Search Main Menu

PROBABILISTIC ROCKFALL HAZARD ASSESSMENT FOR ROADWAYS IN MOUNTAINOUS TERRAIN

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Abstract

A probabilistic rockfall assessment model was prepared to study four roadways in mountainous terrain. The model provides a comparison of relative risk to moving vehicles from rockfall. The model consists of a rockfall hazard estimate, an encounter analysis, and an effects analysis, and is based on available records, derivation of a magnitude-cumulative frequency curve, development of a binomial traffic distribution and subjective probability estimates. The probability of encounter (falling rock hitting moving vehicle) was used to estimate the mean number of encounters per year at each site. It was found that Site 2, the site with the greatest rockfall frequency posed the lowest risk of these four sites due to low traffic volumes. Site 3 with the second highest rockfall frequency, but only the third highest traffic volume had the highest relative risk from rockfall. These conclusions were not apparent from conventional rockfall hazard ratings alone.

Résumé

Un modèle probablistiic pour une évaluation d'écrouler rochers a été préparé pour étudier quatre emplacements de route dans le terrain montagneux. Le modèle fournit une comparaison de risque relatif d'écrouler rochers aux véhicules qui se mouvent. Le modèle se compose d'une évaluation de risque de écrouler rocher, une analyse de rencontre, et une analyse des effets. Le modèle est basé sur les rapports disponibles, une dérivation d'une courbe de fréquence ampleur-cumulative, développement d'une distribution binomiale du trafic et analyses subjectives de probabilité. La probabilité des rencontres (roche en chute heurtant le véhicule mobile) a été employé pour estimer le nombre moyen de rencontre par an à chaque emplacement. On l'a constaté que l'emplacement 2, l'emplacement avec la plus grande fréquence d'écrouler rochers, a posé le plus bas risque de ces quatre emplacements à causé de bas volumes de trafic. L'emplacement 3, avec la deuxième fréquence d'écrouler rochers la plus élevée mais avec seulement le troisième volume de trafic le plus élevé, a eu le risque relatif le plus élevé d'écrouler rochers.

1. INTRODUCTION

Rockfalls are a significant hazard to roadway traffic in mountainous terrain in western Canada. Probabilistic risk assessment was performed to compare conditions at four sites to assist in decisions related to the allocation of resources for new construction. Probabilistic rockfall assessment can be a useful tool for decision-makers faced with the need to best mitigate risk with (often) limited resources.

The term rockfall refers here to rock failures or slides from cliffs, with magnitudes ranging from about 0.001 cubic metres (i.e., about baseball sized) to greater than several thousand cubic metres. Mechanistically, rockfalls occur when destabilising factors overcome stabilising factors or properties of rock blocks. Stability of rock faces depends on physical properties such as geometry, rock type, rock strength, weathering, joint roughness, joint infilling, joint/fracture spacing and distribution. Destabilising factors include precipitation, temperature variations, piezometric pressure, construction, and animal activity. Over large areas and complex terrain, however, such causal factors may not be reliably predictable. The resulting uncertainty can be accommodated by a risk-based approach, where risk is a function of both the likelihood and consequences of rockfall occurrences.

This paper provides guidance to the question, "What is the comparative level of risk from rockfall along these alignments?" by presenting probabilistic rockfall hazard and risk assessments for four roadways.

Figure 1 – Typical Rockfall location at Site 1

The sites were selected from among western Canada's highest ranked roadway rockfall hazard sites based on a quantitative rockslope condition survey. The rockslope condition survey assigned numerical values to ten aspects of the bluff and roadway, including slope height, ditch effectiveness, average vehicle risk, decision sight distance, roadway width, geologic case characteristics, block size and volume of rock per event, climate effects and rockfall history. The higher the total value, the more hazardous the segment. Site 2 had the highest ranking, with Sites 1 and 3 next (nearly equal) and Site 4 the lowest hazard rank. The rockfall hazard ranking for these four sites is given in Table 1. A typical rockfall site is shown in Figure 1.

2. PROBABILISTIC ROCKFALL ASSESSMENT

2.1 Definition

Probabilistic risk assessment does not rely purely on statistical techniques, but these may be incorporated. In this study, statistical analysis was used to stochastically model both rockfall hazard and vehicle traffic. The models were then combined with degree-of-belief conditional probabilities (subjective judgement) pertaining to effects on vehicles and their occupants. Together, the elements comprise a model that estimates the probability of hazardous encounters and the consequences of those encounters to produce a measure of relative risk. This model has three components: Hazard Analysis, Encounter Analysis, and Effects Analysis.

Hazard analysis estimates the probability of a rockfall of a given magnitude from a Magnitude-Cumulative Frequency (MCF) curve, which gives a distribution of rockfall events over time (Hungr et al., 1999).

Encounter analysis estimates the probability of an encounter between a vehicle and a rockfall, that is the probability that a vehicle and a rock will be in the same location at the same time using a binomial distribution for vehicle presence. Three encounter modes are possible.

- Encounter Mode 1: A moving vehicle is hit by a falling rock.
- Encounter Mode 2: A stationary vehicle is hit by a falling rock.
- Encounter Mode 3: A moving vehicle hits a fallen rock.

Only Encounter Mode 1 was evaluated for this study, although Modes 2 and 3 represent valid and significant risks (Bunce 1994).

Effects analysis uses estimated conditional probabilities to assess the likelihood of property damage, personal injury or fatality in the event of a vehicle/rock encounter.

2.2 Event Tree for Assessment of Encounter Mode 1

In Encounter Mode 1, falling rocks hit moving vehicles. The event tree on Figure 2 portrays the overall structure of the assessment and how the three model components are integrated. Several inputs, including a rockfall Magnitude-Cumulative Frequency relationship, rockfall frequency, magnitude, run-out width, average vehicle velocity, and vehicle length, are required to evaluate probabilities for the separate component events.

Branch 1 of this event tree requires the probability of rockfall, P[R]. This is determined by preparing a summary MCF hazard relationship for each site. The second branch of the event tree requires the probability of a vehicle in the run-out zone, P[V]. Branch 3 produces the target encounter probability, P[E], that is the probability that a vehicle is struck by a rockfall. Finally, Branch 4 provides an evaluation of the risk (consequences), that is probability of fatality or injury based on subjective conditional probabilities, given a rockfall/vehicle encounter.

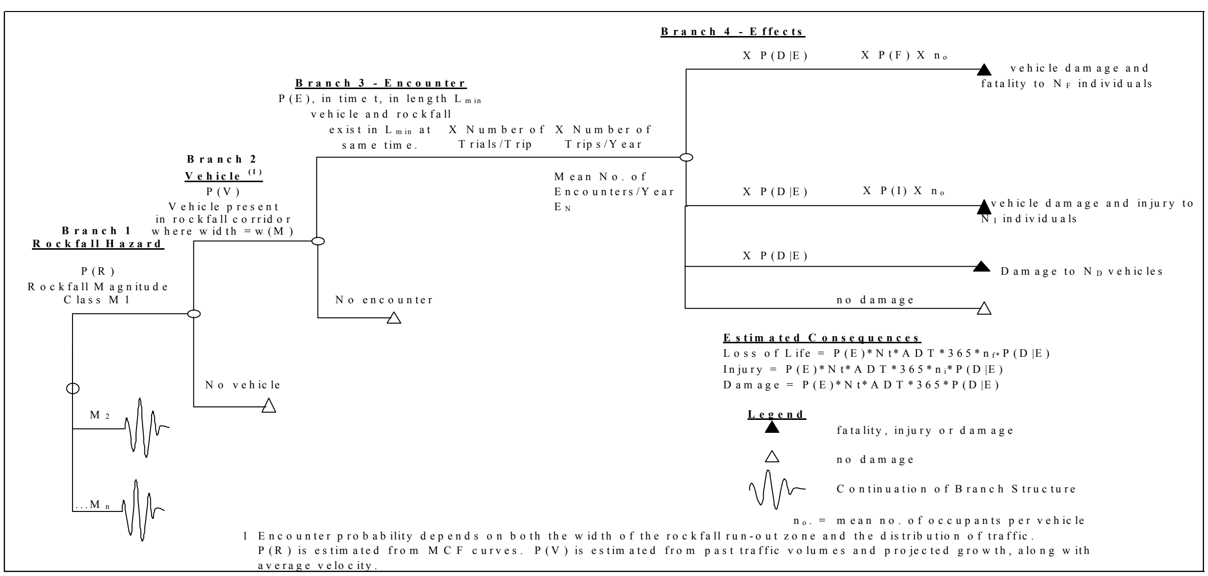

Figure 2 – Event Tree for Encounter Mode 1

Table 1 – Summary of Probabilistic Risk Assessment for Four Sites

Site	Hazard Rating (Condition survey)	Rockfall Condition Survey Rank	Branch 1	Branch 2		Branch 3	Branch 4		
			Estimated Mean Annual Number of Rockfalls (>0.001m^3)	Average Annual Daily Traffic (AADT)	P[V] Probability Of Vehicle Presence in L_{min}	Estimated Annual Mean Number of Encounters E_N	Relative Risk (estimated annual mean number of events)		
							Damage	Injury	Fatality
1	600	2	80	6,050	0.04	0.9	0.6	0.4	0.7
2	700	1	1750	950	0.005	0.3	0.1	0.1	0.1
3	600	3	1650	4,450	0.03	18	7.4	2.7	2.4
4	500	4	13	13,800	0.07	1.1	0.9	0.6	1.3

2.3 Limitations of Probabilistic Assessment

It is important to recognize the limitations to this or any other probabilistic model. Statistical assessments based on observed frequency predict future occurrences based on past events, and thus make “forward-looking” statements. The accuracy of such statements may be affected by a number of physical factors and uncertainties that could cause rock slopes to behave differently in the future than they have in the past, and the same pertains to traffic patterns. Past performance may therefore be an imperfect predictor of future performance.

Risk analysis is a tool that may be used in decision making, as in the case of determining relative risk for allocation of resources for new construction. A formal probabilistic decision analysis would include assessments of the relative cost and benefit of acceptable construction options while considering applicable social, technical, administrative, political, legal and economic factors. Relative risk decision analysis compares options without adopting an acceptable risk criterion per-se.

This risk model provides an assessment of technical factors only and does not, in and of itself, determine the new construction to be carried out at each site. By conducting the risk assessment at four sites the model produces a relative ranking of the rockfall risk at the sites. The calculated risks depend on many factors and simplifying assumptions. Another limitation of this study is therefore that the calculated risks may not necessarily be “correct” on any absolute basis, supposing that such values uniquely exist.

3. ROCKFALL HAZARD ANALYSIS

3.1 General

The first branch in the event tree requires the probability of a rockfall, P[R]. This probability is a measure of rockfall hazard, and was found by generating rockfall magnitude-cumulative frequency relationships for each site. The steps in this construction include Site Characterisation, Database Preparation, and Data Analysis.

3.2 Site Characterisation

The four sites were characterised through a desk study and field mapping that included review of air photos, geologic reports, climate data, and rockfall records. Overview field mapping was conducted at each site. Observations included assessment of the location and dimensions of previous rockfalls and measurement of blocks or pillars that represent possible rockfalls, and mapping of rock type. Possible failure mechanisms were interpreted and summary maps were prepared.

3.3 Database Preparation

A database of rockfall occurrences was prepared using available rockfall records, including road maintenance records and observations from mapping. Valid records were those that included location, date and magnitude. The road maintenance records, compiled since 1993, proved the most useful for analysis. Maintenance workers currently report all rockfalls greater than about 0.01 cubic metres, although it is recognized that data gaps exist.

The number of rockfall records > 0.01 cubic metres at each site ranged from a low of 5 per year to 350 per year.

Rockfalls were sorted into 15 magnitude classes, ordered from smallest to largest and the cumulative magnitudes were then summed. Each rockfall was assigned a return period or frequency, based on the number of rockfalls of similar magnitude for the period of record. Valid data record periods were determined using regression analysis methodology (Hungr et al., 1999).

3.4 Limitations of Data

The rockfall hazard (MCF) models are based on limited data – record periods ranged from two to seven years. It is also likely that many rockfalls have not been recorded even within the recording periods.

Statistical correlation of rockfall to factors such as climate was not attempted, even though there are clear indications at three of the four sites that rockfall frequency increases in the spring, when groundwater pressures increase (through snow runoff) and temperatures cycle near 0°C. It is unknown whether the record period coincided with normal or an extreme period of climate variation (temperature or precipitation).

Correlation of rockfall frequency to climate and other variables should be considered in any future work, to determine if there is a relationship between rockfall frequency and climatic extremes. Such correlation would provide confidence limit constraints when using the current database for forecasting rockfall frequency.

3.5 Magnitude-Cumulative Frequency Relationships

3.5.1 Magnitude –Cumulative Frequency Equation

It has been postulated (Hungr et al., 1999) that the probability relationship for rockfalls can be modeled using a power relationship similar to the Gutenberg-Richter relationship for earthquakes. That is, a relationship can be derived based on frequency (or return period) of rockfalls to allow prediction of the annual probability of occurrence of a rockfall of a given magnitude. The form of the rockfall magnitude-cumulative frequency (MCF) equation is:

$$\log f = a + b \log(m) \qquad [1]$$

where:

- m is the magnitude (volume) of the rockfall;
- f is the cumulative frequency of rockfall;
- intercept a is characteristic of the time interval of recorded rockfalls and the size or length of the study area; and
- slope constant b is characteristic of the rock properties and failure mechanisms.

At each site, MCF relationships (Equation 1) were developed by plotting the rockfall data on a log-log scale and using regression analysis. Additional details on deriving rockfall magnitude-cumulative frequency (MCF) relationships are given by Hungr et al. (1999).

3.5.2 Rockfall Magnitude Bounds

The development of magnitude-frequency relationships required the definition of the upper and lower magnitude bounds.

The smallest rockfall recorded was about 0.01 cubic metres (basketball-size). However, rockfalls as small as 0.001 cubic metres (baseball size) may pose a hazard if they strike a moving vehicle and are therefore considered the lower magnitude bound of interest. Since such small rockfalls are not recorded, the frequency of such events was extrapolated from the frequency of larger rockfalls using the derived MCF relationship. Estimated total mean annual number of rockfalls including rocks as small as 0.001 cubic metres is listed in Table 1.

Establishing an upper bound of expected rockfall magnitude assumes some physical constraint on maximum rockfall volume. We estimated the largest possible future rockfall by defining a Maximum Credible Rockslide (MCR) to be the largest reasonably conceivable rockslide that appears possible at the sites.

A literature search indicated that several very large rock slides or debris avalanches have occurred in western Canada since deglaciation circa 10,000 years ago. Table 2 lists rockslides obtained from Evans (1984), Naumann et al. (1991), Piteau et al. (1978), Jordan (1987) and Hungr et al. (1999). In the last 10,000 years, there have been at least 5 massive rockslides identified in metamorphic assemblages, that is sites similar to the study sites. Excluding the Downie Slide, which is an order of magnitude larger, the average estimated volume is approximately 50 million cubic metres. The five events occurred within valley lengths of 500-km total length. Based on these data, a Maximum Credible Rockslide (MCR) in metamorphic assemblages in western Canada can be represented by a rockslide of 50 million cubic metres with an annual hazard of about 1×10^{-6} per km of corridor, or 1 in 2,000 years over 500 km. This MCR was used at all four sites in development of the MCF.

Table 2 – Massive Landslides in Western Canada

Slide Name	Estimated Size (m^3)	Date
Rubble Creek	30×10^6	1855 AD
Meager Creek	14×10^6	1975 AD
Mount Cayley	5×10^6	1963 AD
Mystery Creek	25×10^6	880 ± 100 YBP
Downie Slide	$1{,}000 \times 10^6$	Min. 6600 YBP
Katz	N/A	3,260 ± 70 YBP
Lake of the Woods	N/A	8,260 ± 70 YBP
Cheam	50 to 150 $\times 10^6$	5,010 ± 70 YBP
Hope (old)	50×10^6	9,700 YBP
Hope (recent)	47×10^6	1965 AD

3.5.3 Summary MCF Relationship for each Site

Summary MCF relationships (Equation 1) were derived based on the upper and lower frequency bounds and the variations in recurrence intervals. The summary MCF curves, shown in Figure 3, are used to calculate the annual frequency of a rockfall of a given magnitude at the four sites.

3.6 Probability of Rockfall, P[R]

Equation 2, derived from Equation 1, provides the annual frequency of rockfall hazard of a given magnitude increment. The probability of a rockfall of magnitude M_i in time Δt seconds is then given by Equation 3. Rockfall probabilities were assessed over the fifteen previously defined magnitude increments.

$$F_i = \log(f_{Mi}) - \log(f_{Mi-1}) \quad (i = 1 \text{ to } 15) \qquad [2]$$

$$P[R_i] = \frac{F_i \Delta t}{(365)(24)(3600)} \quad (i = 1 \text{ to } 15) \qquad [3]$$

3.7 Rockfall Run-out Width

The length of roadway impacted is relative to the rockfall run-out width (as opposed to run-out length) . Available records list rockfall volume but not the run-out width, which requires correlating the two.

Rockfalls less than 1.0 cubic metre tend to be of similar width, length and thickness. The run-out width was therefore taken to be equal to the cube root of the volume. Rockfalls greater than 1 cubic metre tend to be slab or pillar shaped, with thickness often less than half of the other dimensions. As well, larger rockfalls are more likely to bulk and spread, and so have a larger run-out width than the original in-situ slab width. A 6,300 cubic metre rockslide at Site 1, had a run-out width of about 70-m. Another rockslide of 780 cubic metres at Site 1 had a run-out width of about 31-m. In these cases, the run-out widths are within ± 15% of the square root of the rock volume. Therefore, for rockfalls greater than 1.0 cubic metre, the run-out width was taken to be approximately the square root of the volume.

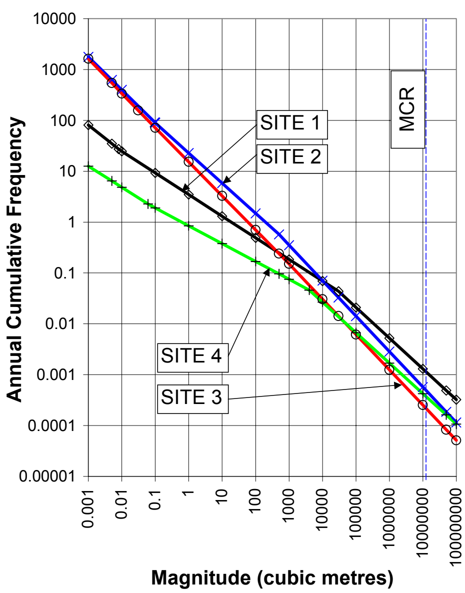

Figure 3 – Summary MCF curves for Sites 1 to 4

4. ENCOUNTER ANALYSIS

4.1 Definition of Encounter

The probability of an encounter, P[E] (Branch 3 of event tree), is dependent on the probability that a vehicle, P[V] (Branch 2) and a rock of a given magnitude, P[R] (Branch 1), will be in the same location at the same time.

4.2 Traffic Distribution

Vehicle Presence at any given location was assumed to be represented by a binomial distribution, based on average vehicle velocity and average daily traffic volume. This allows for the possibility that more than one vehicle may be present in the rockfall run-out zone by treating vehicle presence as a series of Bernoulli trials of equal probability at any location within the run-out zone. A similar method was used by Bunce (1994).

4.3 Traffic Volumes

Daily traffic volumes were obtained for each site, including Average Annual Daily Traffic (AADT) and Summer Average Daily Traffic (SADT) levels as listed in Table 1.

4.4 Probability of Vehicle Presence, P[V]

Since both, P[V] and P[R] are location dependent by definition, it is convenient to adopt a spatial frame of reference of fixed location and dimension where the rockfall run-out zone crosses the roadway. We have defined this spatial distance to be the minimum possible inter-vehicle spacing, L_{min}. By this definition, there can be at most one vehicle in distance L_{min}. To find a reasonable value of L_{min}, we require estimates of average vehicle length, L_V, and average vehicle velocity, V_{avg}.

Short duration traffic counts at Site 1, indicate that trucks make up about 22% of the traffic flow. Using standard design lengths for trucks, cars, and buses, the average vehicle length in the Site 1 study corridor is estimated to be 7.7 m. This average vehicle length was assumed for all four sites.

The average posted speed limit at each of these sites is 90 km/hr, whereas measured velocities at Site 1 indicate an average velocity of about 80 km/hr. We have assumed an average velocity of 80 km/hr at all sites. We note that this is a conservative assumption, because annual risk is reduced if the average velocity increases, since the hazard exposure time is reduced.

Moving vehicles tend to adopt a minimum inter-vehicle spacing, depending on speed. For example, in 0.75 seconds at V_{avg} of 80 km/hr, a vehicle travels 16.7 m or approximately twice the length of the average vehicle. This, intuitively, appears to be a reasonable minimum spacing for vehicles traveling at highway speed. Thus, we adopted a time increment Δt, of 0.75 seconds for this study, resulting in an L_{min}, of 16.7 m.

Each segment of length L_{min} is considered one trial segment. We further define each "trial segment", to have only 0, 1 or 2 vehicles present (maximum one in each lane). To further simplify our assessment, we consider each lane separately, by assuming that the probability of encounter in each lane is independent of the encounter probability in the other lane. Therefore, there can either be 0 or 1 vehicle present in each one-lane trial segment of L_{min} – no other outcomes are possible.

We further assume that the probability of a vehicle being present in a one-lane trial segment is a constant probability regardless of the location of the segment within the study area. Our one-lane trial segment may then be treated as a Bernoulli trial with only two possible outcomes, a vehicle is present or not. We now require the probability of a vehicle in one lane of L_{min}.

The probability V that any one-lane of a trial segment is occupied based on average traffic volume and average velocity as shown in Equation 4. ADT is the average daily traffic at the site.

$$V = \frac{[(ADT)*L_{min}]}{(2\text{ lanes})*(24\text{ hr/day})*V_{avg*}(1000\text{ m/km})} \quad [4]$$

The probability that no vehicle is present, $\overline{V}$, within the one-lane trial segment in time Δt is given by Equation 5.

$$\overline{V} = (1 - V) \quad [5]$$

The next step is to determine the number of one-lane trial segments, F_L, affected by each rockfall. Clearly, larger rockfalls will impact more trial segments. The binomial theorem requires that F_L be an integer greater than or equal to one. Therefore, for rockfalls of magnitude < 500 cubic metres, F_L was selected to be 1. For larger rockfalls, F_L was taken as approximately the ratio of the square root of the average magnitude for that increment to the minimum intervehicle length:

$$F_{Li} = \frac{(M_i - M_{i-1})^{1/2}}{L_{min}} \quad (i = 1 \text{ to } 15) \quad [6]$$

The probability of vehicle presence for each rockfall magnitude increment affecting F_L trial segments can be determined by the following equations. The probability of exactly zero vehicles in F_L trial segments is given by:

$$P[\overline{V}_i] = (1 - V)^{F_{Li}} \quad [7]$$

where i = 1 to 15 for 15 magnitude increments.

By the binomial theorem, the probability of at least one vehicle within the run-out zone is given by:

$$P[V_i] = 1 - P[\overline{V}_i] \quad (i = 1 \text{ to } 15) \quad [8]$$

For small rockfalls, where the run-out width is much less than L_{min}, the use of Equations (7) and (8), with F_L equal to 1 may over-predict the probability of vehicles within the run-out zone. Therefore, for rockfalls with run-out widths less than L_{min} it became necessary to reduce this value by F_c as follows:

$$P[\overline{V}_i]_{small} = (1 - F_c V)^{F_{Li}} \quad [7a]$$

$$P[V_i]_{small} = 1 - P[\overline{V}_i]_{small} \quad [8a]$$

F_c equal to 0.03 was used for rockfalls less than 10 cubic metres, and F_c equal to 0.5 was used for rockfalls between 10 and 100 cubic metres. F_c was calculated from an iterative analysis of Equation (8), using a non-integer value of F_L to provide a target resultant.

The annual probability of a rockfall is determined from the MCF curve for each magnitude increment, and the likelihood of that occurrence, P[R], in time Δt is given by Equation 3. The probability that no rockfall occurs in Δt is then given by:

$$P[\overline{R}_i] = 1 - P[R_i] \quad (i = 1 \text{ to } 15) \quad [9]$$

If event E is the encounter of a rock with at least one vehicle anywhere in the run-out width during time Δt, it's complement, $\bar{E}$, is that there is no encounter. This can happen in three ways:

- there is a rockfall and no vehicle;
- there is a vehicle and no rockfall; and
- there is no vehicle and no rockfall.

By probability Axiom III (Benjamin and Cornell, 1970), and assuming that rockfall occurrence and vehicle presence are independent, the probability of no encounter is determined by equation (10):

$$P[\overline{E}] = p[R \cap \overline{V}] + p[\overline{R} \cap V] + p[\overline{R} \cap \overline{V}] \quad [10]$$

By substitution, Equation (10) can be rewritten as follows.

$$P[\overline{E}_i] = P[R_i]P[\overline{V}_i] + P[\overline{R}_i]P[V_i] + P[\overline{R}_i]P[\overline{V}_i] \quad (i = 1 \text{ to } 15) \quad [11]$$

If P[$\bar{E}$] is the probability of no encounters in time Δt in one trial segment, then P[E] is the probability of one or more encounters.

$$P[E_i] = 1 - P[\bar{E}_i]. \quad (i = 1 \text{ to } 15) \quad [12]$$

Through an expansion of the binomial distribution, we can show that the probability of two or more encounters in time Δt in one trial segment is negligible, that is two rockfall events occurring and encountering the same vehicle. Therefore, the probability of at least one encounter in time Δt in one trial segment is essentially equal to the probability of exactly one encounter. Equation 12 therefore provides the mean number of rock/vehicle encounters in time Δt in one trial segment.

The mean number of encounters in one trip through each of the rock sites can be calculated by multiplying for the number of trial segments per study area, N_T.

$$(E_t)_i = P[E_i] * N_t \quad \text{(i = 1 to 15)} \qquad [13]$$

Finally, the mean number of encounters per year can be found by multiplying the mean number of encounters per trip by the annual number of trips through the study corridor as given in Equation 14.

$$(E_N)_i = (E_t)_i * ADT * 365 \quad \text{(i = 1 to 15)} \qquad [14]$$

5. EFFECTS ANALYSIS

5.1 General

The final step (Branch 4) in this assessment was estimating the effects of a rockfall/vehicle encounter, and this was conducted on the basis of subjective conditional probabilities of damage, injury and fatality. Conditional probabilities require the mean number of persons per vehicle, n_o, as well as the probability of damage, injury or death given an encounter.

As described in the previous section, Equation (14) provides the estimated mean number of encounters per year (by magnitude class). Each encounter will result in one of four possible outcomes: no damage; vehicle damage; injury; or fatality. Injury and fatality outcomes are subsets of incidents causing damage, and for a given accident there may be both injury and fatality as an outcome. Together, these outcomes form a collectively exhaustive set.

We reiterate that these are relative measures and do not represent actual estimates of these outcomes but rather the estimated relative number of these outcomes from site to site.

5.2 Mean Number of Occupants

No data was available on passenger counts for traffic at the four sites, therefore the mean number of occupants was estimated as follows. All vehicles will have, at minimum, a driver. Therefore, the lower bound for mean number of occupants is 1. Using short duration vehicles counts for car/truck/bus ratios and assuming full occupancy, we estimate the upper bound for mean number of occupants is 5.6 occupants.

The actual average number of occupants will fall somewhere between 1 and 5.6. For this study, we have estimated that the mean number of occupants, n_o, is 2.5 persons per vehicle.

5.3 Probability of Damage, P[D|E]

The conditional probability of damage given a rock/vehicle encounter was estimated using a subjective probability approach (Vick, 2002). For rockfalls > 0.01 cubic metres (basketball sized) the probability of damage upon encounter was assumed to be 1.0. For smaller rockfalls, the rock may be small enough to be avoided by a vehicle, and hence the probability of impact causing damage is <1.0. We have estimated a subjective probability value of P[D|E] = 0.1 for rockfalls <0.005 cubic metres, P[D|E] of 0.60 for rockfalls between 0.005 and 0.008 cubic metres, and P[D|E] = 0.75 for rockfalls of 0.008 to 0.01 cubic metres.

The annual mean number of accidents resulting in damage can be calculated as follows:

$$(N_D)_i = P[D \mid E_i] * (E_N)_i \quad \text{(i = 1 to 15)} \qquad [15]$$

5.4 Estimated Number of Fatalities or Injuries

An encounter causing damage may also result in injury or fatality to occupants of the vehicle. We have assumed that the number of injuries and/or fatalities is a function of the volume of the rockfall, with larger rockfalls causing more fatalities on average than smaller rockfalls. The combined number of fatalities or injuries is at most 2.5, our estimated mean number of vehicle occupants.

We have estimated that all occupants of vehicles impacted by rocks of greater than 10 cubic metres would suffer injury or fatality, with increasing probability of fatality with increasing rockfall magnitude. For rockfalls of 1 to 10 cubic metres, we have estimated 75% of all occupants would suffer injury or fatality, and 40% or fewer occupants would be injured or killed by rockfalls smaller than one cubic metre. These estimated conditional probabilities of damage, injury and fatality were applied to the mean number of encounters to produce estimates of annual mean number of accidents causing damage, mean number of injuries and mean number of fatalities.

The mean number of injuries and fatalities can be calculated from the following equations:

$$(N_I)_i = P[D \mid E_i] * (E_N)_i * P[I \mid D_i] * n_o \quad \text{(i = 1 to 15)} \qquad [16]$$

$$(N_F)_i = P[D \mid E_i] * (E_N)_i * P[F \mid D_i] * n_o \quad \text{(i = 1 to 15)} \qquad [17]$$

6. RESULTS

As summarised in Table 1, the annual rockfall hazard is highest at Site 2 and lowest at Site 4 based on mean number of rockfalls. The highest volume of traffic and hence probability of vehicle presence, was at Site 4, followed by Site 1 and Site 3, with the lowest traffic volumes at Site 2.

By applying this probabilistic model, the risk of encounter, and potential effects of damage, injury and fatality was found to be greatest at Site 3 and lowest at Site 2. Surprisingly, the risk was second highest at Site 4, despite the significantly lower mean annual number of rockfalls. The relative risks are presented in Figure 4.

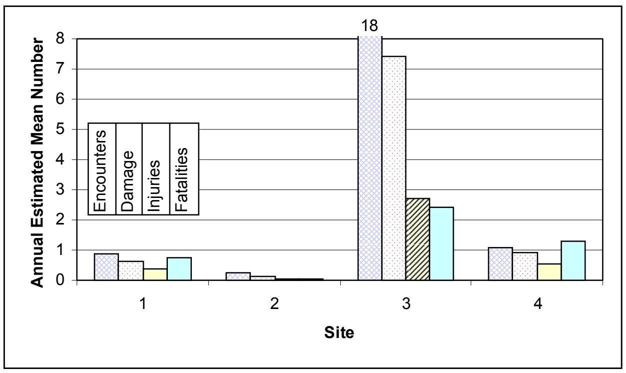

Figure 4 – Summary of Relative Risks at Four Sites

7. SUMMARY OF ASSESSMENT

Risk is defined as the combination of hazard and consequence. We have defined hazard levels by using available records of rockfall, extrapolated to a theoretical maximum credible rockslide to derive Magnitude – Cumulative Frequency curves for four study areas. The consequence of rockfalls is related to the probability of vehicle presence in the run-out zone. The probability of encounter combines the probability of rockfall with the probability of vehicle presence to estimate the mean number of encounters per year. This value can be used to estimate the annual mean number of accidents with damage, mean number of injuries and mean number of fatalities, from Encounter Mode 1.

The quantification of Encounter Mode 1 allows for the comparison of relative risk at four sites with high ratings of rockfall hazard. In this study, it was found that the risks were highest at the site with the third lowest rank from the rockfall condition survey due to the greater number of estimated rock/vehicle encounters. The results of this study were used as inputs during decision making for allocation of resources for new construction, and this site has become the focus for new construction plans.

The confidence of the relative comparisons can be improved through additional research and study to define the risk from other encounter modes, by correlation of rockfall hazard to other variables such as climate, and from research to quantify the conditional probabilities of the effects of an encounter.

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