RISK MANAGEMENT OF ROCK FALL HAZARDS

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ABSTRACT

In mountainous terrain, especially in wet, cold climates with seismic activity, many transportation systems and some urban and industrial facilities are subject to rock fall hazards. Limiting damage and injury from rock falls requires a long-term, risk management plan involving the following tasks. First, the sources of rock falls are identified, and an inventory of hazardous sites is prepared. Second, statistical or subjective methods are used to estimate the frequency of events. Third, a remedial plan is drawn up for the high risk sites to suit the available budget. Fourth, decision analysis can be used to determine the appropriate stabilization measure for the site. Fifth, designs and specifications are prepared for the planned work that are consistent with the required reduction in risk level.

Risk management programs are usually on-going where there are a large number of unstable slopes, and where progressive weathering of the rock results in deteriorating stability with time.

RÉSUMÉ

En terrain montagneux, tout particulièrement dans les climats humides et froids de zones à activité sismique, plusieurs systèmes de transport et installations urbaines et industrielles courent le risque de subir des éboulis. Afin de limiter les dommages et les blessures que les éboulis entraînent, il faut établir un plan de gestion des risques comprenant les travaux suivants. Premièrement, on procède au relevé des sources d'éboulis et on prépare un inventaire des sites dangereux. Deuxièmement, la fréquence des éboulis est estimée au moyen de méthodes statistiques ou subjectives. Troisièmement, on établit un plan correcteur qui vise les sites à risque élevé et respecte les limites budgétaires. Quatrièmement, pour déterminer la mesure de stabilisation appropriée à un site donné, on peut effectuer une analyse décisionnelle. Cinquièmement, on prépare les spécifications de conception des travaux prévus qui correspondent au niveau de réduction de risque nécessaire.

Dans les régions qui comportent de nombreuses pentes instables et où le vieillissement climatique progressif des roches entraîne une détérioration de la stabilité au fil du temps, les programmes de gestion des risques sont habituellement permanents.

1. INTRODUCTION

In mountainous terrain, especially in wet, cold climates with seismic activity, many transportation systems and some urban and industrial facilities are subject to rock fall hazards. The consequences of these events can be serious resulting in damage to vehicles and structures, injury and death, as well as delays to traffic; Figure 1 shows a rock fall event that closed a highway for several days while the fall was removed and source area on the slope was stabilized. Limiting the consequences of rock falls is generally considered to be economically worthwhile. In addition, in many jurisdictions a mitigation program provides some defence against legal cases brought against the highway authority by persons injured in rock fall events. However, it is necessary to balance the cost of rock slope stabilization and protection programs with the cost of the rock fall events and other highway improvements such as re-alignments of hazardous curves. In addition, on public facilities, governments have to evaluate the benefits of rock fall mitigation against many other public protection programs such as policing and fire fighting. A rock fall mitigation programme is essentially a risk management plan that may continue for several decades or be on-going. The programme will involve preparation of a detailed inventory of rock fall hazards and risks from which the highest priority sites are identified for stabilization. Finally, the remedial work that is most appropriate for the site conditions is selected.

2. DEFINITION OF RISK AND HAZARD

In order to evaluate the consequences of rock falls and the benefits of mitigation, it is necessary to clearly distinguish between hazard and risk as discussed below. Figures 2 and 3 illustrate respectively the topographic conditions that define hazard and risk for a cut slope above a highway, and a natural rock face and talus slope above a residential development.

2.1 Hazard

A rock fall hazard is a combination of a source, a triggering event, and a pathway from the source to the at-risk object.

The **source** may be an excavated face or a natural slope, and is defined by the topography and geology of the site. With respect to the topography, the slope angle must be steeper than the angle of repose (about 37 degrees) in order to generate rock falls, and the higher the slope the greater the surface area and the greater the velocity that rock falls can attain. The geological factors that directly influence rock fall hazards are the characteristics of the discontinuities, with the spacing defining the size of rock falls, and orientation defining the likelihood of blocks sliding or toppling from the face. The rock strength is also an important issue since blocks of strong rock remain intact as they roll and bounce down the slope (Figure 2), while seams of weak rock can weather rapidly to create potentially unstable cavities and overhangs (Figure 3). Another factor to consider is possible blast damage to the rock that can produce displaced and fractured blocks on the face.

A rock fall will result from a **triggering event**, often related to the climate or seismicity. Records of rock fall events clearly show that rock fall frequency is strongly correlated with rainfall and freezing temperatures because water and ice pressures acting in cracks loosen and displace blocks of rock (McCauley *et al*. 1985; Peckover, 1975). A related cause of falls in wet climates is the growth of tree roots in cracks in the rock. Another important triggering mechanism in seismic areas is strong ground motions, with records showing thousands of rock falls and landslides occurring for example, during the 1995 Northridge earthquake near Los Angeles (Jibson and Harp, 1995; Harp and Noble, 1993). In addition, Harp and Noble (1993) have established geometric and geologic conditions that result in slopes being susceptible to rock falls during earthquakes.

The ground surface between the source and the at-risk object is the **pathway**, which may include portions of rock face, talus slopes, ditches and developed areas such as roads as shown in Figure 2 and 3. The distance that rock falls may travel along a pathway depends on such factors as the size of the block, the inclination of the slope and the composition and irregularity of the surface, i.e., talus, soft soil or hard pavement. Computer modelling can assist in determining that distance that falls travel from the source area.

2.2 Risk

Any object that is on the pathway of a potential rock fall, is at-risk to damage. For example, in Figure 2a) where the ditch is shallow and with a rounded base, rock falls may roll through the ditch and on to the road where there is a risk that they could damage vehicles. The risk to vehicles increases with increasing traffic frequency and speed, and if there is a high consequence in the event of an accident such as a steep slope below the road.

In Figure 3a), a house located at the toe of the talus slope is at-risk from damage by rocks that roll past the toe of the talus into the “rock fall shadow”. The “shadow” is defined by a line at an angle of about 26 degrees below the horizontal from the crest of the talus slope to intersect the ground surface beyond the talus. The risk would be increased if the house were on the talus where more rocks fall.

Figures 2b) and 3b) show how the risk can be diminished or eliminated when the at-risk object is outside the pathway. In Figure 2b), excavation of the ditch and installation of a barrier to contain falls limits the pathway to the ditch, and reduces the risk of falls reaching the road. In Figure 3b), the house is moved downslope beyond the “shadow” zone and outside the pathway.

3. INVENTORY OF ROCK FALL HAZARDS AND RISKS

For transportation routes with a large number of rock slopes, a first step in assessing the hazards and risks is to prepare an inventory of conditions. Preferably, the inventory would describe the physical characteristics of each slope to define the hazard, as well as the pathway and traffic conditions that define the risk. A well known inventory method, known as the Rockfall Hazard Rating System (Wyllie, 1987; Pierson *et. al*., 1990) assigns scores ranging from 3 points to 81 points to each of the following site parameters:

1. Slope height;
2. Ditch effectiveness;
3. Average vehicle risk;
4. Site distance;
5. Roadway width;
6. Structural geology;
7. Rock shear strength;
8. Block size;
9. Climate;
10. Rock fall history.

Each site parameter is assigned a score according to the arithmetic range of 3, 9, 27 or 81, and the sum of the scores is the hazard rating of the site. This information can then be used rank a large number of rock slopes to identify the most hazardous locations, which can then be used to prioritize stabilization programs.

Examination of the ten parameters that make up the slope rating shows that they are a combination of hazard and risk factors. That is, parameters 1, 6, 7, 8, 9 and 10 are hazards related to the slope condition, while parameters 2, 3, 4 and 5 are risk factors related to the rock fall pathway and traffic conditions. Since hazard and risk factors and essentially independent, a modification to the rating system would be to score the hazards and risks separately, and then take the product of the two. The following example illustrates how the product of the hazard and risk scores clearly distinguishes low and high risk slopes:

Hazard rating for a high slope with adverse geology, (27+3+81+81+27+81) = 300;

Risk rating for low volume road with a good ditch and good sight lines, (3+3+3+3) = 12

Total rating (product), (300 x 12) = 3600.

For the same slope, if the ditch and roadway widths were reduced and the traffic increased, then the **risk rating** would be (27+27+9+9) = 72.

Total rating, (300 x 72) = 21,600.

The total ratings for the two conditions differ by a factor of 6 (21600/3600). In comparison, for the present system where the scores are summed, the corresponding total scores are 312 and 372, which does not distinguish as clearly between low and high risk sites.

4. ROCK FALL MITIGATION MEASURES

The inventory of rock slopes, together with the corresponding hazard and risk rating, will enable a prioritized list of potential stabilization sites to be drawn up. The highest priority sites will generally be those with the highest ratings.

The next step will be to determine the method of rock fall mitigation that is appropriate for the site. These methods are well established in engineering practise (Wyllie and Mah, 2004), and can be classified as stabilization where the work is carried out on the slope, and protection where containment is constructed within the pathway (Figure 4).

4.1 Stabilization Measures

Stabilization measures comprise removal of loose rock on the face by trim blasting and/or scaling (item 3), reduction of water pressures by drilling drain holes (item 6), or reinforcement (items 1, 2, 4, 5 and 7). The general objective of reinforcement is to prevent loosening of the rock since even a small amount of relaxation can result in a significant loss of rock strength.

4.2 Protection Measures

Protection measures can be more economical to construct and maintain than stabilization on the slope, provided that there is sufficient work space at the base of the slope. Excavation of ditches (item 7) is usually an effective protection measure, especially if the outer face of the ditch is steep to contain rolling rock. In the last ten years, a number of high energy net systems have become available that can be customized for each site to provide a high level of protection. Reinforced concrete rock fall sheds also provide a high level of protection, but at a relatively high cost.

5. ROCK FALL PROBABILITY AND RISK CALCULATIONS

The rock fall hazard as defined in Section 2.1 above, can be expressed quantitatively as a probability of a fall occurring during a certain time period, or qualitatively as a hazard rating, depending on the information available. This section describes the determination of rock fall probabilities from rock fall records, from which it is possible to calculate the relative risk to vehicles or structures that lie within the pathway.

5.1 Rock Fall Probability

If records of rock falls are maintained, it is possible to calculate the probability of their occurrence. The following calculations are based on a data set for a transportation system located in steep mountainous terrain on the northwest coast of North America where the winters are cold with many freeze-thaw cycles, and periods of intense rainfall occur. However, no significant earthquake occurred during the time the data was collected.

- Number of rock falls = 682
- Number of years of data = 31
- Number of rock cuts = 118

Annual probability of rock fall on each cut, $p_r = 0.2$

This probability value represents the average rock fall hazard, and is independent of the traffic conditions. The rock fall probability would be a baseline value that could be compared with the frequency of events in the future to assess if stability conditions were deteriorating, as well as the efficacy of stabilization work.

5.2 Calculation of Relative Risk

Figure 5 represents a rock face, in profile, with five at-risk objects within the rock fall pathway at the base of the slope. Assuming that the annual probability of a rock fall on this slope is 0.2, then the relative risk of each these objects being impacted by a fall can be calculated. The calculation just examines the risk to the driver of the vehicle (length = 1 m), and is not concerned with the vehicle being impacted. However, in the case of the passenger train, it is assumed that passengers are at risk over the full length of the train (length = 200 m). The risk of driver impact is the proportion of time that drivers are exposed to rock falls, which can be calculated as follows:

$$Exposure\ \ risk, e = \frac{L\,N}{V\,(86{,}400)} \qquad [1]$$

where L is the length of the cut (m), V is the vehicle speed (m/s), N is the traffic count (vehicles/day) and 86,400 is the number of seconds per day. The product of the exposure risk and rock fall probability is the probability of an object being impacted by a rock fall, p_i, given by:

$$Probability\ of\ impact,\ p_i = e\ p_r \qquad [2]$$

The values of p_i listed on Figure 5 are equivalent to the relative impact risk for each type of object. The list shows that cars have the highest exposure, mainly because of the high traffic count, compared with trains that operate at lower speeds (and have higher exposure times) but have a lower traffic count. The relatively high risk for the house it due to its static location within the pathway, although the calculation accounts for the fact that the 20 m length of the house extends over only 8 per cent of the 250 m long cut. It is also assumed that the house is occupied year round; the risk would be diminished if it were only occupied part of the year.

5.3 Factors Influencing Actual Risk

The calculation presented in Section 5.2 above represents the maximum risk from rock falls to which objects are subjected. In reality, the actual risk is reduced by a number of site specific factors that include:

- Rock falls from the lower part of the slope will probably only travel a limited distance along the pathway and not reach the traffic lanes;
- Small rock falls that cause little or no damage are more frequent than large falls (Hungr and Evans, 1988);
- For rock falls that are on the road in front of the vehicle, avoidance actions such as swerving or braking can be taken. However, in the case of trains, their inability to swerve and stopping distance of up to 1.5 km, means that they are likely to impact any rock fall on the track.

6. OPTIMIZING MITIGATION MEASURES

Figure 4 shows that there are a significant number of stabilization measures that vary widely in their effectiveness in preventing rock falls, and their cost of implementation. For example, localized trim blasting and scaling (item 3) could cost a few thousand dollars, but may have to be repeated as often as every year if the rock weathers rapidly. In contrast, a rock fall shed (item 10), which may cost several million to construct, will provide a very high level of protection for many years.

In selecting an appropriate mitigation measure for a site, the first consideration is the technical aspects of the work such as the size of the blocks of rock and the likely failure mechanism, as well as site conditions such as ditch width and equipment access. Usually, there will be several mitigation options, or strategies, for a site, and it is helpful to have a rational method for selecting the optimum one, particularly because of the uncertainty in their cost and effectiveness.

6.1 Decision Analysis

Decision Analysis, which is a well proven technique for making decisions under uncertainty, and provides a method of evaluating mitigation options (Wyllie, *et. al*., 1979; Raiffa, 1969; Berger and Gerstenfeld, 1971). The basic principle of decision analysis is to determine, for each strategy, the "Expected Cost", *ec* that is defined as:

$$ec = C_c + \sum_{1}^{n} (p_{i,n}\, C_{i,n}) \qquad [3]$$

where C_c is the construction cost, and for each of n type of incident, p_i is the probability of a rock fall (incident) occurring and C_i is the cost of that incident. An important property of the probability values is that the total probability at each chance point is 1.0 because this is the sum of all the incidents that can occur.

Figure 6 is a "decision tree" showing the structure of a decision involving the following three strategies, with a square (□) indicating a decision point:

Strategy S_1 - existing conditions with no mitigation;

Strategy S_2 – stabilization with rock bolts and shotcrete;

Strategy S_3 – construction of rock fall shed.

For each strategy there is a corresponding construction cost (C_c):

C_{c1}, = 0; C_{c2} = \$50,000; and C_{c3} = \$1.5 million.

For all three strategies, the same type of chance incidents can occur as indicated by the circle (○). These incidents include a minor rock fall that causes no damage or delays to traffic and can be removed by regular maintenance operations; a delay to traffic as well as stabilization of the rock fall area; and an impact that results in damage and injury, stabilization work and possibly legal action. The average cost, C_i, of each of these three types of incidents is listed below, assuming for simplicity that the costs are constant for each strategy.

Minor falls	$C_{i,1}$ = \$200;
Delay, stabilization	$C_{i,2}$ = \$10,000;
Impact, delay, stabilization	$C_{i,3}$ = \$1,000,000.

The probability of occurrence of each incident for each strategy, p_i, is determined by a combination of rock fall records, and judgement of the likely performance of the mitigation measure. For existing conditions, there may be information on frequency of impacts and delays, compared to rock falls that result in no disruptions to traffic. The p_i values for the two mitigation strategies can be controlled to some extent by their design. For example, spot bolting would only reduce the frequency of larger falls by a small amount, while pattern bolts, selective shotcrete and mesh would significantly reduce the frequency of all falls.

The Expected Cost of each strategy is calculated using equation [3]. For example, for strategy S_2,

$$\begin{aligned} ec &= C_{c2} + \Sigma\,(p_{i,n}\ C_{i,n}) \\ &= \$50{,}000 + (0.9\ \$200 + 0.09\ \$10{,}000 + 0.01\ \$1E6) \\ &= \$51{,}080 \end{aligned}$$

6.2 Stabilization Design

The expected cost for each strategy shown in Figure 6 demonstrates that Strategy S_2 has the least expected cost and is the most effective option. This result is due to two significant factors related to the values for C_c, p_i and C_i. First, the cost of constructing a shed is much greater than the existing expected cost of rock falls so the cost of this strategy cannot be justified. Second, in order for the rock bolting and shotcreting option to be effective, it is necessary that the work will significantly reduce the probabilities of delays and impacts. That is, delays will need to be reduced by one third and impacts by a factor of ten. Design of bolts and shotcrete that would produce this reduction of probabilities would likely require extensive work on all potentially unstable areas of the slope, and not localized spot bolting.

7. CONCLUSIONS

Rock fall hazards on transportation routes and residential areas can be managed using a risk based approach. This optimizes the costs of stabilization or protection with respect to the cost of accidents resulting from rock falls. A risk based approach is necessary because the costs and effectiveness of mitigation, as well as the frequency and consequences of rock falls are uncertain.

In applying a rock fall risk management program, the following factors usually apply:

- Rock fall mitigation programs are technically well proven;
- The implementation of a consistent mitigation program usually provides, in North America, some legal protection for owners of facilities from law suits brought by victims of rock fall accidents;
- Mitigation programs can be optimized by preparing an inventory of rock slopes together with the hazard and risk at each site. This information, together, with rock fall probability values and Decision Analysis, can be

used to select and design the most economically effective program;

- Mitigation programs will usually be long-term or continuous where there are many slopes on the system and/or the rock weathers faster than the frequency of stabilization work.

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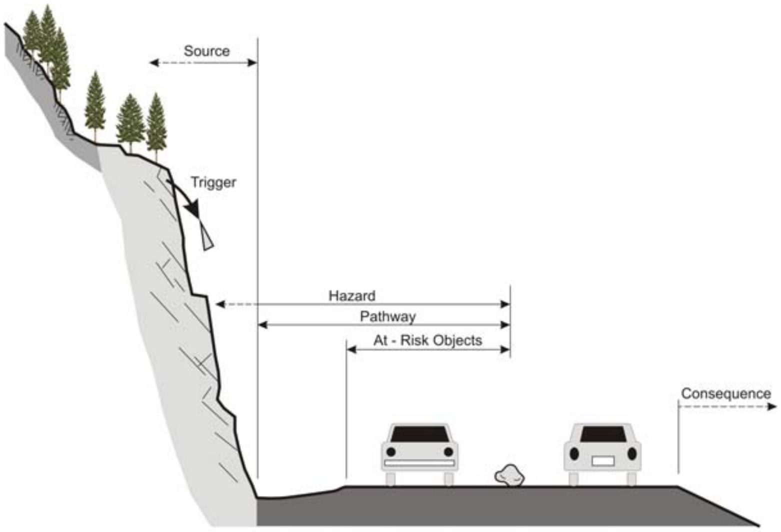
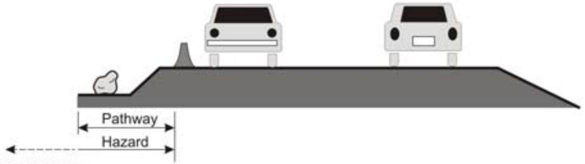
Figure 1 – Rock fall from hazardous slope, with high risk to highway because of minimal catch ditch and short pathway.

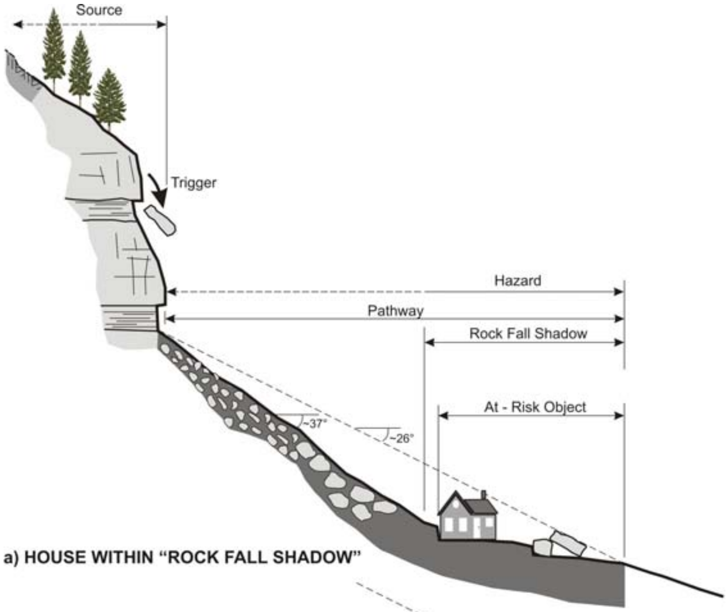


a) MINIMAL CATCHMENT

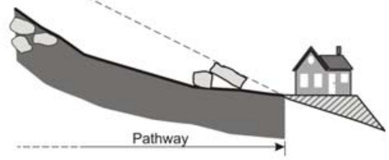


b) EFFECTIVE CATCHMENT

Figure 2 – Hazards and risks on a highway below a rock slope with a ditch to contain rock falls.

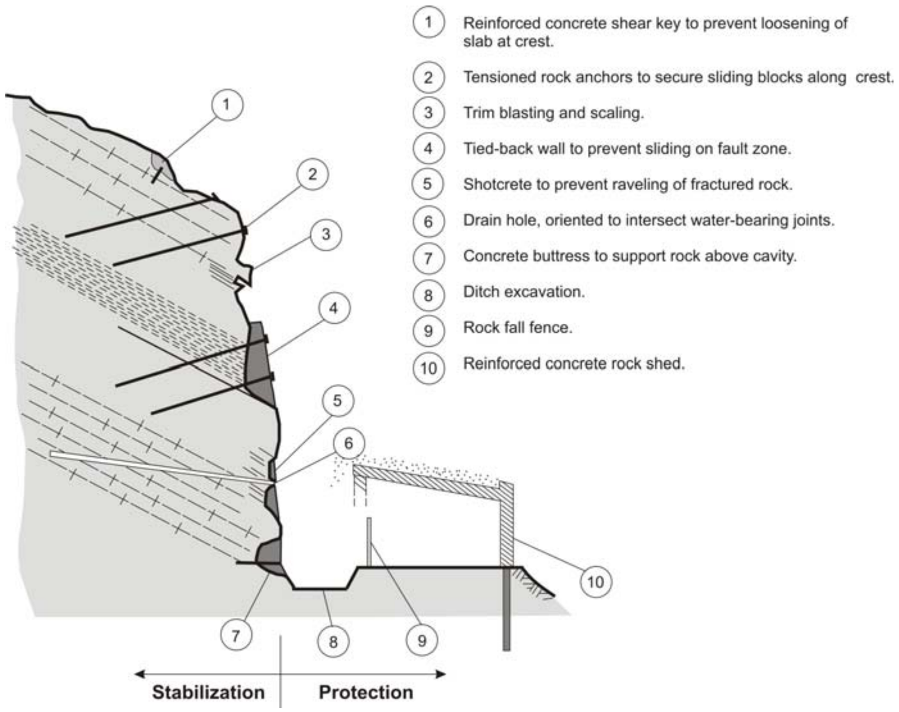


a) HOUSE WITHIN "ROCK FALL SHADOW"



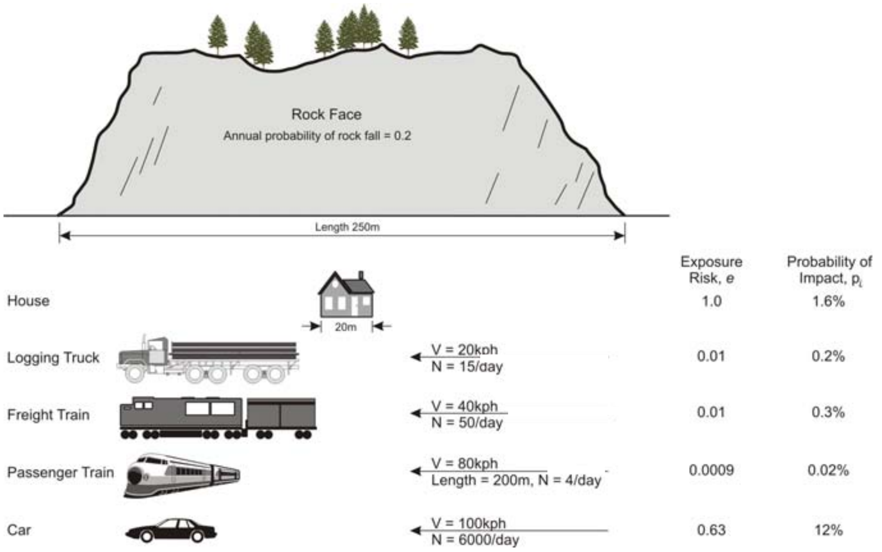
a) HOUSE OUTSIDE "ROCK FALL SHADOW"

Figure 3 – Hazards and risks for a house below a rock slope and talus deposit.



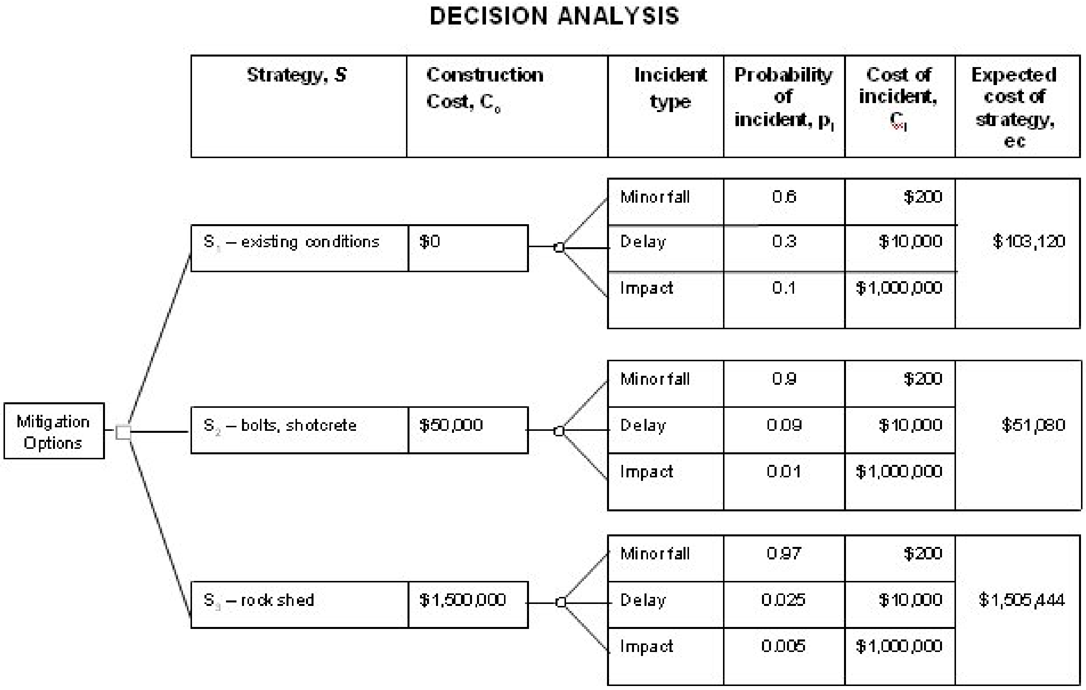
① Reinforced concrete shear key to prevent loosening of slab at crest.
② Tensioned rock anchors to secure sliding blocks along crest.
③ Trim blasting and scaling.
④ Tied-back wall to prevent sliding on fault zone.
⑤ Shotcrete to prevent raveling of fractured rock.
⑥ Drain hole, oriented to intersect water-bearing joints.
⑦ Concrete buttress to support rock above cavity.
⑧ Ditch excavation.
⑨ Rock fall fence.
⑩ Reinforced concrete rock shed.

Figure 4 – Rock slope stabilization and protection measures.



		Exposure Risk, e	Probability of Impact, p_i
House		1.0	1.6%
Logging Truck	V = 20kph N = 15/day	0.01	0.2%
Freight Train	V = 40kph N = 50/day	0.01	0.3%
Passenger Train	V = 80kph Length = 200m, N = 4/day	0.0009	0.02%
Car	V = 100kph N = 6000/day	0.63	12%

Figure 5 – Calculation of relative rock fall risk for different at-risk objects.



Strategy, *S*	Construction Cost, C_o	Incident type	Probability of incident, p_I	Cost of incident, C_I	Expected cost of strategy, ec
S_1 – existing conditions	$0	Minor fall	0.6	$200	$103,120
		Delay	0.3	$10,000	
		Impact	0.1	$1,000,000	
S_2 – bolts, shotcrete	$50,000	Minor fall	0.9	$200	$51,080
		Delay	0.09	$10,000	
		Impact	0.01	$1,000,000	
S_3 – rock shed	$1,500,000	Minor fall	0.97	$200	$1,505,444
		Delay	0.025	$10,000	
		Impact	0.005	$1,000,000	

Figure 6 – Decision tree showing three mitigation strategies and their expected costs.