Computer modeling of catch benches to mitigate rockfall hazards in open pit mines

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ABSTRACT: A computer analysis of bench stability has been developed to account for multiple occurrences of potential slope-failure modes in discontinuous rock masses. Bench-scale plane shears and tetrahedral wedges are simulated and stochastically analyzed to estimate the probability of retaining specified catch-bench widths. This geotechnical information is useful in designing bench configurations to improve pit-slope stability and help alleviate rockfall hazards.

1 INTRODUCTION

Thorough engineering analyses of mine slopes cut in discontinuous rock masses should include investigations of bench stability and the likelihood of retaining serviceable catch benches during the mine life. When bench stability is controlled primarily by rock failures that slide along natural fractures (such as plane shears and tetrahedral wedges), a stochastic computer analysis can be used to evaluate the probability of retaining specified catch-bench widths. If the original slope geometry plan and blasting layout are intended to produce catch benches of a certain width, it is unlikely that such width actually will be retained after blasting and excavation when kinematically viable rock failure modes are present in the benches. Consequently, rockfall hazard assessment and related slope stability safety issues must consider the predicted, operational catch-bench geometry and not the originally designed, ideal geometry.

In fractured rock masses, bench failures most commonly occur in the upper portion of the bench, because the fracture lengths required for failure are shorter here. That is, small plane shears or wedges typically break out along the crest of a bench, due to the higher probability that natural fractures will be long enough here to form kinematically viable failure modes. This characteristic is observed in mine benches, and it should be reflected in the probabilistic outcome of a bench stability analysis. Thus, the probability of retaining a full width on the bench is not as high as the probability of retaining, say, 80% of the original bench width. Probabilities of retaining bench widths increase as the specified widths decrease. Only occasionally do longer fractures occur and allow for larger failures to affect much of the bench face and severely diminish the catch width.

Minor bench instabilities and rockfalls adversely impact mine safety in two key areas. First, as failures break back along the top of a bench, storage capacity for holding rockfall debris is significantly reduced, and falling rock from above may not be caught and retained on the bench. Second, as rockfall debris spills onto the bench below, it reduces the storage capacity of that bench and may even trigger multiple-bench failures. Thus, the capability to predict the size of bench failures and their impact on the catch width would provide key input to designing the bench geometry (i.e. bench height, face angle, and width).

The National Institute for Occupational Safety and Health (NIOSH) Spokane Research Laboratory focuses on safety and health issues in the mining industry. A project began several years ago aimed at mitigating rockfall hazards in open-pit mines and quarries. One aspect of this project has involved the development of computer software to analyze bench stability and back-break characteristics in a hazard-based, stochastic framework. One computer program analyzes plane-shear failure modes in a two-dimensional framework by simulating plane-shear fractures in the bench and then calculating the probability of stability for each one, as well as identifying the corresponding backbreak distance on the bench. By repeating the simulation many times for a given bench, the probability of retaining various bench widths can be estimated. Another computer program analyzes three-dimensional wedges by simulating fractures from two fracture sets and conducting a similar back-break analysis.

A stochastic (or probabilistic) approach is needed because rock fractures in a bench face are numerous and too difficult to analyze individually. For the computer model to generate realistic fracture patterns and subsequent slope failure modes, representative geotechnical input information must be available. This information often can be obtained readily from a thorough geotechnical site investigation.

2 GEOTECHNICAL INPUT

Stability analysis of rock failure modes requires information on the slope geometry, the physical properties of rock discontinuities that define the modes, and local environmental conditions (such as ground water pore pressure). Slope geometry is specified by the engineer, based on actual field conditions or on a proposed slope design plan. Other input data usually must be obtained by geotechnical site investigation procedures.

2.1 *Mapping and analysis of rock discontinuities*

Geotechnical data collection methods, such as scan-line (detail-line) mapping and fracture-set mapping (Miller, 1983), provide important information on fracture orientations, spacings, lengths, and roughness. Typical mapping sites in the project vicinity include natural rock outcrops (if the project is in initial development stages) or available rock slope cuts along roads or accessible mine benches.

The first step in analyzing such field data typically consists of plotting the poles to fractures on a lower-hemisphere stereonet in order to identify fracture sets, which appear as clusters of poles (Hoek and Bray 1978). The interaction of the proposed slope cut with the orientations of these fracture sets allow the engineer to identify potential slope failure modes (i.e. plane shears and wedges, for our particular study). It should be noted that in any rock-slope stability evaluation, the general progression in the engineering analysis is:

1. Use fracture-set **orientations** to identify potential slope failure modes;
2. For the critically oriented sets, evaluate the likelihood of having sufficient fracture **lengths** to form kinematically viable failure blocks; and
3. For fracture sets with sufficient lengths, estimate the **shear strength** so that an engineering stability analysis can be conducted.

In the computer simulation of rock fractures in a set, one should strive to preserve the natural spatial dependence in fracture properties. Spatial covariance or semi-variograms (Isaaks and Srivastava 1989) provide a statistical format for describing the spatial dependence in fracture properties, which has been demonstrated by La Pointe (1980) and Miller (1979). Thus, instead of simulating fracture properties independently in space, the measured spatial continuity can be incorporated using methods described by Miller (1985). To conduct such a fracture-set simulation, each of the particular fracture properties need to be modeled by an appropriate semi-variogram model using the "sill" (sample variance), the "nugget" value (i.e. the semi-variogram value at a separation distance of zero), and the spatial "range" of influence. A probability distribution model for each fracture property also is needed.

An essential input for the stability calculations is the mean length of fractures in a given set. An exponential pdf (probability density function) is assumed for fracture length, then the probability of a fracture being long enough to form a viable failure path through the bench can be obtained directly from the exponential probability distribution. This pdf is a one-parameter distribution, being defined only by the mean value. See Section 3.1 below.

2.2 *Shear strength*

Shear strength along rock fractures typically is estimated in one of two ways: the JRC-JCS method proposed by Barton et al (1972), and by using laboratory direct-shear test data to describe either a linear Mohr-Coulomb failure envelope or a power-curve model (Jaeger 1971).

A general power-curve model has been adopted for use in the NIOSH bench analysis computer programs, given by the following expression:

$$\tau = a\sigma^b + c \quad (1)$$

where: τ = shear strength;
σ = effective normal stress; and
a, b, c = model parameters.

This equation describes a power model with a y-intercept. It reduces to a simple linear model when b equals 1.0, thus making "c" equal to cohesion, and "a" equal to the coefficient of friction (i.e. $\tan\phi$).

The variability of τ, given a predicted value of σ, also is needed in the bench stability analysis. Currently in the NIOSH codes, the shear strength is modeled with a gamma pdf with a standard deviation defined by a user-specified coefficient of variation (CV). This coefficient is given by:

$$CV = s_\tau / m_\tau \quad \text{or} \quad s_\tau = CV(m_\tau) \quad (2)$$

where: s_τ = standard deviation of τ; and
m_τ = mean of τ given by Eq. (1).

Therefore, as the normal stress increases, so does the shear strength and so does the standard deviation of shear strength. Typical values for the shear strength CV range from 0.15 to 0.35. Note that for small values of CV (i.e. less than 0.2), the gamma pdf begins to approximate a normal pdf. The key advantage in using a gamma pdf to describe shear strength is that this particular pdf is defined only for positive values, which means that τ in the computer analysis never can take on unrealistic negative values for low values of σ. Note that small normal stresses are common when analyzing small failure masses along bench crests.

In summary, the required geotechnical input needed for the NIOSH bench stability programs can be summarized as follows:

Bplane.exe (2-d analysis of plane shears)

Bench height (m) and width (m)
Number of back-break cells (typically set so cells are about 1-m wide)
Bench face angle (degrees)
Ground water height above bench toe (m)
Rock mass unit weight (tonne/cu.m): mean, sd
Fracture-set mean length (m)
Fracture-set dip (deg.): mean, sd, nugget value, spatial range (no. of fractures)
Fracture-set spacing (m): mean, nugget value, spatial range (no. of fractures)
Fracture-set waviness (deg.): mean, nugget value, spatial range (no. of fractures)
(Note: waviness is the average dip minus the minimum dip of a fracture, and it represents a measure of large-scale roughness)
Shear strength (tonne/sq.m) terms: a, b, c, CV

Bwedge.exe (3-d analysis of wedges)

Bench height (m) and width (m)
Number of back-break cells (typically set so cells are about 1-m wide)
Bench face angle and dip direction (degrees)
Ground water height above bench toe (m)
Rock mass mean unit weight (tonne/cu.m)

The following input is needed for both the left fracture set and the right fracture set that form viable wedges:

Fracture-set mean length (m)
Fracture-set dip direction (deg.): mean, sd, nug- get value, spatial range (no. of fractures)
Fracture-set dip (deg.): mean, sd, nugget value, spatial range (no. of fractures)
Fracture-set spacing (m): mean, nugget value, spatial range (no. of fractures)
Shear strength (tonne/sq.m) terms: a, b, c, CV
(σ and τ expressed in tonne/sq.m)

3 STOCHASTIC MODELING CONCEPTS

The probability of retaining a specified bench width for given failure modes in a bench can be estimated by simulating potential failure geometries and cataloging the back-break position of each one on the top of the bench. Stability of a given failure geometry can occur two ways: 1) the failure length is not long enough to pass entirely through the bench, and 2) the failure length is long enough to pass through the bench, but sliding does not occur (Miller 1983). The probability of stability for each geometry then is given by the sum of these two probability values:

$$P_{stab} = \text{P(failure path not long enough)} + \text{P(failure path long enough and no sliding)}$$

$$P_{stab} = (1 - P_L) + P_L(1-P_S) \quad (3)$$

Thus, the probability of failure length and the probability of sliding must be computed for each potential failure mass generated in the bench simulation.

3.1 *Probability of failure length*

The probability that a given simulated fracture is long enough to pass entirely through the bench is computed as an exceedance probability using an exponential pdf model for the fracture-set lengths. The exponential cdf (cumulative distribution function) is a one-parameter cdf model given by (Devore 1995):

$$F(x) = 0, \quad \text{if } x < 0$$

$$= 1 - e^{-x/m}, \quad \text{if } x \geq 0 \quad (4)$$

where: m = mean.

The length required for a through-going failure path for a plane-shear fracture is calculated by:

$$x = h/\sin(D) \quad (5)$$

where: h = vertical height of failure mass, as measured from the toe of the failure to the top of the bench; and

D = dip of failure plane (or wedge intersection line for wedge failures).

Thus, the probability that fracture length takes on a value greater than x is given by:

$$P(X > x) = 1 - P(X \leq x) = 1 - F(x) = 1 - (1 - e^{-x/m})$$

$$= e^{-x/m} = P_L \quad (6)$$

Example: for mean length = 1.6m and x = 3m,

$$P(X > 3) = e^{-3/1.6} = 0.153 = P_L$$

In the case of three-dimensional wedges, which slide along the line of intersection, the probability of length sufficient for failure is the joint probability that the left fracture is long enough and the right fracture is long enough:

$$P_L(\text{wedge}) = P_L(\text{left}) \times P_L(\text{right}) \quad (7)$$

After setting the length of the wedge intersection equal to x in Eq. (6), the corresponding P_L(left) and P_L(right) can be computed using the mean length for the left fracture set and the mean length for the right fracture set, respectively.

3.2 *Probability of sliding*

The probability of sliding for a given slope failure mode can be estimated by Monte Carlo methods applied to a limiting-equilibrium analysis, whereby a distribution (histogram) of safety factor values is generated by many repeated calculations using possible realizations of input values. The probability of sliding then is equal to the fraction of safety factors that are less than 1.0. The safety factor is defined as the ratio of resisting forces to driving forces, and a value of 1.0 indicates limiting equilibrium (i.e. the potential failure mass is just on the verge of sliding).

However, even after completing a Monte Carlo simulation study using several thousand iterations, the resulting histogram of safety factors represents only one possible realization of the actual safety factor pdf. A slightly different distribution will result if the simulation is repeated using a different random seed starting value. Thus, questions always arise regarding the number of iterations to use and the repeatability of results.

Fourier analysis provides an alternative to Monte Carlo simulation in estimating the probability distribution of the safety factor, provided that the safety factor equation can be written as the sum of independent pdf's. A computationally efficient way to estimate the actual pdf of the safety factor relies on discrete Fourier methods, which take advantage of the computing speed of the fast Fourier transform (Miller 1982). As presented by Feller (1966), the sum of independent pdf's in the "space" domain is analogous to the product of their Fourier transforms in the "frequency" domain.

For our case, if fracture shear strength is assumed to have a gamma pdf and fracture waviness is assumed to have an exponential pdf (which is a special form of a gamma pdf), then the output safety factor pdf can be described as a gamma pdf. The probability of sliding (P_S) is computed by numerically integrating the area under the discretized pdf of the safety factor to the left of safety factor = 1.0. That is,

$$P_S = P(SF \leq 1.0) \tag{8}$$

Additional information on this analytical method based on Fourier convolution of pdf's was reported by Miller (1982).

4 BENCH STABILITY ANALYSIS

The concept of bench back-break cells is illustrated in Figures 1 and 2. For the plane-shear analysis (Fig. 1), a random starting point is selected near the bench toe and then fracture locations up the bench are simulated by generating spatially dependent fracture spacings. Fracture dips and waviness values also are generated using spatial dependence and assigned to individual fractures previously located on the slope face.

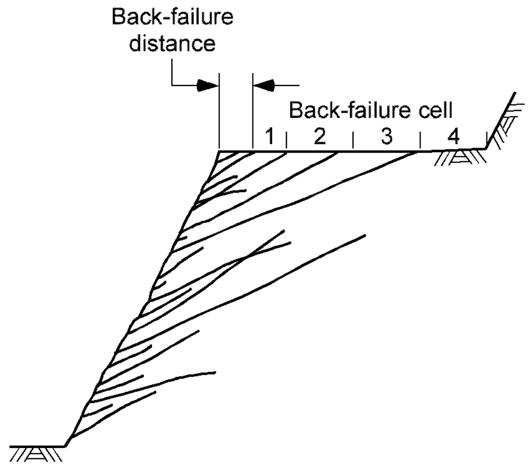


Figure 1. Simulated plane shears (Miller 1983).

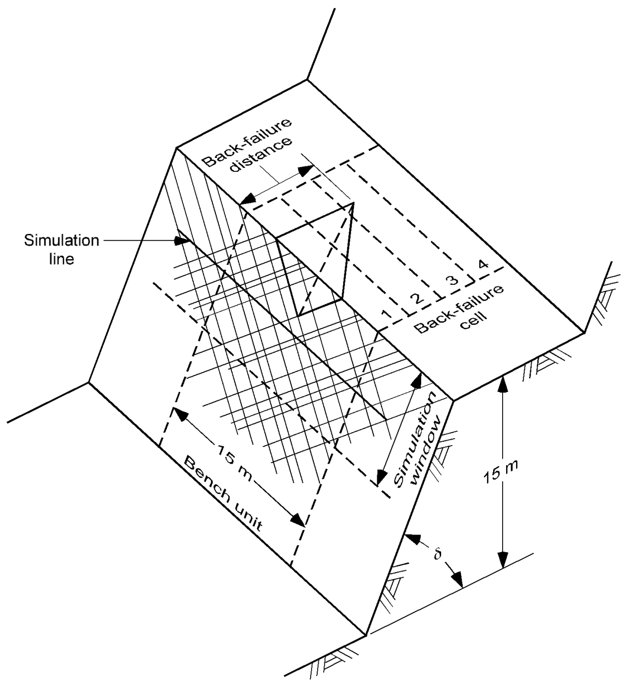


Figure 2. Simulated 3-d wedges (Miller 1983).

By simulating many realizations of a given bench, each of which contains multiple occurrences of the particular failure mode, the probability of stability for any specified back-failure cell can be estimated as follows (Miller 1983):

$$P_{CS} = [(N_T - N)/N_T] + (1/N_T) \sum_{i=1}^{N} \left\{ \prod_{j=1}^{J_i} [(1 - P_{Lj}) \mid s_i + P_{Lj}(1 - P_{Sj}) \mid s_i \right\} \tag{9}$$

where: P_{CS} = probability of cell stability;
N_T = total number of bench simulations;
N = number of bench simulations that have at least one failure path in the specified cell;
s_i = the i-th bench simulation;
J_i = number of failure paths in the specified cell for the i-th bench simulation;
P_{Lj} = probability of sufficient length for the j-th failure path;
P_{Sj} = probability of sliding for the j-th failure path;

For simulating three-dimensional wedges in a bench, a standard length along the bench face must be specified to define an area for probability accumulations. This length typically is set equal to the bench height to provide for "square" units that can be analyzed along the bench face (Fig. 2). The number and size of simulation windows depend on fracture set spacings, lengths, and on engineering judgment (Miller 1983).

5 IMPLICATIONS FOR OVERALL SLOPES

Results from a bench stability simulation study can be used to help select interramp slope angles and overall slope angles. Bench geometry has a direct influence on the overall slope angle as expressed in the following form:

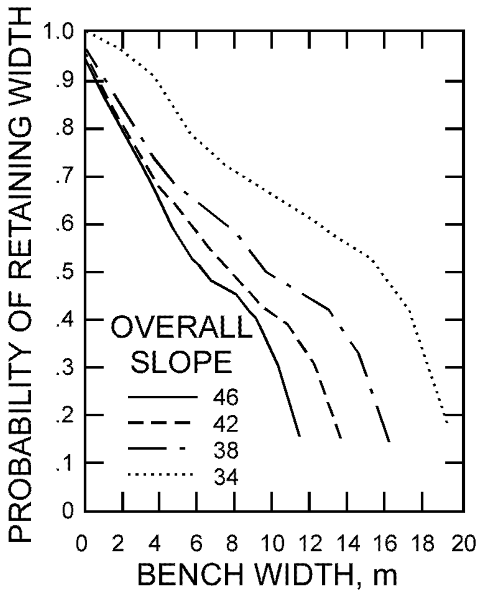
$$\tan(A) = 1 / [(W/H) + (1/\tan B)] \qquad (10)$$

where: A = overall (average) slope angle;
B = bench-face angle;
H = vertical height of bench; and
W = horizontal width of bench.

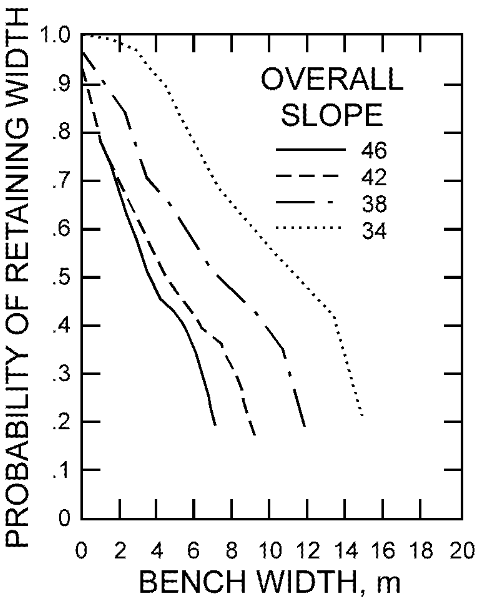
Example: for H = 15m, W = 8m, B = 64 deg.,

$$A = \arctan\{1 / [(8/15) + (1/\tan 64)] = 44 \text{ deg.}$$

If an overall steeper angle is desired, then the W:H ratio of benches must be decreased or the bench faces cut at a steeper angle. However, for typical applications, results from the stochastic bench simulations will guide the engineer in selecting the overall slope angle to minimize extensive loss of catch bench width and thus minimize subsequent rockfall hazards. Relationships between bench geometry, catch-bench width, and overall slope angle can be displayed in graphs, which can be used to predict overall slope angles when the probability of retaining a given catch-width has been specified. Examples are shown in Figure 3.



A. Plane shears; bench angle of 0.5:1 (64 deg.)



B. Plane shears; bench angle of 0.2:1 (79 deg.).

Figure 3. Examples of catch-bench stability graphs.

Failure of a total bench width (i.e. related to the probability of retaining a bench width of zero) will have significant effects on interramp or overall slope stability, because multiple-bench failures often result when sections of benches are lost due to excessive failures of underlying benches. Thus, the design of overall slope angles should provide for very high probabilities (greater than 0.95) of retaining bench widths less than 1 meter.

One way to interpret the probability of retaining a given bench width is to directly relate this probability to the percentage of bench run in a given segment of the pit wall that will display that given bench width some time after bench excavation. For example, a 0.80 probability of retaining 4m wide catch benches can be interpreted as expecting about 80% of the bench run (as viewed horizontally) to have retained widths of at least 4m.

Recent experience in using these bench stability computer programs has indicated that the number of bench simulations for plane shears should be greater than 100 in most cases to provide consistent probabilistic results when repeating the analysis for different random seed values. The user-interface input screen for Bplane.exe currently lists a default value of 100 simulations, with a maximum of 200 allowed. Due to the extensive computational effort in the wedge simulations, Bwedge.exe currently lists a default value of 50, with a maximum of 100 allowed.

Estimated volumes of rockfall debris can be related directly to the probability of retaining given catch-bench widths. If the probability associated with a specified back-break cell is calculated as P_i, then the average failure volume associated with P_i can be estimated as follows:

First, calculate h, the vertical height of an average failure:

$$h = C_i(\sin D \sin B) / \sin(B-D) \qquad (11)$$

where: C_i = back-break distance to center of cell with probability P_i;
B = bench face angle; and
D = average dip of plane-shears or average plunge of wedges in the simulation.

Then, calculate the unit-width area (i.e. the area associated with a 1-m increment along a run of bench):

$$A_i = 0.5h[C_i + (h/\tan B)] \qquad (12)$$

The associated intact volume of rock prior to the failure is then: $V_i = A_i(1m)$ cubic meters of rock per 1m run of bench. A bulking factor (usually, 0.15 to 0.25) then is multiplied by this volume to estimate the volume of loose rock debris lost from the bench crest and which must be contained on the catch bench below. If this volume exceeds the expected storage volume on the lower bench, then the debris can be expected to cascade farther down the overall slope.

6 SUMMARY AND CONCLUSIONS

Computer software for a PC platform has been developed to stochastically analyze rock slope stability, particularly aimed at benches in an open-pit mine. The analysis also could be used for large rock slopes constructed for civil projects. The computer programs simulated potential plane-shear or wedge failure modes and calculates to probability of retaining specified widths on the affected catch benches. Probabilistic estimates of potential failure volumes also can be obtained from this analysis.

Such information is useful in the design and selection of bench geometries and overall slope angles so as to minimize rockfall hazards while maintaining adequate catch-bench widths. Field studies are underway to evaluate and verify the results provided by this type of stochastic analysis. In situations where blast damage or highly-fractured rock will control the back-break of benches, the analysis of structurally controlled failures (plane shears and wedges) will not be adequate to describe bench stability. Also, no allowance has been made in these computer codes for tension cracks that may truncate the failure paths, so the stochastic results may be approximate.

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