rocscience

RocPlane

Planar Sliding Stability Analysis for Rock Slopes

Theory Manual

Persistence and Bench Design

Table of Contents

Persistence and Bench Design 1

1. Introduction 1
2. *RocPlane* Bench Design 1
3. Infinite Joint Length Analysis 2
4. Persistence Analysis 3
5. Bench Design 5
6. Spill Width 9
7. References 10

Persistence and Bench Design

1. Introduction

This document outlines the background theories of the persistence and bench analyses used in *SWedge*. Three topics will be covered:

1. Infinite joint length analysis (deterministic or probabilistic)
2. Persistence analysis (probabilistic)
3. Bench design (probabilistic)
4. Spill Width

2. *RocPlane* Bench Design

The general concepts described in this document also apply to the program *RocPlane*, keeping in mind that *RocPlane* is a 2-dimensional wedge stability analysis program.

Note that the persistence and bench design options in *RocPlane* do not consider tension cracks. Only simple triangular wedges are considered.

3. Infinite Joint Length Analysis

The infinite joint length analysis is the default mode in *SWedge*.

For this approach, wedges are formed according to the deterministic or randomly sampled slope geometry and joint orientations (Figure 1). As this approach assumes that each joint is of infinite length, the largest possible wedge is always formed for a given slope geometry. As such, wedges are only considered “invalid” (cannot form) if the line of intersection dips into the slope or is steeper than the slope angle.

The remaining valid wedges are used in the kinematic analysis to determine the factor of safety for the wedge. For more information on these calculations, the user is referred to the *SWedge* Theory document “**Safety Factor Calculations – Tetrahedral Wedges**”.

If the user would like to restrict the size of the maximum wedge, a number of scaling methods are available in the “Analysis – Scale Wedge” dialog box. These include: joint trace length, joint persistence, wedge volume and wedge weight. If this option is used, each valid wedge will be scaled according to the prescribed limit.

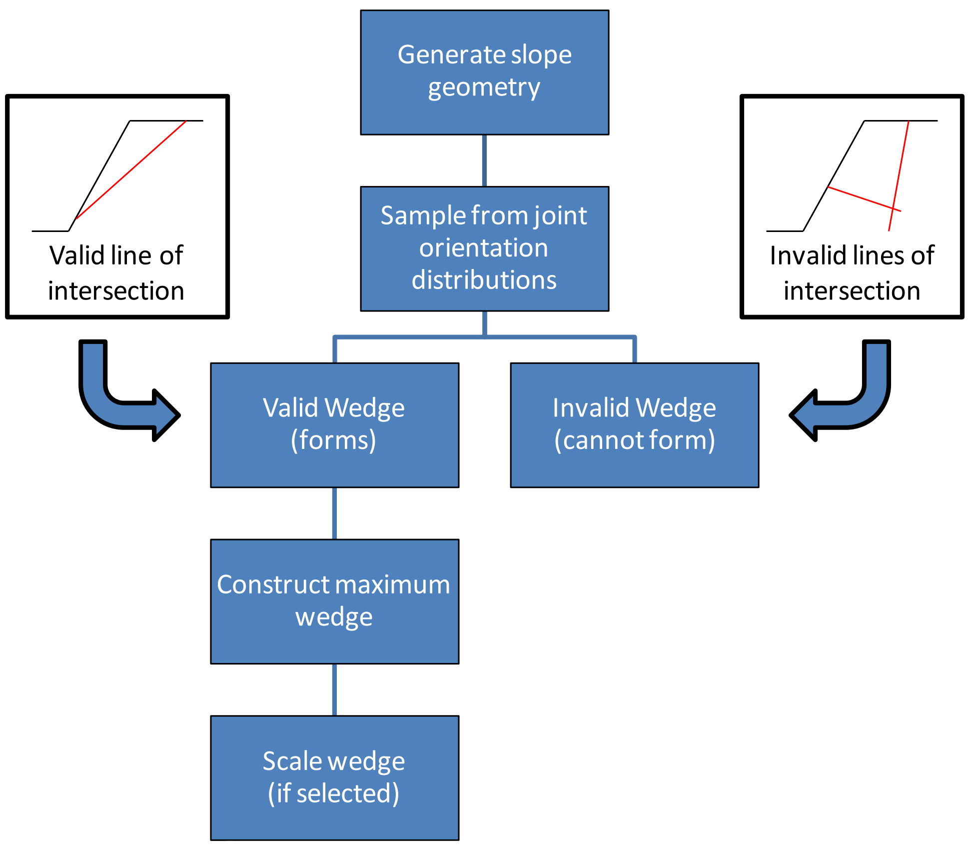

Figure 1: Infinite Persistence Analysis Approach

4. Persistence Analysis

Although scaling results in more reasonable sized wedges, by only considering the maximum possible wedges, smaller wedges (that are more likely to occur) are not considered. This typically results in an overestimation (upper bound) of the probability of failure when conducting a probabilistic analysis.

To perform a more accurate wedge assessment, a finite joint length based on field observations must be used. This is done in *SWedge* by using the Persistence Analysis option (available only for a Probabilistic analysis), which allows the user to define distributions for joint **persistence** or **trace length**.

Furthermore, two different **Joint Spacing** options (**Error! Reference source not found.**) are a vailable for a persistence analysis:

1. **Large** Joint Spacing
2. **Small** Joint Spacing (Ubiquitous Joints)

4.1. Large Joint Spacing

With the **Large Joint Spacing** option, it is assumed that there is only one trace of joint 1 and one trace of joint 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 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 (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.

> 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.

The **Large Joint Spacing** option is a lower bound solution when it comes to probability of failure, as the spacing and persistence condition will limit the formation of wedges.

4.2. Small Joint Spacing

Now consider if there is spacing (repeated joints) associated with the two joint sets joint 1 and joint 2. No longer is there one wedge, but a number of possible wedges that can form on the slope. If a wedge cannot form due to the persistence not being large enough, then a wedge higher up the slope face, which meets the persistence conditions, can form. If this is the case, then the **Small** or Ubiquitous joint spacing model is more applicable. 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 the program will always create a wedge 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.

The Joint Spacing persistence analysis options are summarized in **Error! Reference source not found.**.

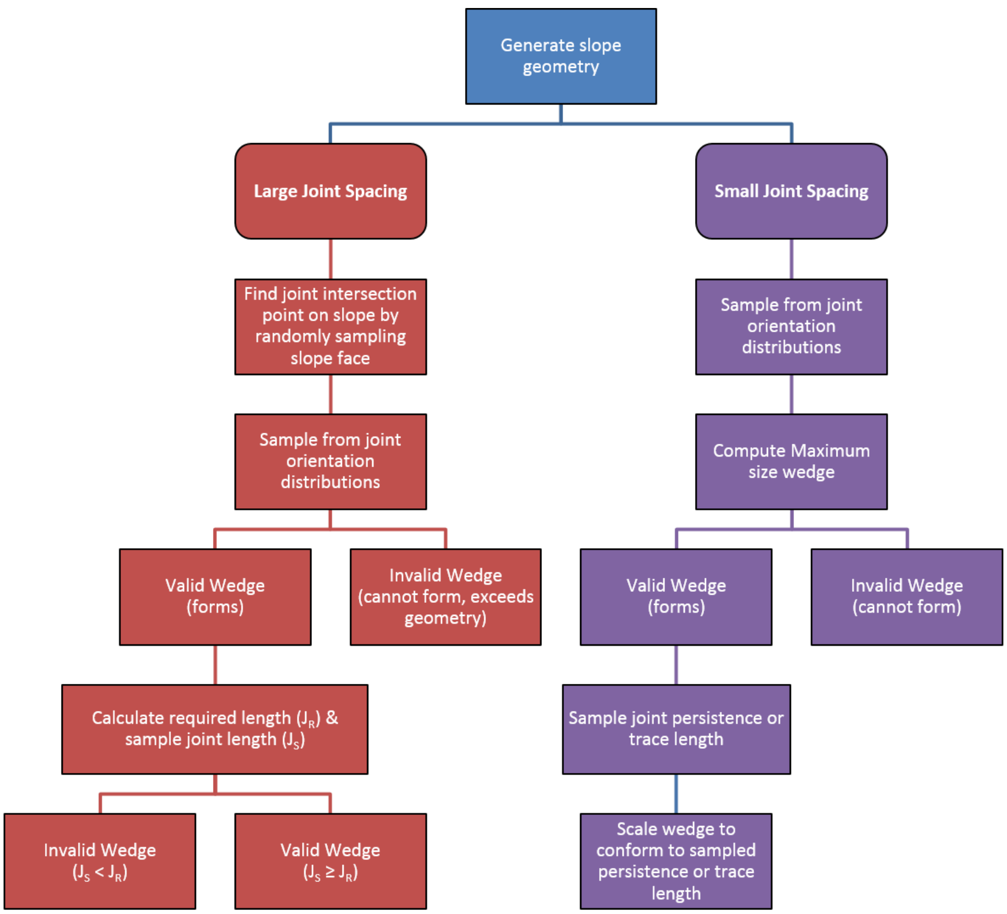

Figure 2: Persistence Analysis Approaches

5. Bench Design

The Bench Design option allows the user to analyze a number of different bench face (slope) angles to assist in the selection of an optimum angle for design. In this case, the "optimum angle" is defined as the steepest interramp angle (IRA) that can be achieved while preserving adequate bench widths. This approach is based on the probabilistic analysis approach described by Carvalho (2012), Gibson et al. (2006), Miller (1983), Miller et al. (2000) and the bench design programs by the National Institute for Occupational Safety and Health (NIOSH) outlined in Whyatt et al. (2004). It also calculates the spill radius for each failed wedge according to the equations in Gibson et al. (2006). It is only available for a Probabilistic analysis type.

A number of different design parameters must be considered when designing catch benches. These are shown in Figure 3.

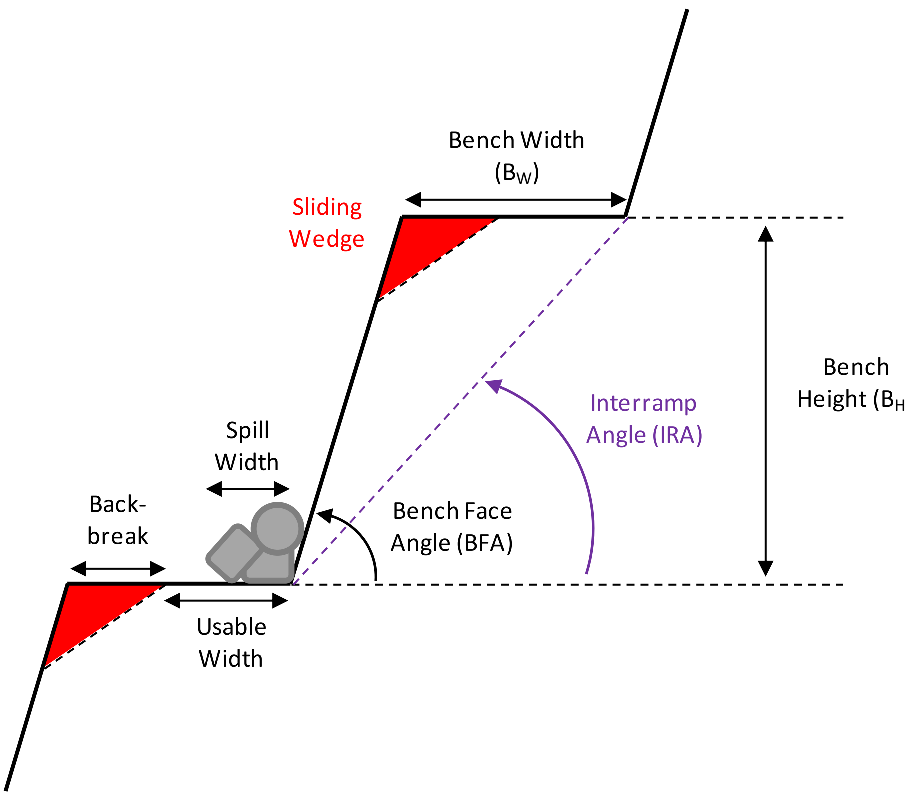

Figure 3: Typical Catch Bench Geometry

To conduct a Bench Design analysis, the user must specify persistence or trace length information for each joint. A fixed bench width or fixed interramp angle (IRA) can be used for the analysis, depending on the design constraints. The bench must also be divided into a series of "Backbreak Cells", the number of which are specified by the user (Figure 4). This allows for the calculation of the Probability of Occurrence, Sliding and Failure for each cell. Finally, a design threshold is specified that is used to determine the minimum bench width for each bench angle.

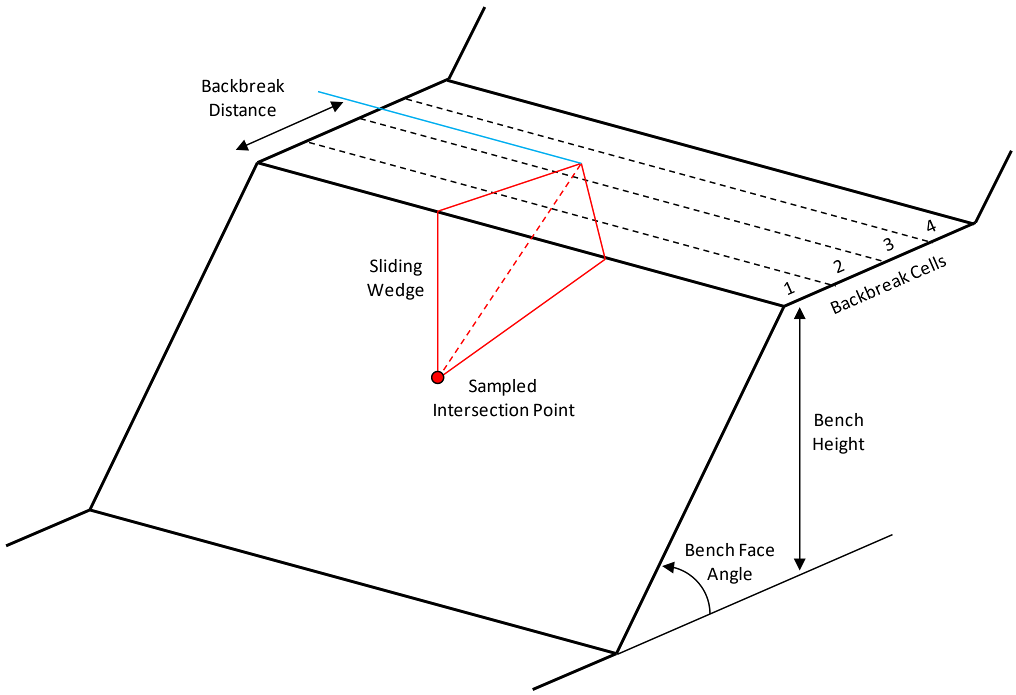

Figure 4: Backbreak Cell Determination

When using the Bench Design option, two analyses are actually performed.

The **first analysis** uses the persistence options (spacing and joint length) described in the previous section to create an accurate set of wedges based on slope geometry, joint orientation and joint length. In addition to determining the volume and factor of safety for each valid wedge, the backbreak distance is used to group each wedge into the appropriate backbreak cell. For the example shown in Figure 4, the wedge would be grouped into Cell #3.

The results of this analysis are used to calculate a number of design parameters for a given bench face angle:

- Total Probability of Failure = # Valid Wedges (FS < 1) / Total # of Samples
- Normalized Frequency for Failed Wedges = # Valid Failed Wedges (FS < 1) / Maximum # Valid Failed Wedges (FS < 1) at a slope angle of 90 degrees. For more information on this approach, the user is referred to Carvalho (2012).
- Cell Probability of Occurrence = # Valid Wedges in a Given Cell / Total # of Samples

A minimum bench width is also calculated for each bench face angle. To do so, two values are recorded for each valid failed (FS < 1) wedge: the backbreak distance and the spill width (based on equations in Gibson et al., 2006). Cumulative distributions are then developed for each parameter. Based on the design threshold defined by the user, a single value is selected for each. The minimum bench width is then calculated as the sum of the design values for backbreak distance and spill width.

A **second, separate analysis** is then performed to calculate the Probability of Sliding for each backbreak cell. This value can be thought of as the probability that a wedge with a certain backbreak distance will slide. It is defined as:

- Cell Probability of Sliding = # Valid Wedges (FS < 1) in a Given Cell / Total # of Valid Wedges in a Given Cell

To calculate this value accurately, a sufficient number of valid wedges must be formed in each cell to fully sample the distributions for joint strength. As wedges with a large backbreak distance are less likely to form due to the limitations placed on joint length, the number of wedges in each backbreak cell will typically decrease as one moves away from the slope crest. As a result, some cells will have an insufficient number of valid wedges after the first analysis is performed.

To overcome this, an additional analysis is run using the Large Spacing persistence approach with infinitely long joints. By using an infinite joint length, nearly all wedges that can form within the problem geometry will. In most cases this will ensure an appropriate number of wedges are formed in each cell. To verify this, the user can run a persistence analysis for the required bench face angle using infinite persistence values. A histogram of “Wedge Width to Crest on Upper Face” can then be used to view the distribution of backbreak distances to ensure that an appropriate number of wedges are located in each cell.

NOTE: It is important to remember that the first analysis and the second analysis used to calculate the Probability of Sliding are SEPARATE. The first focuses on accurately assessing the number of wedges that could occur for a given slope geometry, joint orientation and joint length. This provides a realistic assessment of wedge volume, total probability of failure and the Probability of Occurrence. The second is focused on ensuring there are a sufficient number of samples in each cell to fully sample the strength distributions. This allows the Cell Probability of Sliding to be calculated correctly.

These approaches are summarized in Figure 5.

This concludes the persistence and bench design theory document.

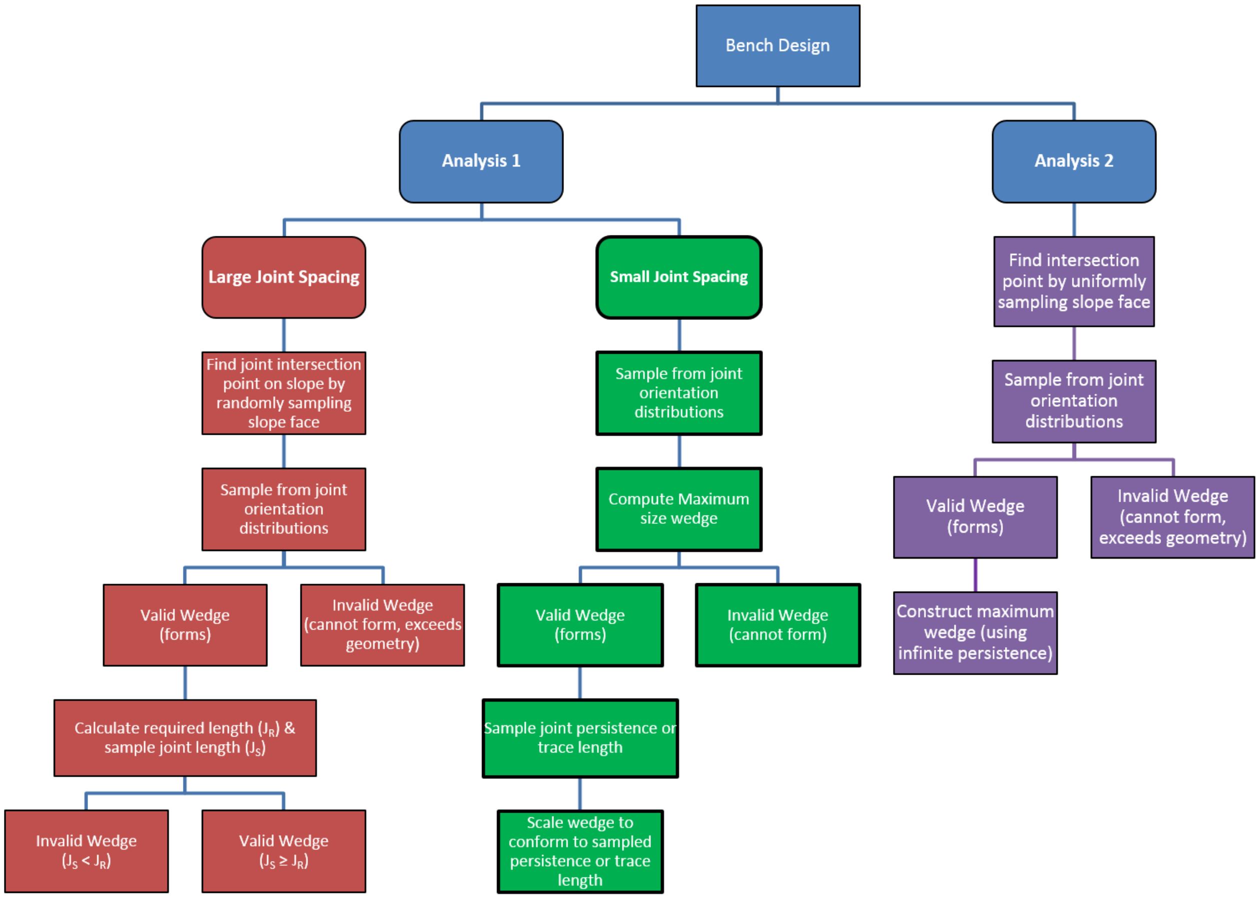

Figure 5: Bench Design Analysis Approach

6. Spill Width

In the *SWedge* program, spill width is calculated using 3-dimensional assumptions as described in Gibson (et al) 2006. In *RocPlane* a simplified 2-dimensional estimate of spill width is used as outlined below.

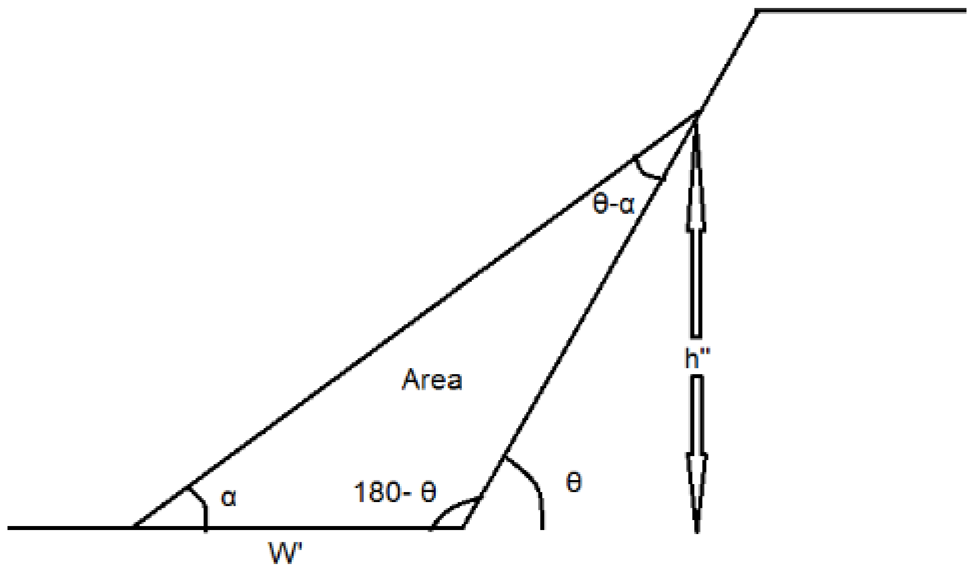

Figure 6: Spill Width Assumption for *RocPlane*

Given:

- Original wedge area = a
- Original bench angle or failure plane angle = θ
- Swelling factor = K
- Angle of repose = α
- Area of failed wedge material = A = Ka
- Spill width = W'

$$W' = \sqrt{\frac{2A\sin(\theta-\alpha)}{\sin\alpha\sin\theta}}$$

$$h'' = \frac{W'\sin\alpha\sin\theta}{\sin(\theta-\alpha)}$$

Note: for wedges which daylight in the upper half of the slope, the failed wedge material rests on the original slope face, and $\theta =$ the original bench angle. For larger wedges, it is assumed that $\theta =$ failure plane angle.

7. References

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

Gibson W.H., de Bruyn I.A., Walker D.J.H. (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.
http://www.rocscience.com/library/pdf/Gibson2006.pdf

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.

Miller S.M., Girard J.M., McHugh E.L. (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.

Whyatt J., Miller S.M., Dwyer J.G. (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