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# Monitoring the landslide at Bramley Drive, Tauranga, NZ

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## ABSTRACT

Omokoroa Peninsula, Tauranga Harbour, is prone to landslides in sensitive pyroclastic soils, especially in coastal bluffs. The largest is the landslide at Bramley Drive that first occurred in 1979, and was reactivated in 2011 and 2012. Since 2012 the landslide has been monitored with laser scans, vibro-and static-CPT, pore water logging at 3 depths, and a borehole inclinometer. Laser scan results track degradation of the scarp and allow development of a preliminary magnitude-frequency curve for failure events on the scarp. To date the borehole inclinometer has shown no obvious shear surface development. However, deformations in phase with the solid earth tides are evident in the cumulative displacement plots. Layers of weak soils separated by sharp boundaries are believed to exaggerate the deformations of the solid earth tides to the extent that they are measurable with a simple inclinometer. Residual deformation after subtraction of the earth tide effects indicate some movement over winter of 2014 associated with sensitive soils at or near the failure surface. The depth of this movement corresponds with a zone of high induced pore water pressures under vibratory CPTu. Pore water pressures indicate two discrete aquifers: an upper aquifer in tephra layers high in the upper part of the sequence that responds to atmospheric pressures; and a second aquifer in the underlying ignimbrites. Pressures in the bottom aquifer are lower than in the overlying aquifer in summer and higher in winter. Large spikes in pore water pressure have been observed during winter of 2014; these coincide with the time of deformation noted in the inclinometer traces.

*Keywords:* landslide monitoring, earth tide, CPTu, pore water pressure, sensitive soil

## 1 INTRODUCTION

Among sensitive soil failures in reworked pyroclastic materials in the Tauranga region, the landslide at Bramley Drive stands out as a particularly large and well-studied failure. This landslide occurs on the coastal margin of Omokoroa Peninsula some 12 km north of Tauranga City. The coastal bluffs at the site are 33 m above high tide, and the landslide debris protrudes onto the intertidal sand flats. The initial failure occurred in early August 1979 and resulted in ~ 20 m retreat of the cliff, and the ultimate removal of several houses (Tonkin and Taylor, 1980). The scarp was fenced off for public safety and remained essentially stable for just over 30 years during which time it developed an extensive vegetation cover. On 11 May 2011 the landslide reactivated during a storm, along with several smaller failures on adjacent slopes (Tonkin and Taylor, 2011a,b). Further reactivations occurred on 26 April and 13 August 2012; no significant movements have been observed since this time.

Three key sequences of material are exposed in the landslide scarp (Briggs *et al.,* 1996): recent eruptives including the Rotoehu Ash (~ 60,000 years) and younger materials with the modern soil developed on top; the Hamilton Ash sequence (~0.08 – 0.38 Ma; Lowe et al., 2001); and the Pahoia Tephras (0.35 – 2.18 Ma; Briggs *et al.,* 1996). A distinctive paleosol on top of the Hamilton Ash sequence separates it from the overlying Rotoehu Ash, and less well developed paleosols exist on some of the units within the sequence. The Pahoia Tephras are a complex unit within the wider Matua Subgroup in the Tauranga region. Whilst some layers are definitely airfall tephras, the unit contains many reworked pyroclastic materials of rhyolitic origin as well as pyroclastic flow deposits (ignimbrite); it is this Pahoia Tephra sequence that contains the sensitive soils associated with landsliding throughout the Tauranga region. Again, a distinctive paleosol separates the Pahoia Tephras from the Hamilton Ashes, and several poorly-developed paleosols exist within the Pahoia sequence.

Tonkin and Taylor (1980) presented a detailed report on the initial landslide, identifying halloysite clays within the complex Pahoia Tephra sequence as likely associated with the failure surface, and recognizing the role of water as a key contributor to the failure. As well, several university theses have concentrated on this failure and similar exposures of sensitive soils in the Tauranga region (Keam, 2008, Wyatt, 2009, Arthurs, 2010, Cunningham, 2013). Major findings of these research projects indicate halloysite as a significant contributor to preconditioning the slope to failure, resulting in long runout of the failed debris due to low activity of the clays, high liquidity indices in normal field conditions, and low in situ permeabilites (Moon *et al.* 2013).

Since September 2012 we have monitored this landslide with laser scans, core and face description, vibro-and static-CPTu, pore water logging at 3 depths, borehole inclinometer measurements, and seismometer, weather and marine tide and wave recordings.  This paper reports some initial findings from the monitoring programme.

## 2 LASER SCAN

Repeated laser scanning (terrestrial LIDAR) has been undertaken at the site since September 2012, shortly after the last reactivation of the main scarp on 13 August 2012. A Trimble VX scanner was used, with multiple scans being combined to give a detailed scan of the scarp, with lower resolution obtained across the debris train. The aim is to monitor the degradation of the exposed scarp, and identify possible precursors to more significant slope failure. To date, scans have been undertaken in September 2012, July 2013, and May, August and September 2014. Airborne LIDAR date from late 2011 gives an additional detailed survey of the scarp.

### 2.1 Initial slide morphology

The initial slide morphology derived from the first terrestrial laser scan in September 2012 shows the scarp to be approximately 60 m wide, with a maximum of 30 m total scarp retreat based on the position of the coastal bluffs on each margin of the failure (Figure 1). The scarp is strongly arcuate, with a steep headscarp comprising the bulk of the feature, flattening out at approximately 25 m below the ground surface at the top of the scarp. Scarp slope angles typically range from 50° to 60° with a maximum of ~ 70° in the steepest southern portion. An extensive train of debris continues from this level along approximately 100 m to the intertidal flats at ~ 33 m below the ground surface. The failure is believed to be rotational, with the base of the failure surface at around 25 m depth. The sensitive nature of the soils means that they have reworked and flowed, being deposited at some distance from the base of the failure.

(A) (B)

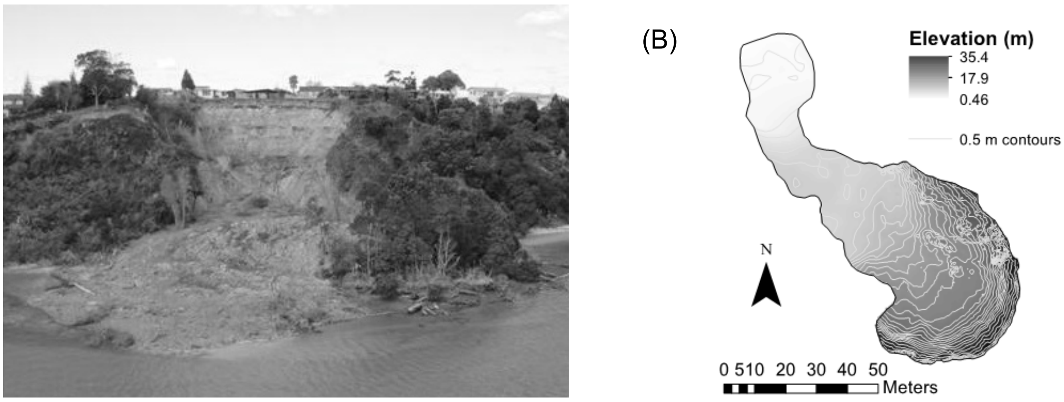


*Figure 1. (A) Landslide at Bramley Drive, Omokoroa, 13 September 2012. Image courtesy Peter Clark, Western Bay of Plenty District Council. (B) Digital elevation model of the landslide scarp and debris runout zone derived from the terrestrial laser scan survey in September 2012.*

### 2.2 Difference maps

By comparing digital elevation maps for each scan time, maps showing changes between scanning intervals can be derived (Figure 2). Comparison of September 2012 scan data with airborne LIDAR data from 2011 (Figure 2A) shows the result of the two events in winter 2012 with approximately 3 – 5 m of scarp retreat in the main scarp area. This gives a volume of ~ 3500 $m^3$ for the two events. Following these larger events less dramatic patterns of modification of the scarp can be recognised. Initial erosion (September 2012 to July 2013) was concentrated in exposed paleosols (Figures 2B and 3A) where blocks of structured soil fell from the face, leaving an undercut above the paleosols. At the same time a small channel was eroded around the base of the scarp, with little of the debris from the fallen soil blocks preserved at the base. This is believed to be the result of water seeping from the base of the scarp and transporting material away from this zone.

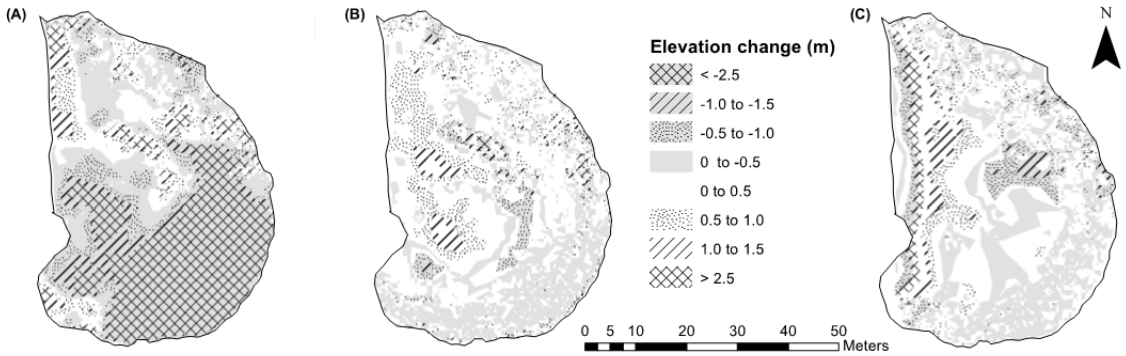


*Figure 2. Change maps determined by subtracting digital elevation maps from successive scan intervals. (A) Late 2011 to September 2012. (B) September 2012 to July 2013. (C) May to September 2014. Note that only the main scarp and upper portion of the debris are shown.*

In early 2013 horizontal drainage was installed at the base of the scarp (Figure 3B) to remove water from the sensitive soil layers at this level. Following installation of the drainage, the small channel has infilled, and a small talus slope has built up at this level (Figure 2C); drainage to remove this water seems to have been critical in allowing the talus to build up at this point. Between May and September 2014, rill erosion on the main part of the scarp has accelerated, whilst the major single event has been a small landslide on the northern margin of the scarp (Figure 3C) that occurred on or about 24 June 2014. This is a planar slide through mostly the tephra layers and the debris has travelled a very short distance at the base. This does not have any of the characteristics of a failure related to the sensitive soil materials, and is interpreted as a simple response of the soils to the oversteepened scarp. An estimate of the volume of this failure is 27 $m^3$ from the scan data.

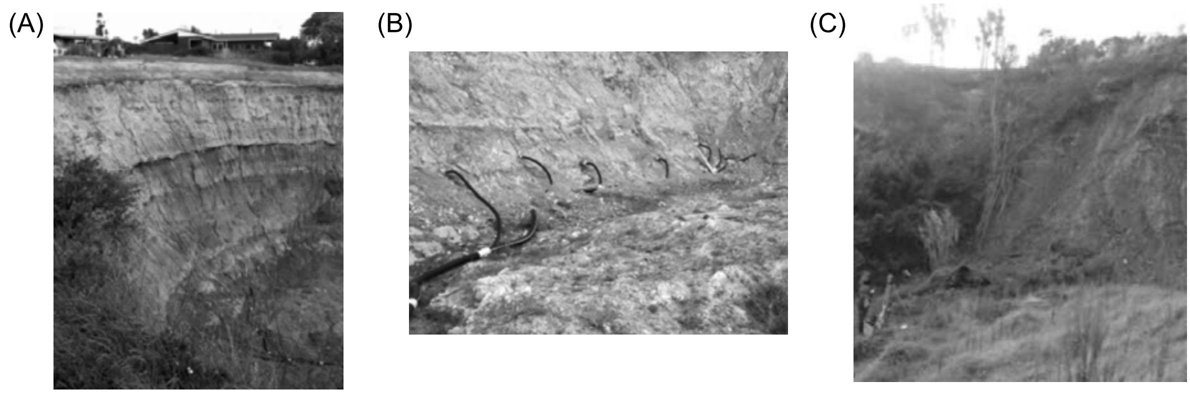


*Figure 3. Pictures of (A) erosion along paleosol, (B) channel at base with later drainage installed, (C) small landslide on ~ 24 June 2014.*

## 2.3 Magnitude – frequency relationships

Using data derived from the laser scanning, literature review, and GoogleEarth images, a very preliminary magnitude – frequency relationship can be derived for the landslide (Table 1). This includes data on 4 known slope movements recorded in reports (Tonkin and Taylor, 1980, 2011a), one small observable failure in historical aerial photos (prior to March 2010), and the one recent landslide recorded in our laser scanning. Estimates of scarp retreat and failure width were derived from GoogleEarth images where better data were unavailable. Volumes are derived from scan data where possible (the two 2011 events have been assigned equal volumes) and calculated assuming a rectangular soil block for older events. A resulting annual exceedance probability versus estimated volume graph shows a logarithmic relationship (Figure 4).

*Table 1: Estimated scarp retreat and volumes for identified failure events.*

| Date | Scarp retreat (M) | Width (M) | Height (M) | Volume ($M^3$) | Rank | Recurrence interval (Years) | Annual exceedance probability |
|---|---|---|---|---|---|---|---|
| Aug-79 | 20 | 60 | 25 | 30000 | 1 | 36 | 0.028 |
| pre-March-10 | 2 | 9 | 25 | 450 | 5 | 7.2 | 0.139 |
| 11-May-11 | 6 | 45 | 25 | 6750 | 2 | 12 | 0.083 |
| 26-Apr-12 | 1.5 | 45 | 25 | 1750 | 3 | 18 | 0.056 |
| 13-Aug-12 | 1.5 | 45 | 25 | 1750 | 4 | 9 | 0.111 |
| 24-Jun-14 | 0.5 | 2 | 25 | 27 | 6 | 6 | 0.167 |

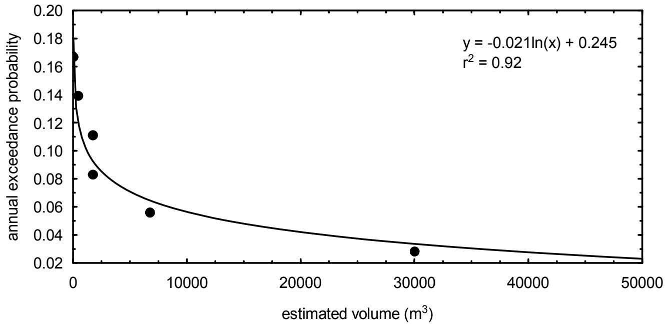


*Figure 4. Annual exceedance probability for estimated landslide volume at Bramley Drive, Omokoroa.*

## 3 CONE PENETRATION TESTING

A cone penetrometer test (CPTu) was undertaken at a site immediately behind the scarp of the landslide in February 2012. The instrument used (GOST) is an offshore CPT instrument developed at Bremen University (MARUM – Center for Marine Environmental Sciences) in Germany. GOST incorporates a small (5 $cm^2$) piezocone, and thus gives high-resolution traces. GOST also has the capacity to undertake vibratory CPTu. At the time of this testing the vibratory capacity was still under development and exact control on the vibration characteristics had not been obtained: frequencies of approximately 15 Hz with vertical vibrations of a few millimetres amplitude were applied. Two separate CPTu runs were undertaken: a static run at 2 cm $s^{-1}$ penetration speed, and a second vibratory run approximately 1 m away with the oscillation imposed on the same penetration rate. The traces of tip resistance and pore water pressure are shown in Figure 5.

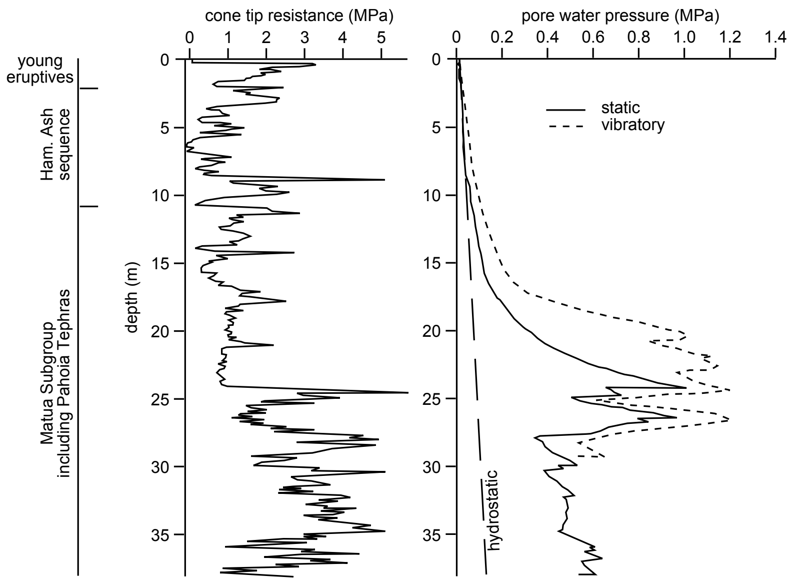


*Figure 5. CPTu traces for static come tip resistance and induced pore water pressure in both static and vibratory modes.*

From the static CPTu trace (Figure 5) it is clear that the stratigraphic units at Bramley Drive show low tip resistance values, with occasional well-defined peaks in the upper 24 m of the profile. These correlate with the paleosols observable in the scarp face, indicating that the elevated tip resistance is a response to soil formation (development of clays and soil structure). A general increase in tip resistance below approximately 30 m is believed to represent the Te Puna Ignimbrite that is exposed in the coastal bluffs on each side of the landslide, but is not seen in the scarp itself. The static induced pore water pressure trace follows the hydrostatic line to approximately 5 m, after which it begins a steady rise, reaching a maximum at approximately 24 m, followed by a sudden drop, then a rise again to 28 m depth. Below 28 m the induced pore water pressure falls to a reasonably steady value within the Te Puna Ignimbrite. The induced pore water pressure under vibratory CPTu shows some potentially significant effects within the Pahoia Tephra sequence. Of particular note are the elevated pore water pressures in response to vibration developed across the entire Pahoia sequence, but most notably between 17 and 20 m where the induced pore water pressures are up to 3 times greater than those developed in the static run. This suggests the potential for flow liquefaction in these materials as a response to cyclic stresses. Pore water pressures developed in the Te Puna Ignimbrite are equivalent to those in the static run.

## 4 BOREHOLE INCLINOMETER

A Digitilt borehole inclinometer from Slope Indicator™ has been used to obtain deformation measurements at weekly to monthly intervals since June 2013. The inclinometer casing is located ~ 5 m behind the central part of the main landslide scarp and extends to a depth of 43 m. The A-axis is aligned at 320°T, parallel with the axis of the most recent movements of the landslide (2011 – 2012 regressions). Thus the A-axis is measuring predominantly a N-S component of any movement, and the B-axis is measuring predominantly E-W movement. Measurements are taken from 42 m to 1 m depths at 0.5 m intervals. Two runs are taken at each measurement time with the instrument turned through 180° between readings in order to cancel any instrument bias errors, and cumulative plots are derived from the difference between measured values for each point and those obtained from the first use of the instrument in June 2013.

### 4.1 Solid earth tides

From results so far it is clear that there is no apparent developing shear surface in the inclinometer data. However, unexpected variability in the measurements exist in terms of wide fluctuations in the overall slope of the cumulative displacement graph between reading times (Figure 6A and B); these fluctuations are of greatest magnitude in the B axis, which is contrary to expectations. A series of hourly measurements on a single day shows the same amount of variation (Figure 6C), though in this case there is a consistent trend in the direction of slope, moving towards the positive (downslope) direction in the early readings, then swinging back to negative values (uphill) in the later readings.

We believe the fluctuations we see to be the result of the solid earth tides. These tides are caused by the distortion of the Earth's mantle as a result of gravitational attraction of the moon (primarily) and sun. There is a dominant west – east variation, but other components exist, giving an elliptical motion for a point on the Earth's surface. These tides cause a semi-diurnal rise and fall of the ground surface of up to approximately 16 cm at the latitude of Bramley Drive. The results can be described in terms of tilt (horizontal) and strain measurements. Good theoretical predictions of the solid earth tides exist. To "correct" for the passage of these tides we have fitted a linear regression line through the entire measured profile. The slope of this linear regression line is then taken as our estimate of the displacement associated with the earth tide. Plotting this measured tilt against the predicted strain of the earth tides (both normalized) shows remarkable agreement in the phases of the measured and predicted displacements, particularly early in the series of measurements (Figure 7A). This excellent phase agreement seems to be confirmation that we are measuring earth tide effects, at least up until April 2014. However, the measured variation is one to two orders of magnitude greater than predicted; possible reasons for this include the effects of ocean tide loading, and exaggeration of the displacement by weak soil layers with different deformation characteristics. Ocean tide loading is caused by movement of water in ocean basins, and particularly the passage of ocean tides across the continental shelf. Estimates of the effect of these are for deformations of approximately 20 % of the magnitude of the earth tide strains, so while they will contribute to the measured deformations, they will not explain the full difference between the measured and predicted values.

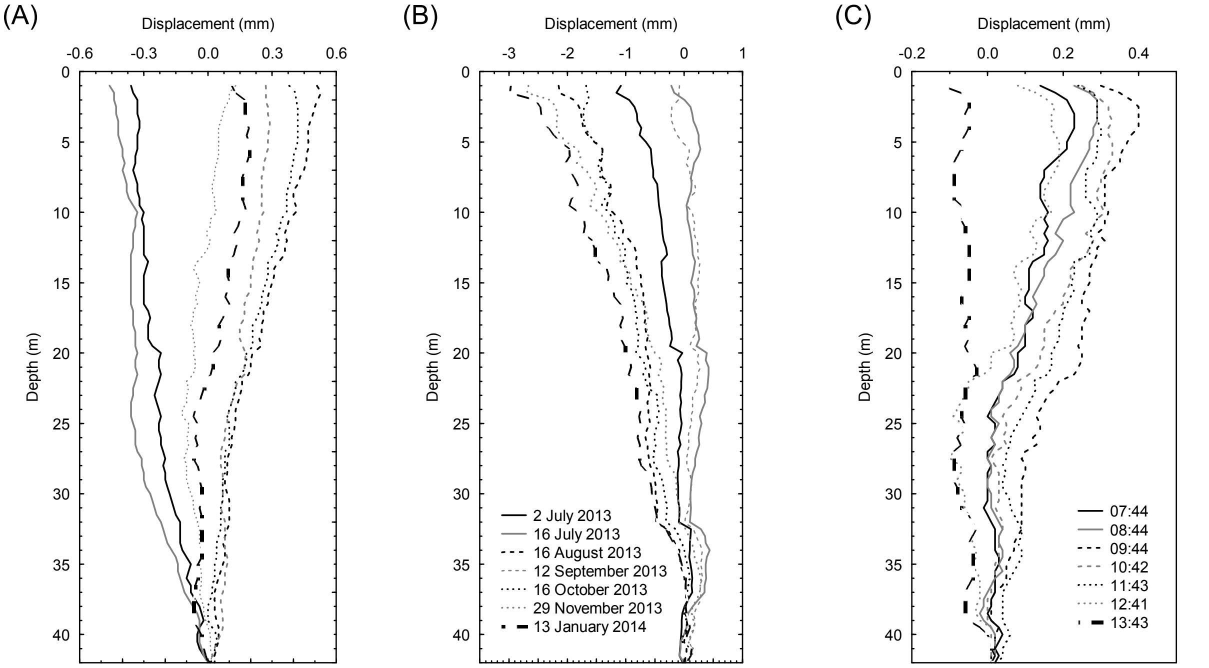


*Figure 6. Cumulative plots of borehole inclinometer data from various dates (A and B), and different times on 22 October 2013 (C). The legend in (B) applies to both (A (A axis)) and (B (B axis)) plots.*

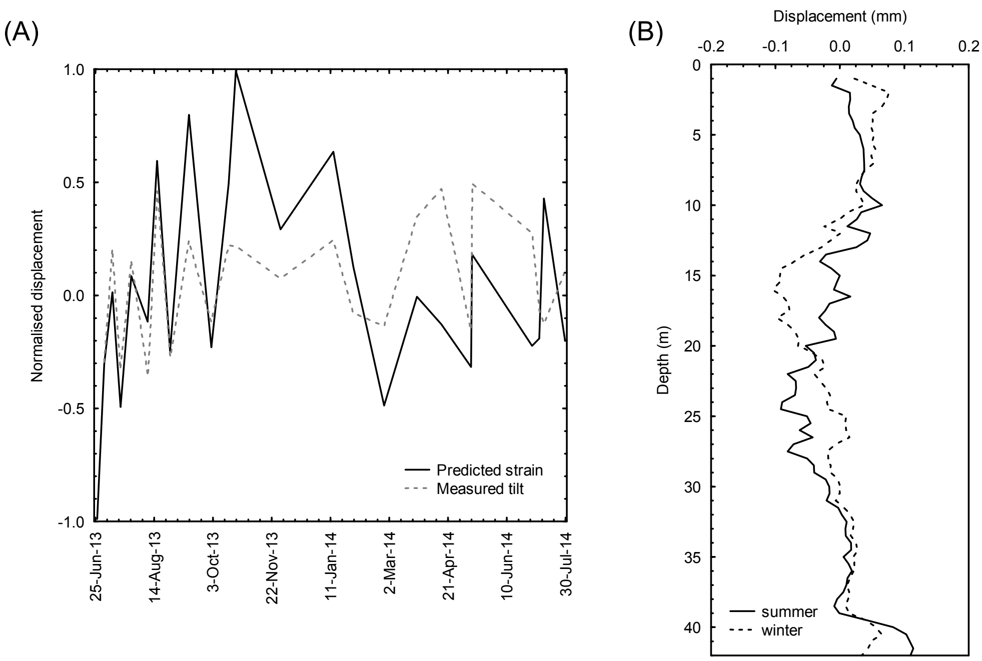


*Figure 7. (A) Predicted earth tide strain versus measured tilt in borehole inclinometer. (B) Average summer and winter 2014 cumulative inclinometer plots after removal of earth tide effects.*

### 4.2 Residual movements

Subtracting the effects of solid earth tides leaves very small residual movements (Figure 7B). These show a mainly consistent profile shape across several measurement times, particularly for the summer period in early 2014. However, in April 2014 there was a distinct change in the profile shape, with the average profile over winter being rather different from the summer profile. The differences observed are in the 17 – 28 m range corresponding with the Pahoia Tephras, and in particular with the zone that showed increased induced pore water pressures under vibratory CPTu.

## 5 PIEZOMETERS

Three pore pressure transducers at depths of 12 m, 21 m, and 27.5 m have been logging continuously since May 2013 (Figure 8). It is apparent that the upper piezometer responds directly with air pressure, the middle one shows a damped response to air pressure, and the lower piezometer does not show a response with air pressure, but displays a lagged response to rainfall. There are clearly two discrete aquifers: an upper aquifer based in the Pahoia Tephras that is open to the atmosphere (this includes both the upper and middle piezometers); and a lower one in the Te Puna Ignimbrite that responds independently of the others. Pore water pressures at the end of summer in May 2013 were lower in the lower aquifer than in the upper aquifer, and conversely for winter 2013. This trend appeared to be continued in summer of 2013 / 14 but the lower piezometer has not shown an increase in pressure again during winter 2014, indicating that it may have stopped working.

From April 2014 the trace has been characterized by sharp increases in pore water pressure in the upper aquifer; these correspond with intense rainfall events and are corroborated by episodes of suddenly rising water levels in standpipes monitored by Western Bay of Plenty Regional Council approximately 300 m along the coast from this site. Notably, the initiation of these spikes coincide with the loss of a clear phase relationship between the measured and predicted earth tide displacements, and with the apparent change in the form of the residual inclinometer deformations.

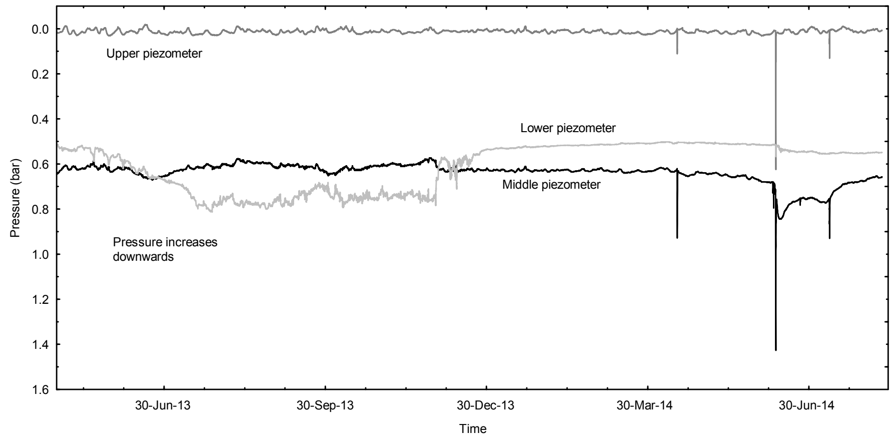


*Figure 8. Piezometer traces from May 2013 to July 2014.*

## 6 DISCUSSION AND CONCLUSIONS

So far, laser scanning is giving good data on the degradation of the scarp. A preliminary magnitude-frequency relationship indicates an annual exceedance probability for larger events involving the sensitive soil materials (reactivations such as seen in April 2012) of approximately 0.06 (or a 17 year return period); smaller events representing simple failure of the oversteepened tephra materials on the scarp have an annual exceedance probability of approximately 0.17 (return period ~ 6 years). Data are sparse at present so this is a very preliminary estimate of the annual exceedance probability based on poorly-controlled data. One aim of the laser scanning programme is to better refine the low-volume portion of this curve by obtaining good-quality data as the present scarp regresses. This may, in addition, allow precursory movement before larger retrogression events to be identified. Consequently, the laser scanning is now being undertaken on an approximately monthly basis.

Earth tide effects are surprisingly important in the inclinometer data: they are almost two orders of magnitude greater than expected; and we should not be able to identify them using a borehole inclinometer given the known sensitivity of the instrument. We assume the measured variations are so large due weak soil / soil boundary effects on deformation associated with earth tides. Beaumont and Berger (1974) note that material zones with reduced seismic wave velocity compared with surrounding rocks will produce measureable changes in the earth tide tilt and strain. Kohl and Levine (1995) expanded on this by modeling the strain-induced tilt developed around a boundary between two regions of different material properties – in their case a weathering boundary in granite. They show that for this simple model, strain-induced tilt tides can be as much as 75 % of the strain tide. Consequently, successive layers of contrasting elastic properties, such as the tephra sequences at Bramley Drive, may cause considerable exaggeration of the overall strain. This exaggeration of the tilt on the inclinometer may have implications for other Bay of Plenty sites that are routinely monitored for landslide movement, creating an additional error that needs to be removed from inclinometer traces.

The spikes in the piezometer data starting in April agree closely with the time at which: (1) the inclinometer goes out of phase with the solid earth tides; and (2) the averaged inclinometer profiles show a shift at 20 – 24 m depth. Water mass itself will impact on deformation characteristics of materials; Mentes et al. (2014) show that addition of water within a slope causes the largest downslope tilts of a variety of environmental factors considered. We assume that the changing profile over winter is a response to additional water in the sensitive soil layers. Vibratory CPTu data show materials sensitive to cyclic stresses at this depth. Quite why the spikes have started to occur so prominently this year, yet did not occur last winter we don't know. The soils are fully saturated under normal field conditions (Wesley, 1973, 2010; Moon et al., 2013), so rapid transmission of a pore water pressure spike following a rainfall event is expected. The relatively low permeability suggested by the CPTu data means that the rapid recovery of the pore water pressure back to pre-rainfall values is surprising. At present no obvious direct link between elevated pore water pressure and borehole inclinometer deformation is apparent, but this may reflect the relatively coarse sampling interval of the inclinometer.

Future work will focus on continued monitoring, and considering the development of fractures in these sensitive rhyolitic materials in response to elevated pore water pressures.

## 7 ACKNOWLEDGEMENTS

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