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PREDICTION OF STEP PATH FAILURE GEOMETRY
FOR SLOPE STABILITY ANALYSIS

PRÉDICTION DE LA GÉOMETRIE DES RUPTURES EN ECHELON
POUR L'ANALYSE DE STABILITÉ DE TALUS ROCHEAUX

DIE PROGNOSE DES TREPPENFÖRMIGES ABGLEITEN
FÜR DEN STABILITÄTSBERECHNUNG IM TAGEBAU

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PREDICTION OF STEP PATH FAILURE GEOMETRY FOR SLOPE STABILITY ANALYSIS

by
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ABSTRACT

In jointed rock a potential mode of slope failure is a step path where the failure surface follows a combination of joints from two sets. This step path geometry can be defined using the dip, length, spacing, and overlap characteristics. The sets that make up the step path should have similar strikes; usually, one set is shallow dipping (20° - 50°) and the other steep dipping (50° - 90°).

Detail line mapping or joint set mapping is used to acquire the data for estimating the distributions of the joint set characteristics. These distributions are Monte Carlo sampled and the results are used in an algorithm of logic and decision making. The algorithm assumes the flattest step path will be followed by the failure. The step path follows a flat joint until the last steep joint is intersected. The path proceeds up the steep joint to the next flat joint. When joint lengths are short relative to joint spacings, the step path may not be continuous over the specified slope height. An estimate of percent intact rock can be made from the number of rock bridges required to complete the step path geometry for the specified slope height.

The step path modeling gives distributions of both step path angles and percent intact rock. These distributions can then be used in conjunction with Jaeger's step path stability analysis to determine the probability of failure.

Preliminary field checking at the Cyprus Bagdad mine and at Bamangwato Concessions' Pikwe mine indicates an average step path angle can be predicted. Additional work is required to relate stress conditions to the step path geometry, to include more than two joint sets in the model, and to develop a more complex algorithm to predict other than the flattest step paths.

INTRODUCTION

Failures along planar geologic structure are common in jointed rock where the rock substance has a higher strength than the potential failure surface. A common failure mode is simple plane shear. If a daylighted continuous structure is present, such as a fault or a set of bedding planes (Figure 1), the stability analysis is reasonably straightforward (Jaeger, 1971). Basically, the resisting shear stress is estimated from test results on samples from the failure surface, and from field measurements on the surface's roughness.

The daylighted structure is often a discontinuous joint set comprised of individual joints with lengths shorter than the distance from the toe of the slope to the ground surface (Figure 2). Where there is sufficient intact rock between joints to prohibit simple plane shear, a more continuous failure geometry defined by geologic structure is required before failure can occur. One possible geometry is the step path, where the potential failure surface steps up along steeply dipping cross joints to the next joint of the flatter dipping daylighted set (Figure 3).

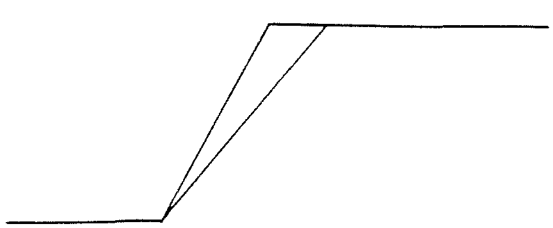

Figure 1. Continuous Plane Shear

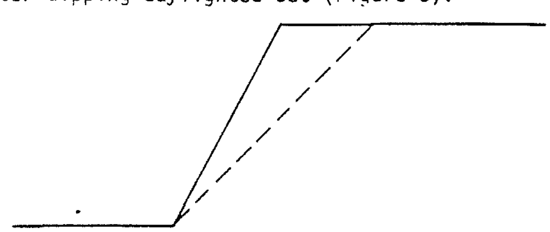

Figure 2. Discontinuous Plane Shear

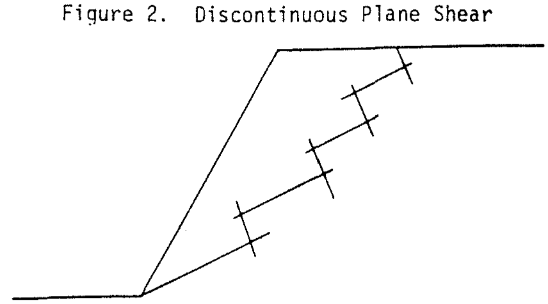

Figure 3. Step Path

The current method of step path failure analysis for rock slopes calculates the resultant angle of the step geometry, termed the step path angle, and the percent intact rock (Figure 4). The step path angle is then used in the stability analysis. Difficulty occurs in calculating the step path angle, which is controlled by the characteristics of the included joint sets. Previously reported methods (Barton, 1972; Jaeger, 1971; and Jennings, 1970) to calculate the step path angle have the following problems:

1) The use of mean values for the joint set characteristics produces only 1 step path angle when actually a distribution of step path angles should be determined.

2) The required data on the area of intact rock are practically impossible to measure.

To resolve these problems, a 2-dimensional probabilistic model has been developed. This model determines a possible path of lowest shear strength by randomly sampling the distributions of dip, length, spacing, and overlap. The solution is iterative, resulting in distributions of both step path angles and percent intact rock. These distributions can be used in a probability of failure analysis.

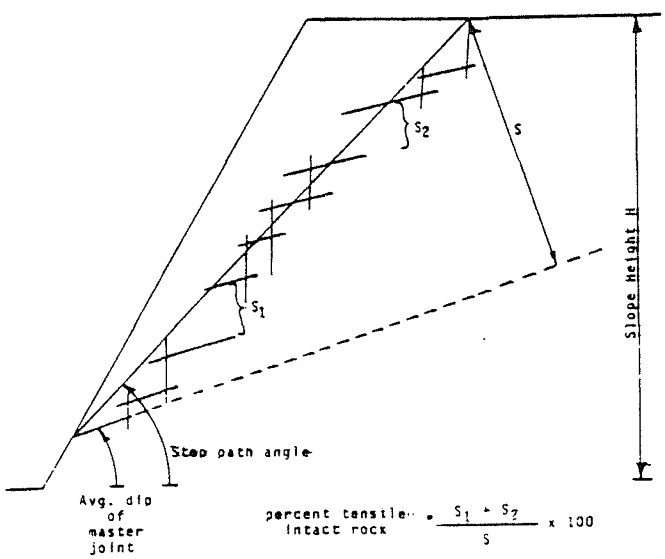

Figure 4. Step Path Angle and Percent Intact Rock

DESCRIPTION OF STEP PATH MODEL

The step path geometry is formed by the interaction of 2 joint sets that have similar strikes. The master joint set is gently dipping (usually 20° - 50°), while the cross joint set is steeply dipping (usually 50° - 90°). The path with least resistance is the one with continuously intersecting cross joints and master joints (Figure 5). Intact rock "bridges" may occur if the fracture lengths are short in comparison to the fracture spacing (Figure 6).

Assumptions for the minimum resistance step path

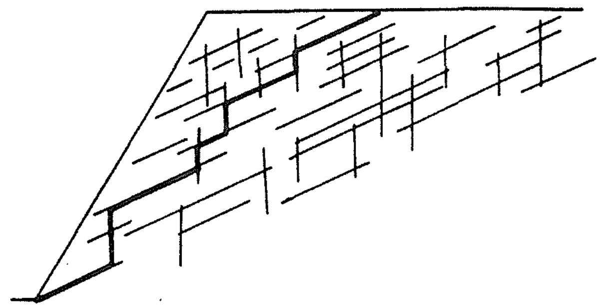

Figure 5. Continuous Step Path

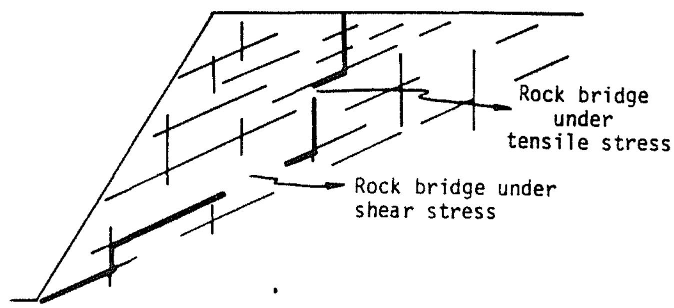

Figure 6. Step Path Separated by Rock Bridges

model are as follows:

1) At least 2 fracture sets characterize a step path geometry. The master joint set is daylighted by the slope, and the cross joint set is steeper than the master set.

2) Fracture set characteristics, including dip, length, spacing, and overlap, can each be described by a mathematical distribution.

3) The fractures are parallel to the slope with the sides unrestrained, resulting in a geometry suitable for 2-dimensional analysis.

4) Under tensile stress, a pre-existing fracture will propagate to intersect the first fracture, but not beyond.

5) A rock bridge is more likely to fail in tension than in shear.

6) Cross joints that do not intersect, but that fall within approximately 5 cm of the end of a master joint, are still taken to allow the step path geometry to continue to the next master joint.

7) The flattest path will be followed, that is, the step path will follow a master joint to the cross joint farthest out (Figure 7). The path will then follow the cross joint until it intersects and continues along another master joint.

INPUT FOR STEP PATH MODEL

Distributions of fracture dip, length, spacing, and

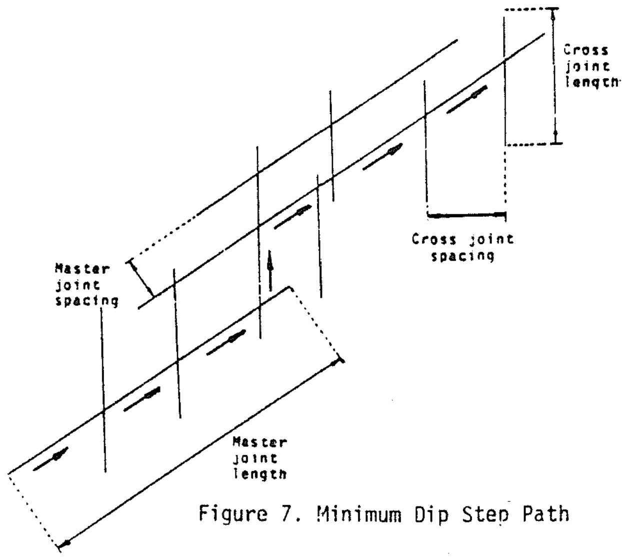

Figure 7. Minimum Dip Step Path

overlap for each joint set are required input. These distributions are generated from data obtained by detail line mapping or by joint set mapping at the site. Studies to date (Call, Savely and Nicholas, 1977) show that these characteristics usually have the following distributions:

1) dip — normal distribution
2) length — negative exponential distribution
3) spacing — negative exponential distribution
4) overlap — uniform random distribution (0 to 1)

Other types of distributions may occur. The only requirement is Assumption 2-- that the fracture characteristics can be described by mathematical distributions.

Additional input parameters for the step path model include:

1) vertical slope height
2) number of step path angles to be generated
3) initializers for random number generator
4) minimum possible spacing for master joint set
5) maximum length of intact rock in shear (approximately 5 cm)

GENERATION OF STEP PATH MODEL

A logic flow chart and a step path diagram (Figure 8) indicate the processes for generating a step path. The points of major decision on the step path are numbered and correlate to the points on the flow chart.

The modeling process begins with the definition of a 2-dimensional (x-y) coordinate system. A dip, a length, and an overlap are sampled from the appropriate distributions of the master joint set. This sampled master joint is placed at (0,0) according to the selected overlap. Then, a cross joint is sampled for dip, length, spacing, and overlap. If this cross joint intersects the master joint, another cross joint is sampled. Resampling continues until a cross joint no longer intersects the master joint. This last, nonintersecting joint indicates that the previously sampled joint is the joint farthest out from the end of the master joint. The step path then follows up the last intersecting cross joint (Assumption 7). Another master joint is subsequently sampled for dip, length, spacing, and overlap. The modeling process continues until a continuous step path ends when either the top of the slope is reached or the first cross joint is beyond the end of the master joint.

Often, the continuous step path height is less than the full slope height, and a new master joint must be sampled for dip, length, spacing, and overlap. The sampled spacing value is stored and used later in the calculation of percent intact rock. The x-y coordinate of the base of this second step path is calculated, and the regular modeling process continues. If the second step path combined with the first step also ends before reaching the full slope height, a third step path is simulated. This process continues until a combination of continuous step paths is produced that reaches the full slope height. Individual continuous step path heights and step path angles are stored, along with the spacings between combined, continuous paths.

For a combined step path height that equals the full slope height, an overall step path angle and a total percent of intact rock are computed (Figure 4). The individual step path heights and angles can be displayed in histograms for greater understanding of the step path geometry and characteristics.

Generally, 100 to 300 step path angles, and percentages of intact rock, are generated. The step path angles and percentages of intact rock usually fit a normal or log normal distribution and are sampled for input to the probabilistic stability analysis (Figure 9).

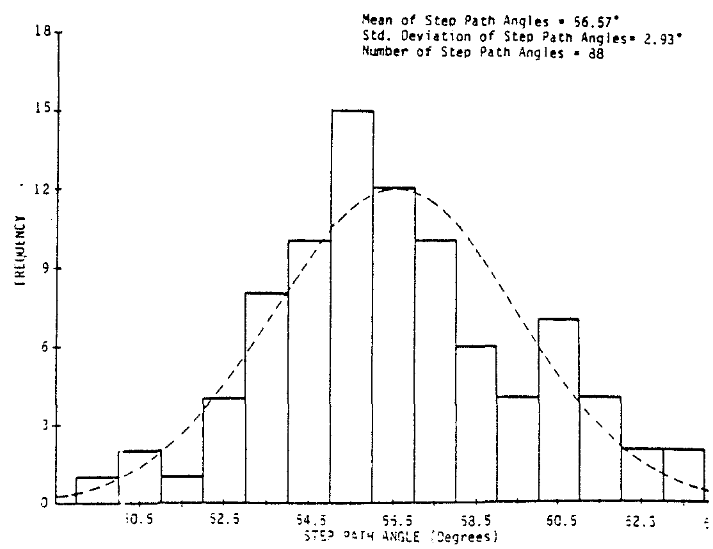

Figure 9. Step Path Angle Distributions

SENSITIVITY ANALYSIS OF STEP PATH MODEL

The step path model was developed as part of the CANMET slope stability study and the slope design for

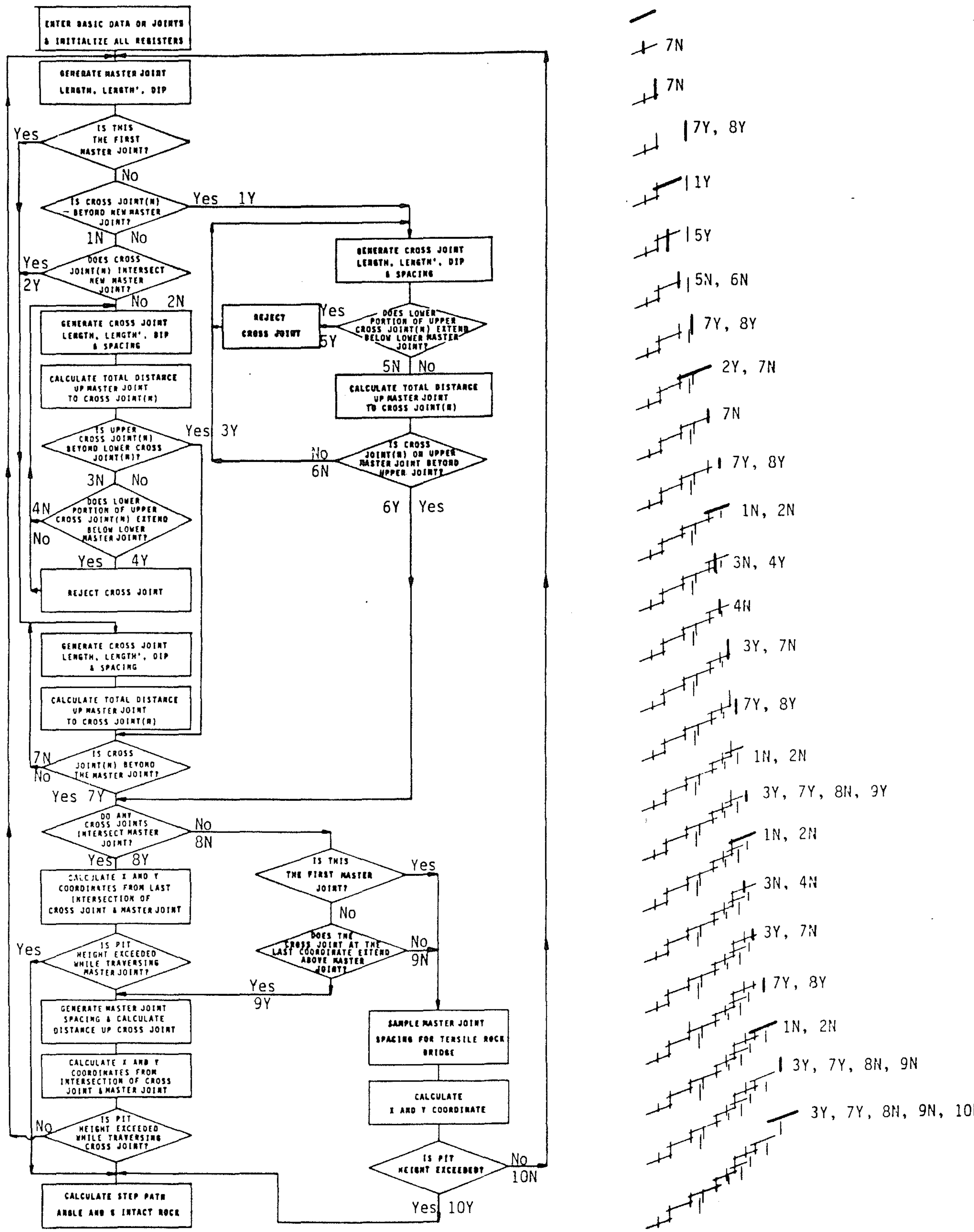

Figure 8. Logic Flow Chart for Step Path Modeling

Bamangwato Concessions' Pikwe mine. The geologic structure orientations in the metamorphic rocks in Bamangwato's Pikwe open pit showed 2 possible step path failure geometries that could affect the hanging wall slopes (Figure 10). An extreme value length analysis run on the "45" set showed a joint was unlikely to have sufficient length to extend from the toe of the slope to the ground surface. The most probable failure mode was interpreted as a step path combination of the "45" set (the master joint set) and either the "north-south" vertical set or the "foliation" (cross joint sets).

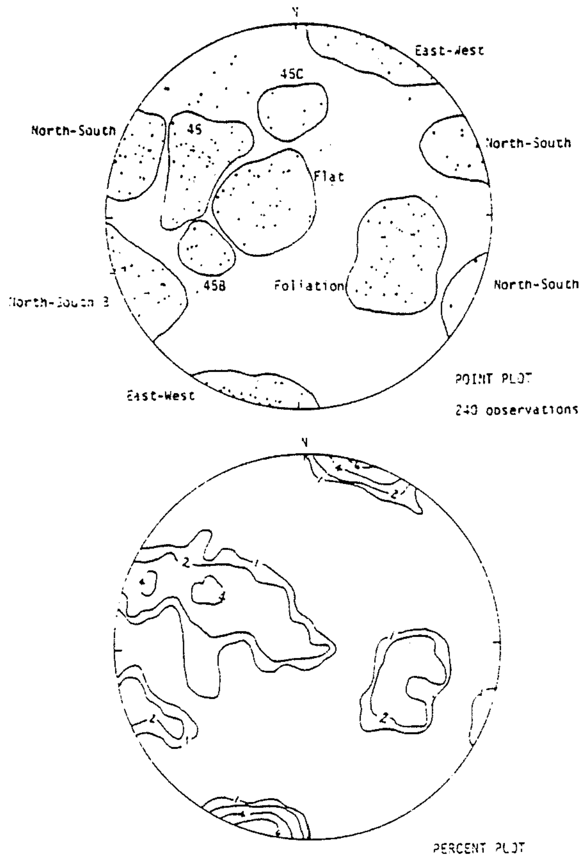

Figure 10. Lower Hemisphere Schmidt Plots of Pikwe Hanging Wall Structure

The combination of the "45" set with the "north-south" vertical set was tested for the sensitivity of step path angle to slope height. The step path geometry was simulated for slope heights of 5 m, 15 m, 25 m, and 75 m. A cumulative frequency plot of the results is shown in Figure 11. In this example, slope heights above 25 m created only small differences in the median for the step path angle (Figure 12). Slope heights less than 25 m had steeper mean step path angles. These results are attributed to the fracture characteristics. A single joint at low slope heights has more effect on the step path angle calculation than a single joint at high slope heights because higher slope heights require a larger number of joints to create the step

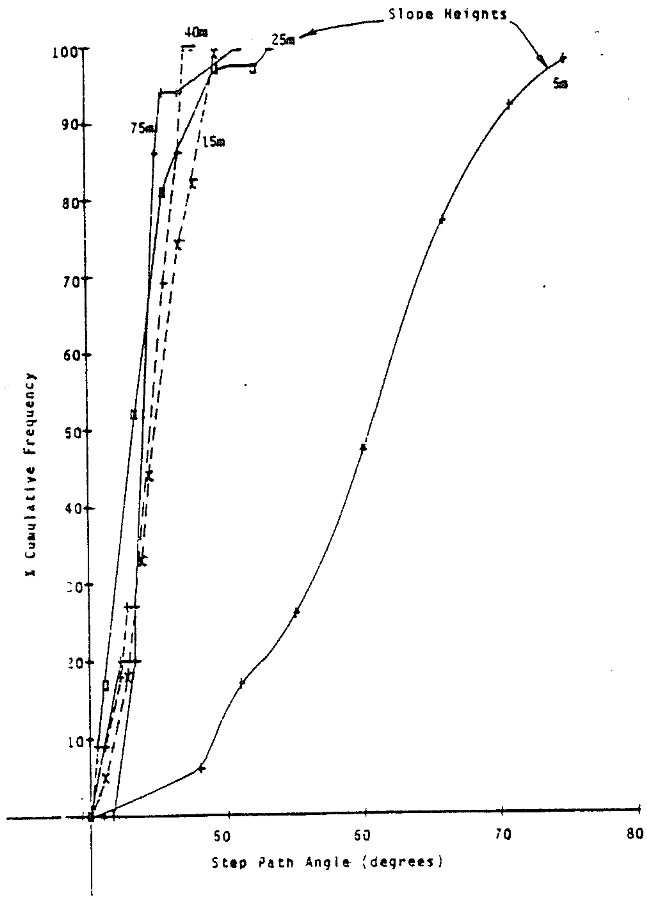

Figure 11. Step Path Angle Cumulative Frequency Curves at Various Slope Heights

path. This also means that the standard deviation of the step path angle tends to tighten with increased slope height as the central tendency of the step path angle is approached. A similar relationship occurs with percent of intact rock; beyond a certain slope height the mean percentage value does not change significantly.

The sensitivity of master joint length and joint spacing distributions on the calculated value for the step path angle was tested for the "45" set combined with the "foliation". At Pikwe, the length and spacing distributions were defined as negative exponential:

$$Y = e^{-\frac{x}{\mu}}$$

where:

Y = dependent variable in cumulative percent
x = length or spacing
μ = mean length or mean spacing

The median ($y = .5$) length and spacing were varied one parameter at a time.

Cumulative distribution curves were produced to

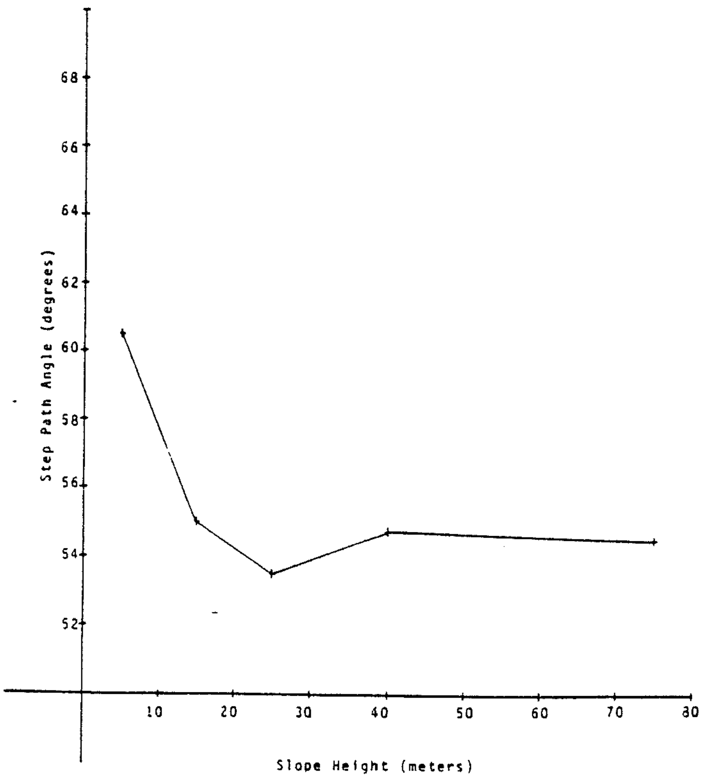

Figure 12. Median Step Path Angle Versus Slope Height

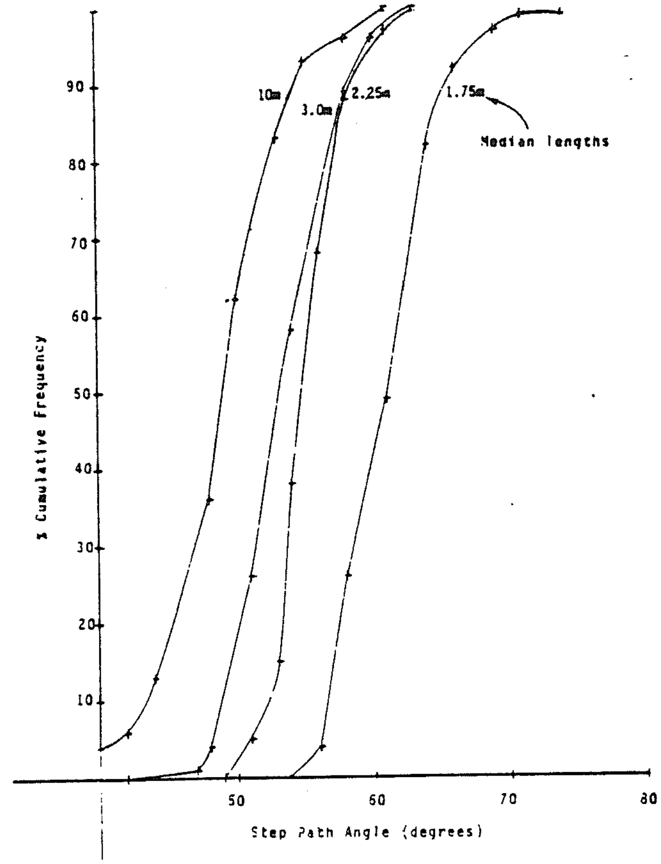

Figure 13. Step Path Angle Cumulative Frequency Curves at Various Median Master Joint Lengths

show the changes in continuous step path angle with changes in either length or spacing of the master joint set (Figures 13 and 14).

This exercise shows the step path angle to be most sensitive to short median lengths (Figure 15). At Pikwe, for median lengths over 3 m, the step path angle is relatively stable. Even doubling the median length to 6 m still gives a step path angle value within 3 degrees of the value calculated at 3 m. Therefore, development of an accurate length distribution appears most critical when short fractures are suspected. The percent intact rock decreases as the mean length increases.

Spacing has a marked effect on step path angle calculations (Figure 16). As the median spacing increases, the value calculated for the step path angle also increases. It is necessary to develop accurate spacing distributions for input to the step path model. The mean percent intact rock generally decreases as the spacing decreases.

FIELD CHECK OF STEP PATH MODEL

A slope stability investigation of Cyprus' Bagdad copper mine was initiated to determine the optimum slope design for pit expansion. A failed step path geometry was apparent at a detail line mapping site. A Schmidt plot of the joints defining the step path was made (Figure 17). Using the distributions of fracture characteristics from the detail line mapping, a step path model was generated. The geometry mapped in the field, and the computer model geometry, compare well (Table 1).

Another step path geometry, located north of the first site, was noticed and mapped in detail. The reciprocal of the estimated mean lengths was used to approximate the length and the spacing distributions of the fracture sets. Monte Carlo sampling of these distributions to generate the step path geometry resulted in a calculated mean step path angle of 40.8°, with a standard deviation of 4.4° and a mean percent intact rock of 0.3%. This mean step path angle value is 4.?° lower than the 45° step path angle measured in the field. However, both the measured step path angle and the mean computer generated step path angle are within one standard deviation of each other. The value measured in the field represents only one measurement from the distribution of possible step path angles. Where this measurement actually occurs in relation to the true mean is a matter of conjecture and may explain the 4° difference between the measured and the computer generated mean step path angles.

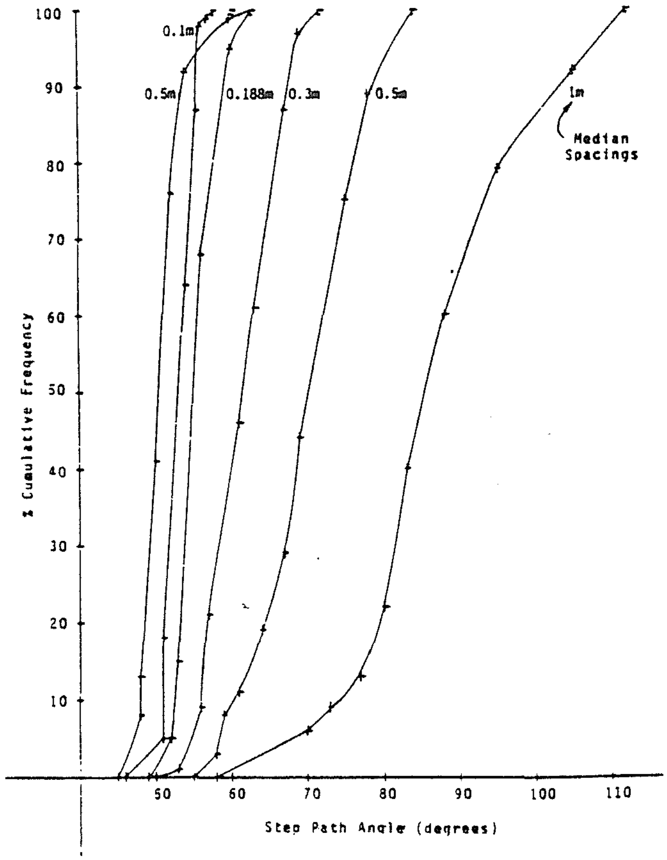

Figure 14. Step Path Angle Cumulative Frequency Curves at Various Median Master Joint Spacings

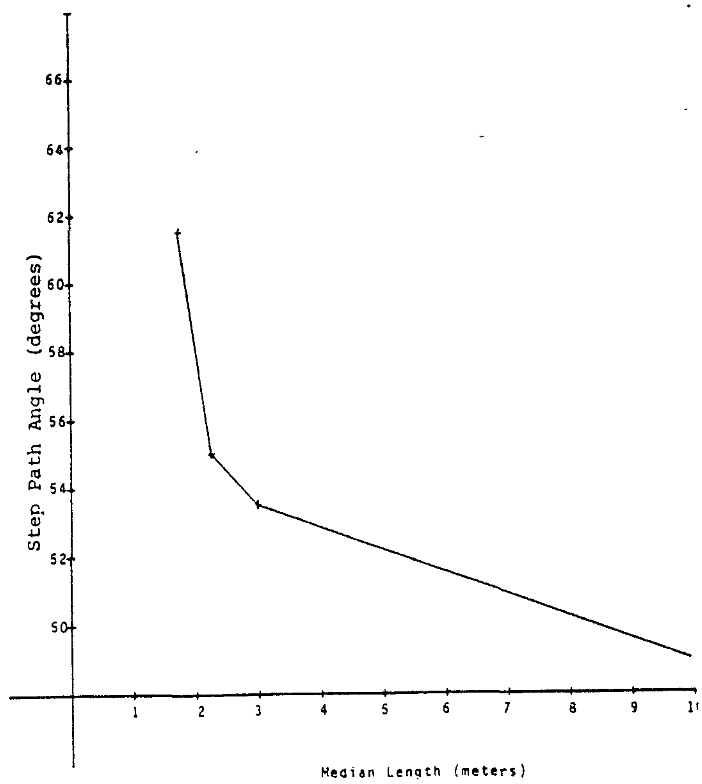

Figure 15. Step Path Angle Versus Median Master Joint Length

Table 1.
Comparison of Mapped with Computer
Generated Step Path Geometry at Cyprus-Bagdad

	Master Joint			Cross Joint			Step Geometry		
	Mean Dip	Mean Spacing	Mean Length	Mean Dip	Mean Spacing	Mean Length	Mean Step Path Angle	S.D. of Step Path Angle	Slope Height
Mapped in Field	43°	1.5'	12'	90°	4'	18'	60°	-	18'
Computer Generated Using Detail Line Structure Data	44.15° SD = 15.33°	1.86' SD = 2.35'	9.20'	90.51° SD = 11.31°	1.32' SD = 1.78'	13.66'	60.02°	8.21°	40'
							60.47°	5.86°	80'
							60.30°	5.65°	120'
							59.19°	4.21°	200'
							59.54°	3.69°	280'
							59.70°	3.28°	360'
							59.69°	2.69°	480'

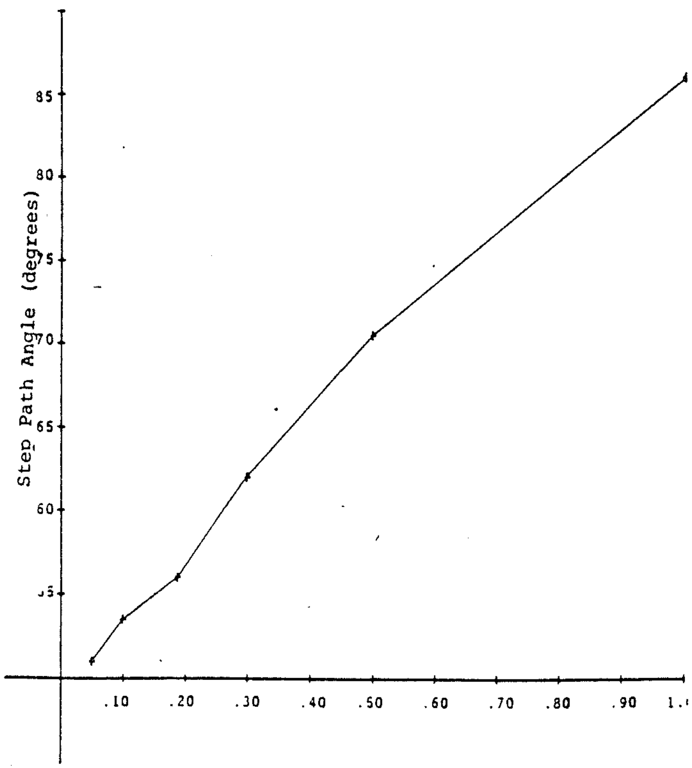

Figure 16. Step Path Angle Versus Median Master Joint Spacing

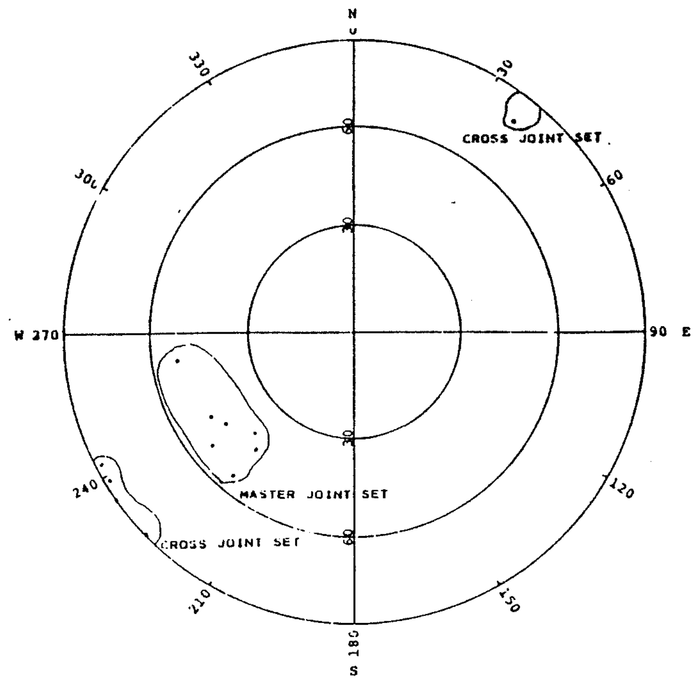

Figure 17. Lower Hemisphere Schmidt Point Plot of Step Path Structure, Bagdad Mine

CONCLUSIONS

In rock slopes were fracture lengths are not sufficiently long to produce full slope failure, a combination of 2 joints can form a step path geometry. It is possible from the distributions of dip, length, and spacing to predict the minimum resistance step path geometry. Distributions of both the step path angles and percent intact rock result from the step path model.

Preliminary field checking at Bamangwato Concessions' Pikwe mine shows the calculation of the step path angle to be sensitive to the spacing distribution. Sensitivity to the length distribution decreases as the slope height increases above about 25 m.

At the Cyprus-Bagdad mine, comparisons were made between observed step paths and computer generated step paths. Agreement within 1 standard deviation of the true value can be expected. It is likely that the model predicts the average step path angle more closely for high slope heights.

Additional work is required to develop a more complex algorithm to predict other than the flattest possible step paths, to include more than 2 joint sets in the model, and to relate stress conditions to the step path geometry. By storing the location of all master joints and cross joints generated, a steeper, more continuous path can be defined. This creates a higher probability of failure, P_F, (Call and Kim, 1978) but the volume of material in the failure is less.

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