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Validating the rockfall risk models developed for the Port Hills of Christchurch, New Zealand

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ABSTRACT

The Canterbury earthquake sequence triggered thousands of rockfalls in the Port Hills of Christchurch, New Zealand, with over 6,000 falling on 22 February 2011. We carried out assessments of the risk to life faced by an individual living below rocky bluffs where life safety is threatened by the hazard of falling debris in the form of isolated boulders rolling and bouncing at high speed for long distances downslope. This risk is expressed as the annual individual fatality risk, and is the probability (likelihood) that a particular person will be killed by rockfall in any year at their place of residence. We initially validated the risk models for the main 22 February 2011 earthquake by comparing the expected number of house hits to the observed number of house hits. To further validate the assumptions used in the risk model we carried out a questionnaire survey, comprising telephone interviews with former residents of red-zoned Port Hills properties, to quantify occupancy rates and probabilities of people being present in the dwellings at the time of the earthquake. This paper presents selected results from this survey.

The survey was used to interview the householders of 70 red zoned properties from across the Port Hills suburbs. 196 persons were normally resident in those 70 properties, which represent about 14% of the properties red-zoned because of slope instability in the Port Hills. Boulder rolls or cliff collapses directly impacted 27 of the 70 respondent properties either on 22 February 2011, or afterwards. None of the residents had been killed or seriously injured, though some had suffered considerable cuts and bruises and others thought they had been lucky to escape unharmed. The risk assessment method used by GNS Science for CCC and CERA in support of zoning decisions for boulder rolls was used to estimate the probabilities of death for each person present in properties impacted by boulder roll

The main reason that people were not killed or seriously injured at the surveyed properties was that most of them were not at home. Re-running the GNS Science risk assessment calculations for surveyed properties impacted by boulder rolls on 22nd February 2011 taking into account these factors suggests that, had the earthquake occurred at night and all the residents been at home, several deaths would have been expected among the surveyed properties.

Introduction

The 2010/11 Canterbury earthquakes, New Zealand, triggered many mass movements in the Port Hills of Christchurch including rockfalls, rock and debris avalanches and slides and associated cliff-top cracking and soil slumps (Figure 1). The 2010/11 Canterbury earthquakes commenced on 4 September, 2010 (New Zealand time UTC + 12 hours) with the M_W 7.1 Darfield earthquake, situated 45 km west of the Port Hills. The Darfield earthquake caused damaging levels of ground shaking and liquefaction in Christchurch but relatively few rockfalls in the Port Hills. Sadly, the damage and loss inflicted by the Darfield earthquake was eclipsed by the M_W

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6.2 Christchurch earthquake of 22 February 2011 at 12:51 in the afternoon local time, which occurred directly under the Port Hills, and generated extreme ground motions—exceeding 2.0 g in places. Of the mass movements triggered in the Port Hills by the Canterbury earthquake sequence, rockfalls and debris avalanches were the most abundant type (e.g., Figure 2) with the highest risk to people and buildings (Massey et al., 2014). Rockfalls, debris avalanches and cliff-top cracking were also notably triggered by aftershocks on 16 April, 13 June and 23 December, 2011 (Massey et al., 2014).

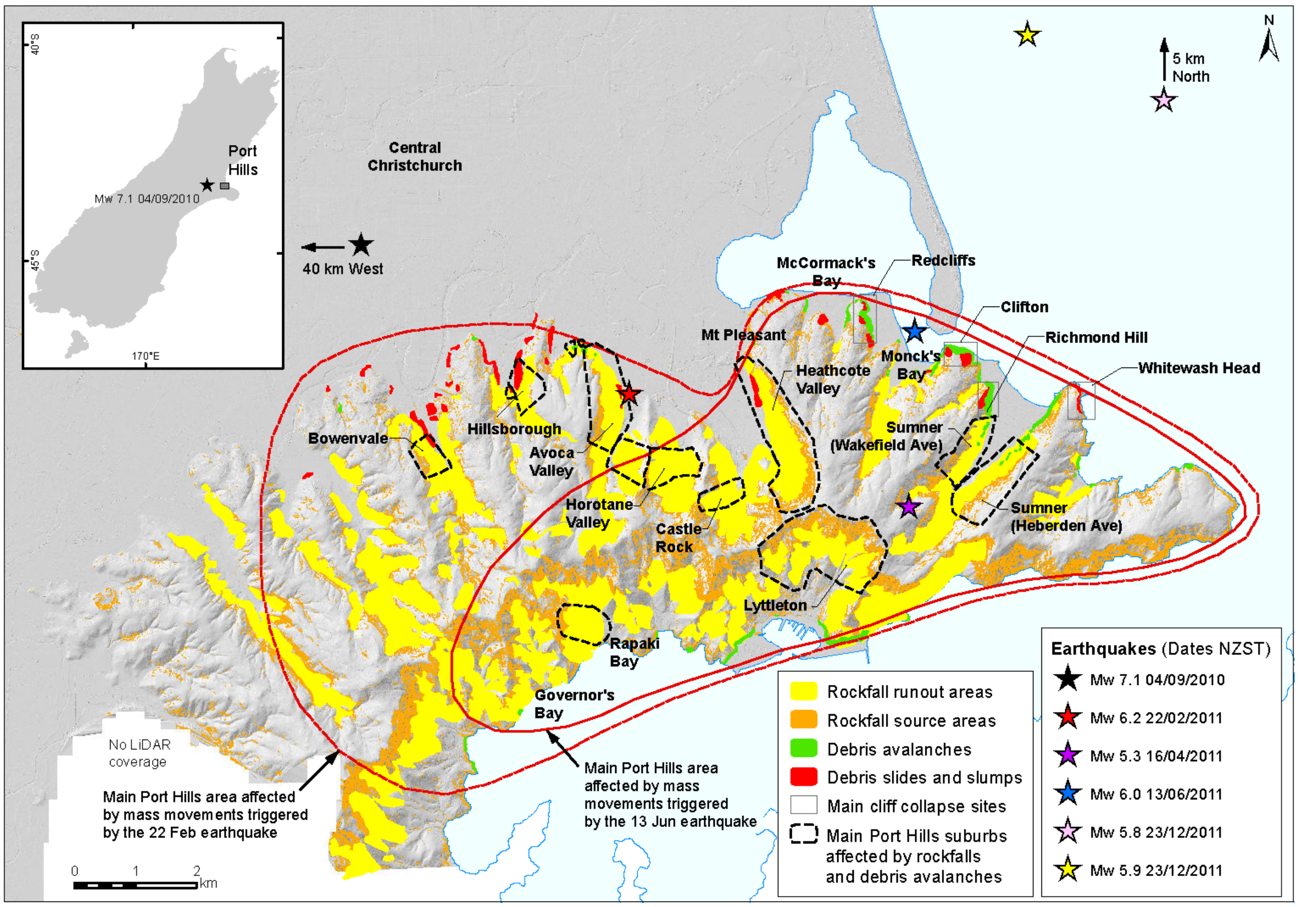

Figure 1. Map showing the location of the landslides generated by the main 2010/11 Canterbury earthquakes, and the locations of the main suburbs in the Port Hills.

Around 100 Port Hills homes were severely impacted by rockfall and cliff collapse during the 22 February 2011, earthquake. Five people were killed by debris avalanches and cliff-top recession (locally referred to as cliff collapses) but none by individual boulders (rockfalls), locally referred to as “boulder rolls”, despite more homes being affected by the latter than the former. Approximately 560 homes were red-placarded because of concerns around slope collapse and rockfall, and of these, around 450 homes were subsequently issued with Section 124 notices, issued by Christchurch City Council (CCC) under the Building Act (Macfarlane and Yetton, 2013). The majority of these homes were subsequently “red zoned” and made the subject of offers to purchase from the government.

A questionnaire survey was carried out to explore the discrepancy between the extensive damage to property and minimal harm to people, and to learn any lessons from those directly affected by boulder roll and cliff collapse hazards. This was done to help prevent future harm from such hazards, and to help validate the models of boulder roll and cliff collapse risk used in assessments for CCC and the Canterbury Earthquake Recovery Authority (CERA), on which red zoning of Port Hills homes were based.

Figure 2. Left photograph: view from outside a home in Sumner showing impacts from rockfalls. Right photograph: view taken from inside the same home looking out towards the person in the left photograph.

Approach

The questionnaire was designed to elicit information on: 1) the number of persons normally resident at the property; 2) the number present at the property between 12.51 and 13.50pm on the 22 February 2011 (the time of the main 22 February 2011 earthquake), and their locations around the property; 3) the locations and reasons for being elsewhere if residents were not at home at the time of the earthquake; and 4) The experiences of residents, with particular focus on any impacts on the property and/or resident's close encounters boulder roll and cliff collapse hazards. For the purpose of this study "property" refers to the land parcel, both the dwelling and the garden. The survey questionnaire is provided in Taig et al. (2015), and was used as a framework for each interview; many respondents were eager to talk about their experiences and offered substantial additional information; several interviews became conversations of some length. Ethics approval was obtained for the survey via Massey University.

Sample selection and survey process

In almost all cases the population targeted for the survey were the occupiers of properties in the Port Hills that were included in the governments residential "red zone" offer because of the high risk to life from boulder roll or cliff collapse hazards. In most cases the people surveyed were also the owners of the properties. Prior to each survey, checks were carried out (using ArcMap-

GIS software) into the current status of each property in terms of its Section 124 status, red-zoning and the location of any rockfall onto the property on 22 February 2011, or subsequently. In line with the approved ethics process, a check was also carried out of residents' surnames against the published list of those killed in the 22 February 2011, earthquake in order to be aware of any possible particular sensitivity. Traced householders were then telephoned systematically. The first step in each call was to establish that the contact was indeed the householder of the relevant red-zoned property, the second to establish whether they would be willing to participate in a survey. Participant's responses were anonymous and the data and analysis and assessment of the results have been generalised across the sample. A conscious decision was made to try to focus the survey on residents of red-zoned properties, and in particular those properties known to have been impacted by falling rocks. This is expected to have produced a source of bias in the householders interviewed. Fewer than 15% of red-zone property owners were interviewed, and the properties of those interviewed represented 20–30% of those impacted by boulder roll and cliff collapse hazards.

The GNS Science boulder roll calculations (contained in Massey et al., 2012a,b) of risk for the properties impacted by boulder roll were rerun with the revised assumptions corresponding to the survey findings, and using boulder locations specific to the actual impact locations at each property.

Results

As was expected, the primary reason that more people were not seriously hurt by rockfall is that the majority were not at home. Figure 3 provides a breakdown of the locations of the 196 people normally resident at the 70 respondent properties at the time of the 22 February 2011, earthquake.

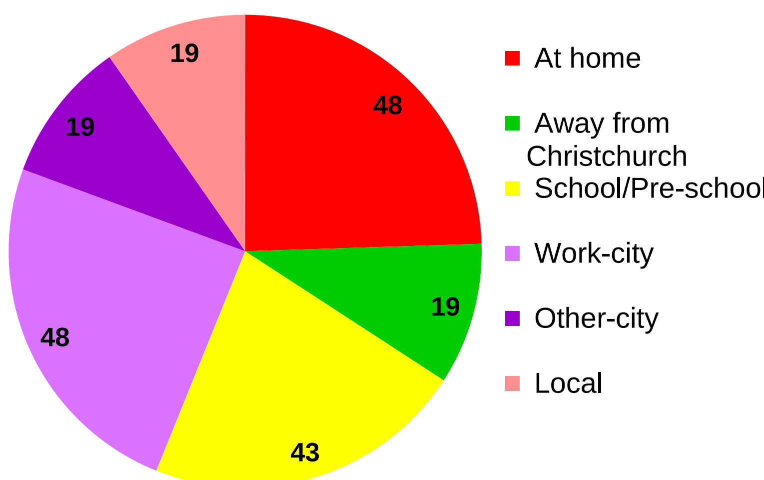

Figure 3. Surveyed property residents – Locations at 12:51 on the 22 February 2011.

Only 48 out of 196 residents (exactly 25%) were at home at the time of the earthquake. Figure 4 shows how their locations within their properties were distributed in relation to the areas of the property closest to, furthest from, and intermediate in relation to the hazard (furthest up-slope corresponding to closest to the hazard for properties below a slope, nearest to the cliff edge for cliff-top properties). Our interpretation of Figure 4 is that people who were at home were evenly distributed around their properties in relation to the areas more or less at risk from boulder roll and cliff collapse hazards. What was clear in discussing parts of homes with the respondents was that a large majority of homes had bedrooms to the rear/uphill side of their properties and living spaces to the front/downhill side, to take advantage of the Port Hills views. Thus cliff-top properties tended to have their living spaces nearer the cliff edge and hazard, while properties below slopes tended to have bedrooms at the back nearest to the slope and the hazard, and living spaces at the front, further from the hazard. The corollary is that we would expect there to be a distinct difference between the two types of property between day and night. Cliff top householders would tend to be in the higher risk parts of their property by day and the lower risk by night. For householders living below slopes the situation is reversed, with more people in higher risk parts of their properties by night than by day.

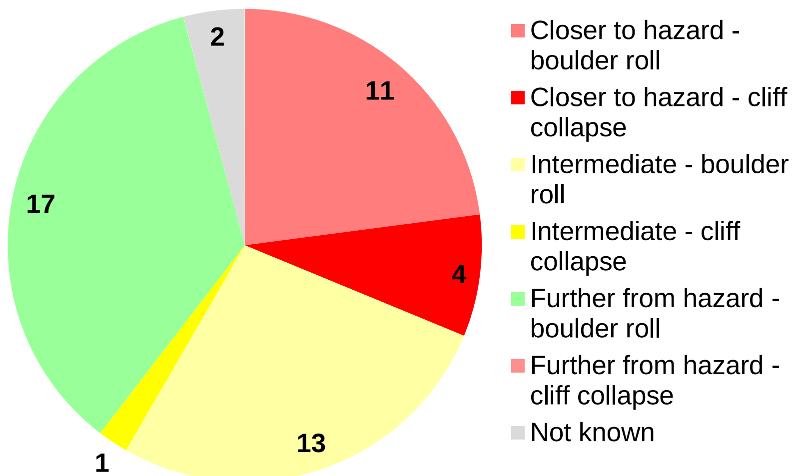

Figure 4. At home residents of surveyed properties – Locations at 13:50 on the 22 February 2011.

The respondents spanned a good geographic mix from around the Port Hills suburbs, as shown in Figure 5, with the Heathcote Valley and Sumner particularly well represented. As is clear from Figure 5, a far higher proportion of surveyed properties were below than above slopes. It should be noted that the respondents comprised a roughly equal mix of men and women. Of the 70 surveyed properties, 27 had at some stage suffered direct impact from falling rocks, 23 of the properties were impacted on 22 February 2011, two about a week later (one respondent noted that this was after rainfall), and three during the 13 June 2011 earthquake, of which one had previously also been impacted on 22 February 2011. The majority of the impacts involved boulders rolling downhill and into the properties. The 27 impacted properties were home to 79 residents. None were killed or seriously injured, because either: a) they were out at the time (51); b) the boulder(s) did not reach them at their location on their property (19); c) the boulder(s) reached or passed their location but missed them (8); and d) the person successfully evaded multiple boulders (1).

The primary reason, as was anticipated from the large proportion of all residents sampled in the survey who were not at home, was that people were out at the time of the 22 February 2011, earthquake. The second most important reason is that the hazard (boulder roll or cliff collapse) did not extend as far onto the property as where persons at home were located. This represents a known factor of pessimism in the risk assessment methodology developed by Massey et al. (2012a, b), for CCC and CERA and is explored more fully below. Finally there were nine people who were within range of the hazard (boulder roll in all cases) but were missed by it. These were the "lucky escapes" from boulder roll impacts; their stories are told in Taig et al. (2015). Several residents reported having been aware of boulders approaching and taking some sort of evasive action, and one man successfully dodged several boulders.

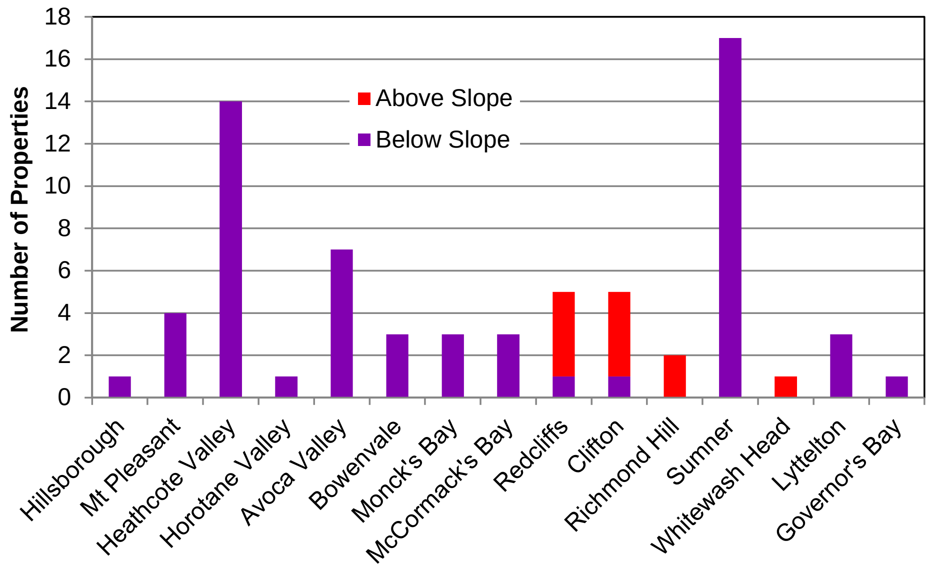

Figure 5 Distribution of surveyed properties across the Port Hills Suburbs exposed to boulder roll and cliff collapse hazards. For suburb locations refer to Figure 1. N properties = 70.

While it is possible that none of these people would have been seriously injured without the action they took, their behaviour illustrates the significant possibility that people who are awake and alert at the time of a boulder roll incident may be aware of approaching boulders and able to take some effective evasive or protective action. A number of respondents' properties had been damaged in such a way that they considered it very likely there would have been fatalities had the rockfall event occurred at night. As regards cliff top recession, all four occupants of affected properties survived because the recession did not extend as far as the rooms in which they were located. One Redcliffs property had suffered severe cliff collapse onto it, inundating the whole property, but fortunately no one was at home at the time.

Risk Assessment implications of survey findings

The survey data on cliff collapse is too sparse to be of statistical value in validating (or otherwise) the risk assessment methods developed by GNS Science for CCC and CERA. The boulder roll data, though, provides some interesting insights into the assumptions used in the GNS Science risk assessments, in particular: a) the GNS Science assessments adopted the assumption that any boulder reaching a property would travel through the whole extent of the property; b) people were randomly distributed across the whole slope width of their property; and c) the assumption of a fixed value of vulnerability (probability of death if in the path of one or more boulders). In contrast the survey found that: a) boulders mostly stopped towards the rear of properties; few penetrated through to the middle or front of houses; b) people when at home in the middle of the day are mostly indoors and fairly evenly distributed about their homes; and c) people appear to have capacity to be alert to boulders approaching them and to take evasive action.

The following results were derived from repeating the GNS Science calculations (contained in Massey et al., 2012a,b) of risk for the properties impacted by boulder roll with revised assumptions corresponding to the survey findings (a) to (c) above. Boulder locations are taken specific to the actual impact locations at each property. People are assumed to be distributed as shown in Table 1. The survey showed that many people were aware of boulders approaching (either through hearing them or seeing them) and were able to take effective evasive action. To take this into account, the GNS Science assumption of a constant vulnerability (probability of death if in the path of one or more boulders) of 50% (Massey et al., 2012a, b), was split into values of 50% for daytime and 90% for night-time. Given the uncertainty associated with such estimates, the estimated risk levels were grouped into broad categories (0–3%, 3–10%, 10–30% and 30–100%).

Table 1. Assumed distribution of people within Port Hills properties subject to boulder impact.

Location	% Day time spent	% Night time spent
Garden	10%	0%
Rear of house	30%	80%
Middle of house	30%	10%
Front of house	30%	10%

The results are shown in Figure 6 – note that the chart includes all 22 properties impacted by boulders (including those impacted after the 22 February 2011, earthquake), and that it is based in each case on a “typical person” spending their time at home split among areas of the property as shown in Table 1. The results show that the number of properties at moderate to high risk levels (10% and above), adopting the CCC/CERA assumptions, give a very good match to those numbers adopting the actual night-time assumptions. The mismatch is at the low end of the risk levels, where the CCC/CERA assumptions over-predict the number of properties in the low risk categories (3-10%) and under-predicts the number of properties in the very low category (0-3%). The most significant factor of pessimism built into the CCC/CERA risk calculations is that every boulder impacting a property is assumed to travel through the whole length of that property, and that people spend their time at home uniformly distributed across the whole property. When this assumption is replaced by the spread of distances travelled by actual boulders and the typical distributions of people as in Table 1, along with the assumptions of lower vulnerability during daytime, the daytime risk levels drop considerably. The night-time risk levels are less affected as the majority of people are assumed to be at the rear of houses, and to be less able/likely to be aware of and take evasive action as boulders approach.

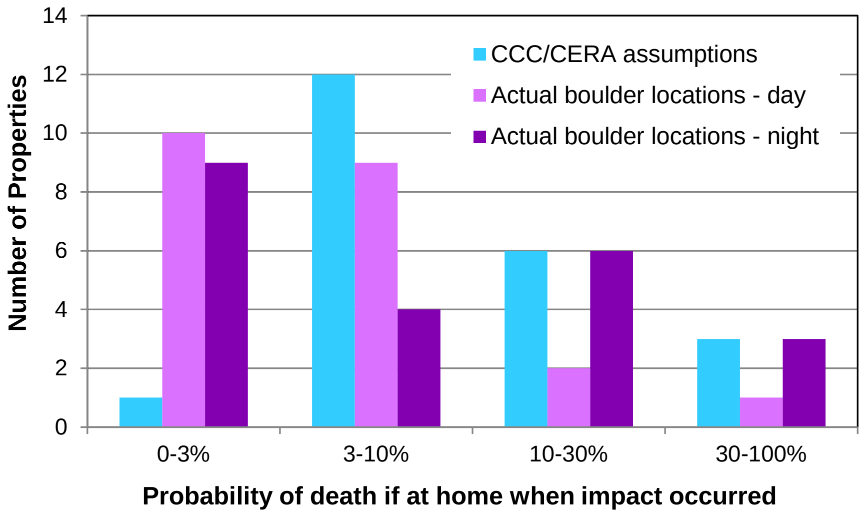

Figure 6. Effect of alternative assumptions on "boulder roll" risk at impacted properties. Total number of properties impacted = 22.

Predicted numbers of deaths given the 22 February 2011 earthquake

The expected number of people killed as a result of the 22 February 2011, earthquake in ALL dwellings (houses only) within the residential areas included in the pilot boulder roll assessment area (i.e. not just those dwellings whose owners were interviewed in this survey) have been estimated using the rockfall risk model, which is detailed in Massey et al. (2012a,b). To do this, the results from the survey were used to estimate the number of residents in dwellings during the day at the time of the 22 February 2011, main earthquake. From the survey results, the number of people in dwellings at the time of the earthquake was 26, out of a total of 46 dwellings whose residents were contacted during the survey, and whose dwellings were affected by rockfalls in the assessment area. This means that the mean occupancy of surveyed dwellings was 0.57 people per dwelling, or about one person per two dwellings. For the same dwellings the night time occupancy was 2.7 people per dwelling. Based on these data, the probability of a person being home on the day of the earthquake was 0.21 (21%). The estimated number of deaths adopting these parameters is between 0 and 3, assuming the day-time occupancy and probability of a person being present and between 3 and 17 if the night-time occupancy and probability of person being present is assumed. Actual deaths in the assessment area from boulder rolls were zero, although several near misses and an injury were logged by the survey.

Conclusions

The main reason that people were not killed or seriously injured at the surveyed properties was that most of them were not at home at the time of the main earthquake on 22 February 2011. A second important reason that people who were at home at the time their property was impacted by falling rocks and cliff-top recession were not seriously hurt was that in 2/3 of cases the hazard stopped short of the part of the property in which they were present. Nine people who were at home at the time of boulder rolls impacting their property were level with or uphill from the final resting place of the boulder(s) involved; these represented the "luckiest escapes". One in particular had dodged numerous boulders; two others had vacated locations destroyed by boulders within 1 minute or less of the impacts occurring. The risk assessment assumptions used by GNS Science for CCC and CERA in support of zoning decisions for rockfall gave (as intended) moderately pessimistic results in comparison with the same assessments made based on actual rockfall and people locations at the times of boulder impact. The primary reason for this was the assumption in the CCC/CERA assessments that every boulder travelled through the whole length of any property it impacted. The results adopting the GNS Science assumptions compared well with the results based on actual rockfall and people locations, adopting night time occupancy and vulnerability. The survey revealed three reasons why the human impact of boulder rolls on surveyed properties would likely have been considerably worse had the impacts on their properties occurred at night: 1) more people would have been at home; 2) most people would have been in bedrooms to the rear (uphill) side of their properties, with a considerably higher proportion of them within the travel range of boulders than during the day (several respondents described beds and/or bedrooms as having been "destroyed" by boulder impacts); and 3) several respondents noted without prompting that they had heard and/or seen boulders approaching their property and been able to take evasive action.

Acknowledgments

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