NIOSH COMPUTER PROGRAMS FOR BENCH CREST FAILURE ANALYSIS IN FRACTURED ROCK

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SYNOPSIS

A package of bench design programs is being publicly released by the National Institute for Occupational Safety and Health (NIOSH). These programs are designed to provide a probabilistic estimate of the likelihood that various widths of catch bench will be retained. Program modules address the mechanisms of plane, plane step path, and wedge failure. Results are drawn from statistical and geostatistical descriptions of fracture characteristics and other input parameters, and reported as the statistical chance that a given width of catch bench will survive, that is, that a catch bench will remain wide enough to catch rolling and sliding material and prevent such material from posing hazards to miners operating below. The capabilities and application of this software are demonstrated through a case example. Comparing bench width estimates obtained using geologic data with actual widths is a key step in verifying that a program is appropriate for particular site conditions and that proper statistical descriptions of fracture parameters for that site have been developed. Such verification efforts improve confidence, and hence usefulness, of this method for designing future slope benches. Development and release of these programs appears particularly timely given recent progress in photoanalysis methods, which promise to greatly reduce the cost of collecting fracture data.

INTRODUCTION

This paper was developed as part of a research program addressing accidents associated with failure of mine slopes initiated by the Office of Mine Safety and Health, National Institute for Occupational Safety and Health (NIOSH). It describes one part of the program aimed at improving design tools to enhance reliability of catch-bench design, a key safety element of slope design. Associated tasks include identification of hazardous geologic conditions (Girard and McHugh, 2000), continuous (as opposed to point) monitoring of large-scale slope movement (Dwyer, 2003), and development of techniques to warn of small-scale raveling and rock falls (McHugh, 2004).

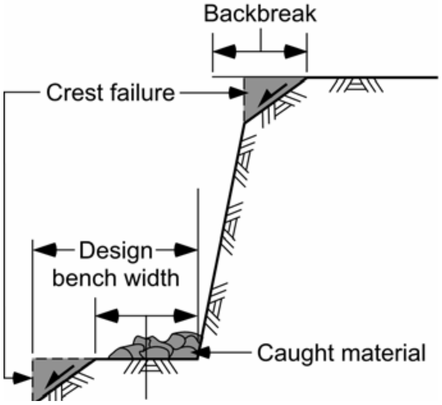

Figure 1: Typical catch bench geometry.

Catch-bench crests are often broken or unstable in surface mines (Figure 1). This is particularly true in highly fractured rock where many joints of limited persistence weaken the crest. Crest stability is important for two reasons. First, benches designed to catch raveling, sliding, and rolling slope material must be wide enough to halt and collect this material. Second, bench crests with low factors of safety may be unsafe to work on, particularly when heavy equipment is being operated near the crest.

Bench crests are often allowed to fail locally (Figures 1 and 2) since perfect catch benches are usually uneconomic. Most failures occur during excavation, but other failures may occur after weathering, vibration, freeze-thaw cycles, etc. These failures can be tolerated so long as a minimum functional bench width is maintained.

The reliability of catch-bench design is best described statistically, particularly when failures involve small-scale, pervasive geologic features. This problem has received considerable atten-tion, including a Ph.D. dissertation developed by one of the authors (Miller, 1982). This work, refined somewhat over the intervening years, is the basis for the set of programs described in this paper. The programs provide a statistical estimate of the probability that bench crests will fail and to what extent and are based on statistical descriptions of fracture set properties. Program modules—Bplane, Bstepp, and Bwedge—are written for plane, step path, and wedge modes of failure, respectively.

Two developments have made updating and release of this software particularly timely. First, computer speed has increased sufficiently to enable interactive and essentially instantaneous execution of these programs on a personal computer. Second, the task of inputting fracture data, traditionally a laborious task conducted by a geologist in

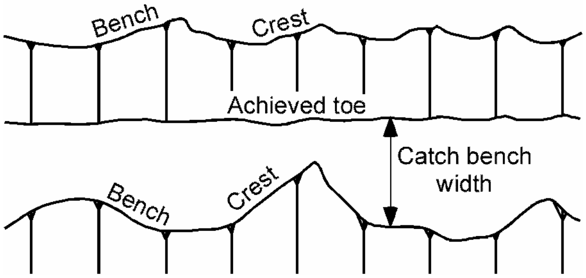

Figure 2: Plan view of realized bench width (after Ryan and Pryor, 2001).

proximity to an outcrop or bench face, is on the verge of a similar revolution. Research on remote and automated fracture mapping, particularly in mines where fracture traces are uncovered, is being pursued by a number of groups throughout the world and appears close to fruition. NIOSH is supporting some of this work at the University of Arizona through its grant program. Taken together, these two developments promise a breakthrough in the practicality and cost-effectiveness of work that was of more academic than practical interest some 20 years ago.

This paper briefly reviews slope ground fall accidents, provides an overview of software capabilities, and then reviews an example application. Detailed case studies, a user's guide, and other references are available from the corresponding author and will be posted on the NIOSH Web site.

BENCH SAFETY

Accident statistics collected by the Mine Safety and Health Administration (MSHA) have shown that loose material moving down slopes and bench failures pose significant safety hazards to miners. From 1995 through June of 2004, surface ground control accidents have contributed to 44 fatalities. Of these, 33 accidents occurred in metal/non-metal or sand and gravel mine,s while the remainder took place at coal mines. As can be seen in Figure 3, approximately 55% of the fatalities (24 out of 44) were a direct result of highwall failures or individual rock falls striking workers in the pit below. Failures of unstable ground or highwall benches beneath operating equipment are also a major concern.

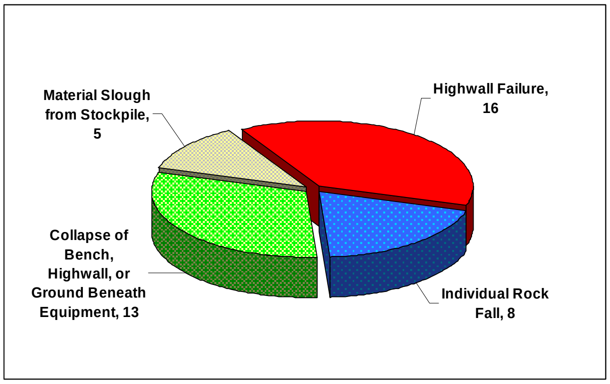

Figure 3: Number of deaths attributed to highwall failure and rock falls, 1996-2004.

The importance of bench integrity is well illustrated by two of these accidents. One occurred on the evening of October 5, 1998, early in the night shift. A large piece of rock fell 6 m from the highwall to a safety bench, split, then fell an additional 17 m onto the cab of a drill, destroying the cab (Figure 4). The rock measured about 2 m long, 2 m wide, and 1.2 m thick.

Another fatal accident occurred on the morning of September 2, 1998, when a 67-year-old bulldozer operator with 40 years of mining experience was maneuvering his Caterpillar D8 along a bench in a limestone quarry in Oregon. The outside edge of the bench collapsed, and the dozer rolled sideways 2-1/2 times to the bottom of the pit, coming to rest on its side. The dozer was equipped with rollover protection and a seat belt. The operator was not wearing the seat belt and was fatally injured.

Figure 4: Cab crushed during slope failure (MSHA fatalgram, www.msha.gov).

SOFTWARE CAPABILITIES

The Bplane, Bstepp, and Bwedge programs are designed to assess the extent of small-scale failures along the crest of benches where rock blocks slide along natural fractures (as plane shears and tetrahedral wedges). Failure along a joint set complicated by cross jointing and failure of small bridges of intact rock (a step path) in a plane failure geometry is also considered.

These programs are ideal for cases where large numbers of discontinuities of limited extent can be grouped into fracture sets. They also assume that discontinuity characteristics, including length, spacing, and dip, can be reasonably described by statistical functions that are consistent throughout a design sector.

Plane Shear Failure

A plane shear failure occurs when a block defined by fractures and bench geometry slides along a single failure surface. The plane shear failure mode is said to be “kinematically viable” if the average strike is parallel or nearly parallel to the strike of the slope face and the dip is flatter than the dip of the slope face (Hoek and Bray, 1981, p. 150). Failure will extend laterally along the bench to cross-cutting fractures, changes in bench strike, and/or newly created fractures that provide 'release surfaces' (Figure 5). It is assumed that these surfaces will provide little resistance to sliding (that is, failure), so they can be neglected in assessing the stability of the block.

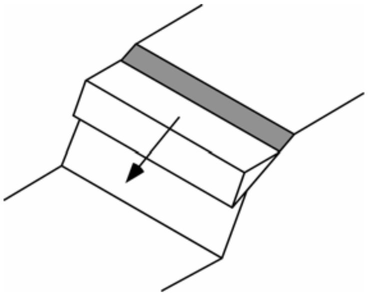

Figure 5: Idealized plane shear failure.

Step-Path Plane Failure

The availability of a single sliding surface long enough to permit plane shear failure may be comparatively rare in slopes cut in rock in which single fractures are short. However, a more complex failure path comprised of multiple fractures is much more likely to provide the continuous path needed for sliding. From a two-dimensional standpoint, the most likely situation in practice is that two conjugate fracture sets form a stepped geometry (Jaeger, 1971). Both sets strike parallel or nearly parallel to the strike of the slope, and sliding occurs on the flatter dipping set. Figure 6 illustrates typical step path geometries in a fractured rock slope.

Step path failure geometries typically have lower probabilities of stability than plane shear geometries of similar scale. The differ-ence lies primarily in the treatment of rock bridges. Bridges are considered to prevent absolute failure in the plane shear model, but are checked for failure in the plane step path model. Experience has shown that for 12- to 20-m-high benches cut in crystalline rock with a tensile strength of 500 to 2,000 t/m^2, the probability of sliding is nearly zero when the fraction of intact rock exceeds approximately 0.08. Thus, where bridges constitute 8% or less of the total length, step paths that include bridges are likely to have a higher risk of failure than comparable plane shear paths. Failure becomes increasingly unlikely as the proportion of bridge length on the failure surface approaches 8%. The Bstepp program considers failure to be impossible if the proportion exceeds 8%.

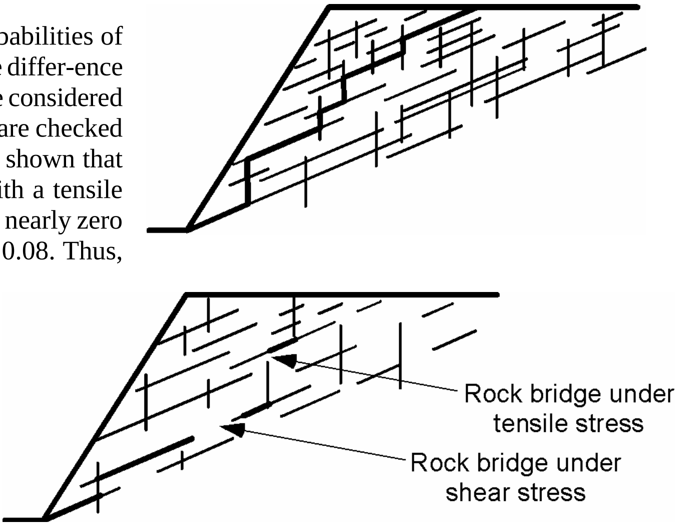

Figure 6: Examples of step path geometries in a rock slope (from Call and Nicholas, 1978). *Top,* Continuous step path; *bottom,*. discontinuous step path with intact rock bridges.

Wedge Failure

Wedge-shaped blocks often are created in benches by two fractures that the intersect both the bench and slope surfaces (Figure 7). Failing wedges move along the line of intersection formed by the fractures, maintaining contact on each fracture plane. In the absence of pore pressure, sliding will occur only when the inclination of the intersection line is steeper than the friction angle of the fractures. The steepest intersection lines are usually those that bear nearly perpendicular to the slope face.

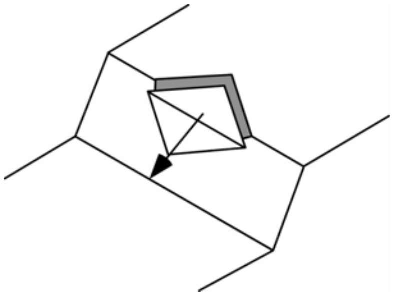

Figure 7: Idealized wedge failure.

Program Input and Operation

Required geotechnical input falls into three main classes: fracture-set geometry, fracture shear strength, and rock mass properties. Because intact material is assumed to remain intact, the only rock mass properties considered are density and groundwater level. Any planes of weakness within the rock mass can be considered fractures with cohesion. Most program input is in the form of statistical parameters for variograms and appropriate probability distribution functions, rather than constants.

The essential core of these programs is computation of the probability of sliding for a given potential failure mass. The fracture geometry of that failure mass is constructed with spatial rock-fracture simulations. For instance, Bplane 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 by 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. The Bstepp program conducts plane simulations for step paths in a similar manner. The Bwedge computer program analyzes three-dimensional wedges by simulating fractures from two fracture sets and testing whether they form unstable wedges.

The factor-of-safety (SF) equation used to evaluate the probability of sliding is assessed with the point estimation method for the rock slope failure mode (such as plane shear, step path, or wedge). This method provides reliable estimates of the mean and standard deviation of the factor-of-safety probability distribution (Miller et al., 2004). A gamma probability density function is used for modeling this probability distribution, because it allows only positive values and is flexible enough to provide symmetrical shapes and right-skewed, exponential-type shapes for the factor-of-safety distribution. This distribution can be integrated numerically from 0 to 1 to obtain the probability of sliding (P_S = the portion of the factor-of-safety distribution where SF ≤ 1.0). The overall probability of failure, P_F, for the potential slope failure mass is the joint probability that the rock discontinuities are long enough to allow kinematic failure (P_L) and that sliding occurs along the rock discontinuities (P_S). That is, $P_F = P_S P_L$.

INTERPRETING ANALYSIS OUTPUT

Program results are reported as a probability that various bench widths will be retained for a given failure mode (that is, a particular failure mechanism that involves a particular set of features). The probability of retaining a particular bench width will be the joint probability of individual probabilities calculated for each failure mode. Joint probability is calculated by multiplying individual probabilities and applies individually to a short section of bench, not the entire bench. In the case of wedge failure, the probability gives the odds that any section of a bench as long as it is high will not trigger any failures that reach deeper into the bench width than a particular value. In other words, the proportion of bench segments that lose a section of the bench as wide as the length of the segment will be 1 minus the joint probability of retention. For example, a 0.80 probability of retaining 4-m-wide catch bench means that 80% of the bench run will retain a width of at least 4 m.

The probability of losing all the bench is also an important consideration. Not only do such failures eliminate any capability for catching loose material, but they may undermine overlying benches, leading to larger-scale failures. Thus, the design of overall slope angles should provide for very high probabilities (greater than 0.95) of retaining bench widths less than 1 m.

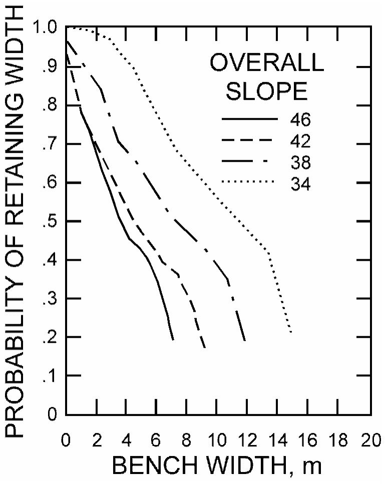

Figure 8: Typical results showing probability of retention for various bench widths and slope angles.

Results are typically plotted as a curve relating the probability of retaining bench width versus bench width. Individual curves are calculated for each bench slope angle. Since bench geometry has a direct influence on the overall slope angle, similar plots can be made for overall slope angle (Figure 8). The relationship between bench geometry and overall slope angle can be expressed as—

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

where A = overall (average) slope angle; B = bench face angle; H = vertical height of bench; and W = horizontal width of bench. For example, if H = 15 m, W = 8 m, B = 64°, then $A = \arctan\{1/[(8/15) + (1/\tan 64°)]\} = 44°$.

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. For typical applications, results from bench simulations will guide the engineer in selecting the overall slope angle to minimize extensive loss of catch-bench width and thus minimize subsequent rock fall 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-bench width has been specified.

SOFTWARE TESTING AND FIELD VERIFICATION

Verification of the software was an important part of this work and was pursued on two levels. The first level was simply verification that the calculated results were mathematically correct and numerically accurate. At this level, verification included the author's substantial experience with the program and his ability to recognize unreasonable results. Verification included dozens of parametric studies and results of unpublished 'stress tests' conducted by students at Montana Tech of the University of Montana, the University of Arizona, and the University of Idaho. These student beta testers found new and interesting ways to crash the programs, often through inappropriate and unrealistic inputs. This experience led to the implementation of screens to evaluate reasonable input parameters and refinement of numerical procedures.

Verification also included comparisons of program predictions based on local fracture set characteristics with actual bench crest failure patterns. This mode of verification has the advantage of testing assumptions underlying the code as well as testing whether the assumptions underlying the programs were sufficiently close to real conditions to provide insights into design decisions. This has been pursued through collection and development of case studies (for example, Ristau, 1994; Whyatt et al., 2004). One of these, which provides a good example of Bwedge use, is summarized in the remainder of this paper.

Overall, verification of the accuracy and usefulness of this software has been the cornerstone of this research. Since NIOSH cannot warranty this software (like any software publisher), case studies and other verification efforts are the user’s assurance that reasonably accurate results are produced.

LUZENAC CASE STUDY

This study was undertaken to demonstrate use of the Bwedge computer program in an evaluation of wedge failures in the bench of a mine pit slope. Work included collecting and analyzing geologic data, comparing expected and observed bench crest performance, and conducting sensitivity studies of fracture and bench design parameters. The study was conducted by students at Montana Tech in cooperation with Luzenac America’s Yellowstone Mine and NIOSH.

Luzenac America’s Yellowstone Mine is located southwest of Ennis, MT, along the east slope of the Ruby Mountains. Presently the mine consists of two approximately 90-m-deep open pits. The study focused on a section of a single bench within the north wall of the south pit in hydrothermally altered dolomite of Precambrian age. The dolomite is heavily fractured, with the fractures forming at least four major sets.

Five representative wedge failures in this area were mapped and described by the mine geologist. Descriptions included fracture orientations and conditions. Three of these wedges had clearly moved, but not by much. Remnants of two other wedges that had failed previously were not seen.. Two sets of fractures delineating these and similar wedges were mapped by the student teams along a 90-m-long scan line on the study bench using tape and a Brunton compass. The first of these fracture sets was labeled the 'foliation' set and formed the left side of the wedges. The second and sparser of the sets was the 'joint' set.

A number of rock samples collected during the field mapping were tested to determine the frictional strength of the fractures and rock density. Tilt tests of friction angle were conducted in the field using rock fragments found along the bench. These tests showed natural fractures had an average friction angle of 38.7°. Samples were also taken to the Spokane Research Laboratory and cut to determine the friction angle of saw-cut surfaces. Laboratory tests on these surfaces showed an average friction angle of 30.7° with a range of from 25° to 34°. Rock density tests on three rock fragments showed that average density was 2.76 g/cm^3.

The characteristics of each fracture set were described statistically and geostatistically for analysis by the Bwedge program. The students developed a full set of parameters describing variability of fracture dip direction, dip, spacing, persistence, and waviness from the mapped fractures. Although the defined fracture sets were not ideal for this purpose and included a wider range of orientations and fewer fractures (especially for the joint set) than would be desired for a full-blown characterization study, the data were sufficient for the students to estimate all the required parameters. These values are listed in Table I.

Table I: Fracture set characteristics

Parameter	Mean	Standard deviation	Nugget	Range
Foliation joint fracture set characteristics				
Dip direction, deg	108.7	11.70	80.00	16.56
Dip, deg	72.35	8.35	62.08	18.92
Persistence, m	2.63	1.82	2.54	17.62
Spacing, m	1.16	1.21	1.05	6.20
Waviness, m	Minimum	1.0	Maximum	12.0
Joint fracture set characteristics				
Dip direction, deg	214.8	18.44	247.93	4.78
Dip, deg	51.80	13.87	148.66	4.72
Persistence, m	3.81	3.07	5.05	6.38
Spacing, m	1.89	2.13	2.62	5.27
Waviness, deg	Minimum	0.0	Maximum	22.0

A first-cut analysis of wedge stability was developed as shown in Figure 9. Bench slope, average fracture-set orientation, and the wedge formed by 'average' fractures were plotted to show that the wedge formed by this set daylighted in the bench face. The plunge of the fracture set intersection beneath this wedge was found to be steeper than a 35° friction angle circle, which is a typical joint friction angle. Thus, failure of such a wedge would be likely. Plane failure on the joint set is also possible, but its apparent dip in the bench cross section is flatter than the plunge of the wedge fracture plane intersection. Thus, wedge failure will be preferred where both are possible. This tendency is evident in the predominance of wedge failures observed in the field.

These input values overestimated retention of the bench crest, but correctly matched retention of portions of the bench further from the crest (Figure 10). This result is surprisingly good, especially considering that it did not incorporate extensive disruption of the outer portion of the bench by blasting, as noted by the mine geologist.

An attempt was made to explore the effects of blasting on the bench model by weakening fracture strength. The friction angle was decreased from in situ to saw-cut values, and the stabilizing influence of fracture waviness was removed. Bwedge runs using these weaker values more closely fit observations for the outer bench, but also underestimated retention deeper into the bench, which is less affected by blasting. This suggests that the student's set of parameters may well describe fracturing in situ prior to blasting. To the extent that this proves to be the case, the overall slope angle could be steepened through more careful blasting. If all blasting effects were removed, and a 90% probability of maintaining a minimum bench width was desired, benches could be narrowed by a full meter, which would steepen the overall slope angle by about 5°, to roughly 45°.

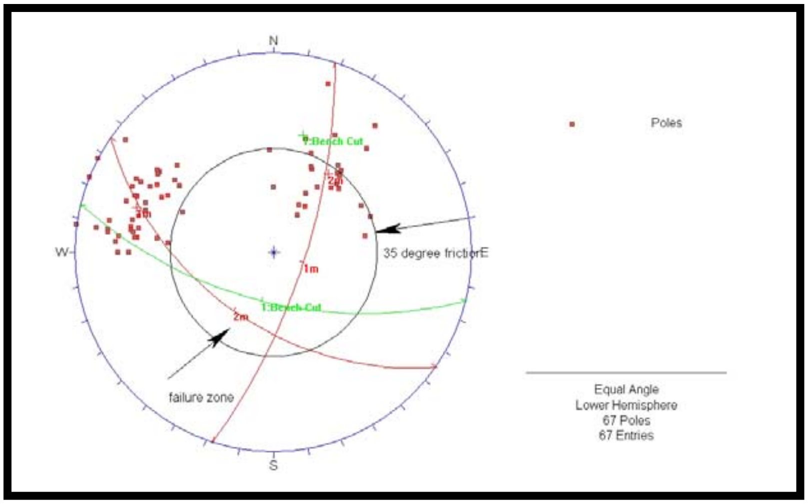

Figure 9: Stereonet plot of joint poles, joint set average orientation, and pit slope.

Of course, the level of confidence needed for such a design study requires a somewhat larger field data set. Other operational and safety factors beyond the scope of this software should be considered. However, even with a limited data set, this case makes clear the power of this software to add new insights and precision to the design process.

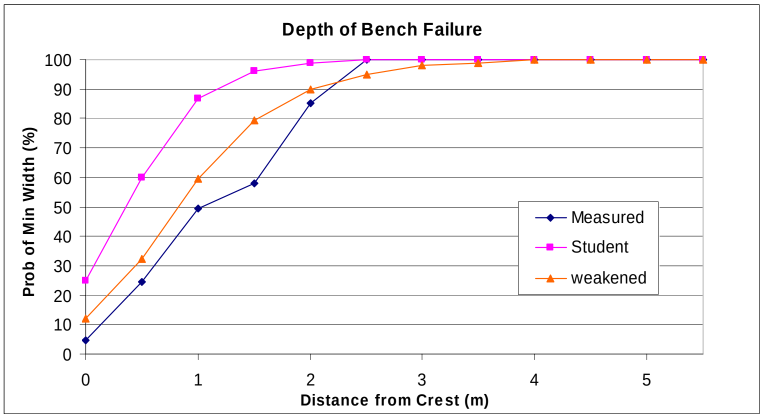

Figure 10: Estimated probability of stability at various depths into the bench crest based on measurements, a model using the student set of fracture parameters, and a set of weakened parameters.

SUMMARY AND CONCLUSIONS

Computer software for a PC platform was developed to analyze bench crest failures stochastically in slopes excavated in heavily jointed rock. Three programs in the package analyze plane, plane step path, and wedge modes of failure using statistical descriptions of fracture sets and other relevant parameters. The programs are based on routines developed some 20 years ago and look particularly useful in light of recent advances, such as interactive execution of computations and automated fracture mapping, which promises to reduce the expense of fracture mapping, particularly where fractures are exposed in mine slopes and road cuts. The software and related manuals and case studies are available from the corresponding author and at the NIOSH Web site. Extensive efforts have been made to verify program operation and check results against real cases. However, complete confidence in the software requires verification under local conditions. As this confidence is gained, these programs should be valuable tools for robust designs of safe catch benches.

ACKNOWLEDGEMENTS

Extensive validation as well as the case study described in this paper were undertaken as a class project for Montana Tech's GeoE 5150 Slope Stability Analysis and Design course during the fall semesters of 2000, 2001, and 2002. Luzenac America provided a field test site at its Yellowstone Mine, an open-pit talc mine near Cameron, MT. Mike Cerino, Luzenac geologist, provided invaluable support, particularly for the final 2002 field campaign and follow-up data collection. We gratefully acknowledge the efforts of Dr. Mary MacLaughlin, the course instructor, and her students—Dean Brower, Russell Sheets, Zachary St. Jean, Whit Adams, Kathryn Clapp, Jeremy Dierking, Meagan Duneman, Ben Johnston, Jennifer King, Renee Kockler, Tye Lasich, and Nate Majerus. The students collected field data, analyzed results, and identified faults in the Bwedge program.

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