The assessment of rockfall hazard at the base of talus slopes

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Received September 25, 1992
Accepted March 18, 1993

Fragmental rockfall is characterized by the independent movement of individual rock fragments after detachment from a rock face. The continued operation of the process leads to the accumulation of talus slopes. On talus slopes the rockfall shadow extends beyond the base of the talus and consists of scattered boulders that have run out beyond the base of the slope. The landing probability of boulders in the shadow is examined; return periods of the order of 1000 years relative to a house site are typical. Rockfall behaviour particularly with respect to runout into the shadow can be assessed using geological evidence, empirical methods, physical modelling, and computer-based analytical models. An empirical minimum shadow angle of 27.5° (i.e., the angle between the distal limit of the shadow and the top of the talus slope) is suggested and would be useful in rockfall vulnerability studies at the base of talus slopes as a first approximation to shadow limits. It is preferable to the use of the rockfall fahrböschung as proposed by several authors. A random collision lumped mass model (ROCKFALL) is outlined. ROCKFALL uses two restitution coefficients and a transition to rolling criterion. ROCKFALL is used to analyse two fatal rockfall accidents in southern British Columbia, at Hedley in 1939 and Sunnybrae in 1983, which are documented in detail. An additional nonfatal incident is also analysed (Barnhartvale in 1974). Results based on an initial calibration were encouraging. Documentation of the three rockfall incidents shows that, in each case, rockfall fragments impacted on homes at equivalent shadow angles of 30° or more. This would suggest that a review of existing development within rockfall shadow areas at the base of talus slopes may be in order.

Key words: rockfall, dynamics, talus slopes, landslides, British Columbia

Introduction

Rockfall (Fig. 1) is a slope process involving the detachment of rock fragments and their fall and subsequent bouncing, rolling, sliding, and deposition (Varnes 1978; Hutchinson 1988). A rockfall event may involve the displacement of a single fragment or several pieces. It may also begin by the detachment of a more or less coherent block that then disintegrates during the course of movement. Rockfall is a common process in mountain terrain where its continued occurrence forms talus slopes (Rapp 1960a, 1960b; Church et al. 1979), accumulations of rock fragments at the base of a source rock slope.

This paper is concerned with assessing the hazard presented by events at the lower end of the magnitude spectrum, the “fragmental rockfall” of Hungr and Evans (1988, 1989), near the base of talus slopes. Fragmental rockfall is characterized by a more or less independent movement of individual particles, as opposed to the sliding or mass flow of coherent or broken rock typical of a rock avalanche. In general, fragmental rockfall involves relatively small detachments (<10^7 m^3), although there is no well-defined volume limit.

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Low-magnitude fragmental rockfall is distinguished from larger rockfalls (>10^6 m^3). These invariably disintegrate and are transformed into a rapid movement of unsorted fragments termed a sturzstrom (Heim 1932), rock avalanche (McConnell and Brock 1904), or rockfall avalanche (Varnes 1978) where inclusion of the term rockfall implies an episode of free fall during the movement.

Hung and Evans (1989) compiled rockfall accident statistics for Canada and found that rockfall has caused only four deaths in houses and nine deaths on transportation routes in this century. Even allowing for the fact that the records are incomplete, this number is surprisingly small. It may be compared with casualties in the mountainous regions of Europe where in Italy in 1969, for example, a rockfall from Monte San Martino caused eight deaths in the town of Lecco (Eishacher and Clague 1984).

This paper enlarges on previous work (Hung and Evans 1988, 1989), which gave partial results. It addresses the problem of assessing rockfall hazard on and beyond the base of talus slopes. Periodically a rockfall occurs in which one or more larger boulders bounce and roll down the talus slope and move beyond its margin, coming to rest at some

Fig. 3. Typical downslope distribution of mean grain sizes in a talus deposit (data from Worobey 1972).

distance from the slope base (Fig. 2). It is these boulders that constitute the greatest hazard in the vicinity of talus slopes, and uncertainty about their behaviour poses a major difficulty in rockfall-vulnerability assessment in mountain-
Fig. 4. Schematic diagram of the characteristic rockfall path profile. A–C is the talus slope, with mean angle \( \beta_1 \), and C–D is the rockfall shadow, with a shadow angle \( \beta_2 \). \( \beta_1 \) is the substrate angle.

![Diagram of rockfall path profile](image)

Fig. 5. Landing- and impact-probability distributions calculated for the talus slope shown in Fig. 3.

![Graph showing landing and impact probabilities](image)

ous regions. This has emerged as an important problem in planning resource development in the vicinity of rock slopes in Canada (e.g., Ballivy et al. 1984; Boyd 1991) and is the primary focus of this paper, since, as noted above, although rockfall damage to buildings at the base of talus slopes is relatively rare, the indirect costs of sterilization of land endangered by rockfall are in the order of tens of millions of dollars. Continuing development pressure in the mountainous areas of Canada will necessitate more rigorous geotechnical analysis of potentially hazardous sites.

The nature of rockfall deposition on and beyond talus slopes is investigated. Several methods of rockfall analysis are examined and a numerical analytical model (ROCKFALL) is outlined. Three case histories of rockfall accidents at the base of talus slopes in the mountains of British Columbia are described and are analysed with ROCKFALL.

**The behaviour of rockfall fragments on talus slopes**

**Deposition on talus slopes**

The depositional pattern exhibited in talus slopes reflects certain regularities. An important aspect is the natural "gravity" sorting by size observed by many authors (e.g., Rapp 1960a, 1960b; Gardiner 1970; Kotarba and Strongquist 1984; Brundsen et al. 1984; Statham and Francis 1986) wherein the coarsest boulders are found at the base of the slope. Size sorting contributes an important roughness component to the talus slope surface, which becomes the characteristic path profile for successive rockfalls.

A typical example of size sorting on talus slopes is shown in Fig. 3, derived from data collected on a talus cone in the Similkameen Valley, southern British Columbia by Worobey (1972). The mean particle size is seen in this instance to increase gradually from about 5 to 10 cm over approximately 300 m of slope length. Approximately the lowermost 40 m of the cone surface is built up of boulders with characteristic sizes of 1 m or greater. The slope angle reduces to as little as 15° in the coarse basal accumulation. The relatively low variation of grain size in the upper part of the cone is probably the result of redeposition by surficial talus flows, which are common in the area.

**Rockfall path profile**

A rockfall-dominated talus slope exhibits a typical profile as seen in Fig. 4. Finer talus fragments accumulate below the apex (point A) at an angle of approximately 38°. Lower down, the talus angle ranges from approximately 32 to 38°. The lowermost part of the talus deposit contains the largest fragment sizes, and the talus slope angle sometimes falls...
to 10 or 20°, as shown between points B and C. Point C is the base of the talus deposit. Beyond this point the slope is no longer completely covered by talus fragments.

The average talus angle is $\beta_1$ (Fig. 4). The surface to the right of point C (Fig. 4) is termed the substrate surface, consisting of material and landforms predating the talus deposits. That part of the substrate surface covered discontinuously by scattered large boulders that have rolled or bounced beyond the base of the talus (C–D in Fig. 4) is referred to here as the rockfall shadow. The “shadow angle” is defined as the angle between the outer margin of the shadow and the apex of the talus slope ($\beta_2$ in Fig. 4). The distal part of the shadow often contains only very few boulders, which are sparsely distributed on the surface.

Spatial distribution of rockfall impact on talus slopes

Talus cone slope angles remain fairly constant during their gradual formation. As a result, it can be assumed that a relatively uniform thickness of material is added to the entire cone surface over any long period of time. The probability of a unit volume of rock fragments landing at any particular location on the cone surface must then be approximately constant.

In the Similkameen Valley of British Columbia, talus cones (exposures of the Mazama Ash deposited 6600 years BP; Clague 1980) can be found at a typical vertical depth of 3 m (Worobey 1972). The corresponding mean vertical growth ($V$) rate of the talus surface is $3/6600 = 0.00045$ m/year. The rate of growth in the direction normal to the cone surface is approximately $\cos 34^\circ$ $V$, i.e., 0.00037 m/year (cf. Luckman 1988).

The probability of fragments landing on a given square metre plot of the surface is a function of the mean particle diameter:

\[ f_1 = \frac{R_n}{D_c^3} \]

where $f_1$ is the frequency of landings per year per square metre of cone surface, $R_n$ is the surface growth rate in the normal direction in metres per year and $D_c$ is the characteristic dimension of the mean rock fragment, defined as the side of a cube with the same volume as that occupied by the fragment in the deposit.

The mean grain size of talus deposits increases with distance from the apex. Consequently, by [1], the frequency of landing decreases. The frequency variation shown by the
from the talus toe, measured at another site in the Similkameen Valley.

The landing probability in the shadow area was estimated by surveying the distribution of boulders in strip-like segments concentric on a talus cone. The measurements were made on a plot of land 200 m wide, extending from the toe of the talus cone to the distal margin of the shadow. The distribution of boulder frequency versus distance from the toe is shown in the form of a histogram with a spacing of 20 m (Fig. 6). The boulders lie on a river terrace with an estimated age of about 5000 years. (J.M. Ryder, personal communication, 1987).

The landing probabilities are calculated by dividing the boulder landing counts given in Fig. 6 by 5000 and by the survey area of $20 \times 200$ m. The resulting values are shown as open triangles in Fig. 5. The two segments of the landing probability curve show continuity of slope, although they originate from two different sites.

In Fig. 5 the landing probability estimates in the steep central part of the talus slope are severely distorted by the frequent occurrence of talus flow movements. The probabilities estimated near and beyond the margin are, on the other hand, representative of individual particle deposition.

Impact hazard affecting a structure situated on or near the talus cone derives not only from fragments landing at that location but also from those crossing the location and destined to land farther down the slope. This impact frequency, $f_m$, can be estimated by integrating numerically the landing probabilities over an influence area sketched in Fig. 7:

$$[2] \quad f_m = f_i \frac{r}{r_1} dr = f_i \frac{r_1 - d}{r_1}$$

where $i$ is a counter of sampling points regularly spaced at a slope interval, $d$ is the downslope from the point in consideration, and $r$ is defined in Fig. 7. The point considered is located halfway between a pair of sampling points, as shown in Fig. 7. The calculation results are given as the solid line in Fig. 5 in terms of events per metre width.

Return period $T$ of impact events at various locations can be estimated as

$$[3] \quad T = \frac{1}{f_m} W$$

where $W$ is the width of the area considered. The resulting return periods for a 10-m-wide house site are indicated in Fig. 8. At 50 m from the talus margin, the impact probability is 0.0005 events/m, and the corresponding return period for a 10-m house site is 1900 years. A housing subdivision located at the same distance and covering an area 200 m wide would face a probability of being struck by a single boulder of 1 in 95 years.

Short-term probabilities can vary considerably from the long-term average. There is some evidence that rockfall rates have decreased throughout the Holocene (e.g., Worobey 1972). In this case, the estimated return periods represent a lower limit estimate.

**Prediction of rockfall behaviour. I. Geological evidence**

In some cases, it is possible to ascertain the past behaviour of a rock slope over a long period on the basis of geologi-
Fig. 10. Profiles of 16 surveyed rockfall paths from British Columbia (modified from Hungr and Evans 1988). The profiles have been plotted with the talus apex as a common point. A, base of the talus slope; O, distal margin of the rockfall shadow; □, either known source areas or the crest of the source cliff. 1, Hedley; 2, Similkameen A (Sweatlodge)*; 3, Similkameen B (rockslide); 4-Similkameen C (kame); 5-Similkameen D (Winters Creek); 6-Similkameen E (campground); 7, Similkameen F (speedway); 8, Pakaist; 9, Sunnybrae; 10, Barnhartvale*; 11, Silverhope A; 12, Silverhope B; 13, Silverhope D; 14, Silverhope C; 15, Hope North*; 16, Stawamus Chief (asterisks denote sites where fresh debris was found in the rockfall shadow area).

### Table 1. Rockfall: Preliminary Model Parameters

<table>
<thead>
<tr>
<th></th>
<th>Large rocks on talus (1000 – 20 000 kg)</th>
<th>Small rocks on clean rock (20–100 kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal restitution coefficient ($k_n$) (no crushing)*</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td>Tangential restitution coefficient ($k_t$)ψ</td>
<td>20.8</td>
<td>0.9</td>
</tr>
<tr>
<td>Yield contact force $F_y$ (kN)γ</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>Initial contact stiffness $C_i$ (kN/m)γ</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Stiffness reduction ratio $R^*$</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Rolling friction coefficient ($μ_r$)</td>
<td>0.52</td>
<td>0.52</td>
</tr>
</tbody>
</table>

* $V_n = V_n^0$, where $V_n^0$ is normal velocity component after impact.
ψ $V_t = V_t^0$, where $V_t^0$ is tangential velocity component after impact.
γ For definition see Fukueta (1985).

...cal evidence. Such information can then be extrapolated so as to predict the reach of future rockfall within a given return period.

An example is provided by the evaluation of rockfall hazard at the community of Silverhope (Fig. 9A) in southwestern British Columbia. The community is located on an alluvial fan in front of a deltaic terrace. Immediately behind the terrace, cliffs composed of massive Eocene quartz diorite and hornfels rise to a height of 600 m (Fig. 9). Extensive talus deposits, and numerous large boulders that have rolled beyond the talus margins, testify to rockfall activity, although this activity appears to predate the development of the extensive forest cover (Fig. 9). No rockfall accidents have been reported since the site was settled in the 1950s.

The rockfall shadow at Silverhope is well defined (see profiles 11–14 in Fig. 10). The terrace surface beyond the rockfall shadow is underlain by a deposit of cross-bedded sand containing no gravel or boulders, which is exposed in a small borrow pit (Fig. 9). The sand is of deltaic origin, deposited in standing water. However, no lake has existed at
the site in the Holocene. Therefore, the surface of the deltaic terrace must be at least 11,000 years old, dating back to the last stages of glacial ice retreat from the valley (J.J. Clague, personal communication, 1986). The area immediately outside the well-defined rockfall shadow therefore has a probability of less than 1 : 11,000 of being reached by rockfall from the cliff in a given year.

The general frequency of rockfall in this area was indicated by a detailed inspection of talus deposits beneath cliff fronts totalling approximately 2700 m in length. The talus deposits are partly forested and heavily moss covered (Fig. 9). Only six rock fragments were found whose appearance indicated that they have been deposited within the last year, their sizes varying from 0.01 to 0.1 m$^3$. The average frequency of fragments in this size range falling onto the talus apron therefore works out to 0.04 per year per 100 m length of cliffs, which is within the range of the frequency–magnitude curve described by Gardner (1980). No fresh fragments or tree damage associated with rockfall were identified within the rockfall shadow area.

Not all sites provide sufficient evidence to allow such reasoning. If it were not possible to reliably date the substrate surface, if weathering conditions change (e.g., because of deforestation or a recent major instability), or if there were boulders of glacial or debris-flow origin impossible to distinguish from rockfall deposits, then this method may not provide satisfactory answers.

Prediction of rockfall behaviour. II. Empirical evaluation

Two related empirical measures have been suggested to estimate the run-out distance of rockfall fragments at the base of talus slopes, viz., the rockfall fahrböschung and the minimum shadow angle.

Rockfall fahrböschung

The equivalent of a rockfall fahrböschung has been suggested by Onofri and Candian (1979) in their analysis of 98 rockfalls triggered by the 1976 Friuli earthquake in Italy. The rockfall fahrböschung ($\beta$) is the angle between the highest point of the rockfall source scar and the stopping point of the longest run-out boulder for any given rockfall. Onofri and Candian (1979) found the limits of $\beta$ to be 28.34 and 40.73$^\circ$. They found that the values of $\beta$ had a Gaussian distribution and were able to assign probabilities to the various values of $\beta$. Toppe (1987) uses the same parameter to estimate rockfall runout. Although he does not specify the nature of his field data, he reports that 50% of rockfall fragments stop within $\beta = 45^\circ$ and 95% stop within $\beta = 32^\circ$. These values contrast strongly with those of Onofri and
Candian (1979) who found that 50% stopped within $\beta = 33.5^\circ$ and 72% stopped within $\beta = 32^\circ$. The calculation of the rockfall fahrböschung requires the measurement of the starting and end points for individual rockfalls.

**Minimum shadow angle**

We suggest an alternative approach, following Lied (1977), where an empirical run-out angle, the minimum shadow angle ($\beta_2$), defined in Fig. 4, is keyed to the apex of the talus slope and not to the source area of the rockfall on the rock slope above. The approach does not necessitate the start and end point of each rockfall to be located, since the effect of rockfall activity is integrated over time by considering the longest boulder runout in a given rockfall shadow.

A minimum value for ($\beta_2$) has been suggested by several authors. Lied (1977) proposed that it should be in the range of 28–30$^\circ$, and Hestnes (1980) suggested a value of 25$^\circ$, although neither author discussed the bases of these estimates.

In this work, 16 profiles of rockfall paths from southwestern British Columbia have been compiled (Fig. 10). The profiles have been plotted so as to join at the talus apex as a common point.

The points, representing the limit of the shadow, plot consistently just below a line inclined at 27.5$^\circ$, irrespective of the height of the source cliff, length of path, or the substrate angle, and represent a minimum shadow angle. The slopes in Fig. 10 are from locations both in the sparsely forested arid interior of British Columbia and in the humid southern Coast Mountains where there is dense forest cover outside the most active talus areas.

The use of an empirical minimum shadow angle of 27.5$^\circ$ would appear to be a useful method for the preliminary estimation of maximum rockfall reach, since the authors have observed that the same angle applies at many other sites in British Columbia.

Flatter angles sometimes result where the talus and (or) the substrate surface is relatively smooth. For example, a shadow angle of 24$^\circ$ has been measured by the authors for a single 4-m-diameter boulder rolling or sliding over the smooth surface of a glacier near Whistler, B.C. Rapp (1960b, p. 98) documents a rockfall in which a boulder ran out to a shadow angle of 23$^\circ$ on a surface partly covered by grass and snow. Some rockfall profiles from the Italian Alps (Govi 1977; Govi and Sorzana 1977; Fenti et al. 1977; Paronuzzi 1988, 1989) also suggest a flatter minimum shadow angle may result where the talus surface is relatively smooth.

In addition, the impact of large rockfalls on loose talus may form flow-like slides that may run out beyond the rockfall shadow limit. Kolderup (1955) describes an example from Norway in which the flow slide generated by such a process ran out to an equivalent shadow angle of 22$^\circ$ and destroyed two farmhouses.

**Interpretation**

In our investigations we have observed that long rockfall trajectories on moderate slopes tend to be dominated by rolling. This is in agreement with full-scale experimental observations made previously by such workers as Ritchie (1963), Broili (1977), and Kirkby and Statham (1975).

This observation helps to explain the concept of a limiting shadow angle discussed above. The kinetic energy acquired by the fragment in the initial fall is largely lost in the first impacts on the talus surface near the top of the slope. Thus, regardless of the height of fall, each fragment begins rolling near the top of the slope and its final runout into the shadow is approximated by projecting the slope of the energy line, i.e., the rolling friction gradient, from the top of the talus slope. The value of $\beta_2$ would thus appear to be the lower limit of the rolling friction angle for large boulders rolling over finer talus, and its variation would be expected to reflect differences in the surface characteristics of both talus slope and substrate.

The limited horizontal reach of boulders from Stawamus Chief (profile 16, Fig. 10) confirms that the initial momentum from fragments falling from a near-vertical source is practically lost in the first series of impacts. Long horizontal reach is achieved only where fragments are able to build up sufficient horizontal and rotational momentum by travelling over a long inclined segment of talus slope.

The rockfall fahrböschung ignores the marked asymmetry in energy expenditure noted above and is dependent on the height of fall. In assessing rockfall vulnerability at the base of a talus slope, use of the fahrböschung to delimit run-out distances requires knowledge about future detachment locations on the rock slope above. A conservative approach in these circumstances may involve taking the minimum fahrböschung angle from the top of the rock slope (Toppe 1987) which would overestimate the runout at a site.

**Prediction of rockfall behaviour. III. Development of an analytical model**

In recent years, many investigators turned their attention towards computer-based analytical models, simulating the

**Bouncing mode**

ROCKFALL is based on a lumped mass model with separate normal ($k_n$) and tangential ($k_t$) restitution coefficients (Azimi and Desvarreux 1977; Azimi et al. 1982; Wu 1985), one of which ($k_n$) is momentum scaled to allow for plastic deformation during impact.

The assumption of constant restitution coefficients is reasonable only in cases where each impact involves approximately the same level of momentum normal to the contact surface. This is obviously not the case on paths where, for example, the first impact on the talus surface follows a long free flight from the high cliff.

According to full-scale experiments by Broili (1974), 75–86% of the kinetic energy gained in the initial fall is lost in the first impact. Subsequent impacts, involving lesser normal momenta, consume much less energy. It is for this reason that the bilinear contact deformation model developed by Falcetta (1985) was incorporated in ROCKFALL (Hung and Evans 1989).

Preliminary calibration of the model for large rocks was achieved using the results of Broili (1977). Figure 11 shows a simulation of one of the experiments reported by Broili (1977) in which a camera recorded three modes of motion: (i) the initial fall from a height of 210 m, (ii) a sequence of bounces, and (iii) a long segment dominated by rolling movement. The three modes are simulated by ROCKFALL in Fig. 11A. According to Broili’s observations, as reproduced in Fig. 11B, the length of the zone of bouncing increased with decreasing volume of the rock fragment released. This result is plotted in Fig. 11B over a range of 0.5–10 m$^3$. By trial and error iterations of ROCKFALL, we have been able to approximate the experimental relationship as shown by the broken line in Fig. 11B, by using ROCKFALL parameter values given in the first column of Table 1.

For preliminary purposes only, in the absence of more detailed calibration, these parameters are considered applicable to impact of large rocks (1000 – 20 000 kg mass) on talus surfaces, without heavy vegetation.

It is unlikely that the same parameters would apply for smaller rocks bouncing on different surfaces. For small rocks contacting clean rock surfaces, we have back analysed the results of experiments carried out by Wu (1985). The model parameters providing a reasonably good fit to these results are given in the second column of Table 1.

It must be stressed that more detailed calibration based on controlled experiments is necessary.

**Transition to rolling mode**

The bouncing-only model does not simulate correctly that stage of rockfall movement when bounces become negligibly short and rolling begins. It is therefore necessary to provide a transition at some point into a rolling mode, simulated by a frictional model.

Several different criteria for transition between the bouncing and rolling mode were tried, including a limiting length of bounce, limiting time, and velocity. With all of these, there were problems with numerical instability of the model, as they allowed bounces of extremely short length or low amplitude. The most satisfactory results were finally reached with our transition to rolling criterion described in the following paragraphs.

ROCKFALL calculates the “energy head” of the fragment at every point during its descent, as indicated by the broken line in Fig. 11B. While in trajectory, the fragment has a constant energy “head", $E$:

$$E = z + \frac{V^2}{2g}$$
where $V$ is the length of the velocity vector, $z$ is the fragment elevation, and $g$ is acceleration due to gravity.

After an impact, the velocity component normal to the path is reduced by a ratio $k_n$ and the tangential velocity component by $k_t$. It can be shown that the resulting incremental loss of energy ($\Delta E$) is

$$\Delta E = \frac{V^2}{2g} \left[ \left( \frac{k_n^2 + k_t^2 \tan^2 \theta}{1 + \tan^2 \theta} \right) - 1 \right]$$

where $\theta$ is the angle of incidence prior to the impact. Thus, the kinetic energy is reduced in each impact by a ratio ranging from $k_n^2$ for very flat trajectories, through $(k_n^2 + k_t^2)/2$ for $45^\circ$ impacts, to $k_t^2$ for steep trajectories approaching the perpendicular.

The "energy line" resulting from plotting the relationship in [4] appears as a series of steps, separated by horizontal lines (Fig. 11A), the length of which equals the trajectory length $\Delta L$. When the ratio $\Delta E/\Delta L$ is less than the tangent of the slope angle, the fragment accelerates continuously and the energy line rises above the path. When the ratio becomes greater than the slope gradient, the fragment decelerates and the trajectories rapidly become shorter. Deposition of the fragment then occurs.

In ROCKFALL, a transition into rolling mode is made when, during three consecutive bounces, the ratio between the kinetic energy head lost in an impact and the horizontal length of the corresponding bounce ($\Delta E/\Delta L$) is greater than the rolling-friction coefficient, i.e., the rolling movement mode becomes more efficient than the bouncing mode. When there is a change in path-slope, such as at the crest of a small cliff, the fragment may temporarily move back into trajectory.

For long slope segments that have slope angles $\leq 45^\circ$, ROCKFALL generally predicts rockfall fragment paths that
are dominated by rolling movement. This is exemplified by the long travel paths simulated in the Hedley and Sunnybrae examples below, and it is in agreement with the empirical observations of Ritchie (1963). Under such circumstances, the variation and even the absolute value of the restitution coefficients are of secondary importance compared with the magnitude of the chosen rolling-friction coefficient.

Case histories of rockfall accidents at the base of talus slopes

Three case histories of rockfall accidents at the base of talus slopes in British Columbia were investigated in detail. The sites were visited in September 1987 and data collected on the geology of the detachment zone and the geometry of the path. Detailed theodolite surveys were conducted on the path and eyewitnesses were interviewed in the first two cases discussed.

Hedley, B.C., January 17, 1939

Hedley is a small mining community located in the Similkameen Valley in the interior of British Columbia. Part of the community was situated directly beneath the rock faces and talus slopes of Stemwinder Mountain (Fig. 12). A rockfall from Stemwinder Mountain struck the town at 01:00 on Burns Night, January 17, 1939, killing two people and damaging several houses.

The slopes above the townsite are underlain by the Upper Triassic Nicola Group, consisting of an interbedded, folded, and sheared sequence of basalts and limestone.

The source of the 1939 rockfall is above the apex of a large talus cone consisting of relatively uniformly graded basalt fragments. Most of the talus surface consists of cubical fragments with median sizes of approximately 40 mm, ranging from 10 to 150 mm. The surface is susceptible to shallow talus sliding and is free of vegetation. Its profile is uniform at 35°.

The source area of the rockfall has been identified with the help of eyewitnesses. It is a large asymmetric wedge scar. One side of the wedge formed along a faulted contact plane between basalt in the footwall and recrystallized limestone in the hanging wall, dipping at a mean angle of 52°, a few degrees to the left of the sliding direction. The opposite side of the wedge consists of a series of near-vertical cross joints striking perpendicular to the fault plane.

Light-coloured, relatively fresh rock at the upper end of the scar, some 50 m above the talus, indicates that the volume of the detached rock was about 5000 m³. A few large limestone boulders lie on the talus surface about 100 m below the apex. These boulders have a median size of approximately 0.7 m and a range of 1.5 m and are partly buried by the fine basaltic talus.

The limestone rock that formed the rockfall is laminated but strong and sparsely jointed, tending to break into large blocks. In contrast, the underlying basalt is closely fractured.

No traces of the rockfall path were found on the talus, except for the few remnant boulders mentioned above.

The 1939 accident occurred in a newly built part of town known as the Ready Cash subdivision, consisting of two streets parallel to the toe of the talus cone (Figs. 12 and 13). Several boulders reached the subdivision, as reconstructed by arrows in Fig. 12. The boulders ranged from 1 to 2 m in size. Four houses were severely damaged (Fig. 14). A number of persons were awakened from their sleep by the walls of their bedrooms crushing under impact (Fig. 14).

Fortunately, as noted above only two deaths occurred. The rockfall impact in the subdivision took place within the rockfall shadow at an equivalent shadow angle of 30°. The rockfall fahrböschung for the Hedley event is 34°.

Meteorological data from Hedley were analyzed for the 1939 event but do not suggest an obvious meteorological trigger for the rockfall.

The discontinuity patterns in the southeast face of Stemwinder Mountain indicate that similar conditions of detachment exist for future rockslide failures along the face. Although houses were moved from the run-out area of the 1939 event (B.C. Order in Council 1576), several homes at...
the present Hedley townsite are located beneath rockslopes and talus that are within the zone defined by the empirical minimum shadow angle of 27.5°.

The profile of the longest rockfall path is shown in Fig. 15. The path was simulated with ROCKFALL, and the calculated reach distance agrees well with the actual experience. The results of the computer simulation again confirm the predominant rolling mode of movement. It is noted that the analysis could for practical purposes be replaced by one based on a frictional model.

*Sunnybrae, B.C., November 23, 1983*

Sunnybrae is a small community in the British Columbia interior located on the north shore of Shuswap Lake (Fig. 16) across from the town of Salmon Arm. The community lies at 350 m above seal level (asl) directly beneath the precipitous faces of Bastion Mountain (Fig. 16), which extends to 1300 m asl. The cliffs are made up of metamorphosed limestone of the Sicamous Formation.

The steep, sparsely forested slopes extending from the foot of the cliffs down towards the lakefront are underlain by weak schistose bedrock units, thinly mantled by fine-grained talus derived from the same rock. The bedrock is exposed in numerous small cliffs and outcrops on the slope.

Only very few boulders can be observed in the wooded rockfall shadow area surrounding Sunnybrae. It appears that the main product of weathering of the slope above is a relatively fine grained talus material.

Comparison of photographs of the precipitous faces of Bastion Mountain taken in 1905 and 1983 by Geological Survey of Canada field personnel indicate little change in the morphology of the faces and therefore limited rockfall activity in that time interval. In 1959, however, a substantial rockfall from the main face of Bastion Mountain (Fig. 1) occurred, suggesting that rockfall is a continuing, if infrequent, process in the vicinity of Sunnybrae.

At 01:50 on November 23, 1983, a wheel-shaped boulder of 6 x 6 x 2 m detached near the base of the limestone cliffs, rolled, and bounced down a path 790 m long. It partly destroyed a house at the north end of Sunnybrae and killed two inhabitants (Fig. 17). The boulder demolished approximately one half of the house, leaving the other half rela-
tively intact. A person sleeping in that part of the house escaped injury. A second house was missed literally by a few centimetres (Miller 1983).

The release point of the boulder is shown in Fig. 16. It is in a vertical part of the cliff face some 25 m above its base. The rock is banded crystalline limestone, light to dark grey in color and very strong.

The boulder separated along an exfoliation joint dipping 70° to the south (down the rockfall path). The upper edge of the fragment separated from the rock above along a curving near-horizontal joint, leaving an arch-like overhang over 2 m deep. The exfoliation joint can be observed to continue upwards into the overhang. It appears partly open, and slight groundwater flow issues from it, staining the face below (the rockfall boulder was reported by Miller (1983) to have had brown staining on one face). The eastern lateral boundary of the block was defined by a joint dipping approximately 50° to the west.

It is clear that the detachment of the boulder resulted in the creation of an overhang more exposed than that which existed before. The possibility cannot be ruled out that the event of November 1983 was initial to a series of detachments from the same source area and with similar mechanics.

The travel path of the boulder was reconstructed by surveying the marks left along its path, most of which were still discernible in 1987 (Fig. 18). The marks were of two types: (i) impact craters, typically 4 × 1 m in plan and 0.3–0.5 m deep; and (ii) elongated rolling marks, resembling a trench 2 m wide and 0.5 m deep, up to 30 m long. As shown in the profile in Fig. 18, the boulder moved by rolling throughout most of its descent. A long bounce occurred below the crest of the lower cliff, followed by several shorter bounces and abrupt changes in direction, due to topographic detail (see plan in Fig. 18). Small fragments broke off from the boulder at several places near the end of its path. These fragments were generally found far from the impact craters, indicating that they separated during rotation of the boulder.

A simulation of the rockfall path using ROCKFALL appears in Fig. 19. The boulder mass was assumed to be 150 t, so most impacts were plastic. It is of interest to note that the length of the parabolic trajectory at the lower cliff in the simulation is very close to the length observed. Therefore, the velocity estimate shown in the upper part of the figure appears realistic. The analysis indicates that the relative shortness of the path, characterized by an equivalent shadow angle of 34° and a rockfall fahrböschung of 35°, is due to the
plastic energy losses incurred in bouncing below the lower cliff (Fig. 19). Had it continued rolling, the boulder may have travelled farther. It is of concern that many homes are located beneath these cliffs within the zone defined by the empirical minimum shadow angle of 27.5° discussed above.

Barnhartvale, spring 1974

The Barnhartvale subdivision is located within the City of Kamloops in the interior of British Columbia. The western part of the community is located at the foot of some prominent east-facing rock slopes and associated talus (Fig. 20). The rock is intensely jointed metavolcanics of the Cache Creek Group, with prominent joint sets dipping at about 50° into and out of the slope. These discontinuities form numerous detachment surfaces for fragmental rockfall, a fact which is reflected in the substantial talus accumulation downslope.

We have been able to reconstruct the event using a 1:2500 orthophoto with 10-m contours and our 1987 field observations.

In the spring of 1974, a boulder measuring about a metre in diameter, fell from about 775 m asl on the rock slope, bounced, and rolled over the talus slope and beyond its base. The rock severely damaged a house on Lot 16, Ronde Lane at 592 m asl. Fortunately no one was hurt. Impact took place at an equivalent shadow angle of 30°. The rockfall fahrböschung is 34°.

The incident led to the implementation of the following mitigative measures: scaling of the rock slopes, which included the removal of problematical rock masses by blasting; the excavation of a protective ditch at the base of the talus (Fig. 21); and the erection of a wire-mesh fence as a further protective measure.

Analysis of the 1974 rockfall with ROCKFALL, using similar model parameters to those used in the analysis of the Hedley and Sunnybrae incidents, simulates the path and run-out distance of the boulder (Fig. 22A). It also shows the effect of the ditch in stopping similar boulders (Fig. 22B) from moving into the rockfall shadow.

Conclusions

Rockfall is a common process in mountainous terrain where its long-term operation leads to the accumulation of talus slopes. Although deaths from rockfall in Canada are small in number, the indirect costs of land alienation because of rockfall hazard are very significant. In western Canada the costs of such land sterilization are in the order of tens of millions of dollars. As development pressures increase, techniques for assessing the vulnerability to big boulder impacts beyond the base of talus slopes have become a priority.

A new terminology for use in rockfall hazard analysis is suggested. The area beyond the base of a talus slope that is reached by large boulders is termed the rockfall shadow, and the shadow angle is defined as the angle between the apex of the talus slope and the distal margin of the shadow. The angle between any point in the shadow and the apex of the talus slope is termed the equivalent shadow angle.

Rockfall impact probability is a strong function of the distance from the source area. Within the rockfall shadow area return periods of the order of 1000 years relative to an individual house site are typical. Calculation of both landing and impact probabilities indicate that for the talus studied, a housing development located at 50 m from the talus margin, covering an area 200 m wide along the talus base, would face a probability of being struck by a single rockfall boulder of 1 in 95 years.

The prediction of rockfall behaviour in the shadow was carried out using geological, empirical, and analytic methods. The evaluation of geological evidence can be helpful in assessing the probability of a defined shadow limit being violated and for establishing probabilities of impact within the shadow.

An examination of 16 talus profiles from southwestern British Columbia yielded an empirical minimum shadow angle of 27.5°, which is thought to correspond to the rolling-friction angle for the slope surfaces in question. This angle would be useful in a first approximation to shadow limits and is preferable to the use of the rockfall fahrböschung as proposed by several authors.

The analytical lumped-mass model (ROCKFALL), which was developed, utilizes two restitution coefficients and a transition to rolling criterion. The model calculates the energy head of a boulder during its travel and was initially calibrated with reference to some full-scale Italian experiments. Although further calibration is necessary, results from the analysis of three rockfall incidents at the base of talus slopes in southwestern British Columbia were encouraging. In all cases the ROCKFALL simulation of boulder runout agreed almost exactly with that observed in the respective incidents.

The documentation of the three rockfall incidents shows that, in each case, rockfall fragments impacted on homes
Fig. 20. View of Barnhartvale subdivision, Kamloops, British Columbia, in the vicinity of the 1974 rockfall, showing proximity of homes to talus slopes and source rock slopes. Arrows show protective ditch seen in Fig. 21.

Fig. 21. Protective ditch excavated following the 1974 Barnhartvale rockfall, photographed in 1981.

Fig. 22. Rockfall simulation of the Barnhartvale rockfall. (A) The 1974 rockfall. (B) The 1974 rockfall with protective ditch.
at equivalent shadow angles of 30° or more. This would suggest that a review of existing development within rockfall shadow areas at the base of talus slopes may be in order.

Acknowledgements

This paper is an outcome of joint research undertaken by the Geological Survey of Canada and Thruber Engineering Ltd. under the Government of Canada Unsolicited Proposal Program. The research was funded by Supply and Services Canada (Unsolicited Proposal Fund), Energy, Mines and Resources Canada (Geological Survey of Canada) and Transport Canada (Transportation Development Centre). The authors acknowledge the assistance of the following people who contributed by providing helpful information, advice, and (or) encouragement related to this study in its various stages: M. Church, J.J. Clague, D.M. Cruden, D. Fieber, D.R. Lister, J.C. Leighton, W.H. Mathews, G.C. Morgan, N.R. Morgenstern, G.E. Miller, H. Nasmith, L. Peckover, J.M. Ryder, N.A. Skermer, and P.J. Woods. The authors also wish to thank Helen Moore, a survivor of the Hedley rockfall accident, for assistance in assembling data on the Hedley incident; and the Similkameen Indian Administration and Chief Ross Albert of the Cook’s Ferry Indian Band for allowing access to Indian lands.


