

Research Article

Rockfall in the Port Hills of Christchurch: Seismic and non-seismic fatality risk on roads

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Abstract: Numerous rockfalls released during the 2010–2011 Canterbury earthquake sequence affected vital road sections for local commuters. We quantified rockfall fatality risk on two main routes by adapting a risk approach for roads originally developed for snow avalanche risk. We present results of the collective and individual fatality risks for traffic flow and waiting traffic. Waiting traffic scenarios particularly address the critical spatial-temporal dynamics of risk, which should be acknowledged in operational risk management. Comparing our results with other risks commonly experienced in New Zealand indicates that local rockfall risk is close to tolerability thresholds and likely exceeds acceptable risk.

Key words: fatalities, natural hazard, quantitative risk analysis, road infrastructure, rockfall.

Introduction

The 2010/2011 Canterbury earthquake sequence triggered widespread mass movements in the Port Hills area of Christchurch, the largest metropolitan centre of New Zealand's South Island. Most significantly, the magnitude 6.2 M_w Christchurch earthquake on 22 February 2011 generated previously inexperienced large ground motions, particularly with respect to vertical ground accelerations (Fry *et al.* 2011; Bradley *et al.* 2014). High shaking intensities initiated large-scale mass movements across the Port Hills, an approximately 65 km² area located between Christchurch and its main seaport Lyttelton (Dellow *et al.* 2011; Hancox *et al.* 2011a). Among rock avalanches and slides, associated cliff-top cracking, soil slumps and avalanches (referring to the scheme of Keefer 1984), rockfalls with over 6000 boulders were released.

As a consequence, Canterbury Earthquake Recovery Authority (CERA) and Christchurch City Council (CCC) commissioned investigations to quantify the risk imposed by the rockfall hazard (Massey *et al.* 2012a). Rockfall hazard

was quantified for residential homes exposed on a suburb scale following the landslide risk management framework introduced by Fell *et al.* (2005) and revisited by the Australian Geomechanics Society (2007). As a result, rockfall risk levels were identified being considerably higher than it was understood before the 2010/2011 events.

However, geomorphological and photographic evidence derived during post-event field assessments (Hancox *et al.* 2011b) and GIS data of rockfall run-out distances (CCC n.d.) showed that rockfalls also affected key parts of the road network (Fig. 1). Many boulders were released on 22 February, 2010 and during a M_w 6.0 aftershock on 13 June 2011, particularly in the Sumner area, on Summit Road and around Governors Bay (Dellow *et al.* 2011). As parts of this road network are important for local commuter traffic and transport of goods between Christchurch and Lyttelton harbour, an assessment of rockfall risk is necessary. Moreover, information on available traffic volumes suggest highly variable patterns of traffic flow that, as a consequence, will strongly influence corresponding fatality risks.

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Accepted: 18 July 2017

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Figure 1 Rockfall impacts Summit Road on the main Port Hills ridgeline following the 4 September 2010 and 22 February 2011 earthquake events (photo kindly provided by Graham Hancox, GNS Science).

In the past decades, research efforts in risk assessment for traffic infrastructure addressed many hazard types, such as landslides (Benn 2005), rockfall (Bunce *et al.* 1997; Hungr & Beckie 1998; Roberds 2005; Ferlisi *et al.* 2012; Michoud *et al.* 2012) and snow avalanches (Schaerer 1989; Kristensen *et al.* 2003; Margreth *et al.* 2003; Zischg *et al.* 2005; Hendrikx & Owens 2008; Wastl *et al.* 2011). They all pursue either qualitative or quantitative approaches; however, most of them are static. Hence, the risk model introduced by Wilhelm (1997) for the European Alps was identified to best match the available risk setting for this case study, mainly due to its comprehensive quantification of a waiting-traffic scenario. Originally designed for avalanche hazards, we modified the original equations for a set of scenarios that better reflect the discontinuous distribution of rockfall across the hazard zone: in contrast to snow avalanches, boulders will only hit certain points or follow specific run-out paths.

In our study, four main objectives were addressed in detail: (i) quantifying the annual collective and individual fatality risk for moving traffic on Tunnel Road and Dyers Pass Road; (ii) identifying the spatial-temporal dynamics of the most vulnerable elements at risk (i.e. commuter traffic) and calculating the related variations in risk; (iii) assessing the dynamic risk levels associated with traffic jams; and (iv) comparing our risk estimates to commonly tolerated risk levels for natural hazards in New Zealand.

Study area

The approximately 65 km² large Port Hills area south-east of Christchurch is dominated by ridges up to 500 mASL, hillslopes and sea cliffs. The region is a popular residential area and renowned for recreational outdoor activities. Geologically, the area represents the northern part of the eroded, extinct Lyttelton basalt

volcano of Miocene age (Forsyth *et al.* 2008). Bedrock of the Port Hills comprises layers of weathered basalt lava flows that are mostly covered by much younger deposits of loess and colluvially reworked loess and weathered basalt (Bell & Trangmar 1987). The lava flows and scoria in particular were the main sources of rockfalls triggered during the Canterbury earthquake sequence and the type of rock outcrops within these strata were the basis for categorising different rockfall source areas (Massey *et al.* 2012a). As a consequence, risk estimates were calculated for each individual source area and corresponding boulder catchment.

The affected rockfall area is accessible through a dense network of smaller roads that are linked by major arterial roads (Fig. 2). Several road links also cross the Port Hills, such as Tunnel Road, Dyers Pass Road, Sumner-Evans Pass Road and Bridle Path Road. Tunnel Road, including the Lyttelton Road Tunnel, is the most prominent connection in terms of traffic volume while the Sumner Lyttelton Corridor via Evans Pass is an important road link between Christchurch and its cargo-port in Lyttelton. The other two road connections are less frequently used but may serve as bypass routes if main roads are closed. In fact, during the rockfall-induced closure of Sumner Road (as of 1 August 2016) over-sized vehicles and vehicles carrying dangerous goods access the port via Dyers Pass or Gebbies Pass or use the tunnel during explicit night-time closures.

Method

We used existing datasets that describe rockfall hazard through frequency-magnitude bands for earthquakes and non-seismic triggering events, boulder production rates, boulder size distribution and associated run-out distances. The data were derived after the 2010/2011 rockfall events (Massey *et al.* 2012a,b) and made available by the regulatory authorities (CCC n.d.). Additional data collected included a spatial dataset of the road network (Land Information New Zealand 2015) and traffic volume data in hourly resolution (CCC 2014). All data were processed using GIS and the probability of being hit by boulders was calculated for each road segment intersecting rockfall hazard zones¹. The remaining parameters needed for the risk computation were adopted from the literature, including physical vulnerability (Bunce *et al.* 1997; Finlay *et al.* 1999; Australian Geomechanics Society 2007), average car size (Land Transport NZ 2004), vehicle speed (CCC 2015), vehicle occupancy (Sullivan & O'Fallon 2010) and long-term traffic volumes (New Zealand Transport Agency n.d.), see Table 1.

Risk – at its simplest – may be described as the probability of occurrence of a (natural) process times the

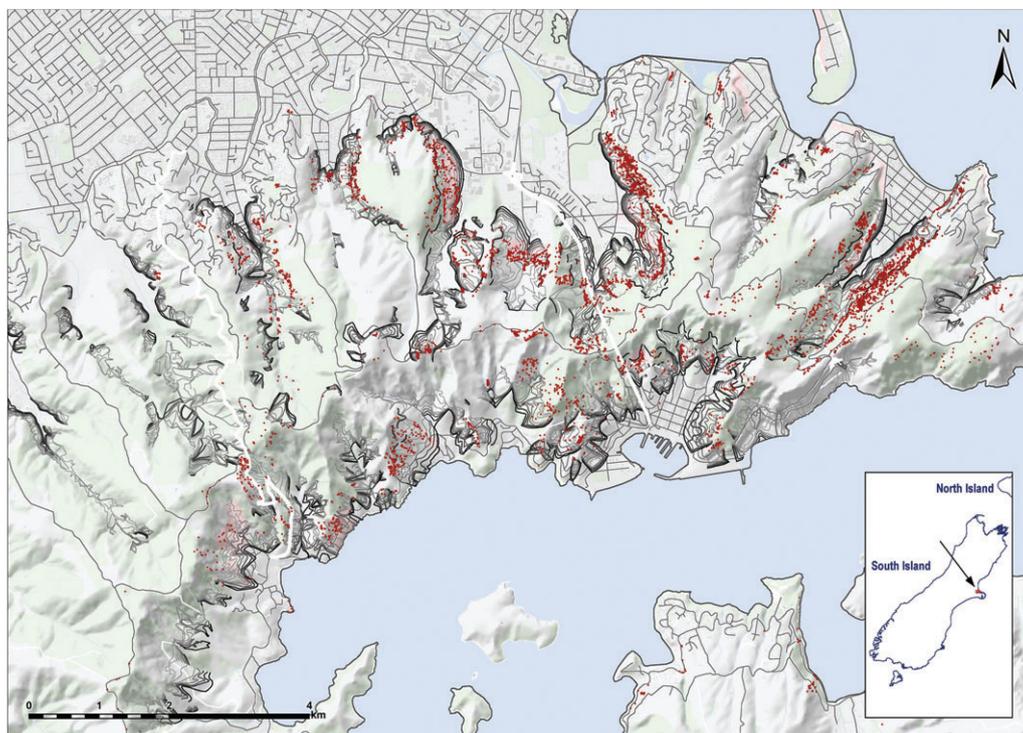


Figure 2 The Port Hills road network and the extent of boulder release (dots and thicker dark lines) during the 2010/2011 earthquake sequence. Sources: Land Information New Zealand 2015, CCC n.d.

expected loss. Generally, two epistemic means expressing risk exist: in qualitative terms or in quantitative terms, where risk is expressed as a one-dimensional probability estimate, averaged over space, time and context (Renn 2008). Drawing on a quantitative risk assessment (QRA) framework allows risk to be expressed as an objective and reproducible measure which can then be compared from one location to another (Corominas *et al.* 2014). QRA therefore spatially integrates hazard with exposed elements and their vulnerabilities in order to estimate the expected loss (Fuchs 2009).

In this study, we used a QRA framework for landslides (Fell *et al.* 2005; Australian Geomechanics Society 2007), focusing on risk analysis (Fig. 3). Based on the frequency of occurrence of triggering events and corresponding rockfall runout (hazard analysis) we quantified the spatial and temporal probabilities of elements at risk (i. e. individuals in vehicles) and estimated their vulnerability (consequence analysis). In this context we defined vulnerability as the probability that a particular life will be lost ($V_{D:T}$), thus highlighting the physical component of vulnerability (Fuchs 2009). The results were then combined using a probabilistic equation (Eq. (1)) to estimate the fatality risk (R_{LoL}). That is,

$$R_{LoL} = P_H \cdot P_{S:H} \cdot P_{T:S} \cdot V_{D:T} \quad (1)$$

where P_H is the annual probability of the rockfall event, $P_{S:H}$ is the probability of spatial impact of a rockfall hitting any object, $P_{T:S}$ is the temporal spatial probability that any object is present at a given location and $V_{D:T}$ is the probability of loss of life given the impact (vulnerability). All input data are provided in Tables 1–3.

Probability of rockfall release

Rockfall triggers in the Port Hills include earthquakes and heavy rainstorms. Each process can be further divided into different magnitude-frequency bands. As each triggering band is independent of the other, the fatality risk is also calculated separately. Consequently, the overall risk estimate is expressed as the sum of the incremental risk values of all magnitude-frequency bands (Hung *et al.* 1999). The probability of occurrence of a specific boulder release is given by the annual frequency of a triggering event. In this respect we incorporate the results of Massey *et al.* (2012a,b) who derived annual frequencies of future earthquake events and the corresponding boulder release rates (Table 2).

Moon *et al.* (2005) point out that the full possible range of triggering events should be considered for hazard analysis. Thus, we also integrate a set of non-seismic triggers into our overall risk analysis by including four bands of representative rainstorms. Although their overall contribution to observed boulder release was low in

Table 1 Input data for the quantitative risk analysis (see Eqs (2)–(8)).

Parameter	Description	Tunnel Road	Dyers Pass Road	Dimension
AADT	Annual average traffic volume	11 189	3405	vehicles per day
v	Vehicle speed	100	70	km h ⁻¹
Q	Overall road length	1588	1625	m
L_{\max}	Maximum length of endangered road	1194	1240	m
a	Avg. distance between vehicles	214	493	m
L	Length of effectively endangered road	$P_{S:H} \times r_i$		m
r_i	Length of i -th road segment [range]	[5.9;266.2]	[2.5;345.1]	m
$P_{S:H}$	Probability of boulders affecting r_i	f(frequency/magnitude band)		1
L_W	Length of waiting traffic line	2445	724	m
a_w	Average distance between standing vehicles		10	m
Δt	Duration of traffic jam		0.5	h
z	Daily commuter passages (5 days/week)		2	1
β	Vehicle occupancy		1.53	1
D	Vehicle length		5	m
d	Diameter of design boulder		1	m ³
$V_{D:T}$	Physical vulnerability		1	1

the Christchurch earthquake event, rainfall events can significantly contribute to boulder release numbers particularly during high-frequency/low-magnitude events (Massey *et al.* 2012b). All data concerning event frequency and corresponding boulder-release were available on a suburb-scale basis across the Port Hills (Massey *et al.* 2012a,b) and were used accordingly (Table 3).

Probability of boulders hitting a vehicle

The probability of a vehicle being hit by rockfall involves boulders reaching or intersecting the road. We extracted boulder release rates and runout distances from a compiled boulder dataset (CCC n.d.). These data are based on 2D and 3D rockfall modelling results and field mapping (for seismic release) and a range of historical records (for non-seismic release). The 2D modelling is primarily based on the shadow-angle approach (Lied 1977; Evans & Hungr 1993) which relates the maximum runout distance to the rockfall source area by calculating the angle between the toe of the source area and the boulder stopping position. Runout distances range between shadow angles of 31° (boulders stopping near the source area) and 21° (the presumed maximum boulder runout distance), see Figures 4 and 5.

The probability that one boulder of the total number of boulders N passes the same portion of slope increases with each following boulder. The probability of any boulder hitting a vehicle can be derived by incorporating the binomial theorem (Benjamin & Cornell 1970; Eq. (2)).

$$P_{S:H} = 1 - (1 - P_{1(S:H)})^N = 1 - \left(1 - \frac{2D+d}{r_i}\right)^N \quad (2)$$

Since the studied roads cross several shadow lines the probability of vehicles being affected is continuously

changing due to the varying hazard probability. Hence, each road section was assigned to its respective (maximum) shadow-angle value and the corresponding $P_{S:H}$ value which was estimated from the existing suburb-wide data. Moreover, as the length of the effective hazard zone varies across all magnitude-frequency bands, the spatial probability $P_{S:H}$ and thus the temporal probability term $P_{T:S}$ also varies.

Probability of vehicles being present

$P_{T:S}$ represents the probability that one or more vehicles are present on any endangered road section r_i . We invoked the equation provided by Wilhelm (1997), which provides a set of assumptions regarding the vehicle-rockfall encounter probability by integrating vehicle distance and speed. In the original equations, any endangered road section is expected to be covered by the hazard process on its full length r_i . To better reflect the expected discontinuous rockfall coverage on the road, we modified the equation and calculated the effective endangered section by multiplying r_i with the expected occurrence of boulder impacts $P_{(S:H)i}$ (Eq. (3)).

$$P_{T:S} = \frac{DTV}{v \cdot 24} \cdot \sum_{i=1}^n r_i \cdot P_{(S:H)i} = \frac{L}{a} \quad (3)$$

For moving traffic, we assumed constant traffic flow over space and time. However, in order to highlight the temporarily elevated impact-probability during traffic jams (Schaerer 1989; Hendrikx & Owens 2008) we also incorporated a waiting traffic scenario: the expected waiting traffic line is therefore modelled as the relationship between all vehicles involved in a waiting traffic line L_w/a_w and the rockfall-exposed part of that road L/Q (Wilhelm 1997; Eq. (4)).

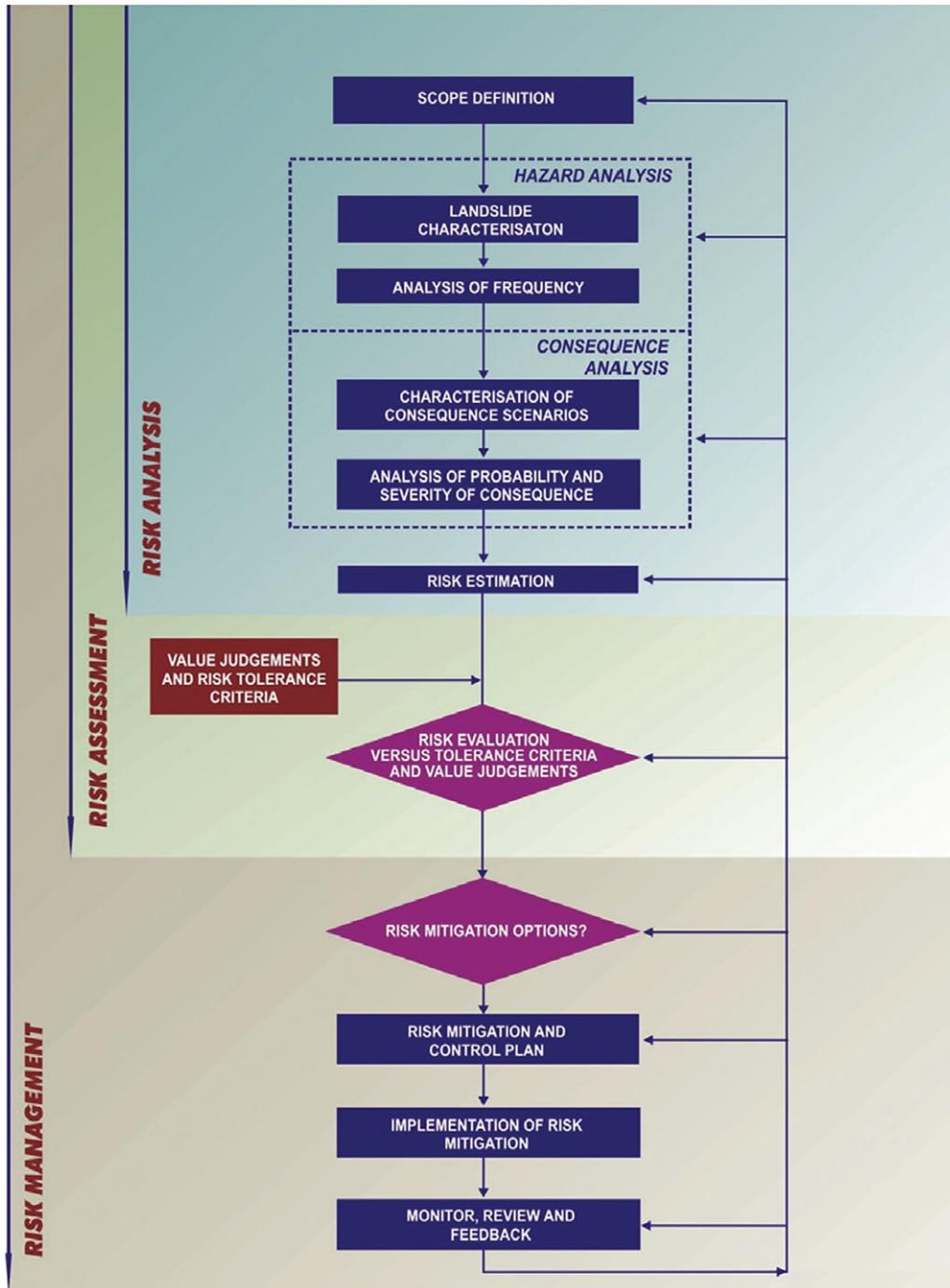


Figure 3 The landslide hazard risk framework (Australian Geomechanics Society 2007) based on Fell *et al.* (2005). The risk analysis section indicates the main scope of our study.

$$P_{T:S}^W = \frac{L_w}{a_w} \cdot \frac{L}{Q} = \frac{\Delta t \cdot v \cdot L}{(a - a_w) \cdot Q} \quad (4)$$

Vulnerability

We defined vulnerability of people inside vehicles taking a physical approach (i.e. the probability of a person

being killed) and set a conservative value of 1.0. This was assumed to match a proposed available size-dependent vulnerability value for boulders larger than 1 m³ with high kinetic energy (Ferlisi *et al.* 2012). Additionally, we also allowed for drivers losing control and causing a fatal accident.

The resulting risk equations for the annual collective (CR) and individual fatality risk (AIFR) are:

Table 2 Annual frequency of an earthquake occurring at varying intensity (measured in peak horizontal ground acceleration (PGA) and categorised into four intensity bands) as described by Massey *et al.* (2012a).

PGA band [g]	Event frequency (averaged over 2012–2052) [a ⁻¹]	Expected boulder release (Castle Rock)	Expected boulder release (Sector 9 West)
j_1 [0.1–0.4]	0.12	0.1	0.1
j_2 [0.4–1.0]	0.03	17	9
j_3 [1.0–2.0]	0.003	283	155
j_4 [2.0–5.0]	0.0002	2800	1550

Note that boulder release rates from the cumulative source area differ across Christchurch suburbs.

$$CR = \sum_{j=1}^8 \left(P_H^j \cdot \frac{L_j}{a} \cdot V_{D:T} \cdot \beta \right) \quad (5)$$

$$CR_W = \sum_{j=1}^8 \left(\frac{P_H^j \cdot L_W}{L_{\max'} + q_j'} \cdot \frac{L_W \cdot L_j'}{a_w(L_{\max'} + q_j')} \cdot V_{D:T} \cdot \beta \right) \quad (6)$$

$$AIFR = \sum_{j=1}^8 \left(P_H^j \cdot \frac{L_j \cdot z \cdot 236}{v \cdot 8760} \cdot V_{D:T} \right) \quad (7)$$

$$AIFR_W = \sum_{j=1}^8 \left(P_H^j \cdot \frac{L}{Q} \cdot \frac{\Delta t \cdot z \cdot 236}{8760} \cdot V_{(D:T)} \right) \quad (8)$$

where j represents the respective frequency-magnitude band for seismic triggers (j_1 to j_4 ; Table 2) and rainfall events (j_5 to j_8 ; Table 3). Equations (6) and (8) calculate risk assuming a constant waiting traffic line and thereby represent the worst-case scenario (WC). However, traffic jams are likely to form only at traffic peaks. We therefore included a waiting traffic scenario (WT) where the probability of traffic jams occurring is at 10%; for the remaining time period we assumed constant traffic flow as described in Eqs (5) and (7).

Results

Collective fatality risk

For the moving traffic scenario, the collective fatality risk estimate for Tunnel Road equalled $3 \times 10^{-2} \text{ a}^{-1}$, or one deadly road accident every 33 years. Overall, the four

seismic frequency-magnitude bands contributed less to fatality risk in the moving traffic scenario (MT) than the rainfall triggering bands (9×10^{-3} compared to 2×10^{-2}) mainly due to the high single risk value in the lowest non-seismic triggering band (0–15 years return period). The applied waiting traffic scenario (WT) representing a 10% chance of waiting traffic during a rockfall event was assigned a risk value CR_W of $3 \times 10^{-1} \text{ a}^{-1}$ which translated into a risk increase of one order of magnitude (i.e. one fatality every 3.3 years).

The CR value on Dyers Pass Road was $4 \times 10^{-3} \text{ a}^{-1}$, or one fatality every 250 years. Compared to Tunnel Road, seismic risk levels contributed more to the aggregated risk estimate although the 0–15 years rainfall triggering-band remained highly influential on the fatality risk. For the waiting traffic scenario, CR_W was $1 \times 10^{-2} \text{ a}^{-1}$, implying a 250% greater risk than Tunnel Road. Figure 6 summarises the CR estimates for all scenarios.

Individual fatality risk

The annual individual fatality risk (AIFR) estimate was calculated for highly-exposed individuals, which were defined as those commuters who use Tunnel Road (or Dyers Pass Road) twice per day, 5 days per week, with $2 \times 10^{-6} \text{ a}^{-1}$ on Tunnel Road and $7 \times 10^{-7} \text{ a}^{-1}$ on Dyers Pass Road. When calculating the waiting traffic scenario (experiencing waiting traffic during one working trip a week), the respective values (AIFR_W) increased to $9 \times 10^{-6} \text{ a}^{-1}$ and $3 \times 10^{-6} \text{ a}^{-1}$. In the worst case scenario (i.e. commuters stuck in traffic for 0.5 h

Table 3 Effective frequency of four representative rainfall events and their corresponding boulder release rates.

Return period of design rainstorm [a]	Effective annual frequency of rockfall event [a ⁻¹] Castle Rock	Expected boulder release (Castle Rock)	Effective annual frequency of rockfall event [a ⁻¹] Sector 9 West	Expected boulder release (Sector 9 West)
j_5 [<1–15]	0.13	2	0.07	1
j_6 [15–100]	0.02	20	0.1	5
j_7 [100–1000]	0.003	142	0.01	78
j_8 [>1000]	0.0003	283	0.0007	155

Boulder release is estimated from all available data (i.e. databases and pre-historic records; Massey *et al.* 2012a). Release rates during rainstorms with high (j_7 band) and extreme magnitude (j_8 band), however, were only available based on estimations using geomorphic evidence and the potential impact of storms occurring with a frequency of >1000 years (Massey *et al.* 2012b). They represent best estimates and are thus connected to substantial uncertainty.



Figure 4 Shadow angle lines (in white) depicting maximum rockfall runout on Tunnel Road (black dots: mapped boulders of the 2010/2011 earthquake sequence). Sources: Land Information New Zealand 2015, CCC n.d.

each work trip), risk estimates exceed these values by almost one order of magnitude due to a high number of exposed vehicles. Table 4 summarises the AIFR estimates for all scenarios.

Discussion and conclusion

The present risk estimates provide first insights into rockfall fatality risk on arterial roads across the Port

Hills. Consequently, resulting risk should be evaluated against tolerable and acceptable risk levels. Adoption of this procedure is in line with the formal QRA requirements as proposed by the Australian Geomechanics Society (2007), and can facilitate subsequent risk management options. Accordingly, the risk estimates should be carefully examined with respect to (i) data quality and resulting sensitivity of the applied model; (ii) how they relate to existing assessment criteria; and (iii) the practical usability of the final risk estimates.



Figure 5 Shadow angle lines (in white) depicting maximum rockfall runout on the studied section of Dyers Pass Road (black dots: mapped boulders of the 2010/2011 earthquake sequence). Sources: Land Information New Zealand 2015, CCC n.d.

Data quality

Knowing hazard frequency is essential to the overall confidence level of risk estimates (Bunce *et al.* 1997), but calculating a realistic probability for future hazard events typically depends on fairly unpredictable conditions (e.g. seismic activity). In this respect, Massey *et al.* (2012b) identified the probability-density distribution of triggering ground motions in the Port Hills as the least-well determined parameters. Similarly, the limited availability of frequency-magnitude relationships for rockfall-

triggering and local topographic effects also contributes to uncertainty. Particularly for rainstorms with return periods that considerably exceed the instrumental records (high-magnitude/low-frequency), boulder release rates only represent a first-order approximation based on geomorphic evidence or design storms that serve as potential scenarios rather than actual events (Table 3).

In addition, a short record of hazards may not include the unusual union of circumstance (Hendrikx & Owens 2008) and may ultimately underestimate the long-term

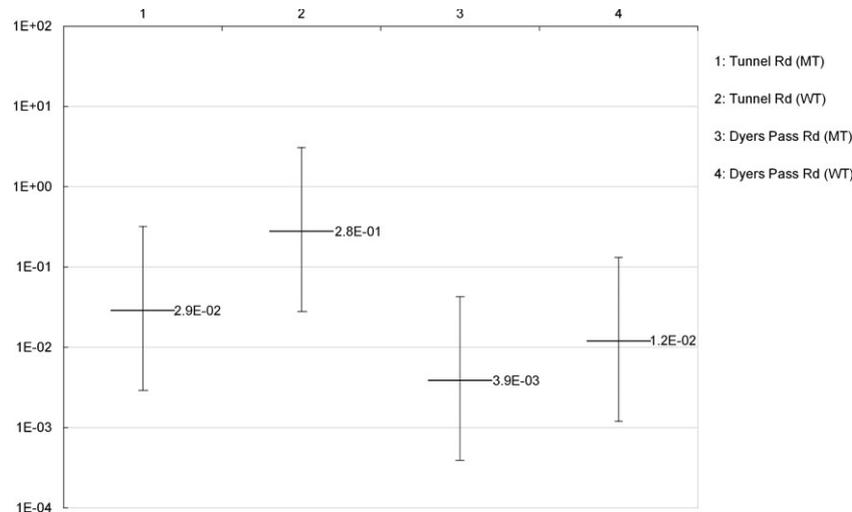


Figure 6 Collective fatality risk estimates for the moving traffic (MT) and waiting traffic (WT) scenario on Tunnel Rd (far left, left) and Dyers Pass Rd (right, far right); confidence intervals $\pm 10^1$.

residual risk. Since we adopted the same data as Massey *et al.* (2012a, 2012b) we applied the same levels of confidence which are one order of magnitude either way.

Seismic triggers are shown to dominate risk in all triggering bands except the high-frequency/low-magnitude band. The high risk value of the non-seismic band j_5 (return period <15 years) can mainly be attributed to the disproportional influence of the event frequency P_H , particularly on Tunnel Road. Based on our data, even the limited boulder release during these low-magnitude rainfall events is made significant in terms of risk by their high frequency. In contrast, in the equivalent seismic frequency-magnitude band (j_1) virtually no boulders will be released by the small shaking intensities (Massey *et al.* 2012a). Consequently, rockfall risk equals zero despite the almost identical event frequency compared to the j_5 band. In effect, using aggregated risk values for a whole set of triggering agents conceals such cross-band variations.

All other data were derived from public databases and the literature and contribute additional uncertainty. The long-term increase of traffic volumes (observed 8% since 1975; New Zealand Transport Agency n.d.); a lack of heavy traffic volume (and corresponding decrease of exposed vehicle numbers due to a greater vehicle length); varying vehicle occupancy rates (lower

occupancy for work trips entailing a risk decrease of about 25%; Sullivan & O’Fallon 2010); and poor parametrisation of vulnerability (existing estimates for rockfall hazard span as large as 0.1 to 1.0 across different scenariosⁱⁱ; Finlay *et al.* 1999, Bunce *et al.* 1997).

Particularly, short-term fluctuations of road traffic can significantly affect the final risk estimate (Fuchs *et al.* 2012). Both studied roads show strongly diurnal traffic behaviour (CCC n.d.) with distinct peaks in the mornings and the evenings. On Tunnel Road, the number of exposed vehicles during rush-hour (5 to 6 p.m.) is double the average figure and would entail a similar increase of the CR value. Furthermore, the potential formation of a traffic jam was shown to be even more influential in terms of increased risk levels. For the WT scenario, the societal risk (CR) on Tunnel Road would increase by a factor of 10 while for the individual risk the impact is less distinct (factor 4). On Dyers Pass Road the corresponding WT factor equals 3 for both societal and individual risk. The worst-case scenario (WC) entails an additional risk increase by a factor of 8 and 7, respectively. Hence, calculating any static risk value (i.e. without including these temporal variations) will significantly underestimate the true risk level, and risk estimates derived from moving traffic underestimate the risk in times of accentuated road traffic.

In order to quantify such effects, a comprehensive sensitivity analysis should be carried out that, in turn, would lead to an increased range in the risk estimates (Fuchs *et al.* 2012). In our view, the validity of the present risk estimates can be effectively improved by more reliable data, particularly regarding event frequencies and fine-scale rockfall modelling. In contrast, due to the highly volatile character of moving elements at risk, additional traffic counts may not fundamentally improve the results

Table 4 Individual fatality risk for the moving traffic (MT), waiting traffic (WT) and worst-case (WC) scenario on Tunnel Rd and Dyers Pass Rd; confidence intervals of $\pm 10^1$ have to be applied.

	AIFR _(MT)	AIFR _(WT)	AIFR _(WC)
Tunnel Road	2.2×10^{-6}	8.8×10^{-6}	6.8×10^{-5}
Dyers Pass Road	9.6×10^{-7}	2.9×10^{-6}	2.1×10^{-5}

as long as the static character of probabilistic risk analyses is preserved. Within the approach we apply, these issues can only be tackled by comparing such scenarios.

Risk assessment

The presented risk figures provide a first-order estimate on the rockfall hazard on Tunnel Road and northern Dyers Pass Road. Subsequently, risk levels were evaluated against 'Risk Tolerability Criteria' (Australian Geomechanics Society 2007). That involves making judgements about the estimated risk, either by comparison to other risks or existing tolerable risks (i. e. risks within a range that society can live with so as to secure certain benefits), typically referring to the individuals most at risk. However, adoption of this procedure entails several key challenges: (i) risk estimates and thus tolerability values are inevitably approximate; (ii) risk tolerability can vary spatially (Leroi *et al.* 2005), temporally and across social scales (Geotechnical Engineering Office 1998); and (iii) QRA is only one input to the decision process around tolerability that may also be influenced by political, social and legal issues (Fell *et al.* 2005).

For natural hazards, only few tolerability criteria exist and they are typically restricted to a technical-normative approach. The Australian Geomechanics Society (2007) recommended as starting point a tolerable AIFR value of 10^{-5} a^{-1} for *existing* landslides. It follows existing recommendations for mass movements where corresponding tolerability values are set between $3 \times 10^{-5} \text{ a}^{-1}$ and $1 \times 10^{-5} \text{ a}^{-1}$ (Geotechnical Engineering Office 1998; Arnalds *et al.* 2004; Bruendl 2009)ⁱⁱⁱ. Taig *et al.* (2012) identified a tolerable risk range from 3×10^{-5} to 10^{-3} a^{-1} based on natural hazards risks experienced by the New Zealand population. While they suggest a suitable starting point at 10^{-4} a^{-1} , Enright (2015) argues that this arbitrarily high threshold appears to be balancing an overestimation of risk and should be lowered to 10^{-5} a^{-1} . On Tunnel Road and Dyers Pass Road, only the calculated risk figures for the worst-case scenario (WC) eclipse the 10^{-5} a^{-1} threshold with 7×10^{-5} and 2×10^{-5} , respectively. However, given the confidence intervals of at least one order of magnitude in each scenario, our waiting traffic and moving traffic scenarios also exceed the tolerability criterion slightly. With respect to acceptable risk (i.e. risks which everyone affected is prepared to accept), risk levels are usually considered to be one order of magnitude lower than tolerable risks (Australian Geomechanics Society 2007). The present estimates would therefore imply unacceptable fatality risks for the Port Hills commuters.

Practical implications

In summary, we have shown how the Wilhelm (1997) model can be modified for rockfall hazard by incorporating the probability term $P_{S,H}$ according to Massey *et al.*

(2014). In contrast, the original WT scenario in Wilhelm (1997) could not be fully adapted because of a lack of data on the frequency of a rockfall event during a road-blocking event. Our assumption of temporarily elevated rockfall risk levels due to very short time-scale seismic aftershock activity and continuous rainfall cannot be supported by the presented results. Moreover, the proposed WT scenario cannot be related to real data on the occurrence of traffic jams because no data about the occurrence of traffic jams were available. We therefore can only point out the adverse potential of waiting traffic on rockfall fatality risk. However, our assumption of higher risk prevailing during traffic jams may reflect reality better than risk assessments based on a waiting traffic line forming only once a year (Bunce *et al.* 1997; Hungr *et al.* 1999; Ferlisi *et al.* 2012).

Generally, the spatio-temporal dynamics of the present risk estimates highlight a fundamental limitation that is inherent to many static risk assessments, particularly regarding natural hazards (Fuchs *et al.* 2012). The conceptual shortcomings of considering risk as static also include the simplifying assumptions that are repeatedly made during the risk computation and covered by the final, aggregate risk estimate. Concerning the practical applicability of such risk estimates it is key to clearly communicate these assumptions (and connected uncertainties) to all stakeholders involved, particularly when expected fatality numbers do not connect to the observed reality. In fact, no traffic fatalities were observed during the 2010/2011 events. The discrepancy between modelling results and fatality records may, at best, serve as a sound basis for communicating (and discussing) risk with the affected general public.

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Endnotes

ⁱWe investigated the rockfall-prone sections of Tunnel Road and a 1.2-km long stretch of Dyers Pass Road, between Victoria Road and Summit Road. The only traffic data that unambiguously relate to the number of pass crossings was available for only this section.

ⁱⁱAccording to AGS, the probability of a person being killed by a rockfall $V_{D,T}$ should be set between 0.3 (damaged vehicles) and 1 (crushed vehicles).

ⁱⁱⁱCompared to man-made structures, people tend to tolerate higher risks that result from natural hazards (Fell 1994; Leroi *et al.* 2005).