provides an overview map showing fissure locations. Earthquake-related spring formation was unprecedented in the Hillsborough Valley, with the formation of at least two dozen new springs. A map of the Hillsborough Valley showing fissure and spring locations, and the location of the lateral compression features, is provided in Figure 2.

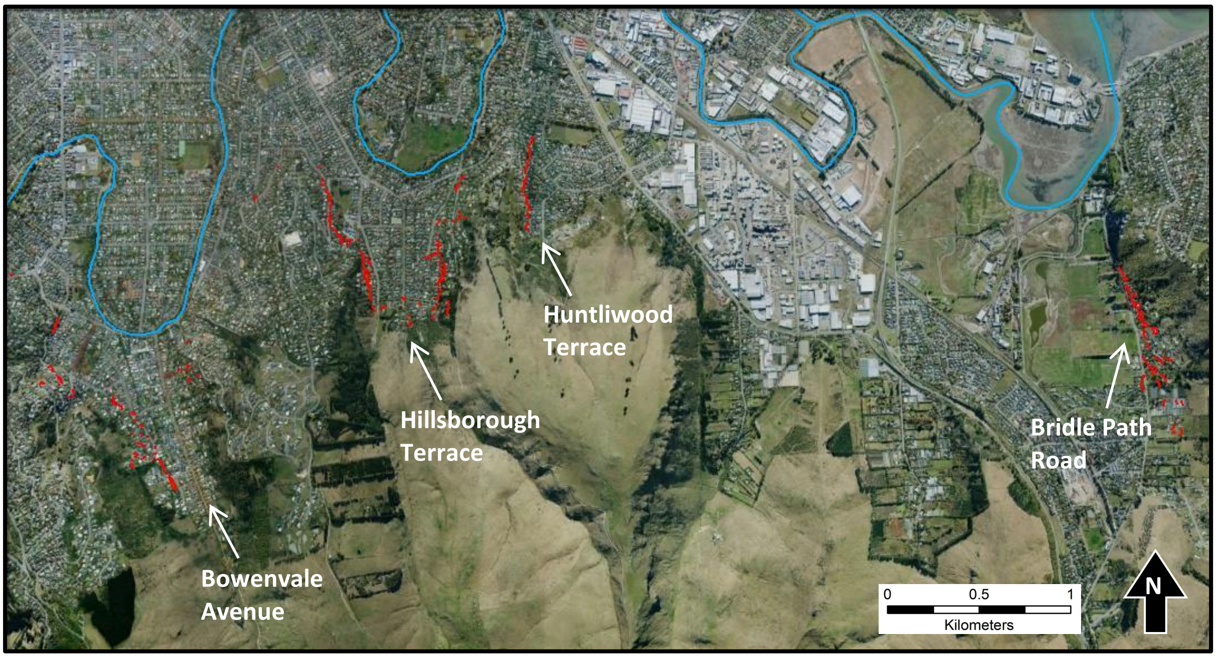

Figure 1: Overview map showing prominent fissure locations (fissure traces marked in red). Background imagery from Google Earth, 2012.

Geology of the Hillsborough Valley

In the Hillsborough Valley, late-Pleistocene loess deposits mantle the andesitic and basaltic lava flows which form the flanks of the valley. These have eroded over time and have been re-deposited in the valley-floor as mixed loess-colluvium (Brown & Weeber 1992). Valley floor loess-colluvium has been recorded to reach 40 m in depth (Bell D.H. pers. com. 2012), and at the mouth of the valley the depth to bedrock is c. 55 m, according to Environment Canterbury well M35/4135 located near the junction of Centaurus Road and Rapaki Road (Brown & Weeber 1994). The primary minerals found in Canterbury loess are quartz and plagioclase feldspar (Raeside 1964).

Laser particle sizing conducted on loess samples from fissure sites in the Hillsborough Valley (Stephen-Brownie 2012) showed a small quantity of fines of up to 20 μm in diameter followed by an incremental curve from 20 μm, peaking at roughly 60 μm, and tapering to 200 μm. All of the samples were poorly graded, with silt and fine sand making up 85 % of the soil.

Hillsborough Valley Fissures

The fissuring on either side of the Hillsborough Valley was mapped through properties from Albert Terrace to Ramahana Road on the western side, and between Vernon Terrace and

Rapaki Road on the eastern side (Figure 2). Fissures were generally contour-parallel, with only minor fluctuations in elevation. On the western side of the valley, a single continuous fissure (Figure 3) was mapped between Centaurus Road and upper Albert Terrace, with minor subsidiary fissures present to either side. The fissures on the eastern side of the valley (Figure 3) were more discontinuous in nature, and had a wider coverage of the hillside by the subsidiary fissures.

Figure 2: The Hillsborough Valley, showing fissure (red) and spring (blue) locations as well as compression zones (yellow). Contour intervals 5 m.

Figure 3: Ground fissuring at number 40 Rapaki Road (left) and number 3 Glenview Terrace (right). Both photographs taken facing south towards the head of the valley. Geological hammer and A4-size paper for scale.

When overlaid onto the geologic map of Christchurch by Brown & Weeber (1992), the fissure traces coincide approximately with the boundary between the bedrock-mantling loess deposits and the colluvial valley fill. In the field it was observed that in most locations the fissures appear at least 20 m (overland distance) below the beginning of outcropping bedrock. Figure 4 shows a schematic cross section through the centre of the Hillsborough Valley, showing the location of the fissure traces and soil types.

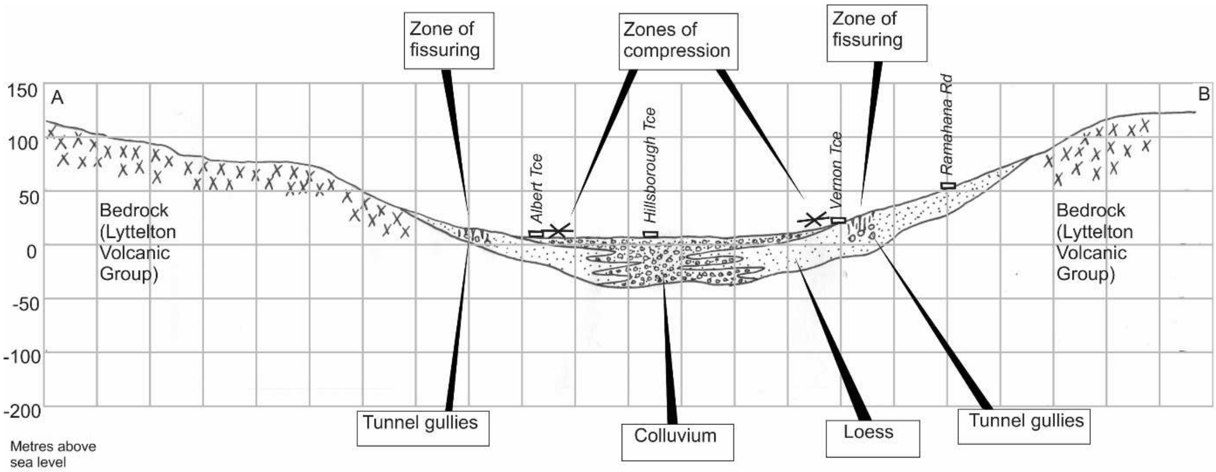

Figure 4: Schematic profile of the Hillsborough Valley, facing northwards.

The fissure traces were alike in appearance at any given location along the fissure trace. There was always some lateral extension (up to 0.2 m) and usually the down-slope side of the fissure trace dropped by up to 0.15 m. Loose soil frequently fell into the base of the fissure; however it was usually possible to extend a rigid tape measure into the fissure by over 1 m, and occasionally to depths of greater than 5 m. Only two instances where the down-slope side of the fissure was higher with respect to the up-slope side (by approximately 0.10 m) were observed. These were at 3 Glenview Terrace and 44a Rapaki Road. Melt-water from heavy snowfall in Christchurch in 2011 caused a large collapse of loess at 3 Glenview Terrace, as the fissure system appeared to link up to subterranean tunnel gullying.

Nearly every section of fissure trace with measureable extension was accompanied by lateral compression features in the valley floor below. The extent of compression was comparable to the total lateral extension in the fissures above. In most of the east-west oriented streets in the Hillsborough Valley, lateral compression was seen in kerbing on the roadside. For example, a plastic outlet pipe in Roscoe Street created a weaker zone in the concrete kerbing, which encouraged compression to be focused in that location (Figure 5).

Figure 5: Kerbing in Roscoe Street. Such evidence of lateral compression was observed in kerbing at many sites in east-west oriented streets in the Hillsborough Valley floor.

Groundwater and Springs

Formation of springs and seepages in valley floors of the Port Hills occurred contemporaneously with both the Darfield and Christchurch Earthquakes. Springs in the Hillsborough Valley formed in close proximity to the valley floor compression features (Figure 2). Three clusters of springs formed in the valley; one where Ramahana Road meets Centaurus Road (near 211 Centaurus Road); another at the junction of Albert Terrace and Leonard Place; and a third centrally located on the western side of Vernon Terrace (spring locations by H. Rutter, Aqualinc, pers. com. 2012).

The property at 211 Centaurus Road has the unique circumstance of being affected by both fissuring and springs, as the northern end of the Ramahana Road-Albert Terrace fissure system extends beneath the house for approximately 5 m, and it is from this fissure trace that the spring is flowing. Following the 2010 Darfield Earthquake, springs at 211 Centaurus Road were discharging approximately 9000 litres of water per day. More recently, discharges measured from the spring at 211 Centaurus Road range between 20 000 L/day (recorded during the cyclone Lusi rainfall event) and a low of 6000 L/day during spring, 2014.

Residents first reported the appearance of springs and seepages on the eastern side of the valley after the Darfield Earthquake, with the Christchurch and June Earthquakes both exacerbating the flow. Spring formation around the intersection of Albert Terrace and

Leonard Place began to flow only after the Christchurch Earthquake. Discharge at 31 Albert Terrace was 3000-3500 litres of water per day.

As the majority of the springs formed in the areas of the valley floor where compression features were also observed, being generally downslope from the fissuring, it is thought that the fracturing resulting from the soil compression led to the development of permeable pathways within the loess/clay cap in the valley floor. This, combined with high measured subsurface groundwater pressures (up to 13 m of head), would allow upward migration of water resulting in the formation of the springs, seeps and wet areas.

Spring water analysis shows a "base flow" of spring water that originates from volcanic (mostly basaltic) bedrock, with a strong rainwater input during storm events. Measured chloride concentrations from springs on Vernon Terrace range between 20 mg/l and 271.6 mg/L, sulphate levels range between 50 to 60 mg/L and Oxygen Stable Isotope values for the spring water range from -7.9 to -8.2 δ18O (V-SMOW). These values correlate with Bank Peninsula bedrock derived groundwater (Brown and Weeber 1994). Rainwater collected in the area had much lower concentrations of chloride ranging from 0.2-15.9mg/l. Spring water chloride concentrations decreased following rainfall events. Both the groundwater piezometer and spring discharge analyses show fluctuations with strong correlation to rainfall events (Figure 6).

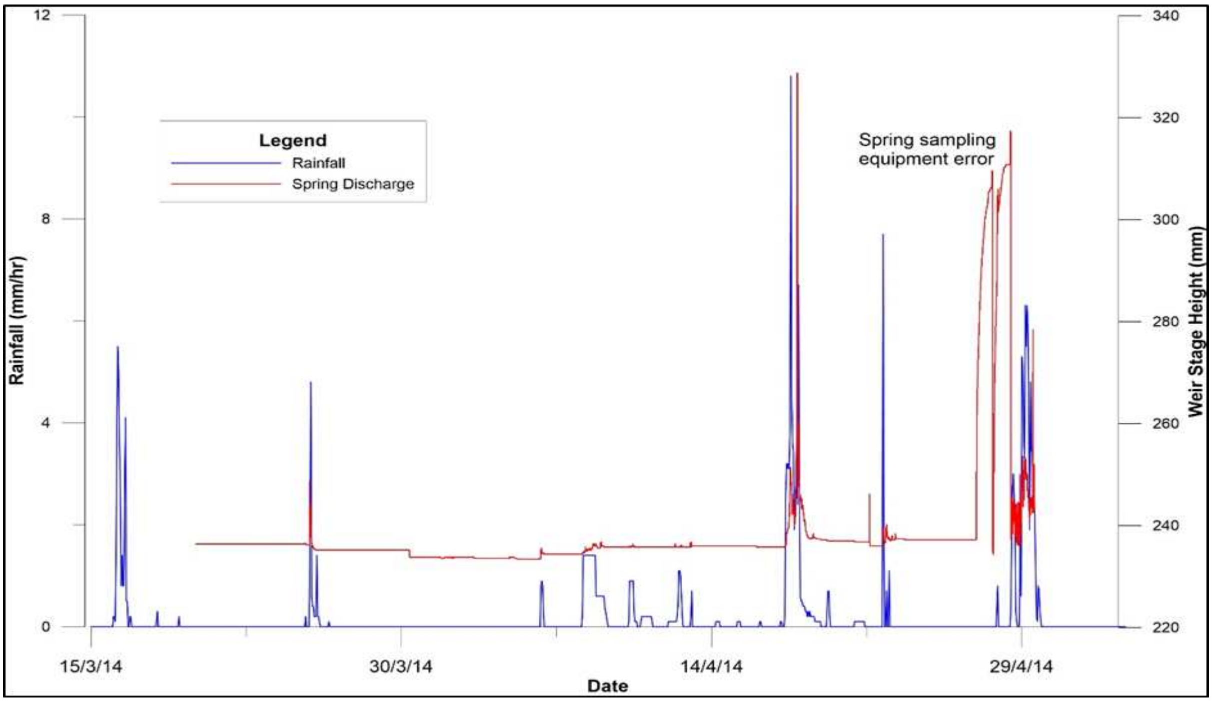

Figure 6: Spring discharge and rainfall volumes during April 2014, at 10 Vernon Terrace. The weir was installed by Aqualinc beneath 10 Vernon Terrace, and it is noted that the apparent pre-rainfall spike in spring discharge around the 29th of April 2014 was caused by sampling equipment error.

Origin/Mechanism

Several authors, for example, Dellow et al. (2011) and Kaiser et al. (2012), have described the Port Hills loess fissuring as incipient deep-seated landsliding. Dellow et al. (2011)

suggested that the Vernon Terrace fissures formed on a pre-historic landslide head-scarp. None of the fissure sites have yet failed catastrophically, even after Christchurch has experienced four wet winters as well as snow fall and further aftershocks. Importantly, drilling in the Hillsborough Valley has not located any basal shear surface which would be fundamental to landsliding.

While spring formation near the toe of the slope is typical of many landslides, it is unlikely that water associated with a surface landslide would be sourced from the depths required for the water to gain the chemical signature of the volcanic bedrock; they would more likely be sourced from surface water infiltration.

The length and linearity of the fissures as well as the lack of *en echelon* or shear cracking between the ends of the fissures and the compression zones also do not correlate well with the theory of landsliding. Furthermore, no large-scale bulging in the toe area has been recorded.

The term “quasi-toppling failure” can describe the soil movement related to the fissuring, while the mechanism responsible is thought to be a complex combination of the “trampoline effect” from the high peak ground accelerations, underlying bedrock fracturing and fault movement, and “lateral spreading” where the cohesive soil mass underwent extension accommodated by tensile or shear failures making the fractured mass subside into softer underlying material (lateral spread definition from Varnes (1978) and Cruden and Varnes (1996)). Intra-loess water coursing and tunnel gullying likely exacerbated the fissuring, given the existence of gross sedimentary layering in the clay- and silt-dominated loessial soils, and some movement may have occurred on these layers.

Conclusions

During the Christchurch Earthquake, movement on a blind oblique thrust fault beneath the Port Hills caused the formation of semi-continuous fissuring of up to 800 m in the Hillsborough Valley. Coincident with the fissuring was the formation of at least two dozen new springs in this valley spatially corresponding to areas of compressional movement of valley floor sediments down-slope from the fissures.

Springs first emerged in the Hillsborough Valley during the Darfield Earthquake of September 2010. During the February 2011 Christchurch Earthquake, the number of springs and their discharge rates increased as the formation of up-slope fissures and corresponding zones of compression in the valley floors provided conduits for the emergence of high-pressure ground water through the clay-rich surface soils of the valley. Spring water analysis shows a “base flow” of spring water that originates from volcanic (mostly basaltic) bedrock, with fluctuations showing additional input is from surface water and rainfall events.

The fissuring, compression and spring formation phenomena have been described as incipient deep-seated landsliding, however a basal shear surface has not been located by drilling. Furthermore, it is unlikely that water associated with a surface landslide would be sourced from the volcanic bedrock.

The term “quasi-toppling failure” can describe the soil movement related to the fissuring, while the mechanism responsible is thought to be a complex combination of the “trampoline effect” from the high peak ground accelerations, underlying bedrock fracturing and fault movement, and “lateral spreading”. Intra-loess water coursing and tunnel gullying likely exacerbated the fissuring, given the existence of gross sedimentary layering in the clay- and silt-dominated loessial soils, and some movement may have occurred on these layers.

It is believed that it is unlikely that the fissure traces are incipient landslides. Should fissures be left unfilled, however, overland flow of rainwater will enter the fissures, ultimately causing further erosion underground, and there is a high likelihood of the development of additional erosion cavities. The subterranean infiltration of water into loess has high potential to cause further ground movement, potentially slumping or sliding, and as such it is important that the all fissures are infilled using bentonite and SAP-20 gravel mixture to prevent water ingress.

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