A SYSTEM OF ROCK FALL AND ROCK SLIDE HAZARD RATING FOR A RAILWAY

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Abstract

A new rock fall hazard rating system is proposed for use along a railway line. The system is oriented towards use in connection with a Quantitative Risk Assessment (QRA) procedure, although its present form concentrates on hazard assessment only. The methodology is based on a dual approach: Small-scale "random" rock fall is assessed based on an empirical correlation between observed frequency of occurrence and a predictive index using rock mass quality classification (modified Barton's Q). An independent assessment of larger-scale, structurally controlled rock failure is based on a subjective, deterministic approach. The entire process results in a searchable database of parameters and indices predicting a range of magnitudes and probabilities relevant to both groups of failures.

Résumé

On propose un nouveau système d'estimation de risque de chute de roche pour usage suivant une ligne ferroviaire. Le système est orienté vers l'utilisation en liaison avec un procédé quantitatif de l'évaluation des risques (QRA). Sa forme actuelle se concentre sur l'évaluation des dangers uniquement, alors que des considérations de risque quantitatif doivent être ajoutées à l'avenir. La méthodologie est basée sur une approche duelle: La chute "aléatoire" de petite taille de roche est évaluée sur une base d'une corrélation empirique entre la fréquence observée de l'occurrence et d'un index prédictif en utilisant la classification modifié de qualité de roche (Barton Q). Une évaluation indépendante de grand échec structurellement controllé est basée sur une approche subjective et déterministe. Le processus entier résulte dans une base de données rechercheable des paramètres et des index prévoyant une gamme des grandeurs et des probabilités concernant les deux groupes d'échecs.

1. INTRODUCTION

Canadian Pacific Railway (CPR) manages rock slopes over more than 2 100 km of track in British Columbia, Alberta, Northern Ontario and the state of New York, incorporating over 1500 rock slopes. A new rating system for rock fall and rock slide hazards along this track system has been developed.

The premise of the new method is that the wide range of rock slope failure magnitudes can be divided into two independent classes: Small-scale "random rock fall" occurs on every slope and is best characterized by an empiracally based correlation against index properties of the slope and the rock mass. Individual detachments have volumes up to approximately 10 m^3. Larger scale failures, on the other hand, always have a definable structurally controlled mechanism. "Structurally controlled" rock slides (or falls or topples) therefore occur on those slopes where unfavourable structure exists. They tend to be larger in magnitude and less frequent than random rock fall and are best characterized by a deterministic analysis or a judgmental assessment. The two types of hazard are handled separately by the proposed hazard rating system.

2. REVIEW OF PREVIOUS WORK

The main purpose of rock fall hazard rating systems for transportation routes is to provide means of prioritizing the relative risks along the length of the corridor in order to properly allocate mitigation resources. (e.g. Wyllie, 1987, Pierson et al., 1990, Abbott et al., 1998). A number of existing systems were reviewed from Canada, the United States, and Europe.

Few systems characterize hazard and risk independently. Furthermore, few take the approach of characterizing the geomechanical properties of the rock mass using an accepted method of rock mechanics classification such as Q (Barton et al., 1974). None of the systems take the approach of considering small volume, random failures by means of objective correlation to an historical database separately from large, structurally controlled rock fall.

3. GENERAL APPROACH

The proposed rating method follows two parallel paths. The "random rock fall" assessment step uses a modified rock mass classification scheme (Barton's Q-method), together with scales to characterize the slope, its overburden, climate and activity signs. The data is compiled into a rating index, showing a correlation against actual frequency of occurrence of random rock fall, as derived from the CPR database. Thus, this part of the assessment utilizes an objective means of probability determination, based on a bi-variate correlation.

The "structurally controlled failure" is assessed, where appropriate, by collecting key data on rock structure and properties, estimating potential detachment volumes and providing a subjective assessment of the probability of failure. The assessment is supported by collecting sufficient data to permit the conduct of simple deterministic slope stability calculations. However, the final estimate of failure probability remains subjective and is therefore based largely on informed judgment and experience of the inspector.

4. STUDY AREA

The study area includes sites from across British Columbia with the majority located in the Fraser Canyon between Hope and Kamloops. Other areas where rock slopes were investigated are adjacent to Kootenay Lake, the Crowsnest Pass, Mt. Stephen, and along the Kicking Horse and the Beaver River. The sites thus represent a wide range of physiography and geology.

5. CPR ROCK FALL DATABASE

Since 1976, CPR information on rock fall incidents, mitigative measure, inspections, and priority ratings has been collected bi-annually and recorded in a comprehensive database with over 2000 records. The rock fall database is categorized by subdivision and site mile.

6. GEOMETRICAL REFERENCE FRAMEWORK

In this study, rock slopes are subdivided into linear segments along which the slope geometry, geology, rock characteristics, failure mode, and degree of existing mitigation are approximately constant. Where required, vertical "levels" or bands are defined at various elevations above the track, using the same criteria

7. FIELD FORM

In order to achieve repeatability, the data collection procedure for the hazard index and discontinuity surveys use standard forms that are completed in the field with the support of a Users' Manual. A sample of the two page field form is shown as Figure 1.

Three types of record categories are contained in the form: Type A are quantitative rating parameters used to derive indices. Type B are the indices themselves, derived by combining one or several Type A categories through prescribed algorithms. Type C are supplementary parameters, quantitative or descriptive, collected primarily for reference, or for potential future use of the database as a repository of information. Most of the records are entered in a searchable database format.

8 RANDOM ROCK FALL HAZARD

8.1 Rock mass characterization (Section 3 of the field form)

Except in very weak rock, the stability of a rock slope is usually dependent upon the characteristics and properties of the discontinuities. Consequently, the classification of the rock mass quality follows the Rock Mass Quality Index (Q) established by Barton et al. (1974) which quantitatively describes six discontinuity characteristics of the rock mass. Because the system was developed for the design of tunnel support in mining, modification of the stress reduction factor, SRF, was required to apply the system to cut and natural slopes.

SRF, as defined by Barton et al., is a measure of potential overstress and of the tendency of zones of weakness to loosen the surrounding rock mass once excavation has taken place. In the development of a rock fall hazard rating system for CPR, the SRF has been modified to account for weakness zones intersecting the rock slope or for rock mass degradation due to mechanical disturbance (for example blast damage). To avoid confusion, we have renamed this factor the "face looseness" or FL. In some cases, the FL has been adapted from the RHRON (Franklin Geotechnical Ltd., 1997) and the work of Harp and Noble (1993). The "FL" is thus defined as shown in Table 1.

Table 1. Definition of the face looseness factor, FL

Definition	FL
Consider either: Loosening due to intersecting weakness zones	
Very tight rock structure, no visible weak or sheared zones.	1
Single shear zones in competent rock (clay free).	2.5
Single weakness zones containing clay, or chemically disintegrated rock	5
Multiple shear zones in competent rock (clay free), loose surrounding rock.	7.5
Multiple occurrences of weakness zones containing clay or chemically disintegrated rock, very loose surrounding rock.	10
Or: Loosening due to mechanical degradation (blasting or natural loosening)	
Most joints tight. Can only be chipped by machine. Typical apertures 0-1mm	1
Most joints tight, a few loose, open as much as 5mm	2.5
Moderately loose, some joints open as much as 2 cm. Readily scaled by machine	5
Significant disturbance, many open joints, as much as 20cm and crushed zones	7.5
Heavily jointed rock mass, many open joints, and loose blocks Easily scaled by hand	10

Figure 1. CPR Rockfall Hazard Rating sample data sheet.

CP RAIL ROCK FALL HAZARD RATING FIELD FORM

1.1 Subdivision ☐ Site Mile ☐ Photographs Roll ☐ Photos ☐

Inspector ☐ Date ☐ Weather ☐

1.2 Location ☐

1.5 Number of rockfall events reported ☐

1.3 NTS coordinates ☐

1.6 Date of last rock fall reported ☐

1.4 Level: ☐ of ☐ Height: ☐ To ☐ m

1.7 Maximum Magnitude ☐

1.8 Slope Type ☐

1.9 Type of inspection ☐

1.10 Mean annual precipitation ☐

1.11 Sketch view (indicate height scale, reference points, east/west)

1.12 Mitigation Measures

Ditch Dimensions:

Width (m) ☐ Depth (m) ☐ % Fill ☐

Ditch effectiveness ☐

Stabilization methods		Year
Scaling	☐	
Trim blasting	☐	
Dowels	☐	
Bolts	☐	
Anchors	☐	
Drainage	☐	
Shotcrete	☐	
Buttress	☐	
Other		

Protection methods		Year
Lock block barrier	☐	
Berm	☐	
Rock fall fence	☐	
Draped mesh	☐	
Rock shed	☐	
Tunnel	☐	
Slide fence	☐	
Other		

Stabilization rating ☐

1.13 State of Activity

	Recent	Old
Tension cracks	☐	☐
Open joints	☐	☐
Detachment scars	☐	☐
Dilated zones	☐	☐
Crushed zones	☐	☐
Buckles or pressure ridges	☐	☐
Toe bulging	☐	☐
Distorted or damaged vegetation	☐	☐
Rocks at toe of slope	☐	☐
Other	☐	☐

Rock fall reported within previous year? ☐

Change from previous inspection? ☐

Evidence of recent activity ☐

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Figure 1 cont'd. CPR Rockfall Hazard Rating sample data sheet.

CP RAIL ROCK FALL HAZARD RATING FIELD FORM

2.1 Vegetation and overburden

Vegetation cover
Overburden type
% Cover:
Max. thickness (m)

Overburden stability index

2.2 Slope geometry

Segment length (m)
Rock face azimuth
Slope height (m)
Slope angle (degrees)
Slope roughness

2.3 Rockmass characterization

Geologic Description

	Modal	Low	High
Rock strength			
Weathering class			
Groundwater			

	Modal	Low	High
Block size (m)			
Persistence (m)			

SMALL SCALE, RANDOM ROCK FALL

RQD
Joint set number, Jn
Joint roughness, Jr
Joint alteration, Ja

Joint water reduction factor, Jw
Face looseness, FL
3.1 Q (RQD/Jn*Jr/Ja*Jw/FL)
3.2 Random rockfall hazard index, RRHI ($\log Q_{rf}/P_a$)

LARGE SCALE, STRUCTURALLY CONTROLLED ROCK FALL

4.1 Mechanism of failure

Description of failure mechanism

4.2 Description of dominant discontinuities

	Dominant discontinuity			Discontinuity Set 2			Discontinuity Set 3		
	Modal	Min	Max	Modal	Min	Max	Modal	Min	Max
Dip									
Dip direction									
Spacing									
Persistence									
Roughness, Jr									
Alteration, Ja									

SUMMARY RATING

	Mechanism	Magnitude (m^3)		Prob. occurrence	Prob. delivery	
		Modal	Maximum		Modal	Maximum
Small scale, random						
Stucturally controlled						

Additional comments

The numerical value of the modifed index Q_{rf} is thus determined by Eq.1.

$$Q_{rf} = \frac{RQD}{J_n} \frac{J_r}{J_a} \frac{J_w}{FL} \quad [1]$$

8.2 Probability of occurrence, random rock fall

In case of random rock fall, the probability of occurrence is equated to the frequency occurrence, estimated on the basis of historical records. Several correlations were tested between parameters recorded in the field form and CPR's historical rock fall database. The number of rock falls at each location was first normalized by the length and height of each segment, essentially obtaining specific rock fall frequency per unit (1 000 m^2) slope area per 26 year period of record (1975 to 2001).

In testing empirical relationships, only rock falls of a magnitude less than 10 m^3 were considered in order to represent small scale, random rock fall.

The first correlation investigated was Q_{rf} vs. specific frequency. In their study of seismic rock fall susceptibility Harp and Noble (1993) found the number of rock falls per site decreasing rapidly with increasing Q_{rf}, with a well defined upper bound. In the present case, the correlation was weak and contained a large amount of scatter. Those slopes having the lowest values of Q_{rf}, less than 1, do not have a correspondingly high rock fall frequency. This may be explained by a bias in reporting in that those slopes having low quality presumably also produce a large number of very low magnitude failures ($<0.1m^3$) but these failures probably are contained by a ditch and/or are not reported.

Several climatic conditions contribute to the frequency of rock fall, though the most significant area precipitation and frequent freeze-thaw cycles (Peckover, 1975). As it is difficult to quantify the contribution of each of these parameters, only the mean annual precipitation was investigated (Farley, 1979). Analysis of specific frequency versus mean annual precipitation (P_a) shows the number of rock fall at a site to increase with precipitation, although again, this correlation suffers from weak trend and large scatter.

After several additional experiments, involving parameters such as intact rock strength, slope roughness and FL, the ratio of Q_{rf} and P_a , called the Random Rock fall Hazard Index, RRHI, was found to provide the best correlation with the probability of occurrence.

$$RRHI = \frac{Q_{rf}}{P_a} \quad [2]$$

Analysis of specific frequency and log RRHI defines a linear upper bound envelope as shown in Figure 2. It suggests a limit of rock fall activity of no more than 1 rock fall per 1000 m^2 of rock face (per 26 years) for a value of RRHI exceeding 0.022.

Thus, an estimate of the specific frequency of a random rock fall event can be derived from Figure 2. The first step is to estimate the number of rock falls per 1000 m^2 from the figure. Then, by multiplying this value by the length and height of the segment, the probability is selected from one of five categories, as shown in Table 2.

Figure 2.

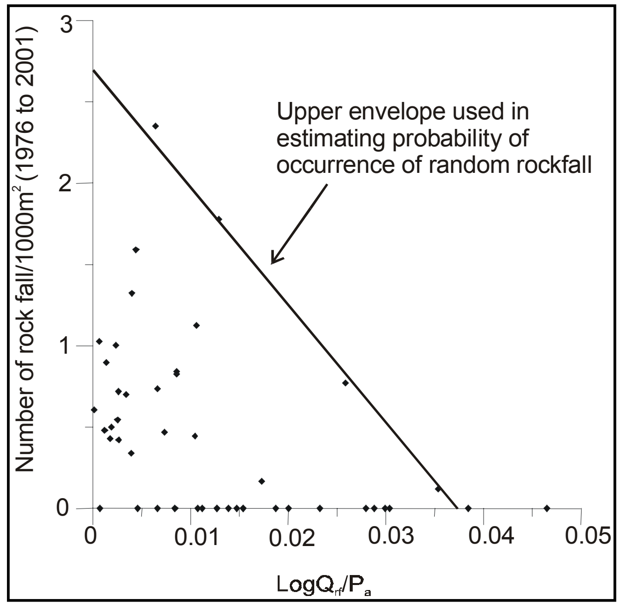

Table 2. Probability Ratings

No. of rock falls	Rating
>13	Very high
6-13	High
2-5	Moderate
0-1	Low

Note: The values in this table are based on a 26 year period of record (1975 to 2001)

The next step is to modify the probability assignment according to the stabilization rating, the state of activity, and the overburden stability index as follows:

Stabilization rating is a subjective measure of the effectiveness of existing stabilization measures (rock bolts, mesh etc.) as shown in Table 3. If the rating is "adequate", the probability of occurrence is decreased by 2 classes. If the rating is "partial", the probability is decreased by 1 class. If the stabilization rating is "none or negligible", the probability classification is not modified. Similar modification is carried out on the basis of the evidence of recent activity (Table 4).

Table 3. Stabilization Rating

Definition	Rating
Stabilization measures have not been implemented.	None
Very little stablilzation measures have been implemented or are deemed ineffective.	Negligible
Some stabilization measures have been undertaken but more is required.	Partial
Methods have been implemented to current standards to actively inhibit detachment	Adequate

Table 4. Evidence of Recent Activity

Definition	Rating
No evidence of recent activity	None
Evidence of recent activity. Limited or no evidence of old activity. Recent activity does not appear to indicate continuing instability	Moderate
Evidence of recent and old activity. Rock fall reported within previous year or change noted from previous inspection. Recent activity indicates continuing instability.	Considerable

The overburden stability index estimates the probability of rock fall originating from coarse overburden (soil) mantling or bordering parts of the rock slope (Table 5). It is independent of the probability derived from the rock slope characteristics. Therefore, its value does not modify the rock fall probability rating, but places limits upon it. If the overburden stability index is "stable", no modification to the probability classification is required. If the overburden stability index is "unstable" the probability class for the sector must be high or greater. If the overburden stability index is "very unstable", the probability class must be high or very high.

Table 5. Overburden Stability Index

Definition	Rating
Frequent ravelling over extensive areas. Precarious positioning of large boulders. Overburden is a major source of rock fall.	Very unstable
Overburden is a source of rock fall but moderate in terms of stability and extent.	Unstable
Overburden is either not present or not considered a significant potential source of rock fall.	Stable

9 STRUCTURALLY CONTROLLED ROCK FALL

9.1 Characterization of the structurally controlled rock failure (Section 3 of the field form).

A deterministic approach is taken where a potential for large-scale, structurally controlled detachment is recognized. For these larger detachments, it is possible to determine the specific mechanism of failure, to analyze its geometry and stability, to make a direct estimate of its size and probability of occurrence.

In order to provide the data for a deterministic assessment, careful mapping of dominant discontinuity sets is completed. Structurally controlled failures are described by the characteristics of the dominant discontinuity sets such as joint sets, bedding planes and surfaces of schistosity and cleavage, or a major individual discontinuity such as a fault or shear. The dominant discontinuity, or set, is the one that appears to control the mechanism of failure.

All data in this section is of Type C, as there is no defined means to combine it into a stability index. Instead, magnitude (volume) and probability of occurrence of such failures are to be estimated by the inspector based on judgement, possibly supported by a simple deterministic analysis.

9.2 Probability of structurally controlled failure

It is not considered feasible to provide an objective estimate of the probability of structurally controlled failure. Therefore, the probability of this type of failure is a subjective estimate made by the inspector after having considered all of the data and indexes completed in the field form such as climate, site history, mitigation rating, evidence of recent activity, rock type etc. The estimated probability is that related to the most likely failure magnitude. The estimate is selected from one of the five categories listed in the second column of Table 3. Although the estimation of frequency of potential rock fall is subjective, the inspector visually inspecting the rock slope is in the best position to make this judgment.

Probability of rock delivery is an estimate, ranging from 0 to 100%, of the likelihood that the detached rock mass will land on the track. It can be a subjective estimate, based on the slope geometry, natural barriers, magnitude of the potential rock fall, and the effectiveness of the protection methods, or it may be an estimate based on rock fall dynamics analysis. It is important to note that the effectiveness of protection methods varies with the magnitude of the rock fall. This is most evident with rock fall catchment nets but affects almost all mitigation methods. Therefore, a separate estimate of $P_{delivery}$ is required for both random and structurally controlled failures.

10. CONCLUSION

This system provides a method of characterizing rock fall hazard adjacent to CPR's track, independent of the associated consequence and risk. The method used to derive the probability of rock fall depends on the scale of the potential hazard, with random, small-scale hazard assessed independently of large-scale, structurally controlled failure. The probability of occurrence of random failure is estimated by means of empirical correlation with the rock mass quality and mean annual precipitation, modified by the effectiveness of remedial measures and the contribution from ravelling overburden. The probability of large-scale failure remains the subjective judgment of an experienced engineer or geoscientist once the failure mechanism and characteristics of the controlling discontinuities have been identified.

For both random and structurally controlled failure, the summary table provides an assessment of the failure mechanism, magnitude, probability of occurrence and probability of the detached rock reaching the track. It is anticipated that this information will subsequently be combined with the consequence of failure to determine risk.

Further refinement and testing of this system should be in the context of full scale operational use in order to benefit from the knowledge of multiple users and to compile a comprehensive range of data for each parameter. A method of quantifying the effect of freeze/thaw cycles may also be considered. Ultimately, consideration of consequence should be combined with the summary hazard rating in order to derive a rock fall risk assessment used to prioritize mitigative measures.

11. REFERENCES

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