

Analysis of rockfall hazards

Introduction

Rockfalls are a major hazard in rock cuts for highways and railways in mountainous terrain. While rockfalls do not pose the same level of economic risk as large scale failures which can and do close major transportation routes for days at a time, the number of people killed by rockfalls tends to be of the same order as people killed by all other forms of rock slope instability. Badger and Lowell (1992) summarised the experience of the Washington State Department of Highways. They stated that 'A significant number of accidents and nearly a half dozen fatalities have occurred because of rockfalls in the last 30 years ... [and] ... 45 percent of all unstable slope problems are rock fall related'. Hungr and Evans (1989) note that, in Canada, there have been 13 rockfall deaths in the past 87 years. Almost all of these deaths have been on the mountain highways of British Columbia.



Figure 1: A rock slope on a mountain highway. Rockfalls are a major hazard on such highways

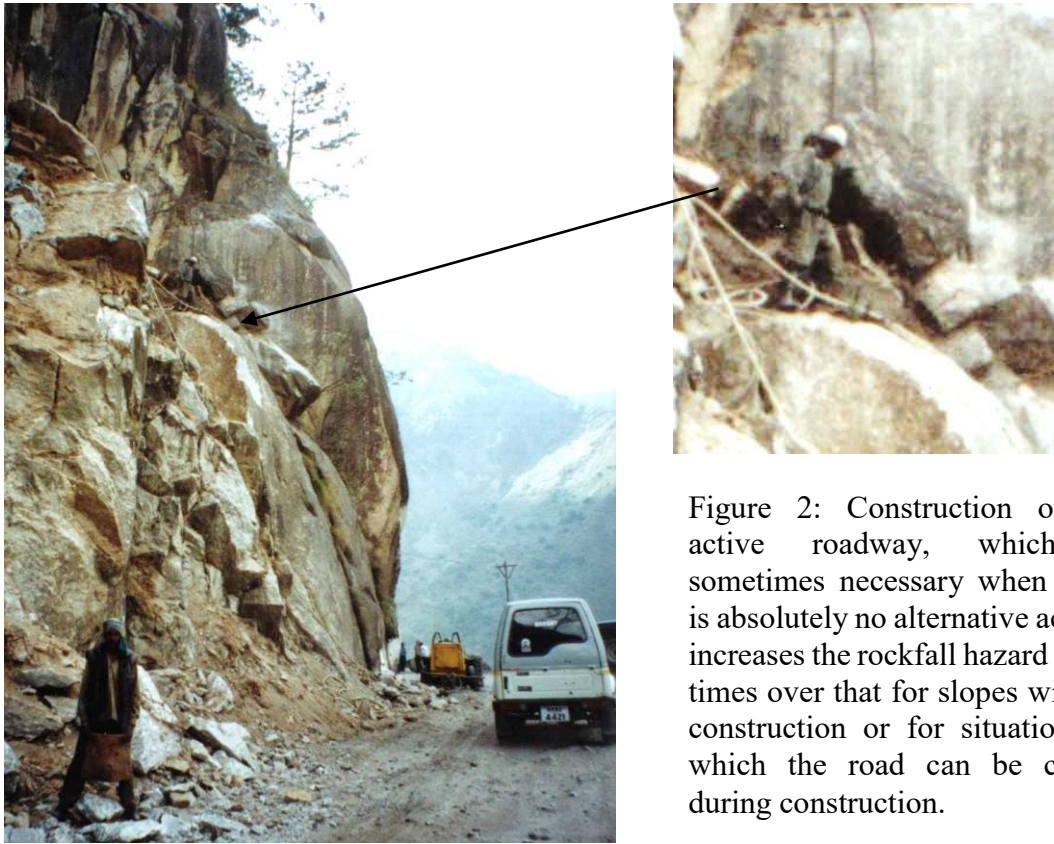


Figure 2: Construction on an active roadway, which is sometimes necessary when there is absolutely no alternative access, increases the rockfall hazard many times over that for slopes without construction or for situations in which the road can be closed during construction.

Mechanics of rockfalls

Rockfalls are generally initiated by some climatic or biological event that causes a change in the forces acting on a rock. These events may include pore pressure increases due to rainfall infiltration, erosion of surrounding material during heavy rain storms, freeze-thaw processes in cold climates, chemical degradation or weathering of the rock, root growth or leverage by roots moving in high winds. In an active construction environment, the potential for mechanical initiation of a rockfall will probably be one or two orders of magnitude higher than the climatic and biological initiating events described above.

Once movement of a rock perched on the top of a slope has been initiated, the most important factor controlling its fall trajectory is the geometry of the slope. In particular, dip slope faces, such as those created by the sheet joints in granites, are important because they impart a horizontal component to the path taken by a rock after it bounces on the slope or rolls off the slope. The most dangerous of these surfaces act as 'ski-jumps' and impart a high horizontal velocity to the falling rock, causing it to bounce a long way out from the toe of the slope.

Clean faces of hard unweathered rock are the most dangerous because they do not retard the movement of the falling or rolling rock to any significant degree. On the other hand,

surfaces covered in talus material, scree or gravel absorb a considerable amount of the energy of the falling rock and, in many cases, will stop it completely.

This retarding capacity of the surface material is expressed mathematically by a term called the *coefficient of restitution*. The value of this coefficient depends upon the nature of the materials that form the impact surface. Clean surfaces of hard rock have high coefficients of restitution while soil, gravel and completely decomposed granite have low coefficients of restitution. This is why gravel layers are placed on catch benches in order to prevent further bouncing of falling rocks.

Other factors such as the size and shape of the rock boulders, the coefficients of friction of the rock surfaces and whether or not the rock breaks into smaller pieces on impact are all of lesser significance than the slope geometry and the coefficients of restitution described above. Consequently, relative crude rockfall simulation models are capable of producing reasonably accurate predictions of rockfall trajectories. Obviously more refined models will produce better results, provided that realistic input information is available. Some of the more recent rockfall models are those of Bozzolo et al (1988), Hungr and Evans (1989), Spang and Rautenstrauch (1988) and Azzoni et al (1995).

Most of these rockfall models include a Monte Carlo simulation technique to vary the parameters included in the analysis. This technique is similar to the random process of throwing dice - one for each parameter being considered. The program Rocfall¹ is a program that can be used for rockfall analyses using a number of probabilistic options. Figure 3 shows a single rockfall trajectory while Figure 4 shows the trajectories for 100 rockfalls using the Monte Carlo simulation process.

Possible measures which could be taken to reduce rockfall hazards

Identification of potential rockfall problems

It is neither possible nor practical to detect all potential rockfall hazards by any techniques currently in use in rock engineering. In some cases, for example, when dealing with boulders on the top of slopes, the rockfall hazards are obvious. However, the most dangerous types of rock failure occur when a block is suddenly released from an apparently sound face by relatively small deformations in the surrounding rock mass. This can occur when the forces acting across discontinuity planes, which isolate a block from its neighbours, change as a result of water pressures in the discontinuities or a reduction of the shear strength of these planes because of long term deterioration due to weathering. This release of 'keyblocks' can sometimes precipitate rockfalls of significant size or, in extreme cases, large scale slope failures.

¹ Available from www.rocscience.com

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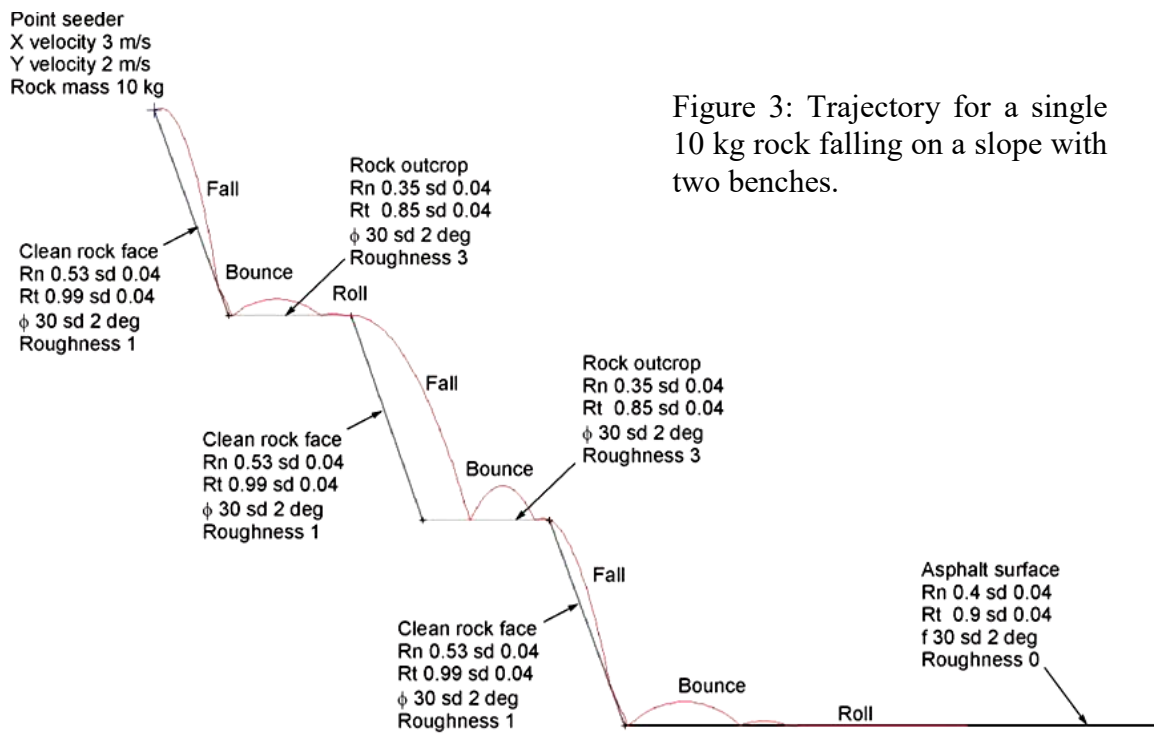


Figure 3: Trajectory for a single 10 kg rock falling on a slope with two benches.

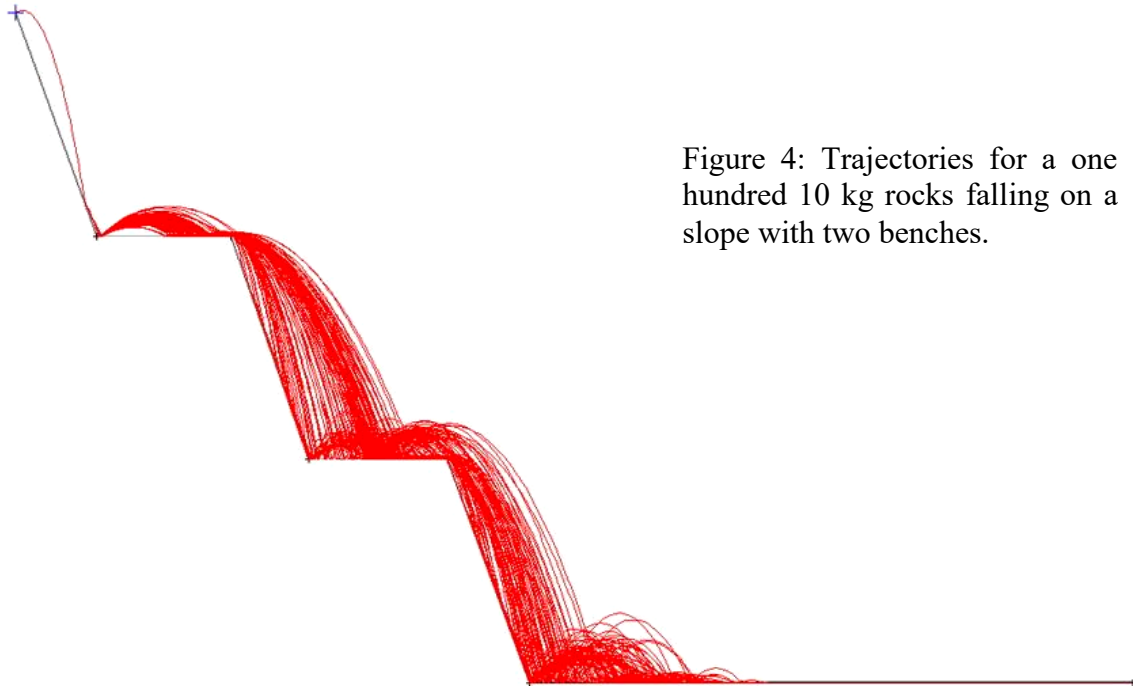


Figure 4: Trajectories for a one hundred 10 kg rocks falling on a slope with two benches.

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While it is not suggested that rock faces should not be carefully inspected for potential rockfall problems, it should not be assumed that all rockfall hazards will be detected by such inspections.

Reduction of energy levels associated with excavation

Traditional excavation methods for hard rock slopes involve the use of explosives. Even when very carefully planned controlled blasts are carried out, high intensity short duration forces act on the rock mass. Blocks and wedges which are at risk can be dislodged by these forces. Hence, an obvious method for reducing rockfall hazards is to eliminate excavation by blasting or by any other method, such as ripping, which imposes concentrated, short duration forces or vibrations on the rock mass. Mechanical and hand excavation methods can be used and, where massive rock has to be broken, chemical expanding rock breaking agents may be appropriate.

Physical restraint of rockfalls

If it is accepted that it is not possible to detect or to prevent all rockfalls, then methods for restraining those rockfalls, which do occur, must be considered. These methods are illustrated in Figure 5.

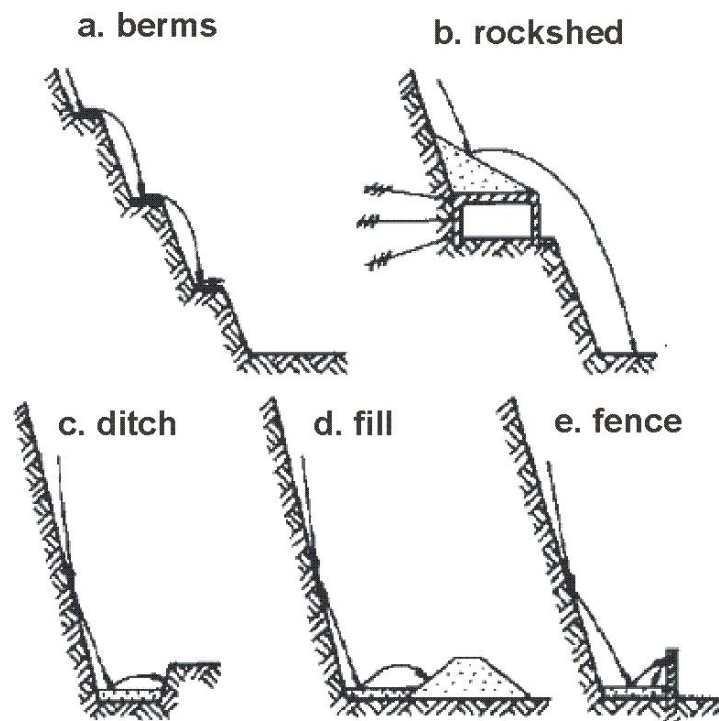


Figure 5: Possible measures to reduce the damage due to rockfalls. After Spang (1987).

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Berms are a very effective means of catching rockfalls and are frequently used on permanent slopes. However, berms can only be excavated from the top downwards and they are of limited use in minimising the risk of rockfalls during construction.

Rocksheds or avalanche shelters are widely used on steep slopes above narrow railways or roadways. An effective shelter requires a steeply sloping roof covering a relatively narrow span. In the case of a wide multi-lane highway, it may not be possible to design a rockshed structure with sufficient strength to withstand large rockfalls. It is generally advisable to place a fill of gravel or soil on top of the rockshed in order to act as both a retarder and a deflector for rockfalls.

Rock traps work well in catching rockfalls provided that there is sufficient room at the toe of the slope to accommodate these rock traps. In the case of very narrow roadways at the toe of steep slopes, there may not be sufficient room to accommodate rock traps. This restriction also applies to earth or rock fills and to gabion walls or massive concrete walls.

Catch fences or barrier fences in common use are estimated to have an energy absorption capacity² of 100 kNm. This is equivalent to a 250 kg rock moving at about 20 metres per second. More robust barrier fences, such as those used in the European Alps³, have an energy absorbing capacity of up to 2500 kNm which means that they could stop a 6250 kg boulder moving at approximately 20 metres per second. Details of a typical high capacity net are illustrated in Figure 6.

Another restraint system which merits further consideration is the use of *mesh draped* over the face. This type of restraint is commonly used for permanent slopes and is illustrated in Figure 7. The mesh is draped over the rock face and attached at several locations along the slope. The purpose of the mesh is not to stop rockfalls but to trap the falling rock between the mesh and the rock face and so to reduce the horizontal velocity component which causes the rock to bounce out onto the roadway below.

Probably the most effective permanent rockfall protective system for most highways is the construction of a catch ditch at the toe of the slope. The base of this ditch should be covered by a layer of gravel to absorb the energy of falling rocks and a sturdy barrier fence should be placed between the ditch and the roadway. The location of the barrier fence can be estimated by means of a rockfall analysis such as that used to calculate the trajectories presented in Figure 3. The criterion for the minimum distance between the toe of the slope and the rock fence is that no rocks can be allowed to strike the fence before their kinetic energy has been diminished by the first impact on the gravel layer in the rock trap.

² The kinetic energy of a falling body is given by $0.5 \times \text{mass} \times \text{velocity}^2$.

³ Wire mesh fence which incorporates cables and energy absorbing slipping joints is manufactured by Geobrugg Protective Systems, CH-8590 Romanshorn, Switzerland, Fax +41 71466 81 50.

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a: Anchor grouted into rock with cables attached.



b: Geobruigg ring net shown restraining a boulder. These nets can be designed with energy absorbing capacities of up to 2500 kNm which is equivalent to a 6 tonne boulder moving at 20 m per second.

c: Geobruigg energy absorbing ring. When subjected to impact loading the ring deforms plastically and absorbs the energy of the boulder



Figure 6: Details of a rockfall net system manufactured by Geobruigg of Switzerland.

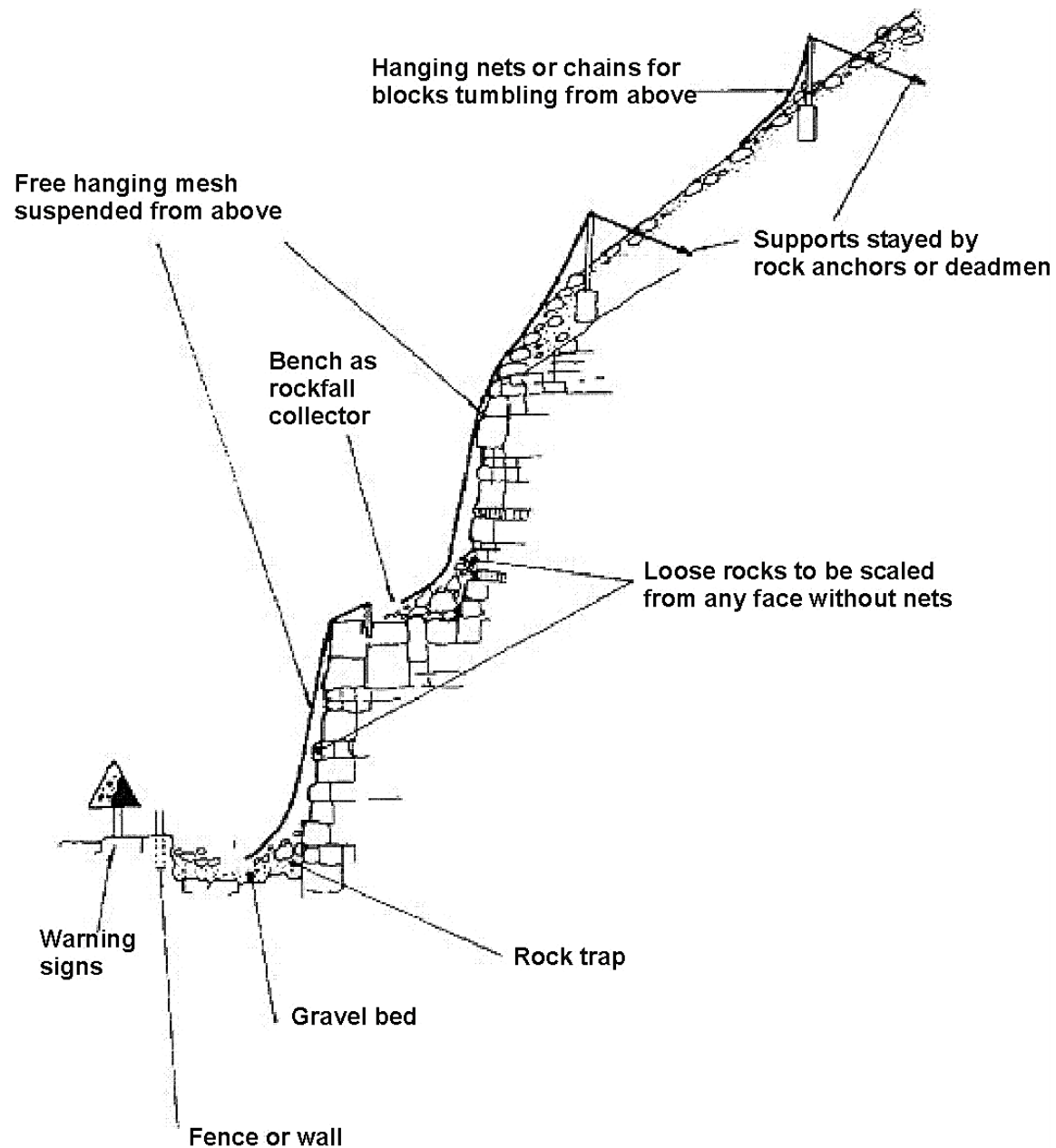
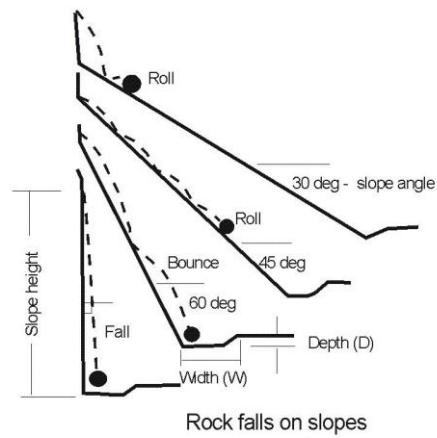


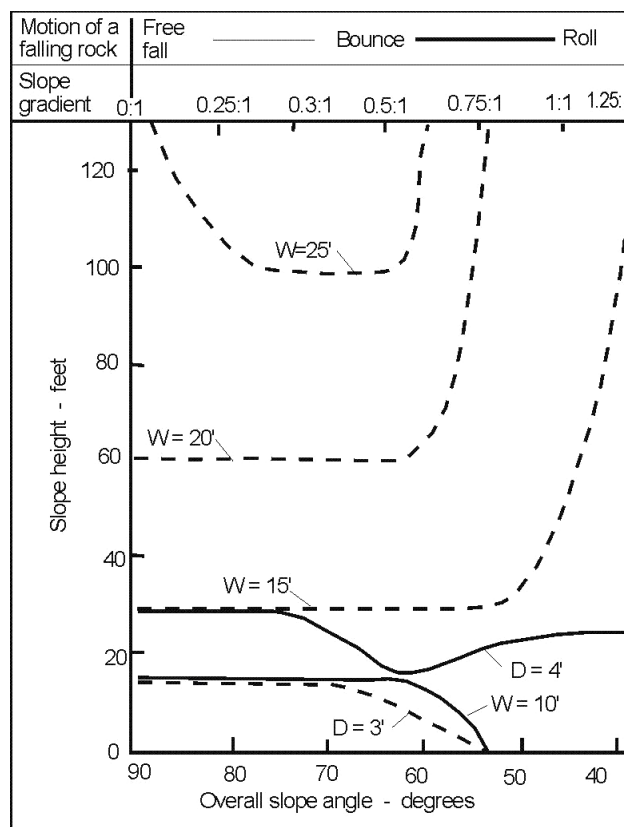
Figure 7: Rockfall control measures. After Fookes and Sweeney (1976).

A simple design chart for ditch design, based upon work by Ritchie (1963), is reproduced in Figure 8.

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Figures taken from FHWA Manual 'Rock Slopes'
November 1991. USDOT Chapter 12 Page 19.



Ditch Design Chart

Figure 8: Rockfall ditch design chart based upon work by Ritchie (1963).

Rockfall Hazard Rating System

Highway and railway construction in mountainous regions presents a special challenge to geologists and geotechnical engineers. This is because the extended length of these projects makes it difficult to obtain sufficient information to permit stability assessments to be carried out for each of the slopes along the route. This means that, except for sections which are identified as particularly critical, most highway slopes tend to be designed on the basis of rather rudimentary geotechnical analyses. Those analyses which are carried out are almost always concerned with the overall stability of the slopes against major sliding or toppling failures which could jeopardise the operation of the highway or railway. It is very rare to find a detailed analysis of rockfall hazards except in heavily populated regions in highly developed countries such as Switzerland.

In recognition of the seriousness of this problem and of the difficulty of carrying out detailed investigations and analyses on the hundreds of kilometres of mountain highway in the western United States and Canada, highway and railway departments have worked on classification schemes which can be carried out by visual inspection and simple calculations. The purpose of these classifications is to identify slopes which are particularly hazardous and which require urgent remedial work or further detailed study.

In terms of rockfall hazard assessment, one of the most widely accepted⁴ is the Rockfall Hazard Rating System (RHRS) developed by the Oregon State Highway Division (Pierson et al. 1990). Table 1 gives a summary of the scores for different categories included in the classification while Figure 9 shows a graph which can be used for more refined estimates of category scores.

The curve shown in Figure 9 is calculated from the equation where, in this case, $x = (\text{Slope height} - \text{feet})/25$. Similar curves for other category scores can be calculated from the following values of the exponent x .

Slope height	$x = \text{slope height (feet)} / 25$
Average vehicle risk	$x = \% \text{ time} / 25$
Sight distance	$x = (120 - \% \text{ Decision sight distance}) / 20$
Roadway width	$x = (52 - \text{Roadway width (feet)}) / 8$
Block size	$x = \text{Block size (feet)}$
Volume	$x = \text{Volume (cu.ft.)} / 3$

⁴ This system has been adopted by the States of Oregon, Washington, New Mexico and Idaho and, in slightly modified form, by California, Colorado and British Columbia.

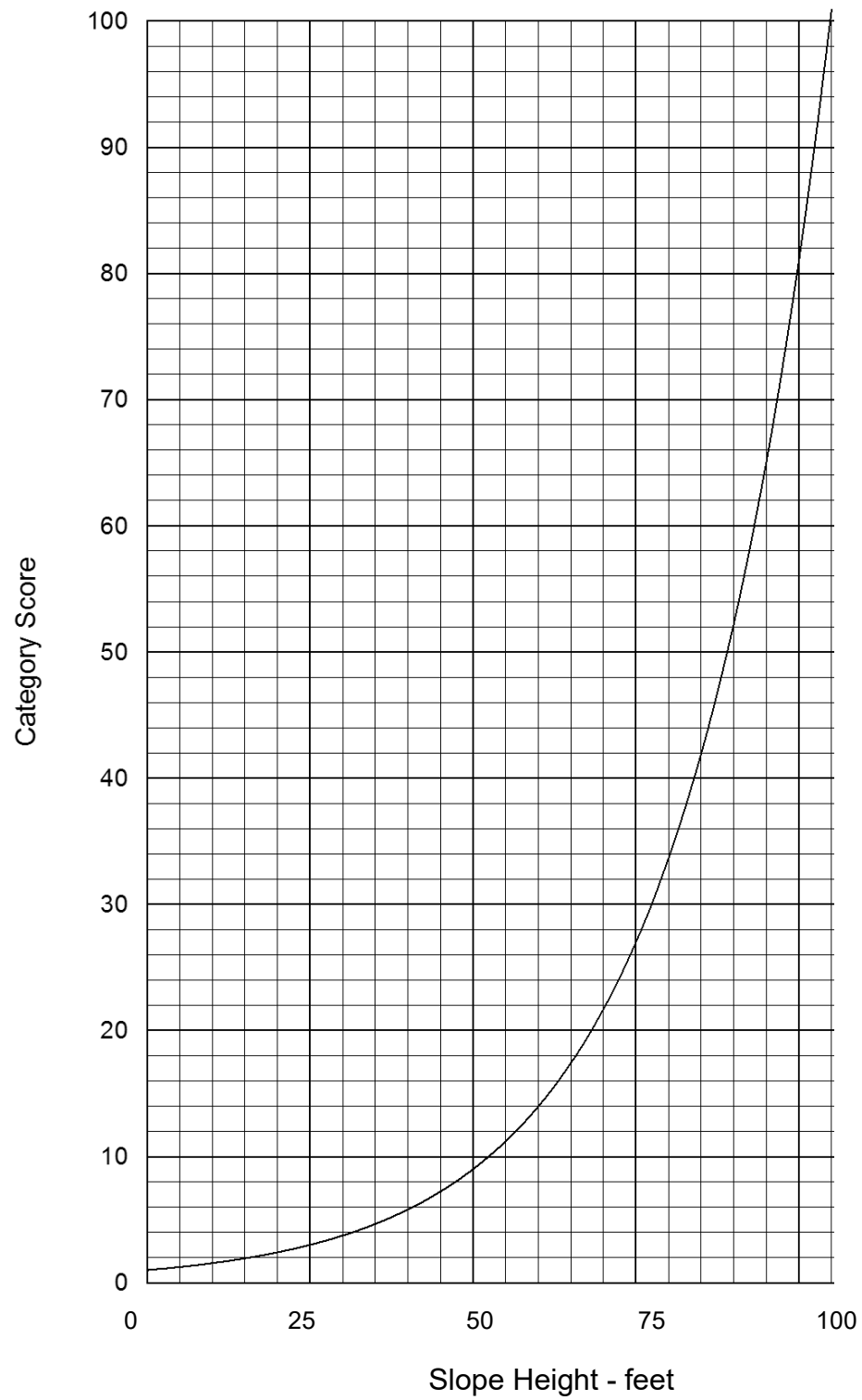


Figure 9: Category score graph for slope height.

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Table 1: Rockfall Hazard Rating System.

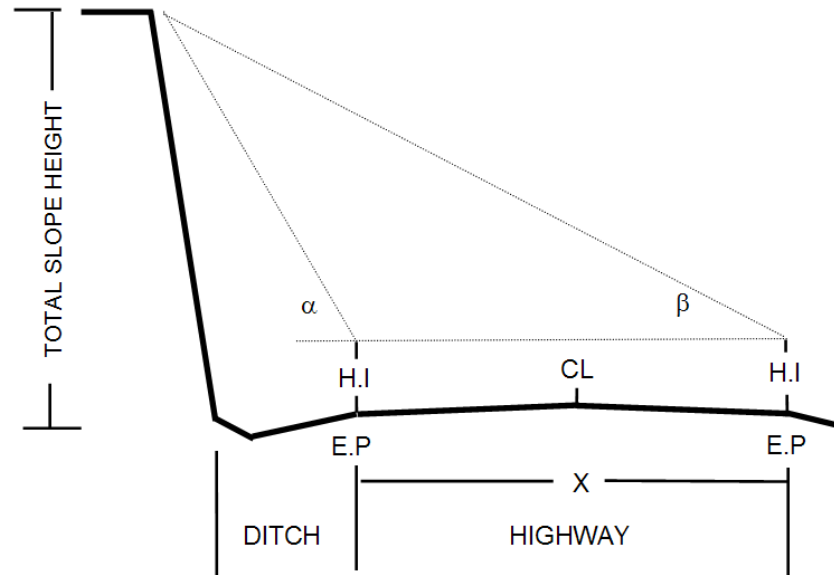
CATEGORY			RATING CRITERIA AND SCORE			
			POINTS 3	POINTS 9	POINTS 27	POINTS 81
SLOPE HEIGHT			25 FT	50 FT	75 FT	100 FT
DITCH EFFECTIVENESS			Good catchment	Moderate catchment	Limited catchment	No catchment
AVERAGE VEHICLE RISK			25% of the time	50% of the time	75% of the time	100% of the time
PERCENT OF DECISION SIGHT DISTANCE			Adequate site distance, 100% of low design value	Moderate sight distance, 80% of low design value	Limited site distance, 60% of low design value	Very limited sight distance, 40% of low design value
ROADWAY WIDTH INCLUDING PAVED SHOULDERS			44 feet	36 feet	28 feet	20 feet
GEOLOGIC CHARACTER	CASE 1	STRUCTURAL CONDITION	Discontinuous joints, favorable orientation	Discontinuous joints, random orientation	Discontinuous joints, adverse orientation	Continuous joints, adverse orientation
		ROCK FRICTION	Rough, irregular	Undulating	Planar	Clay infilling or slickensided
	CASE 2	STRUCTURAL CONDITION	Few differential erosion features	Occasional erosion features	Many erosion features	Major erosion features
		DIFFERENCE IN EROSION RATES	Small difference	Moderate difference	Large difference	Extreme difference
BLOCK SIZE			1 FT	2 FT	3 FT	4 FT
QUANTITY OF ROCKFALL/EVENT			3 cubic yards	6 cubic yards	9 cubic yards	12 cubic yards
CLIMATE AND PRESENCE OF WATER ON SLOPE			Low to moderate precipitation; no freezing periods, no water on slope	Moderate precipitation or short freezing periods or intermittent water on slope	High precipitation or long freezing periods or continual water on slope	High precipitation and long freezing periods or continual water on slope and long freezing periods
ROCKFALL HISTORY			Few falls	Occasional falls	Many falls	Constant falls

Slope Height

This item represents the vertical height of the slope not the slope distance. Rocks on high slopes have more potential energy than rocks on lower slopes, thus they present a greater hazard and receive a higher rating. Measurement is to the highest point from which rockfall is expected. If rocks are coming from the natural slope above the cut, use the cut height

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plus the additional slope height (vertical distance). A good approximation of vertical slope height can be obtained using the relationships shown below.



$$\text{TOTAL SLOPE HEIGHT} = \frac{(X) \sin \alpha \sin \beta}{\sin (\alpha - \beta)} + \text{H.I.}$$

where X = distance between angle measurements
H.I. = height of the instrument.

Figure 10: Measurement of slope height.

Ditch Effectiveness

The effectiveness of a ditch is measured by its ability to prevent falling rock from reaching the roadway. In estimating the ditch effectiveness, the rater should consider several factors, such as: 1) slope height and angle; 2) ditch width, depth and shape; 3) anticipated block size and quantity of rockfall; 4) impact of slope irregularities (launching features) on falling rocks. It's especially important for the rater to evaluate the impact of slope irregularities because a launching feature can negate the benefits expected from a fallout area. The rater should first evaluate whether any of the irregularities, natural or man-made, on a slope will launch falling rocks onto the paved roadway. Then based on the number and size of the launching features estimate what portion of the falling rocks will be affected. Valuable information on ditch performance can be obtained from maintenance personnel. Rating points should be assigned as follows:

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3 points	<i>Good Catchment.</i> All or nearly all of falling rocks are retained in the catch ditch.
9 points	<i>Moderate Catchment.</i> Falling rocks occasionally reach the roadway.
27 points	<i>Limited Catchment.</i> Falling rocks frequently reach the roadway.
81 points	<i>No Catchment.</i> No ditch or ditch is totally ineffective. All or nearly all falling rocks reach the roadway.

Reference should also be made to Figure 8 in evaluating ditch effectiveness.

Average Vehicle Risk (AVR)

This category measures the percentage of time that a vehicle will be present in the rockfall hazard zone. The percentage is obtained by using a formula (shown below) based on slope length, average daily traffic (ADT), and the posted speed limit at the site. A rating of 100% means that on average a car can be expected to be within the hazard section 100% of the time. Care should be taken to measure only the length of a slope where rockfall is a problem. Over estimated lengths will strongly skew the formula results. Where high ADT's or longer slope lengths exist values greater than 100% will result. When this occurs it means that at any particular time more than one car is present within the measured section. The formula used is:

$$\frac{\text{ADT (cars/hour)} \times \text{Slope Length (miles)} \times 100\%}{\text{Posted Speed Limit (miles per hour)}} = \text{AVR}$$

Percent of Decision Sight Distance

The decision sight distance (DSD) is used to determine the length of roadway in feet a driver must have to make a complex or instantaneous decision. The DSD is critical when obstacles on the road are difficult to perceive, or when unexpected or unusual manoeuvres are required. Sight distance is the shortest distance along a roadway that an object of specified height is continuously visible to the driver.

Throughout a rockfall section the sight distance can change appreciably. Horizontal and vertical highway curves along with obstructions such as rock outcrops and roadside vegetation can severely limit a driver's ability to notice a rock in the road. To determine where these impacts are most severe, first drive through the rockfall section from both directions. Decide which direction has the shortest line of sight. Both horizontal and vertical sight distances should be evaluated. Normally an object will be most obscured when it is located just beyond the sharpest part of a curve. Place a six-inch object in that position on the fogline or on the edge of pavement if there is no fogline. The rater then

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walks along the fogline (edge of pavement) in the opposite direction of traffic flow, measuring the distance it takes for the object to disappear when your eye height is 3.5 ft above the road surface. This is the measured sight distance. The decision sight distance can be determined by the table below. The distances listed represent the low design value. The posted speed limit through the rockfall section should be used.

Posted Speed Limit (mph)	Decision Sight Distance (ft)
30	450
40	600
50	750
60	1,000
70	1,100

These two values can be substituted into the formula below to calculate the ‘Percent of Decision Sight Distance.’

$$\frac{\text{Actual Site Distance}}{\text{Decision Site Distance}} \left(\frac{\quad}{\quad} \right) \times 100\% = \quad \%$$

Roadway Width

This dimension is measured perpendicular to the highway centreline from edge of pavement to edge of pavement. This measurement represents the available manoeuvring room to avoid a rockfall. This measurement should be the minimum width when the roadway width is not consistent.

Geologic Character

The geologic conditions of the slope are evaluated with this category. Case 1 is for slopes where joints, bedding planes, or other discontinuities, are the dominant structural feature of a rock slope. Case 2 is for slopes where differential erosion or oversteepened slopes is the dominant condition that controls rockfall. The rater should use whichever case best fits the slope when doing the evaluation. If both situations are present, both are scored but only the worst case (highest score) is used in the rating.

Case 1

Structural Condition Adverse joint orientation, as it is used here, involves considering such things as rock friction angle, joint filling, and hydrostatic head if water is present. Adverse joints are those that cause block, wedge or toppling failures. ‘Continuous’ refers to joints greater than 10 feet in length.

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- | | | |
|-----------|---|---|
| 3 points | <i>Discontinuous Joints, Favourable Orientation</i> | Jointed rock with no adversely oriented joints, bedding planes, etc. |
| 9 points | <i>Discontinuous Joints, Random Orientation</i> | Rock slopes with randomly oriented joints creating a three-dimensional pattern. This type of pattern is likely to have some scattered blocks with adversely oriented joints but no dominant adverse joint pattern is present. |
| 27 points | <i>Discontinuous Joints, Adverse Orientation</i> | Rock slope exhibits a prominent joint pattern, bedding plane, or other discontinuity, with an adverse orientation. These features have less than 10 feet of continuous length. |
| 81 points | <i>Continuous Joints, Adverse Orientation</i> | Rock slope exhibits a dominant joint pattern, bedding plane, or other discontinuity, with an adverse orientation and a length of greater than 10 feet. |

Rock Friction This parameter directly affects the potential for a block to move relative to another. Friction along a joint, bedding plane or other discontinuity is governed by the macro and micro roughness of a surface. Macro roughness is the degree of undulation of the joint. Micro roughness is the texture of the surface of the joint. In areas where joints contain highly weathered or hydrothermally altered products, where movement has occurred causing slickensides or fault gouge to form, where open joints dominate the slope, or where joints are water filled, the rockfall potential is greater. Noting the failure angles from previous rockfalls on a slope can aid in estimating general rock friction along discontinuities.

- | | | |
|-----------|---------------------------------------|--|
| 3 points | <i>Rough, Irregular</i> | The surfaces of the joints are rough and the joint planes are irregular enough to cause interlocking. This macro and micro roughness provides an optimal friction situation. |
| 9 points | <i>Undulating</i> | Also macro and micro rough but without the interlocking ability. |
| 27 points | <i>Planar</i> | Macro smooth and micro rough joint surfaces. Surface contains no undulations. Friction is derived strictly from the roughness of the rock surface. |
| 81 points | <i>Clay Infilling or Slickensided</i> | Low friction materials, such as clay and weathered rock, separate the rock surfaces negating any micro or macro roughness of the joint planes. These infilling materials have much lower friction angles than a rock on rock contact. Slickensided joints also have a very low friction angle and belong in this category. |

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Case 2

Structural Condition This case is used for slopes where differential erosion or oversteepening is the dominant condition that leads to rockfall. Erosion features include oversteepened slopes, unsupported rock units or exposed resistant rocks on a slope that may eventually lead to a rockfall event. Rockfall is caused by a loss of support either locally or throughout the slope. Common slopes that are susceptible to this condition are: layered units containing easily weathered rock that erodes undermining more durable rock; talus slopes; highly variable units such as conglomerates, mudflows, etc. that weather causing resistant rocks and blocks to fall, and rock/soil slopes that weather allowing rocks to fall as the soil matrix material is eroded.

3 points	<i>Few Differential Erosion Features</i> Minor differential erosion features that are not distributed throughout the slope.
9 points	<i>Occasional Erosion Features</i> Minor differential erosion features that are widely distributed throughout the slope.
27 points	<i>Many Erosion Features</i> Differential erosion features are large and numerous throughout the slope.
81 points	<i>Major Erosion Features</i> Severe cases such as dangerous erosion-created overhangs; or significantly oversteepened soil/rock slopes or talus slopes.

Difference in Erosion Rates The Rate of Erosion on a Case 2 slope directly relates to the potential for a future rockfall event. As erosion progresses, unsupported or oversteepened slope conditions develop. The impact of the common physical and chemical erosion processes as well as the effects of man's actions should be considered. The degree of hazard caused by erosion and thus the score given this category should reflect how quickly erosion is occurring; the size of rocks, blocks, or units being exposed; the frequency of rockfall events; and the amount of material released during an event.

3 points	<i>Small Difference</i> The difference in erosion rates is such that erosion features develop over many years. Slopes that are near equilibrium with their environment are covered by this category.
9 points	<i>Moderate Difference</i> The difference in erosion rates is such that erosion features develop over a few years.
27 points	<i>Large Difference</i> The difference in erosion rates is such that erosion features develop annually.
81 points	<i>Extreme Difference</i> The difference in erosion rates is such that erosion features develop rapidly

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Block Size or Quantity of Rockfall Per Event

This measurement should be representative of whichever type of rockfall event is most likely to occur. If individual blocks are typical of the rockfall, the block size should be used for scoring. If a mass of blocks tends to be the dominant type of rockfall, the quantity per event should be used. This can be determined from the maintenance history or estimated from observed conditions when no history is available. This measurement will also be beneficial in determining remedial measures.

Climate and Presence of Water on Slope

Water and freeze/thaw cycles both contribute to the weathering and movement of rock materials. If water is known to flow continually or intermittently from the slope it is rated accordingly. Areas receiving less than 20 inches per year are 'low precipitation areas.' Areas receiving more than 50 inches per year are considered 'high precipitation areas.' The impact of freeze/thaw cycles can be interpreted from knowledge of the freezing conditions and its effects at the site.

The rater should note that the 27-point category is for sites with long freezing periods or water problems such as high precipitation or continually flowing water. The 81-point category is reserved for sites that have both long freezing periods and one of the two extreme water conditions.

Rockfall History

This information is best obtained from the maintenance person responsible for the slope in question. It directly represents the known rockfall activity at the site. There may be no history available at newly constructed sites or where poor documentation practices have been followed and a turnover of personnel has occurred. In these cases, the maintenance cost at a particular site may be the only information that reflects the rockfall activity at that site. This information is an important check on the potential for future rockfalls. If the score you give a section does not compare with the rockfall history, a review should be performed. As a better database of rockfall occurrences is developed, more accurate conclusions for the rockfall potential can be made.

3 points	<i>Few Falls</i> - Rockfalls have occurred several times according to historical information but it is not a persistent problem. If rockfall only occurs a few times a year or less, or only during severe storms this category should be used. This category is also used if no rockfall history data is available.
9 points	<i>Occasional Falls</i> - Rockfall occurs regularly. Rockfall can be expected several times per year and during most storms.

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27 points	<i>Many Falls</i> - Typically rockfall occurs frequently during a certain season, such as the winter or spring wet period, or the winter freeze-thaw, etc. This category is for sites where frequent rockfalls occur during a certain season and is not a significant problem during the rest of the year. This category may also be used where severe rockfall events have occurred.
81 points	<i>Constant Falls</i> - Rockfalls occur frequently throughout the year. This category is also for sites where severe rockfall events are common.

In addition to scoring the above categories, the rating team should gather enough field information to recommend which rockfall remedial measure is best suited to the rockfall problem. Both total fixes and hazard reduction approaches should be considered. A preliminary cost estimate should be prepared.

Risk analysis of rockfalls on highways

The analysis of the risk of damage to vehicles or the death of vehicle occupants as a result of rockfalls on highways has not received very extensive coverage in the geotechnical literature. Papers which deal directly with the probability of a slope failure event and the resulting death, injury or damage have been published by Hunt (1984), Fell (1994), Morgan (1991), Morgan et al (1992) and Varnes (1984). Most of these papers deal with landslides rather than with rockfalls. An excellent study of risk analysis applied to rockfalls on highways is contained in an MSc thesis by Christopher M. Bunce (1994), submitted to the Department of Civil Engineering at the University of Alberta. This thesis reviews risk assessment methodology and then applies this methodology to a specific case in which a rockfall killed a passenger and injured the driver of a vehicle.

RHRS rating for Argillite Cut

Bunce carried out a study using the Rockfall Hazard Rating System for the Argillite Cut in which the rockfall occurred. A summary of his ratings for the section in which the rockfall happened and for the entire cut is presented in Table 2. The ratings which he obtained were 394 for the rockfall section and 493 for the entire cut. Note that this highway has been upgraded and the Argillite Cut no longer exists. However, Bunce's work still provides a good case history for the application of the Rockfall Hazard Rating System.

The RHRS system does not include recommendations on actions to be taken for different ratings. This is because decisions on remedial action for a specific slope depend upon many factors such as the budget allocation for highway work which cannot be taken into account in the ratings. However, in personal discussions with Mr Lawrence Pierson, the principal author of the RHRS, I was informed that in the State of Oregon, slopes with a rating of

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less than 300 are assigned a very low priority while slopes with a rating in excess of 500 are identified for urgent remedial action.



Figure 11: The Argillite Cut on Highway 99 in British Columbia, Canada.

Risk analysis for Argillite Cut

Bunce (1994) presented a number of approaches for the estimation of the annual probability of a fatality occurring as a result of a rockfall in the Argillite Cut. Some of these approaches are relatively sophisticated and I have to question whether this level of sophistication is consistent with the quality of the input information which is available on highway projects.

Table 2: RHRS ratings for Argillite Cut on Highway 99 in British Columbia (after Bunce, 1994).

Parameter	Section where rockfall occurred		Rating for entire cut	
	Value	Rating	Value	Rating
Slope height	36	100	35	100
Ditch effectiveness	Limited	27	Limited	27
Average vehicle risk	7	1	225	100
Sight distance	42	73	42	73
Roadway width	9.5	17	9.5	17
Geological structure	Very adverse	81	Adverse	60
Rock friction	Planar	27	Planar	27
Block size	0.3 m	3	1 m	35
Climate and water	High precip.	27	High precip.	27
Rockfall history	Many falls	40	Many falls	27
Total score		394		493

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One approach which I consider to be compatible with the rockfall problem and with quality of input information available is the event tree analysis. This technique is best explained by means of the practical example of the analysis for the Argillite Cut, shown in Figure 12. I have modified the event tree presented by Bunce (1994) to make it simpler to follow.

In the event tree analysis, a probability of occurrence is assigned to each event in a sequence which could lead to a rockfall fatality. For example, in Figure 12; it is assumed that it rains 33% of the time, that rockfalls occur on 5% of rainy days, that vehicles are impacted by 2% of these rockfalls, that 50% of these impacts are significant, i.e. they would result in at least one fatality. Hence, the annual probability of fatality resulting from a vehicle being hit by a rockfall triggered by rain is given by $(0.333 * 0.05 * 0.02 * 0.5) = 1.67 * 10^{-4}$.

The event tree has been extended to consider the annual probability of occurrence of one, two and three or more fatalities in a single accident. These probabilities are shown in the final column of Figure 12. Since there would be at least one fatality in any of these accidents, the total probability of occurrence of a single fatality is $(8.33 + 5.56 + 2.78) * 10^{-5} = 1.7 * 10^{-4}$, as calculated above. The total probability of at least two fatalities is $(5.56 + 2.78) * 10^{-5} = 8.34 * 10^{-5}$ while the probability of three or more fatalities remains at $2.78 * 10^{-5}$ as shown in Figure 12.

Initiating event (annual)	Rockfall	Vehicle beneath failure	Impact significant	Annual probability of occurrence	Potential number of fatalities	Annual probability of occurrence
rain 33%	no 95%	————— 0.317			nil	
		yes 5%	————— 1.63*10 ⁻²			nil
	no 98%		————— 1.67*10 ⁻⁴			nil
		yes 2%	no 50%	————— 1.67*10 ⁻⁴		
	yes 50%			————— 1.67*10 ⁻⁴		
					two 33% ——— 5.56*10 ⁻⁵	
					3 or more 17% ——— 2.78*10 ⁻⁵	
Annual probability of a single fatality				= (8.33+ 5.56 + 2.78) * 10 ⁻⁵		= 1.67 * 10 ⁻⁴
Annual probability of two fatalities				= (5.56+ 2.78) * 10 ⁻⁵		= 8.34 * 10 ⁻⁵
Annual probability of three or more fatalities				= 2.78 * 10 ⁻⁵		= 2.78 * 10 ⁻⁵

Figure 12: Event tree analysis of rockfalls in the Argillite Cut in British Columbia.

Suppose that it is required to carry out construction work on the slopes of a cut and that it is required to maintain traffic flow during this construction. It is assumed that the

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construction work lasts for 6 months (50% of a year) and that rockfalls are initiated 20% of the working time, i.e. on 36 days. Using the Argillite cut as an example, all other factors in the event tree remain the same as those assumed in Figure 12. The results of this analysis are presented in Figure 13 which shows that there is an almost ten fold increase in the risk of fatalities from rockfalls as a result of the ongoing construction activities.

Initiating event (annual)	Rockfall	Vehicle beneath failure	Impact significant	Annual probability of occurrence	Potential number of fatalities	Annual probability of occurrence	
construction 50%	no 80%			0.40	nil		
	yes 20%	No 98%		9.80*10 ⁻²	nil		
		Yes 2%	no 50%	1.00*10 ⁻³	nil		
			yes 50%	1.00*10 ⁻³	one 50%	5.00*10 ⁻⁴	
				two 33%	3.30*10 ⁻⁴		
				3 or more 17%	1.70*10 ⁻⁴		
	Annual probability of a single fatality				= (5.00+3.30+1.70) * 10 ⁻⁴		= 1.00 * 10 ⁻³
	Annual probability of two fatalities				= (3.30+1.70) * 10 ⁻⁴		= 5.00 * 10 ⁻⁴
	Annual probability of three or more fatalities				= 1.70 * 10 ⁻⁴		= 1.70 * 10 ⁻⁴

Figure 13: Event tree for a hypothetical example in which construction activities on the Argillite Cut are carried out for a period of six months while the highway is kept open.

Comparison between assessed risk and acceptable risk

The estimated annual probabilities of fatalities from rockfalls, discussed in the previous sections, have little meaning unless they are compared with acceptable risk guidelines used on other major civil engineering construction projects.

One of the earliest attempts to develop an acceptable risk criterion was published by Whitman (1984). This paper was very speculative and was published in order to provide a basis for discussion on this important topic. In the time since this paper was published a great deal of work has been done to refine the concepts of acceptable risk and there are now more reliable acceptability criteria than those suggested by Whitman.

Figure 14, based on a graph published by Nielsen, Hartford and MacDonald (1994), summarises published and proposed guidelines for tolerable risk. The line marked 'Proposed BC Hydro Societal Risk' is particularly interesting since this defines an annual

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probability of occurrence of fatalities due to dam failures as 0.001 lives per year or 1 fatality per 1000 years. A great deal of effort has gone into defining this line and I consider it to be directly applicable to rock slopes on highways which, like dams, must be classed as major civil engineering structures for which the risks to the public must be reduced to acceptable levels.

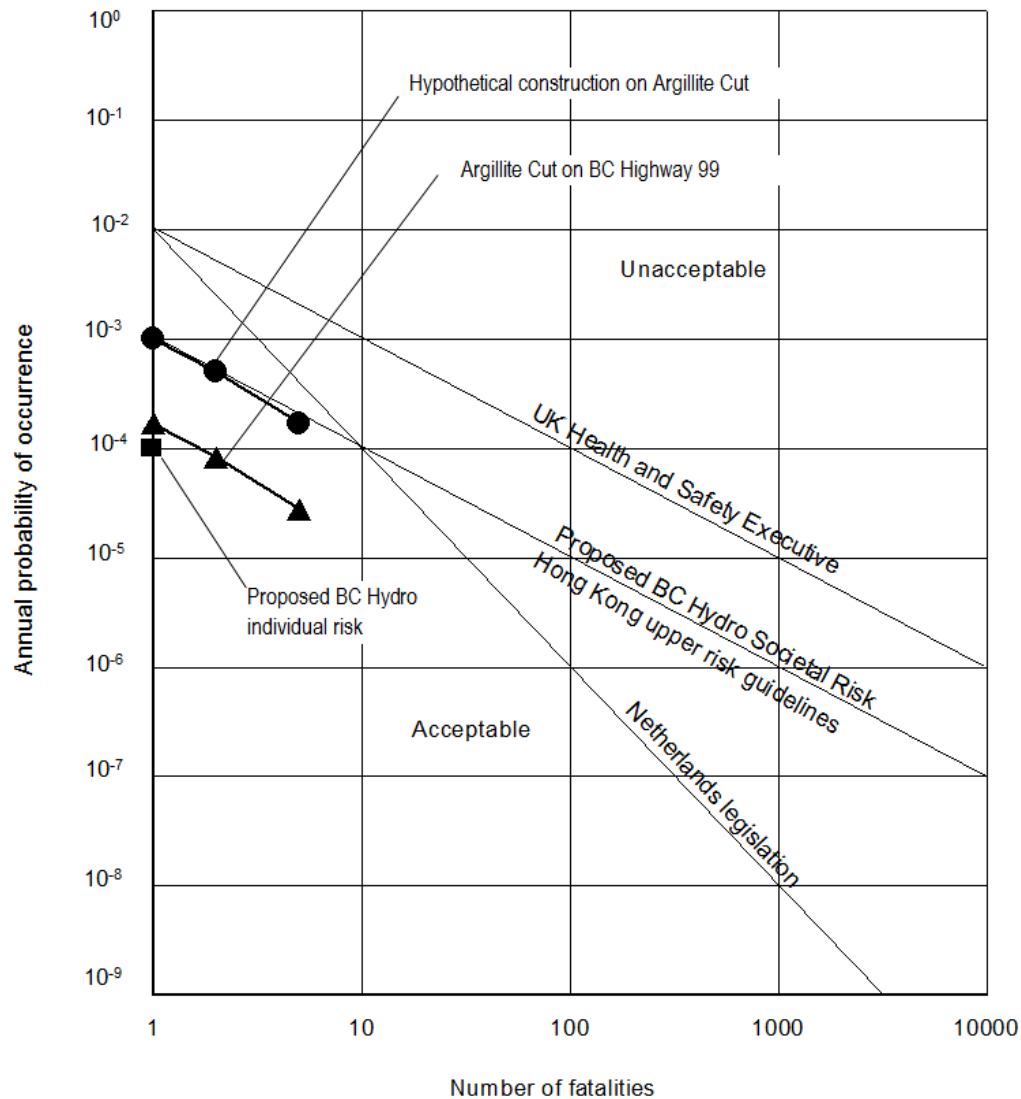


Figure 14: Comparison between risks of fatalities due to rockfalls with published and proposed acceptable risk criteria.

Another point to be noted in Figure 14 is that marked 'Proposed BC Hydro Individual risk'. This annual probability of fatalities of 10^{-4} (1 in 10,000) is based upon the concept that the risk to an individual from a dam failure should not exceed the individual 'natural death' risk run by the safest population group (10 to 14 year old children). Consensus is also developing that the annual probability of fatality of 10^{-4} defines the boundary between voluntary (restricted access to site personnel) and involuntary (general public access) risk (Nielsen, Hartford and MacDonald, 1994).

On Figure 14, I have plotted the estimated annual probabilities of fatalities from rockfalls on the Argillite Cut on BC Highway 99, with and without construction. These plots show that the estimated risk for these slopes, without construction, is significantly lower than the 0.001 lives per year line. The estimated risk for the Argillite Cut slopes during active construction is approximately ten times higher and is marginally higher than the 0.001 lives per year criterion. Given the fact that courts tend to be unsympathetic to engineers who knowingly put the public at risk, it would be unwise to proceed with construction while attempting to keep the traffic flowing. A more prudent course of action would be to close the highway during periods of active construction on the slopes, even if this meant having to deal with the anger of frustrated motorists.

Conclusions

The Rockfall Hazard Rating System and the Event Tree risk assessments, discussed on the previous pages, are very crude tools which can only be regarded as semi-quantitative. However, the trends indicated by these tools together with common sense engineering judgement, give a reasonable assessment of the relative hazards due to rockfalls from cut slopes adjacent to highways and railways.

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