DFNE 2014 – 260

Preliminary selection of optimum bench face angle using uniformly distributed wedges

Langford, J.C.
Hatch Mott MacDonald, Vancouver, British Columbia, Canada
Corkum, B. and Curran, J.H.
Rocscience Incorporated, Toronto, Ontario, Canada

ABSTRACT: Small scale wedge failures, typically defined by joints, bedding planes and foliations, have a direct influence on the selection of an appropriate bench face angle and bench width. Such failures pose a significant safety hazard for the lower working levels and therefore must be considered during design. While Discrete Fracture Networks (DFNs) can be used to assess the stability of bench-scale wedges, there is often limited information on the spatial distribution of discontinuities in the early design stages. This paper presents a new kinematic approach to bench design that utilizes a simplified model for joint spacing in order to assess the stability of bench-scale wedges for a range of bench face angles. To do so, two design approaches are available: a managed approach to slope design and a quantitative hazard assessment. By using the managed approach, an optimum bench face angle is determined by assessing the number of failed wedges and minimum bench width required for each bench face angle and applying a confidence level. For a quantitative assessment, the likelihood of forming different wedge sizes (Probability of Occurrence) and the likelihood that such wedges will slide (Probability of Sliding) are calculated, providing an estimate of the Probability of Failure for various back break distances. Both of these approaches provide valuable information on bench loss and assist the user in selecting an optimum bench face angle. To demonstrate this, an assessment of the bench face angle at the Yellowstone Mine in Montana was completed.

1. INTRODUCTION

Slope instabilities in open pit mines present a significant design challenge in geotechnical engineering. Such failures can be controlled by major structures (e.g. faults or lithologic contacts), which have sufficient lengths to affect overall stability of the open pit, or by more numerous, smaller structures such as joints, foliations and bedding planes. While a number of tools are available to analyze potential large scale slope failures (such as limit equilibrium and finite element techniques), using such methods to design an open pit mine slope may not account for small scale instabilities caused by bench failure. Small scale failures have a direct influence on the selection of an appropriate bench angle and bench width and therefore must be considered when designing an open pit.

While discrete fracture networks (DFNs) provide an advanced tool for the assessment of block stability, there is often insufficient data at the early stages of design for such a rigorous analysis. At such a stage, it is typical that only orientation and persistence information exist for the major joint sets. By assuming a spatial distribution for the wedges across the slope face, kinematic analyses coupled with a random sampling approach can be used to obtain an initial estimate of bench-scale stability. The number of failed wedges and spill width can be calculated for a set bench face angle and confidence level to determine the useable bench width. By comparing the results from a number of bench face angles, the optimum bench face angle can be obtained by using a managed approach to slope design or employing a quantitative hazard assessment.

Such a solution method has been developed by *Rocscience* and incorporated into the most recent version of the program *SWEDGE*. This method is based on the probabilistic analysis approach described by Miller [1], Miller et al [2], Carvalho [3] and the bench design programs by the National Institute for Occupational Safety and Health (NIOSH) outlined in Whyatt et al [4]. Spill radius statistics are also estimated based on the equations provided in Gibson et al [5].

This paper reviews the development and implementation of this approach. To demonstrate its usefulness, a bench analysis is presented for an open pit mine that focuses on the determination of the optimum bench face angle.

2. BENCH DESIGN

The bench plays a critical role in an open pit mine as it limits rockfalls from upper levels of the pit slope from reaching the operational areas in lower levels. In order for the bench to be functional, the usable width must be sufficient to catch spillage from the benches above.

In bench design, the “usable width” is defined as the total width of the bench minus the bench width lost during excavation. The amount lost is also referred to as the "backbreak distance" and is typically caused by planar or wedge failure along the crest. This is shown in Figure 1. This analysis focuses on wedge failure as this is typically the most common bench-scale failure mode.

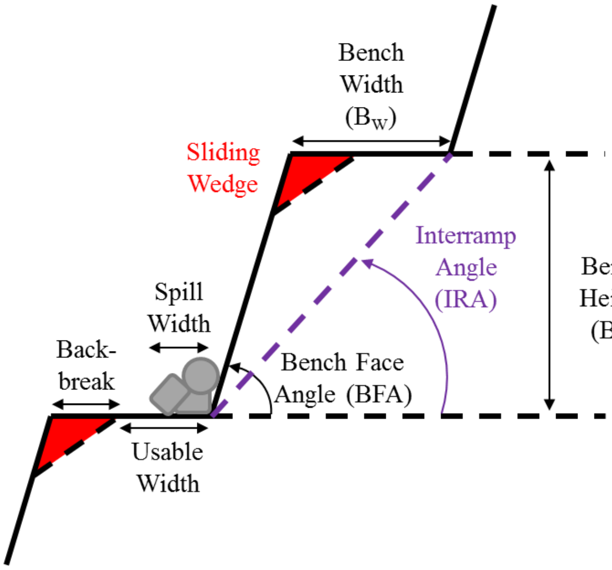

Figure 1: Typical catch bench geometry.

2.1. *Backbreak Distance*

The backbreak distance is defined as the perpendicular distance from the slope crest to the back of a failed wedge, as shown in Figure 1.

Wedges are formed when two joints intersect, resulting in the creation of a block of rock. This block has the potential to slide if the plunge of the line of intersection of the wedge is shallower than the bench face angle. The Factor of Safety (FS) approach can then be used to determine the stability of the wedge by dividing the forces resisting wedge movement by those driving wedge movement. This is shown in the following equation:

$$\text{Factor of safety} = \frac{\text{resisting forces (e.g. shear/tensile strength, support)}}{\text{driving forces (e.g. weight, seismic, water)}}$$

If the driving forces are greater than the resisting forces, the wedge will have a FS < 1 and is expected to fail. Conversely, if the resisting forces are greater (FS > 1), the wedge is expected to be stable. A FS = 1 is considered the critical limit state.

For variable orientations and joint shear strength, a distribution of backbreak distances exists for a given bench face angle. By specifying a confidence level, a representative backbreak distance can be selected for the purposes of design, which will further provide an estimate of the useable bench width. This confidence level will depend upon the level of design required and the potential risk associated with wedge failure.

2.2. *Spill Width*

After a wedge fails, it falls down the bench face and the resultant material accumulates on the bench below. The spill width is therefore defined as the perpendicular distance from the slope toe to the edge of the pile of failed material. This is shown in Figure 2.

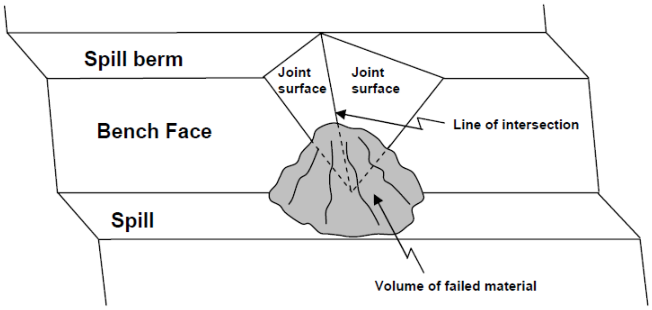

Figure 2: 3-D illustration of wedge failure [5].

While a firm understanding of fracture mechanics and block trajectory are needed to determine the actual spill width, Gibson et al [5] provides a method for estimating this parameter based on the geometry of the wedge and the bench face angle:

$$R = \sqrt[3]{\frac{6KV}{\pi} \times \frac{\tan\alpha - \tan\phi}{\tan\phi \cdot \tan\alpha}} \qquad (1)$$

$$R = \sqrt{\frac{6KV}{L} \times \frac{\tan\alpha - \tan\phi}{\tan\phi \cdot \tan\alpha}} \qquad (2)$$

where:

R = spill width (m)
K = swelling factor (assumed to be 1.5)
V = volume of failed material (m^3)
L = length of wedge (m)
α = bench face angle (degrees)
ϕ = angle of repose of failed material (assumed to be 38 degrees)

Based on Gibson et al [5] the lesser of the two calculated values for spill width is deemed to be the most realistic.

To be effective, the usable width must be greater than the spill width. Similar to the backbreak distance, a distribution of spill widths will exist so a confidence level can be assigned to determine a representative design value for the spill width. Provided the usable width is greater than the spill width for a given bench angle, it can be assumed that the bench width is sufficient.

2.3. *Optimum Bench Face Angle*

As the size of the wedges is controlled by the slope geometry, the usable and spill widths are expected to change as the bench face angle changes.

Shallower bench face angles will typically result in fewer failed wedges (wedges with a more shallow line of intersection will not fail) and reduce the volume of those wedges that do fail (thus decreasing the spill width). While reducing the bench face angle can be used to improve bench stability, it will also increase the overall pit angle and size, meaning a higher stripping ratio will be needed. The goal of bench design is therefore to determine the "optimum" orientation, which is defined as the steepest interramp angle that can be achieved while preserving adequate bench widths.

To select the optimum bench face angle, a number of individual angles must be assessed and compared. Typically, the following design parameters are considered in this comparison: (a) the likelihood of a wedge of any size failing, (b) the likelihood of different backbreak distances (referred to as the Probability of Occurrence) and (c) the likelihood that a wedge with a given backbreak distance will slide (referred to as the Probability of Sliding). When the Probabilities of Occurrence and Sliding are multiplied together, an estimate of the Probability of Failure is obtained for a given backbreak distance, which can be used to assess the risk along the slope.

3. PROPOSED DESIGN APPROACH

To assist in the selection of an optimum be bench face angle, *Rocscience* has developed a bench design approach that uses a probabilistic kinematic analysis to assess the stability of bench-scale wedges over a range of bench face angles. By making an assumption regarding the joint spacing and therefore the distribution of wedges throughout the slope face, an initial estimate of the optimum bench face angle can be obtained.

This approach has been incorporated into the newest version of the program *SWEDGE* and is based on the work by Miller [1,2], Carvalho [3] and the bench design programs by the National Institute for Occupational Safety and Health (NIOSH) [4].

3.1. *Bench Geometry*

To conduct a bench design analysis, the overall bench geometry must first be established. This includes defining the bench height, the range of bench face angles to be considered and the catch bench width.

The bench width is defined using either a fixed bench width or fixed interramp angle, the choice of which depends on the design constraints. By using a fixed bench width, the interramp angle will be calculated based on the bench face angle being considered. This analysis would be used where the width of the bench is defined by an operation requirement. Conversely, the interramp angle can be kept constant, which means that the bench width will change for each bench face angle. In this case, the minimum bench face angle must be greater than the interramp angle to ensure a bench is created.

3.2. *Joint Characteristics*

To define the wedge geometry, the orientation (strike and dip or dip and dip direction) and length (trace length or persistence) of the dominant joint sets must be determined. In the program *SWEDGE*, only two joint sets are considered at a time (referred to as Joint Set 1 and Joint Set 2), however a combination approach involving all joint set pairs can be used where a number of dominant joint sets exist.

Given the complex history of formation of the rockmass, natural variability is present in the joint parameters. A sufficient number of joint measurements must therefore be completed during site investigation to properly characterize the variability in the major joint planes. In doing so, probability distributions can be used to represent these parameters. Random sampling from these distributions ensures that each possible combination is assessed according to the relative likelihood.

3.3. *Joint Spacing Options*

As it is assumed that the spatial location of joints along the bench face is not known for this design approach, an assumption must be made regarding the distribution of wedges in order to assess the bench performance. For this design approach, two joint spacing options are considered: large or small joint spacing. These options are discussed in the following paragraphs and summarized in Figure 3. Both approaches can be used for a conservative assessment (infinite joint length) or with a finite joint length (user defined trace length or persistence).

3.3.1. *Large Joint Spacing*

With the large joint spacing option, it is assumed that there is only one trace of Joint Set 1 and one trace of Joint Set 2 on the slope face. The point of intersection of the two joint planes on the slope face is randomly located somewhere between the toe and crest of the slope, resulting in a uniform distribution of wedge height (measured vertically from this intersection point of the two joints to the slope crest).

Once the intersection point has been selected, orientations for each joint are determined. If a valid wedge forms, the required joint length for the wedge to form (J_R) is calculated for each joint and compared to the deterministic or sampled joint length from user inputs (J_S). If the required length exceeds the sampled length, the wedge is considered invalid, otherwise the wedge is valid and the factor of safety is calculated.

Figure 3: Analysis approaches for a finite joint length.

It is important to note that if the spatial location of the joints is not uniformly random, the wedge height should not be uniformly varied as this could lead to an under- or over-estimation of the probability of failure. This approach is considered to be a lower bound solution when it comes to probability of failure, as the spacing and persistence condition will limit the formation of wedges.

3.3.2. *Small Joint Spacing*

For the Small or Ubiquitous joint spacing model it is assumed that there is spacing (repeated joints) associated with the Joint Set 1 and Joint Set 2. As such, there is no longer one wedge but a number of possible wedges that can form on the slope. If a wedge cannot form at a certain location due to the required joint length exceeding the sampled joint length ($J_R > J_S$), then a wedge higher up the slope face, which meets the persistence conditions, can form.

As such, this model will automatically scale down the wedge size until the persistence conditions are met. So a wedge is almost always formed in each simulation if the geometry of the joints and slope creates a kinematically feasible wedge. Its size is dependent on the sampled persistence and the geometry of the bench.

The Small Joint Spacing option is an upper bound solution for probability of failure, because a wedge will always be created, independent of any spatial location of the joints on the slope face. The only thing that limits the size of the wedge is the geometry of the bench and the persistence of the joints.

3.4. *Determining the Optimum Bench Angle*

Once an appropriate joint spacing option has been selected, a Monte Carlo approach is used to randomly sample the joint orientations, location of the point of intersection (for the large joint spacing option) and joint length values. Invalid wedges are those that either cannot form due to an invalid line of intersection (dipping into the face or exceeds the slope geometry) or wedges that do not comply with the required persistence values. For each valid wedge, a kinematic analysis is performed to determine the FS value.

Each wedge is also classified according to its backbreak distance. To do so, the bench width is divided into a series of "Backbreak Cells", similar to the procedure outlined by Miller in [1,2]. This is shown in Figure 4. In doing so, the user is able to analyze the number of wedges that occur within that cell as well as the percentage of the wedges that fail.

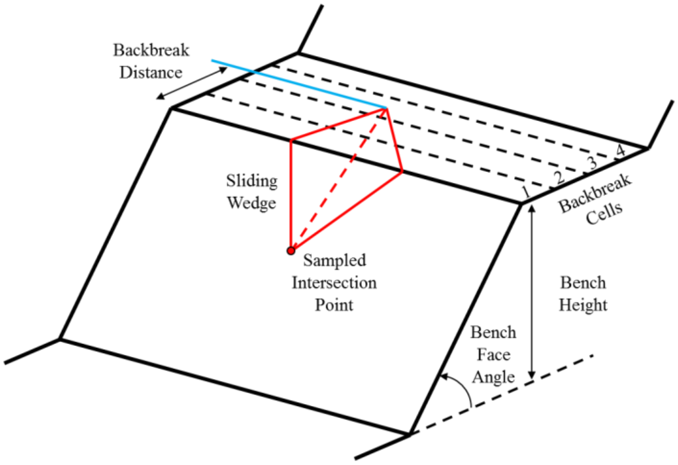

Figure 4: Simulated wedges and backbreak cells.

For each failed wedge, the backbreak distance is recorded and the spill width is calculated according to Equations 1 and 2.

Two approaches are available to determine the optimum bench face angle: managed approach to slope design and a quantitative hazard assessment.

3.4.1. Managed Approach to Slope Design

In open pit mining, it is often acceptable to use steeper bench face angles and allow some failures to occur as long as safety is not compromised. While this will result in a greater amount of failed material on the bench (this is referred to as the spill width), the cost of regular bench cleanups and bench face scaling is significantly less than the cost of excavating additional waste rock when using shallow bench angles.

The managed approach to slope design therefore involves the use of a conservative analysis method coupled with an appropriate confidence level to arrive at an optimum bench face angle. For this approach, infinite persistence is assumed for both Joint Set 1 and 2 and a design confidence level of 75-85% is used, as recommended in [3] and [5].

By using the small spacing option an estimate of the optimum bench face angle can be obtained according to the approach summarized in [3]. In this case, the total number of failed wedges (FS < 1) is determined for each bench face angle. The normalized frequency of failed wedges is then calculated by dividing the number of failed wedges for a given bench face angle by the maximum number of failed wedges at a slope angle of 90 degrees. The optimum bench face angle is then determined according to the design confidence level.

An initial estimate of the minimum bench width can also be obtained using the large spacing option. For each bench face angle, a distribution of backbreak distance and spill width can be calculated for the failed wedges (FS < 1). By selecting an appropriate design confidence level, representative values for usable bench width (based on backbreak distance) and spill width can be computed and summed to calculate the minimum required bench width. For this case, the optimum bench face angle is the steepest angle such that the minimum required bench width is less than the actual bench width (either fixed or based on the interramp angle, as discussed in Section 3.1).

3.4.1. Quantitative Hazard Assessment

While the managed approach can be used to determine the number of failed wedges for each bench face angle, it does not provide information on the expected wedge size and amount of bench loss. To determine this, a Quantitative Hazard Assessment is needed (QHA) that considers finite joint lengths. A QHA calculates the probability that the bench will fail to a certain backbreak distance. Such an analysis is useful on its own, but can also be combined with an estimate of the potential cost of bench loss to calculate the expected risk.

For a given bench face angle, the probability of occurrence is calculated for each backbreak cell. This value represents the likelihood that a wedge will form with a given backbreak distance and is calculated by dividing the number of wedges in a given backbreak cell by the total number of random samples. The probability of sliding for the cell, which refers to the likelihood that a wedge with a given backbreak distance will slide, is then calculated by dividing the number of failed wedges (FS < 1) in the cell by the total number of wedges in the cell. By multiplying these numbers together, a probability of failure is obtained for each backbreak cell.

By assessing the consequence of a wedge failure with a given backbreak distance, the risk associated with that failure can be calculated. Such assessments play an important role in assessing project risk and can be used to justify the installation of support or the use of a shallower bench face angle.

4. CASE STUDY

To demonstrate the usefulness of the proposed design approach, a section of the existing Yellowstone Mine in Montana was examined. Geotechnical information from Gibson et al. [6] was used to assess potential bench stability over a range of bench face angles and select an optimum value. The results were then compared to the existing design to provide an indication of the accuracy of the analysis.

4.1. Study Area

Luzenac America's Yellowstone Mine is located southwest of the town of Ennis in Montana, along the east slope of the Ruby Mountain Range. Two open pits were developed at this site, each to an approximate depth of 90 m.

A detailed study of a 90 m section of a single bench within the north wall of the south pit was completed by Gibson et al. [6] in 2004. This included an assessment of the rockmass quality, discontinuity orientation and spacing and backbreak distances along the bench. This section of the open pit will be used as the study area for this assessment.

The rock has been classified as hydrothermally-altered dolomite of Precambrian age that is overlain by Tertiary age Huckleberry ridge tuff. Severe fracturing of the dolomite has formed at least four major discontinuity sets, which are likely related to movement along a vertical fault striking N-NW through the pit. Given the high degree of fracturing, the rockmass has been described as “Fair’ using the Rock Mass Rating system (RMR) and “Very Poor” according to the Q system.

Benches in the study area are 7.6 m high, striking at 104 degrees with a bench face angle of 62 degrees. The estimated intact bench width is 5.5 m, however backbreak widths range from 0.0 to 2.5 m with an average value of 1.2 m. Backbreak was caused primarily by wedge failures of various sizes along the bench crest. Despite these small-scale failures, the benches were considered to be appropriately designed.

4.2. Geotechnical Characteristics

A total of 67 discontinuity measurements were recorded by Gibson et al. [6]. These measurements are shown plotted on a lower hemisphere, equal angle stereonet in Figure 5.

Two primary discontinuity sets were determined from these data: a foliation plane (average strike/dip of 019/73) and a joint set (average strike/dip of 125/50). These average orientations match those presented in [6]. Two other fracture sets were noted in the area, however they did not contribute to wedge failure and were therefore not considered for this analysis.

The geotechnical information for each joint has been summarized in Table 1. Friction angles were assessed from laboratory testing of saw-cut samples. As the type of fracture (foliation or joint) was not noted in the laboratory test results, all tests were assumed to be done on the foliation plane. A lower expected friction angle with a similar standard deviation was assumed for the joint surface based on field descriptions.

A normal distribution and an exponential distribution were assumed for the friction angle and joint persistence, respectively.

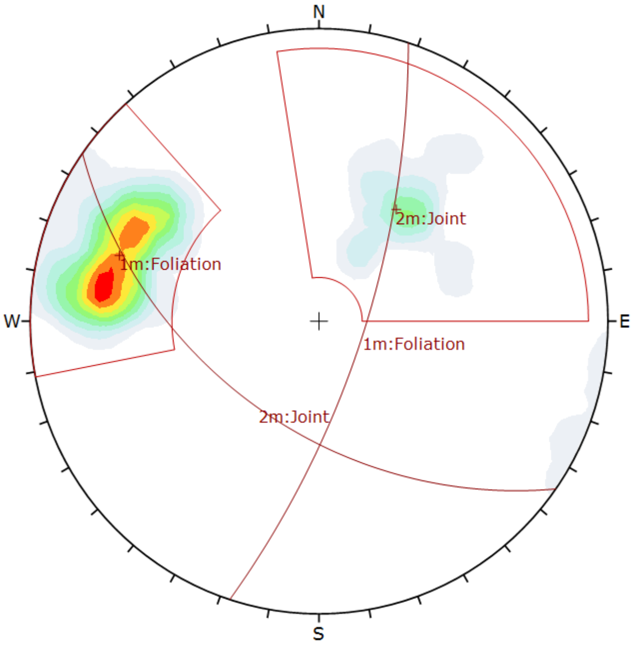

Figure 5: Lower hemisphere equal angle stereonet showing discontinuity measurements from [6].

Table 1: Geotechnical parameters used for study area. Standard deviations for are shown in parentheses.

	Foliation	Joint
Strike/Dip	019/73 (15)	125/50 (21)
Friction Angle (degrees)	31 (7)	25 (5)
Persistence (m)	2.5	2.9
Spacing (m)	1.2	1.9

4.3. Results and Discussion

Using the proposed bench design method summarized in the previous sections and the geotechnical information in Table 1, an optimum bench face angle was determined for the Yellowstone open pit. For this case, bench face angles from 50 to 90 degrees were considered.

The first portion of the analysis considered infinite persistence along both the foliation and joint planes. An 80% design confidence level was used, as per [3,5]. The results of the normalized frequency of failed wedges approach are shown in Figure 6 while the minimum bench angle analysis is shown in Figure 7.

As shown in the figures, an optimum bench face angle in the range of 59-61 degrees is considered to be appropriate for an 80% confidence level for both cases. This suggests the as-built bench face angle of 62 degrees is adequate for the geotechnical conditions present at the open pit.

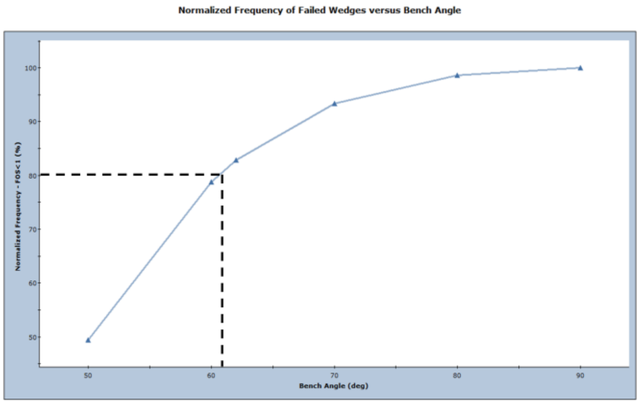

Figure 6: Normalized frequency of failed wedges for a range of possible bench face angles. The 80% confidence level is shown in black.

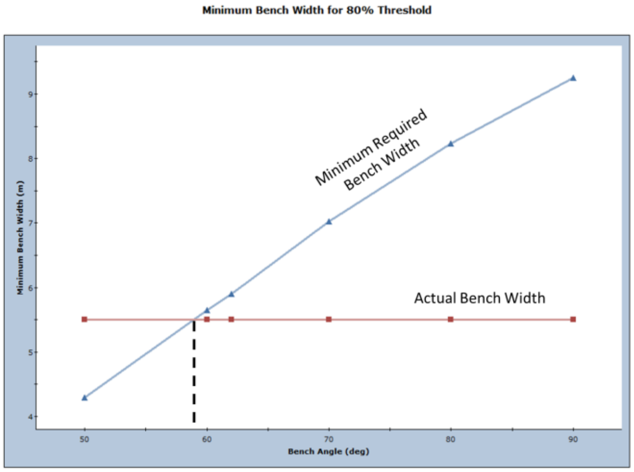

Figure 7: Comparison between minimum required bench width and the actual bench width (5.5 m) for an 80% confidence level.

A quantitative hazard assessment was also performed to assess the probability of failure for various backbreak distances. A small spacing analysis approach was used as the spacing for the foliation and joint planes was significantly less than the height of the bench, indicating repeated joints would be present along the study area.

The results of this analysis are shown in Figure 8. This plot demonstrates that smaller backbreak distances are more likely to occur for each bench face angle (typically less than 2 m for a 5% probability of failure). Further, greater backbreak distances are expected for steeper bench face angles for a given probability of failure.

Assuming an acceptable probability of failure of 5%, a 1 to 2 m backbreak distance could be expected for the purposes of design (depending on the bench face angle). For the actual angle of 62 degrees, a 1.3 m backbreak distance would be expected. This is approximately the same as the average backbreak distance (1.2 m) observed in the study area.

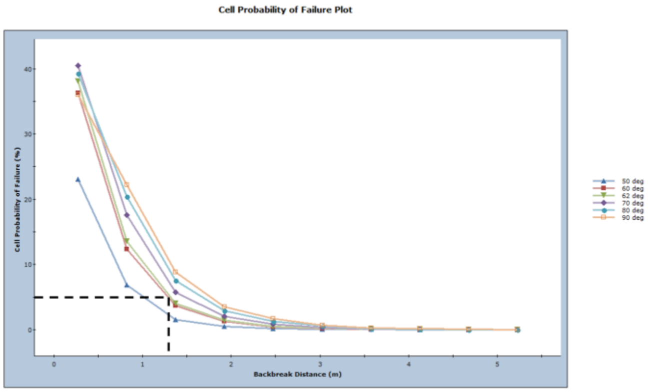

Figure 8: Quantitative Hazard Analysis results for a range of bench face angles. The observed average backbreak distance is shown in black.

5. CONCLUSIONS

A new approach to bench design has been developed that can be used at the early stages of design when limited information on the spatial distribution of joint sets is available. By selecting an appropriate joint spacing option based on observed conditions, an analysis of the potential backbreak distance, spill width and probability of failure for different wedge sizes can be completed. While this approach does not provide the same level of detail obtained when using a discrete fracture network, it does provide valuable information on the useable bench width that can be used during the conceptual or preliminary design stages.

A case study of the Yellowstone Mine in Montana has ben presented. The method described in this paper was used to assess the observed bench scale stability at the project. The case study demonstrated that the bench face angle of 62 degrees is appropriate for the geotechnical conditions at the site. The angle is considered to be sufficiently conservative when using a managed approach to slope design and also provides a sufficient level of confidence (95%) when considering the probability of wedge failure.

ACKNOWLEDGEMENTS

The authors would like to thank Felipe Ignacio Duran del Valle for his assistance in testing the proposed algorithm.

REFERENCES

[1] Miller S.M. 1983. Probabilistic analysis of bench stability for the use in designing open pit mines, Proc. 24th US Symp on Rock Mechanics, 621-629.

[2] Miller S.M., J.M. Girard and E.L. McHugh. 2000. Computer modeling of catch benches to mitigate rockfall hazards in open pit mines, Proc. 4th North American Rock Mechanics Symposium (NARMS 2000), 539-545.

[3] Carvalho J.L. 2012. Slope stability analysis for open pits. Available online: http://www.rocscience.com/library/rocnews/april2002/GolderArticle.pdf

[4] Whyatt J., S.M. Miller and J.G. Dwyer. 2004. NIOSH computer programs for bench crest failure analysis in fractured rock. Available online: http://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/ncpfb.pdf

[5] Gibson W.H., I.A. de Bruyn and D.J.H. Walker. 2006. Considerations in the optimization of bench face angle and berm width geometries for open pit mines, Proc. South African Institute of Mining and Metallurgy (SAIMM) Int Symp on Stability of Rock Slopes in Open Pit Mining and Civil Eng, 557-578.

[6] Whyatt J., M. MacLaughlin and S.M. Miller. 2004. Analysis of bench crest performance at the Yellowstone Mine: a case study.