6th May 2019

Dear Paola Reichenbach,

Thank you for the opportunity to submit a revision to our manuscript *Significance of substrate soil moisture content for rockfall hazard assessment*. Please find in this document detailed responses to the reviews of the manuscript, which includes listed changes to the text and figures, followed by changes to the manuscript highlighted as track changes.

Best Regards,

Louise M Vick and co-authors

Response to review by Greg Stock

We thank Dr Stock for a well-balanced and considered manuscript review. His comments are clear and constructive and where possible all suggested changes to the text and figures have been made.

1. I found it easiest to understand the results as a function of location, so I recommend that the authors make clear in each instance which site the results are from and what soil conditions that site represents. As an example, the caption for Figure 6 should state that these results are from the experimental rockfalls at Mount Vernon, which occurred under wet soil conditions.

We have made these changes.

2. The values that they adjust to account for wet conditions are reported in tables, but I found myself wanting more information on exactly how they derived the adjusted values.

The explanation of the modelling method, when obtaining parameters to better reflect wet soil conditions, has been altered to the following (page 6, lower half): RAMMS parameters were adjusted incrementally until modelled runout paths showed a similar spatial distribution to that of the experimental boulder runouts. For each iteration of the model, parameters were adjusted to more closely represent wet conditions: the parameter κ was decreased by 16% for loess colluvium and 54% for loess, to reflect the longer slip distance through the soil ($1/\kappa$ = impact length); the parameter β was decreased by 16% for loess colluvium and 33% for loess, to reflect the longer impact time ($1/\beta$ = impact time); the μ-values were lowered by 33% for both soil substrates to reflect the decreased friction applied to the boulder over the period of the impact; the drag coefficient was increased by 40% for both soils, to represent the general greater drag on the boulder due to decreased soil hardness. These adjustments to the parameters were considered suitable when the runout envelope of both the experimental rockfall and the modelled rockfall were closely aligned, rather than changing the parameters by a specific pre-determined value.

3. It might be useful if the authors discussed how other models using restitution coefficients to represent boulder impacts with the substrate could be modified to account for wet soil conditions; as is, the discussion is limited to the RAMMS model, which is only one of several rockfall runout models in use.

We have added the following lines to the discussion (page 9, lines 27-31): RAMMS is the only rockfall runout model currently available that represents boulder-substrate interaction as slippage, with parameterisation thereof. Other runout models may require a different approach to representing the change in soil conditions and its effect on the boulder runout, for example reduction of the tradition coefficient of restitution for wet soil conditions, to represent the increased damping effect the soil has on the boulder during impact.

4. Perhaps the impact scarring data would feel more connected if the authors incorporated more discussion as to the usefulness of these measurements.

We have changed the caption and test of Figure 3 to clarify which impact scar depth:length ratios represent which moisture condition. The text has been changed in the results section (page 8, lines 1-5) to: Although both data sets display similar maximum depth:length ratios, the distribution of the values within the Mt Vernon data set (wet conditions) generally show a higher depth:length ratio. Scars that show a greater depth:length ratio are a result of impact of boulders which achieve depth in a shorter space during slippage/contact with the ground (Figure 4a & b). The Rapaki Bay impact scars show a generally lower depth:length ratio, indicative of shallower slippage through the soil during contact with the ground.

The discussion section has also been altered to more clearly link the impact scar dimensions to soil moisture conditions and model parametisation (page 9, lines 5-17).

Dr Stock raises an interesting question: If soil conditions are not known at the time of a rockfall, could they be inferred from impact scar measurements, potentially offering a field-based method of soil characterization after the fact? We interpret this question to be out of interest, rather than a suggested edit, and although we do not address this in text, agree that it is something that could be proposed as a future working direction. We would also suggest that future impact scar work link both boulder size and impact angle to scar morphology, as these likely have a marked effect on the resultant scar size and shape.

5. The authors tend to use passive voice (e.g., "samples were tested"), which leads to some ambiguity as to whether the authors performed certain analyses or whether they are referencing previous work. For example, on page 5, lines 10-13, it is unclear whether the authors inferred the moisture content of the soil at Rapaki Bay, or if this was done by Carey et al. (2014). Use of active voice (e.g., "we tested samples") can help to reduce ambiguity.

The use of passive voice has been altered where necessary to clarify which tests were conducted by the authors, and which test results are referenced from other published research.

6. Regarding the rockfall experiment at Mount Vernon, the authors state that 20 boulders were triggered and mapped, yet figure the caption for Figure 6 indicates 70 experimental rockfall boulders. Why the discrepancy?

We try to make it clear in the methods section- page 5 line 26- that the mapped boulder deposits at Mt Vernon include rockfall boulder fragments. The boulders generally fragmented on first impact, and tracking only one fragment would have been difficult. The test has been changed to: As most boulders fragmented on initial impact, all fragments were mapped as boulder deposits- therefore seventy deposited boulder locations were mapped, from the initial triggering of only 20 boulders.

7. Figure 4 caption: The impact scars in "C" are representative of dry soil conditions (correct?), and thus only show examples of the schematic in panel "A". Are there similar photos of impact scars in the wet soil conditions at Mount Vernon? If so, it would be nice to show examples from both wet and dry conditions.

Unfortunately, photos of scars from Mt Vernon in wet conditions are not good enough for level of quality required for published manuscript.

Response to review by Mark Eggers

We thank Mr Mark Eggers for such a detailed and critical review of the manuscript- it was especially helpful to follow the track changes.

We have accepted most of the suggested changes to the text, and responded to the key points raised that require a more detailed response:

1. Why were the samples taken from this location on the other side of the hill ie the reader will want to know why the samples and testing wasn't done at Rapaki Bay. A sentence saying something like this would help: "Unfortunately no sub-surface investigations could be undertaken at Rapaki Bay. As such testing was carried out on samples taken on similar soil types from a site investigation that was underway at the time of the study", or something like that. Were the samples/testing undertaken specifically for this study or were they part of a separate study (ie Chris White's thesis?). If part of another study and you are using the results you should state this and give a reference? By the way, if the Ramahana Rd and Centaurus Park sample sites are closer to the bottom of the hillslope where more colluvial soil content could be expected compared with Rapaki Bay/Mt Vernon (more upper to mid-slope??) could the grainsize distribution/clay content be different? Just trying to judge how relevant the Ramahana Rd and Centaurus Park test results are to the study sites on the other side of the hill.

Response: This amendment to the text has been added. Yes the soil sample locations were closer to the bottom of the hillslope, however we think that the range of clay contents within the samples shows the changes in mechanical behaviour depending on the clay content, and therefore reflects a range of different actual soil types. This is explain in the text (page 5, line 3-4): Samples were taken from a range of soil profile depths (Table 2), and as such reflect a range of clay and natural moisture content and therefore mechanical properties.

2. It would be useful to know where these 14 samples were taken relative to Rapaki Bay; so the reader can judge their relevance to helping make assumptions about NMC at Rapaki Bay at the time of the earthquake/rock fall event eg do the samples come from SE facing slopes as well? On a slope or on flat ground etc etc

Response: The samples were taken from the northern side of the hills (Lucas Lane, Maffeys Road, Redcliffs, Deans Head, Clifton Hill, Richmond Hill, Wakefield Avenue). This has been added to the text page 5 lines 13-14. Although it would be more ideal to have data from the southern aspect of the hills, as this is the only data that exists from the time period we have to make do.

3. I have a bit of an issue with use of the word 'dry' in this context. This applies throughout the paper. Dry to most people means no water or free from any moisture. While no natural moisture contents (NMC) were tested at Rapaki Bay you have relied on the testing by Carey et al 2014 on samples taken during a similar time of year and similar monthly rainfalls. This testing shows NMC's were low but likely not totally without moisture (3-11% NMC from the Carey et al testing)? Perhaps when 'dry' is first used in the main text some context can be provided (see comment in last paragraph of intro below)?

Response: We agree with the comment, and in this context dry is used as an over-simplification of a sliding scale of behaviours. An amendment to the text has been added in the introduction, lines 11-12 page 2: In this paper the term 'dry' is used to indicate a soil with low natural moisture content, typically well below the plastic limit.

We have added typical atterberg limits of the soil at the end of page 3, start of page 4.

4. Think about two new figures showing the topo/slope morphology of each site eg hillshade maps of the lidar data as used as base maps in Figs 5 and 6 but without the other stuff over the top and with ground surface contours added.

Response: done, these are now figure 2.

5. You should probably elaborate on the test method used for the direct shear testing especially the procedures used for preparation and testing the samples. Given the samples were disturbed the testing must have been on remoulded material. So how was the material placed into the shear box/ring shear, in particular, how much compaction, any pre-shearing ie to simulate residual strengths given the sample is disturbed/remoulded etc etc. An issue with this testing is that the internal structure/fabric of the soil will be lost due to the disturbance. Given the importance of the internal structure of loess in-situ/undisturbed with regard to it's strength properties, does testing on disturbed samples give a realistic estimate of the shear strength changes with moisture content? I suggest you add a short discussion on the limitations of testing the shear strength of loess using disturbed, remoulded samples.

Response: The text has been added/rearranged to read as follows (page 5-6): Testing was in accordance with *ISO/TS 17892-10:2004 Direct shear tests* and *NZS 4402:1996 Test 2.1 Determination of the water content*. Samples selected displayed a spread of both clay contents (Table 1; 5-19%) and natural moisture contents below, near, and above their 16-19% plastic limit (Table 1; 8-22%). The samples were reconsolidated by means of tamping, using the Standard Procter test within the shear-box test sample rings. Twenty-five blows from the hammer were used to compact the soil directly into the shear-box test sample ring, and the method repeated with a fresh sample if the blows from the hammer caused the soil to be compacted to below or >5 mm above the height of the sample ring. The method was considered satisfactory, however there was an unavoidable amount of variation in the density of the samples: the dry density varied between 1658-1954 kg/m3, with an average of 1750 kg/m3. This variation can be attributed to the variable moisture contents of the soils that were compacted, which would have allowed greater or lesser compaction depending on the optimum moisture content for compaction, and the soil's particle-size distribution. The samples were subjected to 20kg, 50kg, and 100kg applied weight (corresponding to 26, 64 and 126 kPa normal stress and overburden depths of 1.45 m, 3.64 m, and 7.28 m respectively with consideration of the average sample density (1750 kg/m^3)), and sheared at a constant rate.

The discussion (page 10 lines 13-20) has also been edited to read the following: The method of linking direct shear test results with soil performance under boulder impact is limiting, as the method of compacting disturbed soil during shear testing means that the internal structure of the soil is lost due to the remoulding. The strength values are therefore not wholly representative of in-situ conditions and greater accuracy in the strength properties of the loess would be achieved by performing similar tests on undisturbed samples.

Furthermore, representing soil conditions as only either dry or wet is a crude representation of actual conditions. Realistically the mechanics of soil behaviour will change continually with incremental increases in moisture content, and we recommend this contribution is further developed to explore the effect a range of moisture conditions will have on rockfall runout. In the future rockfall model parameterisation should be fine-tuned to a range of soil properties.

6. Any further details about the sampling? Where on the site/slope were the samples taken eg next to impact scars? How were the samples collected (small hand dug pit or hand auger?), what depth (especially relative to the depth of the impact scars) etc etc

Response: The text has been edited (page 6, lines 10-12) to read: Thirteen soil samples were taken at the time of the experiments and analysed according to *NZS 4402:1996 Test 2.1 Determination of the water content* to obtain the natural moisture content. Samples were collected as 30 cm tube samples from the base of 13 impact scars equally distributed down the slope.

7. Some simple graphs would really help here with understanding the soil test results eg plot the Mt Vernon NMC results against the testing by Carey et al which will help illustrate the differences between the two datasets. Secondly could plot the monthly rainfall data comparing the Dec-Feb 2013, 2014 data when the Caery et al samples were taken against the Dec 2010-Feb 2011 data when the earthquake/rock fall event occurred. If you do the plots then you can change the text discussing the compare-and-contrast without having to quote strings of numbers.

Response: These have been added as Figure 3a and b.

Significance of substrate soil moisture content for rockfall hazard assessment

Louise Mary Vick[1], Valerie Zimmer[2], Christopher White[3], Chris Massey[4], Tim Davies[5]

[1]Institute of Geosciences, UiT The Arctic University of Norway, Dramsveien 201, Tromsø 9009, Norway
[2]State Water Resources Control Board, 1001 I Street, Sacramento, California 95814, USA
[3]Resource Development Consultants Limited, 8/308 Queen Street East, Hastings, Hawkes Bay, New Zealand
[4]GNS Science, 1 Fairway Drive, Avalon 5010, New Zealand
[5]Department of Geological Sciences, University of Canterbury, Christchurch 8041, New Zealand

Correspondence to: Louise M. Vick (louise.m.vick@uit.no)

ORCHID: https://orcid.org/0000-0001-9159-071X

Abstract. Rockfall modelling is an ~~essential~~important tool for hazard analysis in steep terrain. Calibrating terrain parameters ensures that the model results more accurately represent the site-specific hazard. Parameterizing rockfall models is challenging because rockfall runout is highly sensitive to initial conditions, rock shape, size and material properties, terrain morphology, and terrain material properties. This contribution examines the mechanics of terrain impact scarring due to rockfall on the Port Hills of Christchurch, New Zealand. We use field-scale testing and laboratory direct-shear testing to quantify how the changing moisture content of the loessial soils can influence its strength from soft to hard, and vice versa.

We calibrate the three-dimensional rockfall model RAMMS by back analysing several well-documented rockfall events~~,~~ ~~adopting~~ that occurred at a site with dry loessial soil conditions. We then test the calibrated "dry" model ~~by adopting wet~~at a site where the loessial soil conditions were assessed to be wet. The calibrated dry model over-predicts the runout distance when wet loessial soil conditions are assumed. We hypothesis that this is because both the shear strength and stiffness of wet loess are reduced relative to the dry loess, resulting in a higher damping effect on boulder dynamics. ~~-~~For both realistic and conservative rockfall modelling, the maximum credible hazard ~~must be~~is usually assumed; for rockfall on loess slopes, the maximum credible hazard occurs during dry soil conditions.

1 Introduction

The distribution of rockfall deposits is largely defined by topography, physical properties of the boulder (block shape, size, and geology), boulder dynamics (block velocity, rotations, bounce height, and impact and rebound angles), and substrate properties (Wyllie, 2014; Wyllie and Mah, 2004). Ground conditions will influence how much the kinetic energy of the block is reduced on impact with the substrate (Dorren, 2003; Evans and Hungr, 1993). A block impacting colluvial material or outcropping rock will retain much of its energy due to the stiffness of the surface. If the block impacts softer ground, some of the block's kinetic energy will be dissipated as the soil deforms (Bozzolo and Pamini, 1986). Terrain material parameters in soil slopes will change seasonally, having a variable effect on rockfall runout behaviour; ~~This~~this is especially important for cohesive soils, where the changes in soil deformation behaviour in the plastic and liquid states is significant.

In-situ rockfall experiments and other field data show that ground conditions have an influence on rockfall dynamics (Peng, 2000; Azzoni and de Freitas, 1995; Chau et al., 1998; Giani et al., 2004; Dorren et al., 2005; Ferrari et al., 2013; Volkwein et al., 2018). The analysis of block impact characteristics (~~Parronuzzi, 2009; Leine et al., 2014~~e.g. Leine et al., 2013) allows for development of more realistic numerical simulation models. Within these models, terrain types must be accurately delineated and characterised for results to be meaningful (Dorren, 2003).

Terrain types need to be delineated according to the behaviour that most affects rockfall dynamics, by dividing substrate material into soft and hard portions. Hardness, the amount of plastic resistance to localised impact, will control how much energy is dissipated on boulder impact with the ground. We theorise that the hardness of soil is controlled by the shear strength and stiffness of the soil. These properties will have an effect on the dynamics of rockfall propagation. Where material shear strength and stiffness vary with soil moisture content, it is necessary to determine whether soils are dry or wet, and to assign specific "terrain" parameters to model the frictional forces that will be applied to a boulder during impact as it travels across them. In this paper the term 'dry' is used to indicate a soil with low natural moisture content, typically well below the plastic limit.

Discrete rockfall boulder runout events on the loessial soil slopes of the Port Hills, Christchurch, are affected by variations in soil moisture content (e.g., (Carey et al., 2017)), which can cause soil hardness to dramatically change their effect on rockfall runout. Constraining rockfall modelling parameters to better reflect ~~accurate~~actual rockfall behaviour requires characterising soil hardness changes due to moisture content.

In this paper, we analyse the results from two recorded rockfall events on loessial slopes in the Port Hills~~.~~, Rapaki Bay and Mt Vernon. Both sites have 20 similar substrate material, slope gradient, roughness, aspect and density of vegetation. The three-dimensional rockfall model RAMMS was calibrated to a rockfall event (comprising the fall of multiple rocks) that occurred in dry conditions (Borella et al., 2016). The calibrated model was then tested by forecasting rockfall runout on ~~the same slopes~~a different slope when the loessial ~~soils were assumed to be~~soil was wet. This was done to provide a data set and methodology for practitioners to apply when carrying out rockfall hazard and risk assessments under both wet and dry soil conditions.

2 Geological Setting

The Port Hills form part of Banks Peninsula, a volcanic edifice situated to the south east of Christchurch City (Figure 1). It was volcanically active in the mid-late Miocene, 11-5.8 Ma (Hampton and Cole, 2009). Hawaiian-style eruptions resulted in conical basaltic lava flow deposits radiating outwards from three principal eruptive centres and associated local vent structures (Brown and Weeber, 1992; Hampton and Cole, 2009; Hampton et al., 2012). An extended period of volcanic quiescence allowed widespread deposits of aeolian silt, the Banks Peninsula loess, to accumulate on the volcanically-formed slopes (Griffiths, 1973; Goldwater, 1990). These loessial soils are a product of pro-glacial fluvial action and wind transport/deposition (Davies, 2013); the dominantly quartz (>50%) and feldspar (>20%) composition of the soil reflects theschist-greywacke mineralogy of the Southern Alps (Griffiths, 1973; Claridge and Campbell, 1987; Bell and Trangmar, 1987).

Post-depositional slope processes have resulted in reworking of the loess and loose volcanic material to form colluvium on the lower slopes, reaching 40 m thick in some foot-slope locations (Mcdowell, 1989; Jowett, 1995; Claridge and Campbell, 1987). Close to the underlying basaltic bedrock, mixed loess-volcanic colluvium is often recognised in the regolith profile (Bell and Crampton, 1986; Bell and Trangmar, 1987).

2.1 Port Hills Rockfall

The Canterbury Earthquake Sequence (CES) of 2010-2011 on the previously unmapped Greendale and Christchurch fault traces to the west and east of Christchurch produced seismic moments up to Mw 7.1 and high peak ground accelerations (≥1 g,) (Holden, 2011; Cousins and McVerry, 2010; Bannister and Gledhill, 2012; Wood et al., 2010; Beavan et al., 2011; Fry et al., 2011a, 2011b; Kaiser et al., 2012). These large, shallow (<15 km) ruptures triggered large slope failures on the Port Hills, of which rockfalls were the most abundant type and posed the most risk (Massey et al., 2014b). More than 6,000 individual boulders were mobilised, many of which impacted houses and affected the livelihoods of people within the impacted area.

Rockfall is most likely to occur in closely-jointed or weakly-cemented material on slopes of ≥40° (Keefer, 1984). The columnar jointed lava ~~flows~~ of the Port Hills are generally dominated by three to four joint sets (Brideau et al., 2012) which vary somewhat between sites, attributed to variations in the paleotopography (Massey et al., 2014b). Scoria layers are interbedded with lava in some sites, and these have more widely-spaced discontinuities than the lava (Massey et al., 2014b). Rockfall data were collected by a rapid-response group immediately following events of the CES and resulted in a repository of data including 5,719 boulder locations (Massey et al., ~~2014),~~2014b), with their associated earthquake event and ~~volumes~~ boulder dimensions (Figure~~-~~ 1).

2.2 Geotechnical Properties of Loess

Loess is defined as a loosely-deposited aeolian soil of predominantly silt-sized particles. Loess often displays high enough strength and cohesion to allow deposits to be meta-stable in a near-vertical exposure in dry conditions. When dry, the high cohesion of loess has been attributed to several possible mechanisms, including clay cohesion, calcite bonding, and soil suction (e.g. (Goldwater, 1990)). Post-depositional flocculation of cohesive clay grains to the larger silt- and sand-sized grains cause the irregular formation of clay ‘bridges’ between larger grains. As the larger grains within the soil do not touch, the mechanical behaviour of the material is dominated by the bonds between the larger grains (Gao, 1988; Lutenegger and Hallberg, 1988;

Derbyshire and Mellors, 1988). Due to the cohesion between clay particles and negative pore pressure above any water table, loess generally displays a high dry shear strength; up to 180 kPa has been reported in Christchurch in loess _of <10% moisture content (Mcdowell, 1989). However, loess has been observed to lose significant strength and cohesion upon wetting, with cohesion and friction angle generally decreasing with increasing moisture content (Kie, 1988; Mcdowell, 1989; Della Pasqua et al., 2014; Carey et al., 2014). Wetting of the clay bridges and an increase in pore pressure reduces the shear strength of the material (Gao, 1988; Lutenegger and Hallberg, 1988; Derbyshire and Mellors, 1988; Della Pasqua et al., 2014; Carey et al., 2014).

The Port Hills loess is a cohesive predominantly silty soil with minor clay content. Strength parameters of the soil are largely controlled by the moisture content as repeatedly shown in testing (e.g. Tehrani, 1988; Mcdowell, 1989; Goldwater, 1990; White, 2016; Della Pasqua et al., 2014; Carey et al., 2014). A review of these studies (Massey et al., 2014a) shows that it displays high cohesion at moisture contents of <10%, while cohesion values are very sensitive to changes in the moisture content between 10 and 20% tests. Carey et al. (2014) found that at 3% moisture content the loess has cohesion of 45 kPa and a friction angle of 48°. Comparatively at 16% moisture content the soil displayed cohesion of 25 kPa and a friction angle of 28°. At moisture contents less than 15% the soil can display a brittle deformation style~~, the~~. The measured ~~liquid~~plastic limit for the Port Hills loess is a moisture content ranging ~~from~~from16 to 20%, with a plasticity index of between 4 and 8.8, and liquid limit ranging between 22 to 28%, above which the material deforms as a fluid (Hughes, 2002).

3 Study Sites

Two Port Hills rockfall events are compared~~.~~ (Figure 2). The initial RAMMS model calibration at Rapaki Bay (Borella et al., 2016) back-~~analyses~~analysed mapped rockfall deposits from the 22nd February 2011 (NZST) earthquake. The calibrated model is then tested against data from a field experiment at Mt. Vernon conducted on the 12th May 2014. Both slopes (which are within 0.6 km of each other, Figure 1) have similar gradient~~,~~ (Figure 2), aspect, and density of vegetation.

Rapaki Bay is a south-east-facing, moderately inclined (average 25°) slope with grass and tussock vegetation. The source area bedrock ranges from moderately to completely weathered basaltic lava and basaltic lava breccia, and the slope is mantled by loess and loess-colluvium. The slope is situated above a small community; more than 200 boulders were released here during the 22nd February 2011 earthquake, impacting several houses. The slope falls from the peak (390 m asl) to sea level, with a c. 900 m-long runout zone~~, however all boulders stopped short of entering the sea.~~.

Mt Vernon is a south-facing, moderately to steeply inclined (25-35°) slope in the Port Hills. Geology at Mt Vernon is similar to Rapaki Bay, outcropping bedrock also ranges from moderately to completely weathered basaltic lava and basaltic lava breccia (again forming the rockfall sources). The slope is mantled by loess and loess-colluvium. The site was chosen due to its proximity to Rapaki Bay, its similarity in terms of materials, slope gradient, roughness and aspect, and low vegetation density, and because it has a safe zone for physical runout experiments. -There is an obvious discontinuous rockfall source area above a well-constrained long (~700 m) runout zone and the uninhabited valley extends over 1.5 km from the boulder source areas to the nearest road, down slope.

4 Methods

4.1 Mapping and soil moisture at Rapaki Bay

Boulder deposit locations were measured in the field using a handheld GPS. Boulder size (lengths along three axes) and shape was recorded for most mapped boulders. New rockfall deposits were easily distinguished from paleo boulders by fresh rock surfaces and their location on top of the substrate. Impact scars on the substrate were mapped at both sitesRapaki Bay and Mt Vernon with lengths (axis parallel to boulder travel direction) and depths of 140 scars recorded. Additional mapped earthquake boulder data were contributed by the Port Hills Geotechnical Group - only boulder deposit locations were used from this data set. In total 336 boulders were mapped.- at Rapaki Bay.

To assess soil moisture conditions at the time of the earthquake, weather data were accessed through The National Climate Database (CliFlo, www.cliflo.niwa.co.nz) www.cliflo.niwa.co.nz) from the Governors Bay station, 3.5 km south-west of the site and also south-east-facing (Figure 1). The Governors Bay rainfall data is presented in Table 1. Moisture content of the soil at Rapaki Bay was not tested at the time of the earthquake and instead inferred from published testing of 14 Port Hills Loess samples in January and February 2013 and 2014 (Carey et al., 2014; Table 3 (rainfall data)).taken from the northern side of the Port Hills: Lucas Lane, Maffeys Road, Redcliffs, Deans Head, Clifton Hill, Richmond Hill, Wakefield Avenue; Carey et al., 2014).

4.32 Soil testing

MoistureWe conducted moisture content and direct shear tests were conducted on 36 disturbed hand auger and borehole samples of Port Hills loess/loess colluvium from 17 Ramahana Road and Centaurus Park (figure 1). Samples were taken from a range of soil profile depths (Table 1Figure 1). Unfortunately no sub-surface investigations could be undertaken at Rapaki Bay and as such testing was carried out on samples taken on similar soil types from a site investigation that was underway at the time of the study (White, 2016). Samples were taken from a range of soil profile depths (Table 2), and as such reflect a range of clay and natural moisture content and therefore mechanical properties. Testing was in accordance with *ISO/TS 17892-10:2004 Direct shear tests* and *NZS 4402:1996 Test 2.1 Determination of the water content*. Samples selected displayed a spread of both clay contents (Table 1; 5-19%) and natural moisture contents below, near, and above their 16-19% plastic limit (Table 1; 8-22%).2; 5-19%) and natural moisture contents below, near, and above their 16-19% plastic limit (Table 2; 8-22%). The samples were reconsolidated by means of tamping, using the Standard Procter test within the shear-box test sample rings. Twenty-five blows from the hammer were used to compact the soil directly into the shear-box test sample ring, and the method repeated with a fresh sample if the blows from the hammer caused the soil to be compacted to below or >5 mm above the height of the sample ring. The method was considered satisfactory, however there was an unavoidable amount of variation in the density of the samples: the dry density varied between 1658-1954 kg/m3, with an average of 1750 kg/m3. This variation can be attributed to the variable moisture contents of the soils that were compacted, which would have allowed greater or lesser compaction depending on the optimum moisture content for compaction, and the soil's particle-size distribution. The samples were subjected to 20kg, 50kg, and 100kg applied weight (corresponding to 26, 64 and 126 kPa normal stress and overburden depths of 1.45 m, 3.64 m, and 7.28 m respectively with consideration of the average sample density (1750 ~~km~~kg/m^3~~)~~)), and sheared at a constant rate.

4.~~4~~3 Rockfall experiment and soil moisture at Mt Vernon

~~Anthropogenic~~We conducted rockfall experiments, which involved the triggering and recording of 20 boulders at Mt Vernon. The boulders were jacked from the bedrock along cooling joints by inflation of air compression bladders. Each boulder was measured for size and shape, dislodged, captured by video during travel, and impact trail (lines of impact scars) and deposit location were mapped. Locations were recorded with a handheld GPS and dGNSS. ~~Seventy~~As most boulders fragmented on initial impact, all fragments were mapped as boulder deposits- therefore seventy deposited boulder locations were mapped, including pieces from ~~rockfall fragmentation~~the initial triggering of only 20 boulders. Nineteen impact scars were mapped and measured.

Thirteen soil samples were taken at Mt Vernon at the time of ~~testing~~the experiments and analysed according to *NZS 4402:1996 Test 2.1 Determination of the water content* to obtain the natural moisture content. Samples were collected as 30 cm tube samples from the base of 13 impact scars equally distributed down the slope.

4.~~5~~4 Rockfall Modelling Approach

RAMMS::Rockfall, is a rigid-body three-dimensional rockfall simulation programme (Leine et al., 2013). It was chosen as an appropriate tool because: 1) it allows the user to create a boulder population of varying sizes and shapes modelled on point clouds of real boulders, and 2) the parameters that control different aspects of the terrain-boulder interaction process can be sensitively adjusted by the user.

In conventional rockfall models, rock interaction with the substrate is represented by coefficients of restitution, a ratio that defines the change in velocity after impact in both normal and tangential directions (e.g. Volkwein et al., 2011). In RAMMS the process of boulder interaction with a substrate is represented as a function of 'slippage' through near-surface material, a complex interaction with the substrate that includes sliding of a block through material until maximum frictional resistance is reached, and angular momentum generated by contact forces cause the block to be launched from the ground (Glover, 2015; Leine et al., 2013). The slippage can be parameterised (Table ~~2~~3) for hard surfaces (e.g. rock) by decreasing the distance over which impact occurs and its time duration, to better reflect the instantaneous rebound observed in rock-rock interactions.

A robust RAMMS calibration exercise was performed for the Rapaki Bay dataset (Borella et al., 2016; this paper), and checked against other dry ~~conditions~~condition datasets generated from the same earthquake sequence in other locations on the Port Hills. The modelling inputs included a representative sample of 21 mapped boulders with real shapes and sizes, a 3 m DEM (2013 LiDAR) and a terrain map delineated by changes in ground cover (outcropping rock, loess-colluvium, and loess). Following a recent RAMMS update (Bartelt et al., 2016) this calibration exercise was repeated (this paper) to confirm relevance of the results.

Modelling of Mt Vernon boulder runouts was performed using the dry calibrated parameters. A second set of parameters was created to reflect the wet soil conditions assessed by the natural moisture content testing. This was done by modifying the original dry calibrated parameters to incorporate more soil damping as the boulder interacts with the soil (Table ~~2). Parameters~~3). RAMMS parameters were adjusted incrementally until ~~satisfactory results~~modelled runout paths showed a similar spatial distribution to that of the experimental boulder runouts. For each iteration of the model, parameters were ~~achieved. To~~adjusted to more closely represent wet conditions~~,~~: the parameter κ was decreased by 16% for loess colluvium and 54% for loess, to reflect the longer slip distance through the soil (1/κ = impact length~~). The~~); the parameter β was decreased by 16% for loess colluvium and 33% for loess, to reflect the longer impact time (1/β = impact time~~). The~~); the μ-values were lowered by 33% for both soil substrates to reflect the decreased friction applied to the boulder over the period of the impact~~. The~~; the drag coefficient was increased by 40% for both soils, to represent the general greater drag on the boulder due to decreased soil hardness~~,~~. These adjustments to the parameters were considered suitable when the runout envelope of both the experimental rockfall and the modelled rockfall were closely aligned, rather than changing the parameters by a specific pre-determined value.

Inputs to the Mt Vernon model included a representative sample of 5 model boulders, which were based on the measured size and shape of the boulders used in the field experiments. A 3 m DEM (derived from the 2013 LiDAR) was used as the basis for the simulations, and a terrain map delineating field mapped changes in ground cover (outcropping rock, loess-colluvium, and loess) was used to proportion the locations of the various terrain material types across the slope.

The boulder density for both modelling exercises was 2700 kg/m^3, based on previous laboratory density testing of similar rock by others (Mukhtar, 2014).

5 Results

5.1 Soil conditions

Soil moisture tests from the Mt Vernon site in May 2014 showed water contents of between 28-62%. A prolonged rainy period preceded the experiments, with rainfall totals of 267, 263 and 44 mm recorded in March, April and May, respectively (the average totally monthly rainfall recorded since 1989 at the same weather station is 125, 144 and 88 mm for March, April and May respectively, Figures 3A & B; Table ~~3).~~ 1).

Testing conducted by ~~(~~Carey et al., (2014) in January and February 2013 and 2014 (when recorded rainfall for December, January and February was 65, 46, 29 and 105, 33, 48 mm for each year respectively) showed moisture contents ranging from 3.5 to 11%. The Rapaki Bay rockfalls occurred during typical dry summer conditions, when rainfall totals of 58, 50 and 38 mm were recorded for December, January and February, respectively~~.~~ (Figures 3A and B).

~~Low~~Our direct shearing testing of loess samples showed a low moisture content (<10%) of the loess resulted in high cohesion (>35 kPa) for all clay content variations (Figure 4). Increased moisture content correlated with decreased cohesion; samples with 16-17% moisture displayed cohesions of 6-16 kPa for all clay contents. Moisture contents of >19%, above the liquid limit of the soil, displayed <5 kPa for all % clay contents tested. The spread of the cohesion data is large (±14.5 kPa) for varying clay contents at lower moisture contents, noticeable (±5 kPa) for intermediate moisture content and low (±1.5 kPa) for high moisture content. High clay contents correspond to higher cohesion values at low and intermediate moisture content, but the effect of clay content is negligible at high moisture contents.

5.2 Impact scarring

Mapped impact scars in the soil display a wedge-like form, with a clear boulder penetration point at the upslope end and a widening outwards and downslope, and an area of compression (where soil has been compacted and pushed up) with some excavated and overturned soil on the downslope end (Figure ~~4~~6). Impact scar dimensions at both sites when compared (P=0.035) showed variation in minimum, average and maximum depth:length ratio; 0.~~125, 0.22, 0.43 at Rapaki Bay, and 0.~~05, 0.29 and 0.4 at Rapaki Bay, and 0.125, 0.22, 0.43 at Mt Vernon respectively (Figure ~~3).~~5). Although both data sets display similar maximum depth:length ratios, the distribution of the values within the Mt Vernon data set (wet conditions) generally show a higher depth:length ratio. Scars that show a greater depth:length ratio are a result of impact of boulders which achieve depth in a shorter space during slippage/contact with the ground (Figure ~~4a~~6a & b). The Rapaki Bay impact scars show a generally lower depth:length ratio, indicative of shallower slippage through the soil during contact with the ground.

5.3 Modelling

Modelling was performed at Rapaki Bay to ensure that results were the same/similar following RAMMS updates since the publication of the original calibration (Borella et al, 2015). The RAMMS simulation of boulders at Rapaki Bay still compares favourably with the runout envelope of mapped boulders (Figure ~~5~~7). Mapped and simulated boulder distribution within the envelope was compared: the largest proportion of boulders from both data sets were deposited in the upper slope (33° shadow angle), and the middle-lower slope (26° shadow angle). Both data sets showed a maximum runout of to within the 22° shadow zone. The distributions of the data sets were both constrained by lateral ridges and a creek at the toe. A large proportion of the boulders from both data sets were channelled into a gully running parallel with the slope direction.

A RAMMS simulation of Mt Vernon boulder motions was performed using the dry calibration parameters. The runout envelope of the simulated boulders compares unfavourably to the envelope from the experimental rockfall rolling (Figure ~~6~~8). Runout of the simulated boulders is 175 m further downslope. The topography is more constrained than Rapaki Bay, with a channelisation effect that means lateral dispersion wasn't large; however the simulated rockfall showed a divergence of boulder paths into a neighbouring gully, behaviour that was not observed during the field experiments.
An adjustment of parameters from the original values, to reflect wetter soil conditions (Table 4), resulted in a better match between the field-experiment and runout simulation envelopes (Figure ~~6). ~~8).

6 Discussion

Typical natural moisture contents in the Port Hills range from 10 to 25% (Goldwater, 1990). The moisture content at the time of the 22nd February 2011 earthquake was likely between 3 and 11% (Carey et al., 2014), considered representative of ~~dry~~ 'dry' soil conditions~~.~~ for the purposes of this study. Soil moisture contents at the time of the Mt Vernon experiments were tested as between 28 and 62%, due to a prolonged period of heavy rainfall in the months preceding the experiments, weather typical of the autumn season, and thus are considered to be representative of wet soil conditions. High moisture content of the Port Hills Loess correlates well with low cohesion/shear strength. By increasing moisture contents past the liquid limit of the soil, cohesion values decrease from as high as 65 kPa to 5 kPa or less for all samples tested, regardless of the recorded proportion of clay particles within the samples. The amount of clay has an influence over the strength (cohesion) of the soil when dry (8-11% moisture), but in wetter conditions (15-18% moisture) its influence is reduced. When wet (moisture contents of 19-22%, above the plastic limit) the influence of clay content is indistinguishable, with cohesion values at or below 5 kPa. This is likely due to the increase in pore pressure reducing the strength of the particle bonds.

Impact scar morphology displays evidence of the impact process: the soil penetration point and ploughing movement of the boulder - pushing soil forward as it slides in a down-slope motion causing compression and shear - reaches a maximum friction and rotational momentum marking the downslope and widened end of the scar. Overturned soil at the downslope marks the exit point of the boulder from the soil profile. A comparison of depth versus length of impact scars for the two field sites (Figure ~~3~~5) shows that there is (generally) a greater depth relative to length of scarring during the winter when soil is wet, compared to the summer when the soil is dry. (although we acknowledge that the scars have not been liked to boulder size or impact angle, and the interpretations thereof are limited). As the measured soil moisture content at Mt Vernon was above its liquid limit (measured minimum 28%), the lower shear strength for the wet soil results in earlier plastic deformation and higher strain on boulder impact. As a result, the boulder achieves higher penetration depth within the soil during the 'slippage' process. When the soil is dry it is harder, and therefore the boulder does not slip as deeply through the soil during contact with the ground, as shown by generally lower depth to length ratios of impact scars at Rapaki Bay in dry soil conditions (Figure 5). It is likely that the boulder loses less energy to the soil as a result of shallower slippage. As the soil response to impact is mechanically different when the moisture content is different, it follows that the parametrisation of the substrate material within the rockfall model should also be altered.

RAMMS modelling at Mt Vernon, using parameters calibrated to the Rapaki Bay data set (dry conditions), show that runout distance is overestimated when compared with rockfall field runout experiments. Adjustments of some of the RAMMS terrain parameters, to reflect the lowering of shear strength of the loess, (evidenced by both the direct shear testing results and measurements of impact scar depth to length ratio), results in a more favourable match between the actual and modelled runout. All impact scars recorded during mapping at Rapaki Bay and following rockfall experiments conducted at Mt Vernon show a morphology that confirms the efficacy of the 'slippage' model component in RAMMS (and parameterisation thereof), and adjustments to the parameters set to reflect changes in impact dynamics under different soil moisture contents (and therefore strength) is valid. RAMMS is the only rockfall runout model currently available that represents boulder-substrate interaction as slippage, with parameterisation thereof. Other runout models may require a different approach to representing the change in soil conditions and its effect on the boulder runout, for example reduction of the traditional coefficient of restitution for wet soil conditions, to represent the increased damping effect the soil has on the boulder during impact.

We propose that under rapid-loading stress conditions (boulder impact), the proportion of recoverable (elastic) deformation is lower and irrecoverable (inelastic) deformation is higher for wet soil than for dry soil. We also propose that in a soil impact scenario, the irrecoverable stress proportion of the soil deformation in wet conditions results in a greater impact depth in the soil by the boulder due to lower stiffness, as noted by the increase in impact scar depth in wet conditions. Furthermore, the greater plastic or viscous soil deformation under boulder impact loading in wet conditions results in a greater proportion of energy lost to the soil. As boulder motion in rockfall events ends when the kinetic energy is completely dissipated, the runout distance of the boulder will be shorter under wet soil conditions compared to the same soil under dry conditions.

By increasing the duration of slip through soil on impact in RAMMS, the decreased shear strength of the soil under wet conditions is represented. The runout of dry vs wet soil modelling shows that by adjusting the parameters to suit the ground conditions, the actual runout is better represented. Dry soil will produce greater boulder runout distances than the same soil when wet. For hazard analysis purposes, practitioners should consider their terrain representation under different moisture conditions within rockfall models to ensure the maximum possible rockfall runout and hence damage potential has been accounted for.

~~Representing~~The method of linking direct shear test results with soil performance under boulder impact is limiting, as the method of compacting disturbed soil during shear testing means that the internal structure of the soil is lost due to the remoulding. The strength values are therefore not wholly representative of in-situ conditions and greater accuracy in the strength properties of the loess would be achieved by performing similar tests on undisturbed samples.
Furthermore, representing soil conditions as only either dry or wet is a crude representation of ~~a~~ actual conditions. Realistically the mechanics of soil behaviour will change ~~contiually~~continually with incremental increases in moisture content, and we recommend this contribution is further developed to explore the effect a range of moisture conditions will have on rockfall runout. In the future rockfall model parameterisation should be fine-tuned to a range of soil properties.

Conclusions

Rockfall modelling using terrain parameters calibrated to rockfall events during dry loess soil conditions over-simulate runout distance for rockfall events in wet conditions. Under wet conditions loess soil has a lower shear strength and depth of boulder penetration at impact during a rockfall event will be greater, resulting in a higher damping effect to the boulder and therefore a shorter overall runout distance. Rockfall model users should take soil conditions into account to ensure they have allowed for the worst-case runout distance when simulating rockfall events for hazard prediction purposes.

Author contribution

Louise Vick- Conceptualisation, investigation, data curation, formal analysis, visualisation, writing- original draft, writing- review and editing,
Valerie Zimmer- Data curation, formal analysis, writing- original draft
Chris White- Investigation, formal analysis, writing- review and editing
Chris Massey- Funding acquisition, supervision, writing-review and editing
Tim Davies- Funding acquisition, ~~invesitgation~~investigation, validation, supervision, writing- review and editing

Competing Interests

The authors declare that they have no conflict of interest.

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Tables

Sample location	Sample depth (m bgl)	Clay content (%)	Moisture content (%)	Dry unit weight (kg/m3)			ρ (newtons)			τ (kPa)		
				Test 1	Test 2	Test 3	20 kg applied weight	50 kg applied weight	100 kg applied weight	26 kPa applied σ_n	64 kPa applied σ_n	126 kPa applied σ_n
Hand Auger 5	1.0	18.5	9	1758	1709	1767	662	938	1293	84	119	165
Hand Auger 1	2.0	18.4	17	1664	1731	1781	266	463	801	34	59	102
Hand Auger 5	4.0	18.9	19	1689	1796	1775	171	374	801	22	48	88
Hand Auger 4	1.0	15.4	9	1759	1788	1783	691	932	1414	88	119	180
Hand Auger 3	2.0	15.3	17	1658	1663	1710	241	476	796	31	61	101
Hand Auger 2	4.0	15.5	22	1666	1665	1667	201	407	807	26	52	103
Hand Auger 4	3.0	10.2	10	1772	1822	1860	456	752	1145	58	96	146
Borehole 3	2.8	7.6	8	1909	1949	1954	467	772	1209	59	98	154
Borehole 1	7.0	8	16	1684	1724	1735	199	405	763	25	52	97
Borehole 2	5.0	5.6	21	1719	1779	1779	202	52	101	26	52	101

Table 1.

Direct shear test variables for hand auger and borehole samples at various depths and displaying various moisture contents.

Parameter	Function
μ_{min}	Minimum sliding friction
μ_{max}	Maximum sliding friction
κ	Time between μ_{min} and μ_{max} on contact with the ground
β	Time between μ_{max} and μ_{min} as rock leaves the ground
Drag coefficient	Drag force applied to rock during ground contact

Table 2

. RAMMS parameters used to define the slippage model

Series	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2010	66	23	30	24	216	205	64	175	58	49	63	58[1]
2011	50[1]	38[1]	78	99	45	68	75	104	40	138	62	62
2012	48	70	54	38	26	92	110	207	54	103	78	65[2]
2013	46[2]	29[2]	30	69	175	270	71	61	50	77	44	105[3]
2014	33[3]	48[3]	267[4]	263[4]	44[4]	53	84	41	41	36	85	30
Average (1989-2018)	55	49	63	79	103	106	93	107	67	73	60	65

Table 31. Rainfall data (mm) recorded at the Governors Bay weather station in 2011, 2013 and 2014 with the weather station average over 20 years provided for comparison.

[1]Rainfall preceding earthquake rockfall event, Rapaki Bay

[2]Rainfall preceding and during Carey et al (2014) testing, summer 2013

[3]Rainfall preceding and during Carey et al (2014) testing, summer 2014

[4]Rainfall preceding field experiments, Mt Vernon

Sample location	Sample depth (m bgl)	Clay content (%)	Moisture content (%)	Dry unit weight (kg/m3)			ρ (newtons)			τ (kPa)		
				Test 1	Test 2	Test 3	20 kg applied weight	50 kg applied weight	100 kg applied weight	26 kPa applied σ_n	64 kPa applied σ_n	126 kPa applied σ_n

Hand Auger 5	1.0	18.5	9	1758	1709	1767	662	938	1293	84	119	165
Hand Auger 1	2.0	18.4	17	1664	1731	1781	266	463	801	34	59	102
Hand Auger 5	4.0	18.9	19	1689	1796	1775	171	374	801	22	48	88
Hand Auger 4	1.0	15.4	9	1759	1788	1783	691	932	1414	88	119	180
Hand Auger 3	2.0	15.3	17	1658	1663	1710	241	476	796	31	61	101
Hand Auger 2	4.0	15.5	22	1666	1665	1667	201	407	807	26	52	103
Hand Auger 4	3.0	10.2	10	1772	1822	1860	456	752	1145	58	96	146
Borehole 3	2.8	7.6	8	1909	1949	1954	467	772	1209	59	98	154
Borehole 1	7.0	8	16	1684	1724	1735	199	405	763	25	52	97
Borehole 2	5.0	5.6	21	1719	1779	1779	202	52	101	26	52	101

Table 2. Direct shear test variables for hand auger and borehole samples at various depths and displaying various moisture contents.

Parameter	Function
μ_{min}	Minimum sliding friction
μ_{max}	Maximum sliding friction
κ	Time between μ_{min} and μ_{max} on contact with the ground
β	Time between μ_{max} and μ_{min} as rock leaves the ground
Drag coefficient	Drag force applied to rock during ground contact

Table 3. RAMMS parameters used to define the slippage model

Terrain	Calibration	μ-min	μ-max	β	κ	Drag layer coefficient
Outcropping rock	Original	0.7	2	50	0.5	0.3
Talus/colluvium	Original	0.45	2	30	0.6	0.5
	Wet soil conditions	0.3	2	25	0.5	0.7
Loess	Original	0.3	2	30	0.65	0.5
	Wet soil conditions	0.2	2	20	0.3	0.7
Asphalt	Original	0.8	2	200	4	0.3

Table 4: RAMMS terrain parameters (as described in Table 3) for typical Port Hills terrain types, calibrated to the original data set, and adjusted to wet soil conditions.

Figures

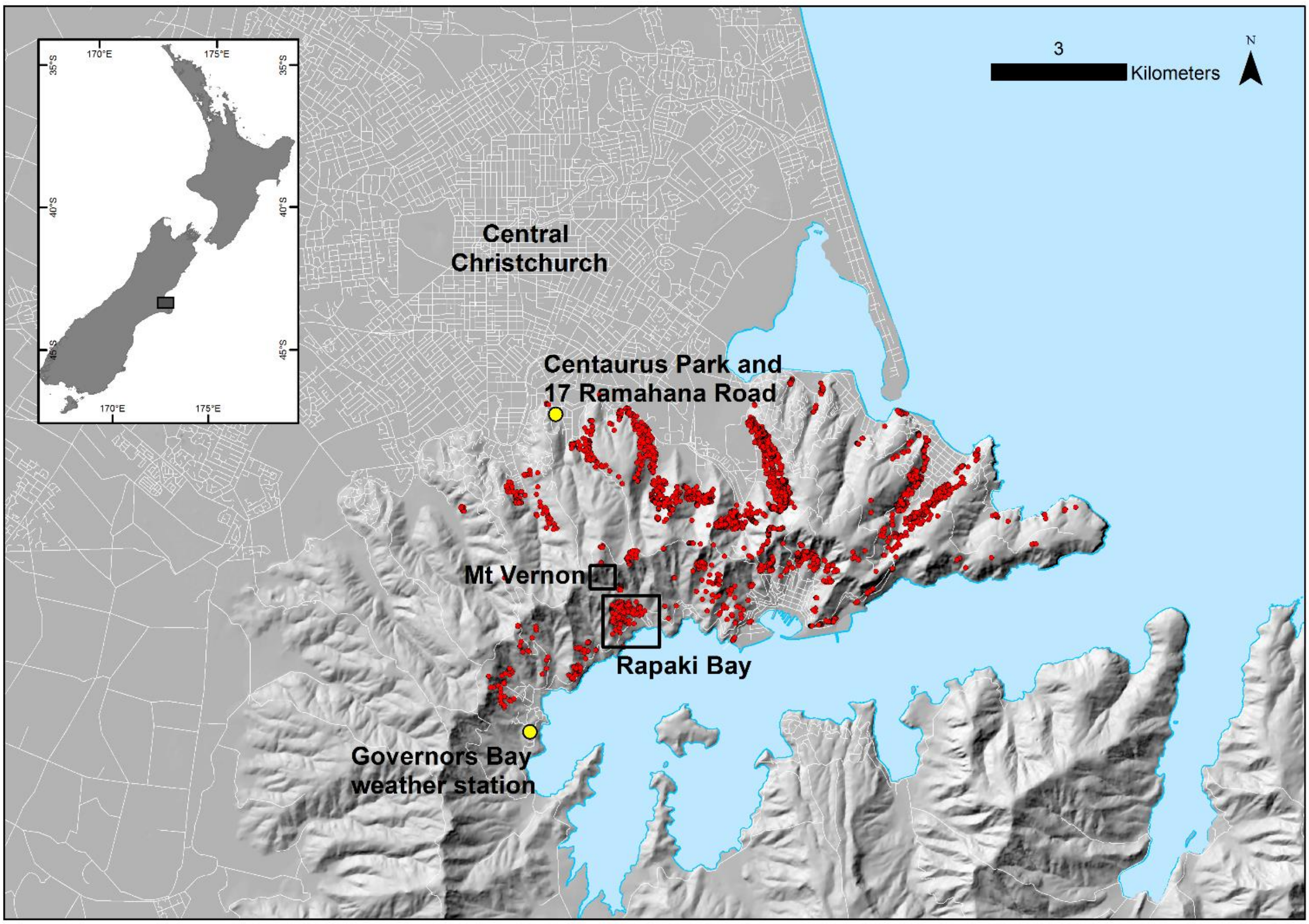
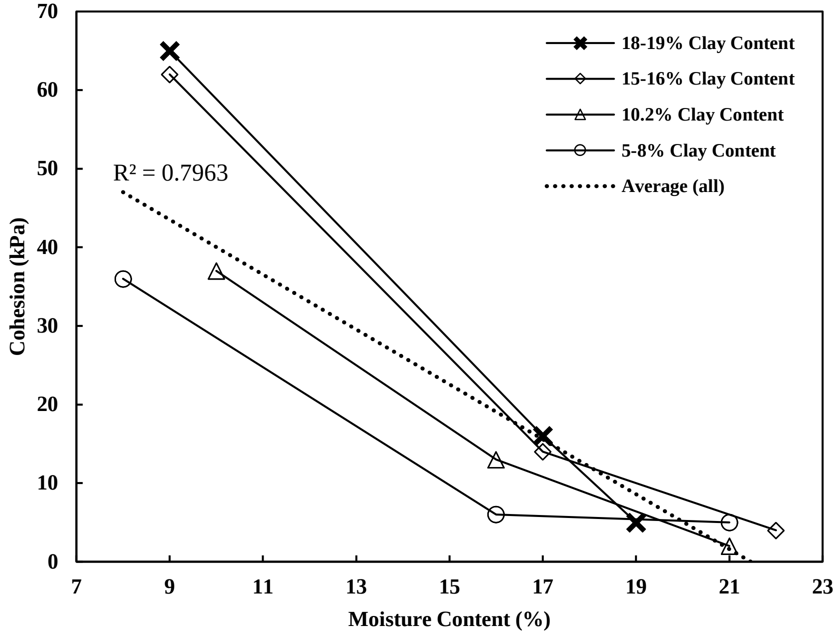


Figure 1: Location map of Christchurch and the Port Hills showing sites examined in this study. Red dots show mapped rockfall deposit locations (n=5,719).



70
60
50
40
30
20
10
0
Cohesion (kPa)
7
9
11
13
15
17
19
21
23
Moisture Content (%)
R² = 0.7963
18-19% Clay Content
15-16% Clay Content
10.2% Clay Content
5-8% Clay Content
Average (all)

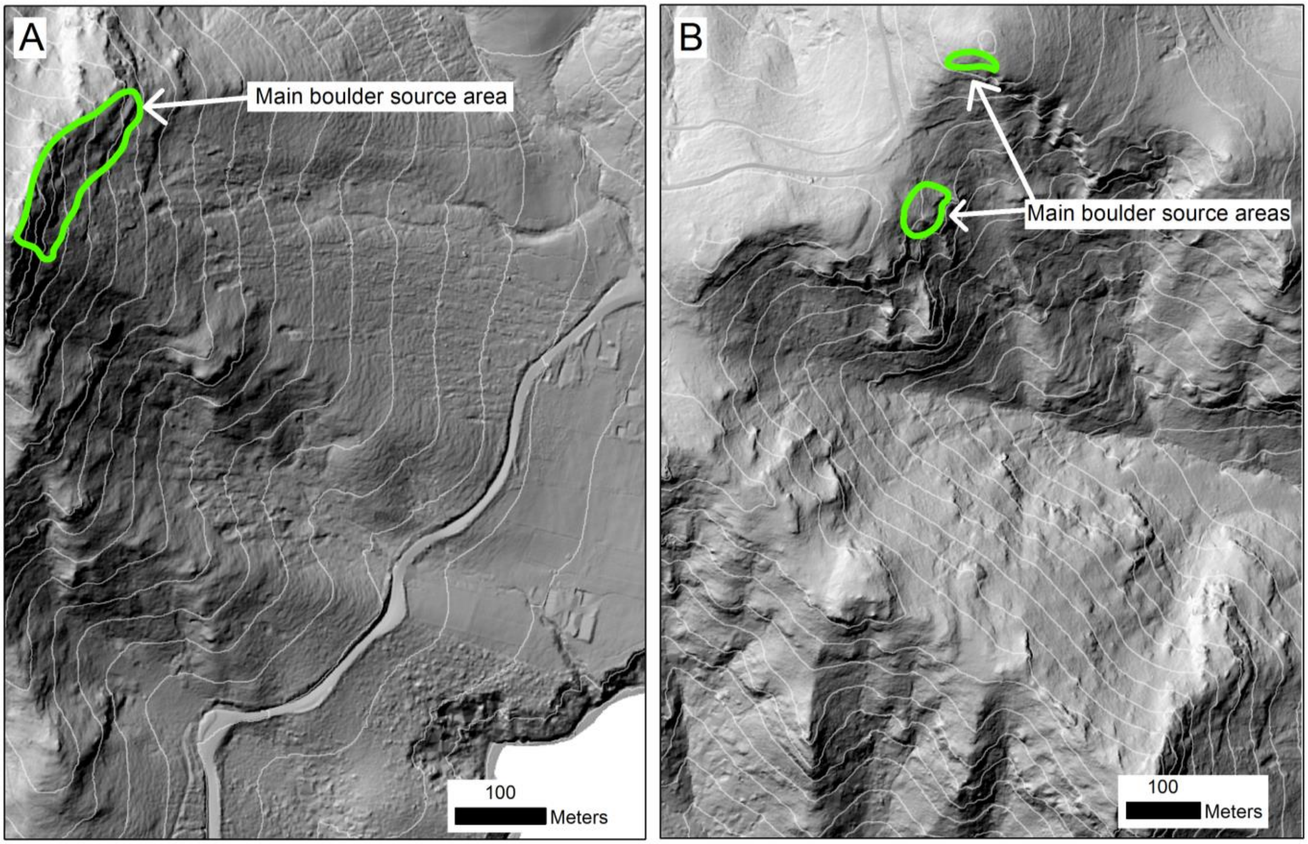


Figure 2. Hillshade topography of the Rapaki Bay (A) and Mt Vernon (B) field sites. Hillshade derived from 2015 Lidar, overlaid with 20 m contour intervals and showing the boulder source location for the rockfalls.

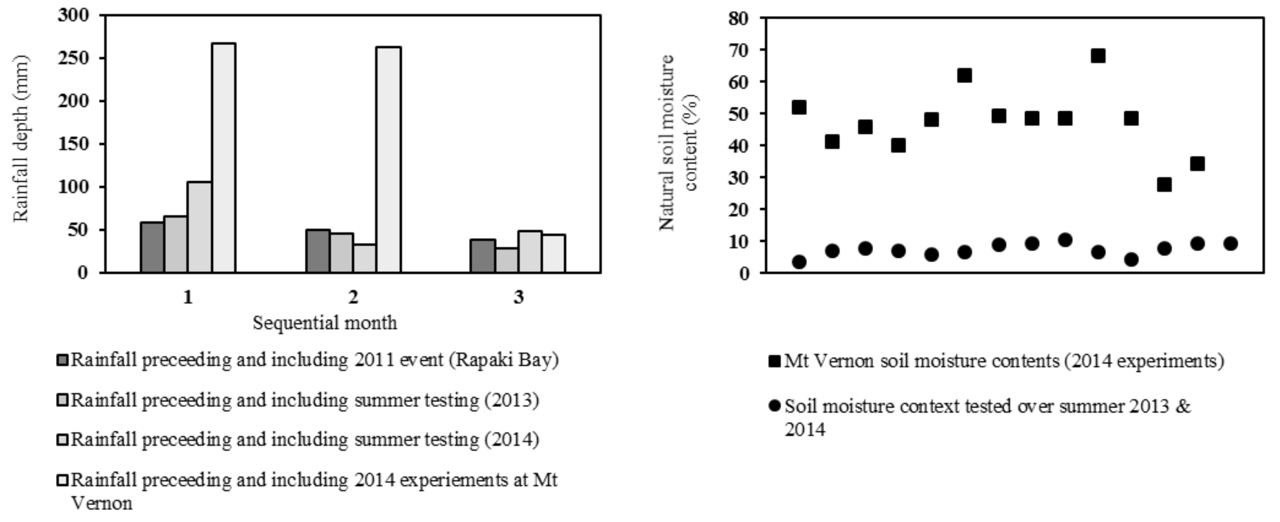


Figure 3. A. Rainfall in the months preceeding and during key events of this study: The 2011 earthquake rockfall event at Rapaki Bay, summer soil testing on the Port Hills in 2013 and 2014, and the rockfall exeriments conducted at Mt Vernon in 2014. B. Natural soil moisture contents as tested during the summer testing of 2013 and 2014 (Carey et al., 2014), and as tested during the Mt Vernon rockfall experiements.

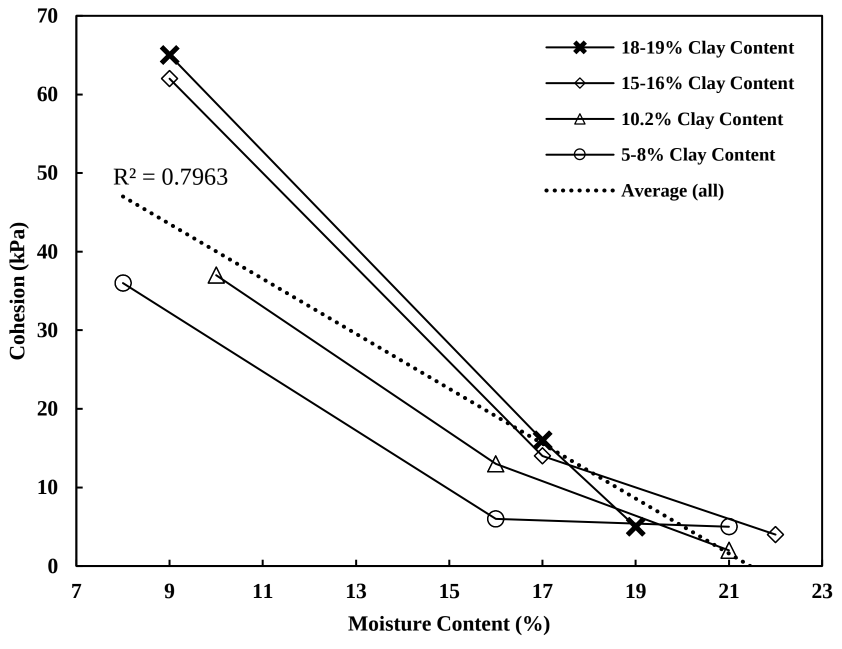
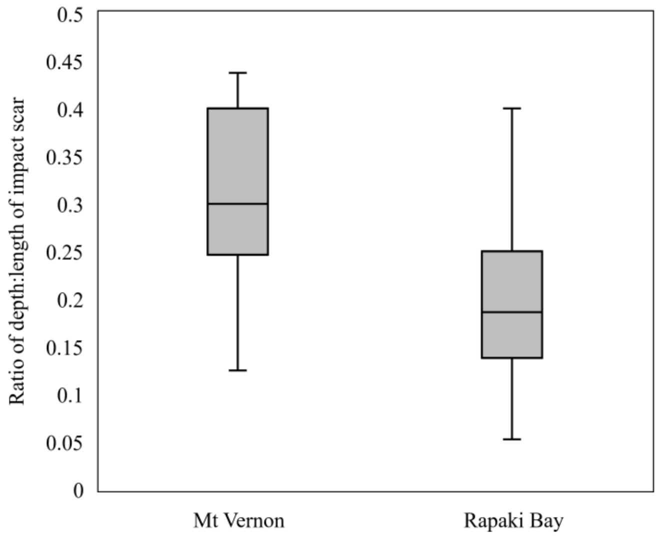


Figure 4. Cohesion of loess at varying moisture contents, when loess clay content is varied.



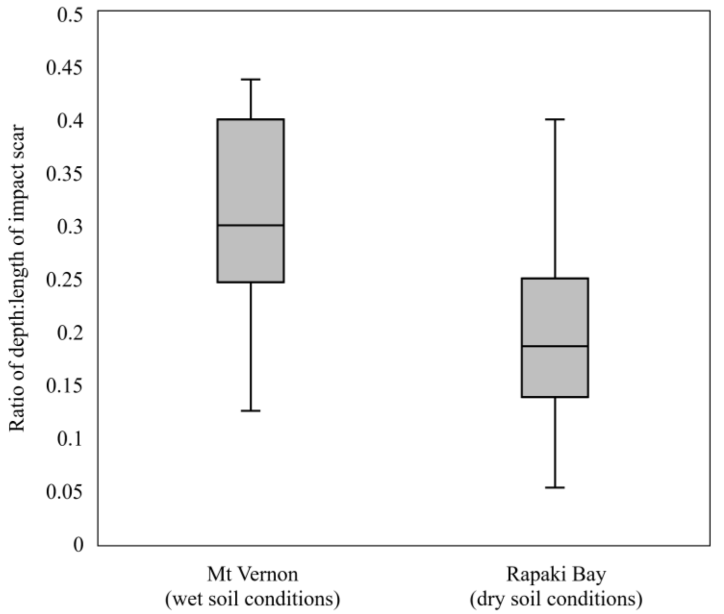


Figure ~~3~~5. Depth vs. length of impact scars measured at Rapaki Bay (n=140) in dry soil conditions and Mt Vernon (n=19~~).~~) in wet soil conditions. P=0.025.

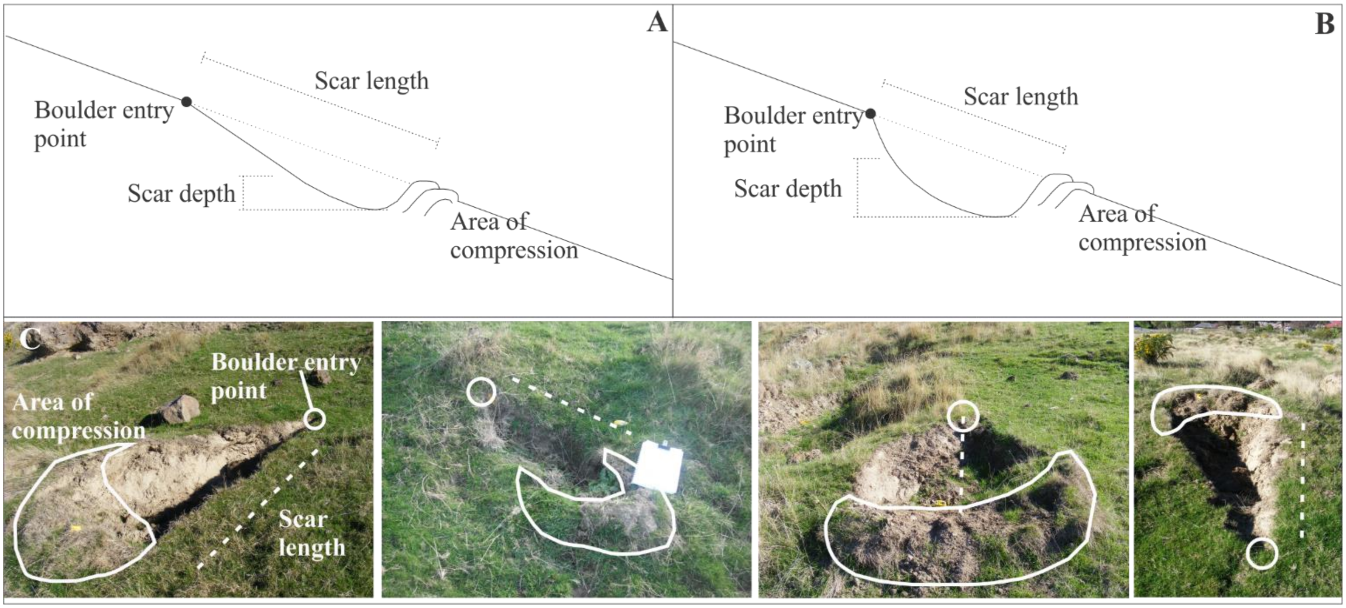


Figure 46. A. Schematic representation of impact scar morphology, where depth:length of the scar ratio is low (a),, representing dry conditions, and high, representing wet conditions (b).B). C. Images of impact scars from Rapaki Bay showing typical scar morphology from four different boulders (c)..

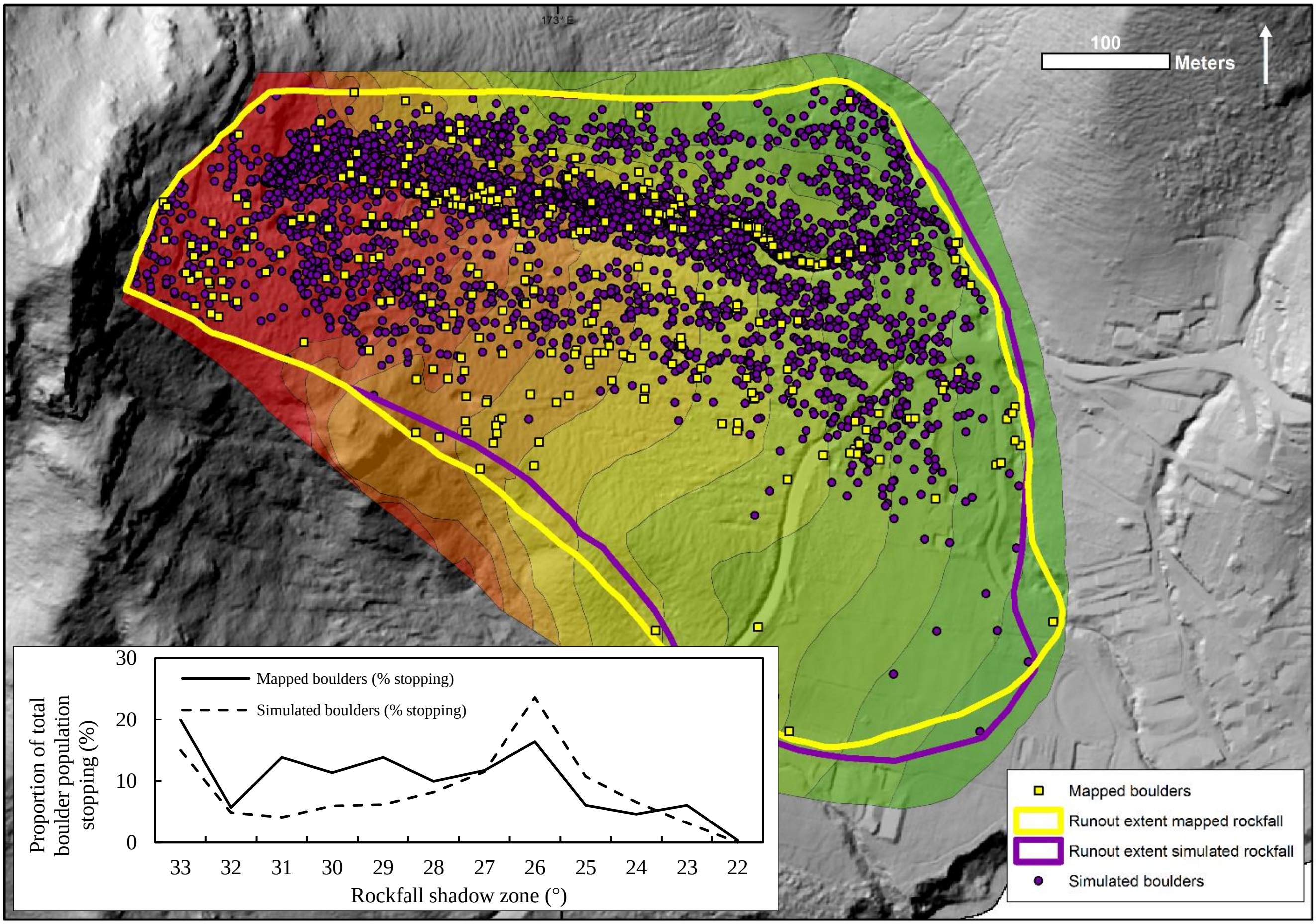


Figure 57. Mapped (yellow squares, n=281) and simulated (purple circles, n=5292) rockfall boulder stopping locations within each shadow zone (the zone between projected shadow angles, after (Evans and Hungr, 1993)) at Rapaki Bay. Shadow zones are displayed from highest (darkest red=33°) to lowest (darkest green=22°). Runout extent of mapped (yellow line) and simulated (purple line) boulder populations are compared using envelopes. Inset: Proportion (%) of mapped and simulated boulders stopping within shadow zones.

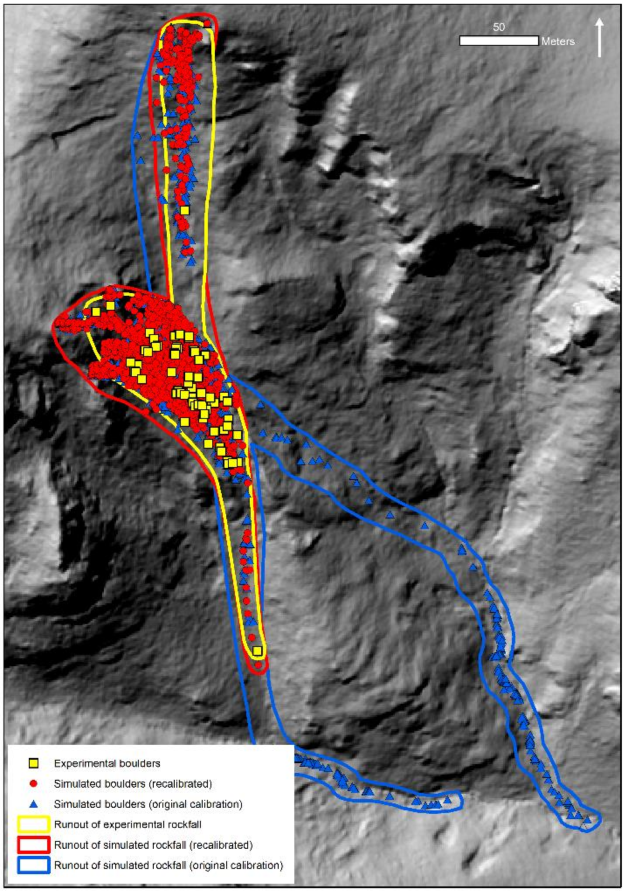


Figure ~~6~~8. Comparison of Mt Vernon experimental rockfall (n=70) runout envelope (yellow line) with simulated rockfall using the initial calibration parameters (blue line = dry) and modified parameters (red line = wet) (boulder n=1800).