CONSIDERATIONS IN THE OPTIMISATION OF BENCH FACE ANGLE AND BERM WIDTH GEOMETRIES FOR OPEN PIT MINES

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ABSTRACT

The inclination of any pit wall composed of stacks of benches is limited by the overall quality and structural complexity of the rock mass in which the slope is situated. For a bench stack angle that satisfies the stability criteria, various combinations of bench height, bench face angle and berm width can be used in the slope design. The bench face angle and berm width geometries must be chosen to fit the bench stack angle but must provide a berm that will be capable of catching the volume of failed wedge material from the bench faces above. Other considerations for bench height and berm width are equipment size, ore selectivity and blasting design.

This paper studies the effects of different slope configurations on slope performance as it relates to wedge stability, volume of rock safely contained on berms, and rockfall. Optimisation of the geometry is carried out based on the need to minimise the volume of failed material which limits the effectiveness of the berm. This will reduce the number of rocks that can continue to fall further, reaching geotechnical safety berms or pit ramps, that put safety of personal and equipment at risk.

For general study it is most effective to investigate and compare the performances of each of a wide range of geometrical combinations of bench height, bench face angles and berm widths that fit a variety of different bench stack angles. These analyses were conducted for a predetermined bench stack height and three different bench stack angles.

1 INTRODUCTION

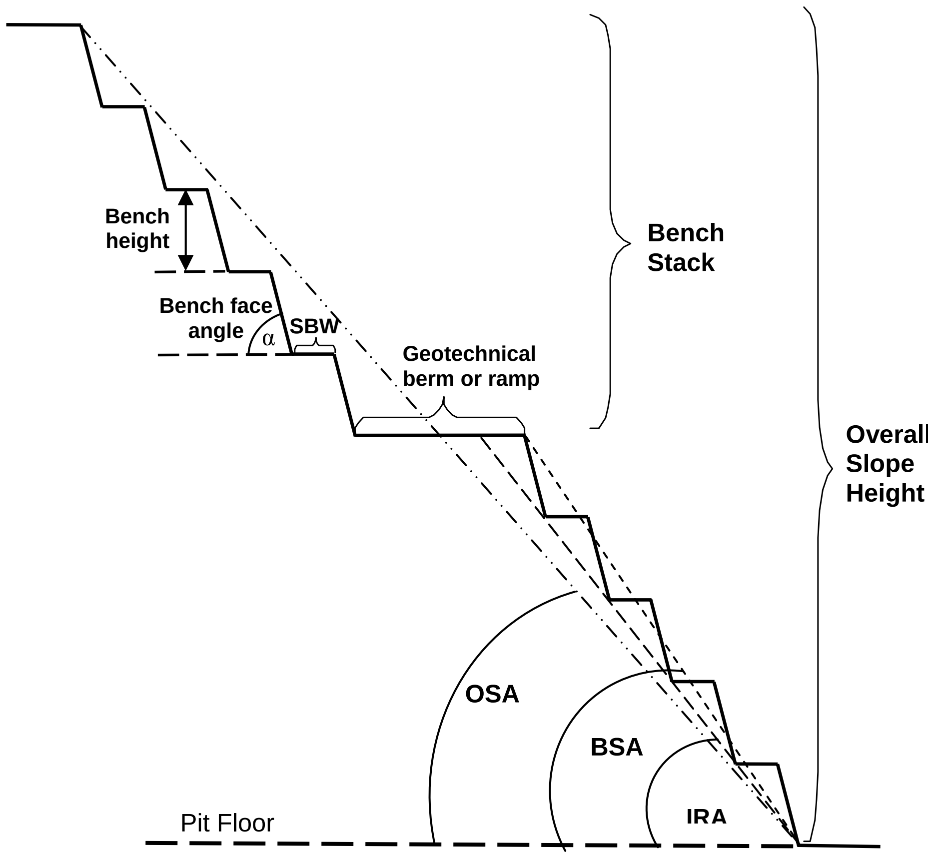
1.1 Focus of the Study

There are several factors that together contribute to open pit slope geometry. The large scale geometry, that is the overall pit slope angles or the slope angles of individual bench stacks, is governed largely by the quality of the rockmass and its stability within the context of the stresses imposed. Major structures such as faults, thrust or shears, or pervasive fabric such as bedding or foliation may also govern the bench face, stack or overall angles of a pit slope. The most suitable large scale geometry is usually identified by empirical rockmass analysis and numerical modelling methods, and is not within the scope of this paper.

Individual bench stacks, which are separated by ramps or geotechnical catch berms, are composed of a number of benches and spill berms. For a bench stack angle (BSA - measured from toe to crest) that satisfies the stability criteria for the rock mass in which it is situated, various combinations of bench height, bench face angle and berm width can be used in the slope design. All geometrical pit slope elements referred to here are illustrated in Figure 1. The bench height, bench face angle and berm width geometries must be chosen to fit the BSA but must provide a berm that will be capable of catching the volume of failed wedge material from the bench faces above. It can therefore be seen that bench and berm geometry is governed in combination by the BSA, and by the structural fabric of the rock mass which allows for wedge failures to be generated.

This paper studies the effects of different slope configurations at bench and spill berm scale that fit a given BSA. Optimisation of the geometry is the key aim. This is carried out based on the need to minimise the volume of failed material, which limits the effectiveness of the berm, and which may overflow the berm and fall further down the pit slope. This material may need to be removed from benches in order to catch the maximum volume of material that might be generated from further wedge failures, and to reduce the number of rocks that can continue to further fall onto the berms below, putting personal safety and equipment at risk.

Two different approaches can be taken with regards to the optimisation of slope geometry. Bench heights, bench face angles and berm widths can be specifically selected so that volumes of failure material are minimised and so that failed material can most effectively be retained on the spill berm immediately below. The bench stack angle is then calculated from the designed geometrical elements. This approach can be used where the local rockmass properties and operational limitations have been well determined on sites. Alternatively, for general study it is most effective to investigate and compare the performances of each of a wide range of geometrical combinations of bench height, bench face angles and berm widths that fit a variety of different bench stack angles. It has been necessary to conduct the latter approach for this study, using a generic rockmass structural fabric and applying less limiting factors than would be applied for a site-specific study



Where: IRA = Inter Ramp Angle measured from toe to toe; BSA = Bench Stack Angle, measured from toe to crest;

OSA = Overall Slope Angle; SBW = Spill Berm Width

Figure 1: Sectional illustration of pit slope geometrical elements

1.2 Method of the Study

To study the effect of different combinations of bench face angle and bench height on slope performance, a fixed bench stack height of 100m was chosen. Three different bench stack angles (46°, 52° and 58°) were used for analysis of wedge failure and for rock fall, with combinations of 4 different bench face angles (65°, 75°, 85° and 90°) and 3 different bench heights of 16.7m, 20m, and 25m evaluated for each. These bench heights correspond to 4, 5 and 6 benches in a stack respectively.

The selection of the bench height is, however, most often a function of the equipment size and its reach and the required selectivity of the ore. The designs of blasting for wall stability are an additional criterion.

The wedge failure mechanism and volume of failed material are illustrated in Figure 2. This refers to a simple wedge, with no tension crack.

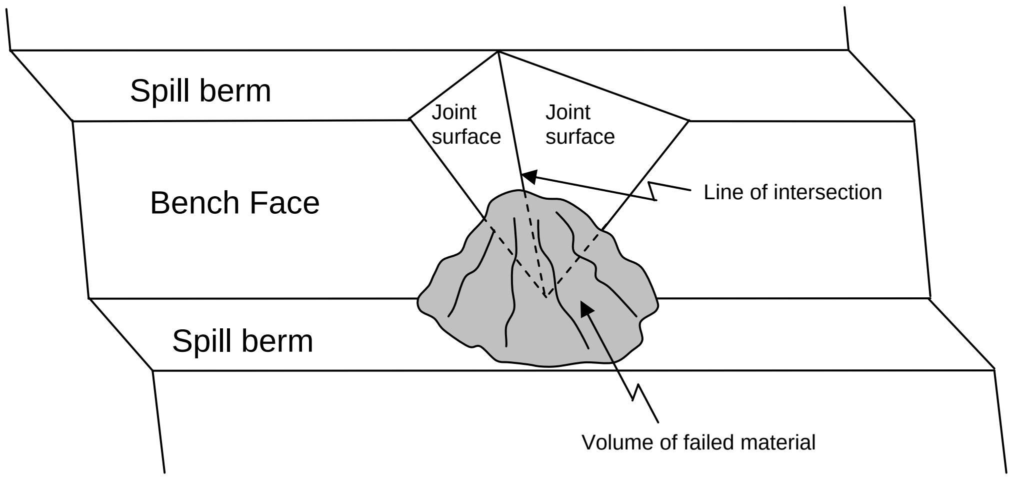


Figure 2: 3-D illustration of wedge failure

Other modes of failure common in hard rock slopes, such as planar and toppling failure, have not been analysed. Planar failure essentially requires one major plane along which sliding failure occurs, with release planes on either end. Planar failure is practically mimicked by highly asymmetric failure wedges where one joint surface is at a very oblique angle to the bench face and sliding occurs mainly on this surface (refer to Figure 3). Toppling failures rarely involve very large volumes of material and although they may certainly play a role in governing bench face angle, they do not present a significant factor in overall bench and berm design.

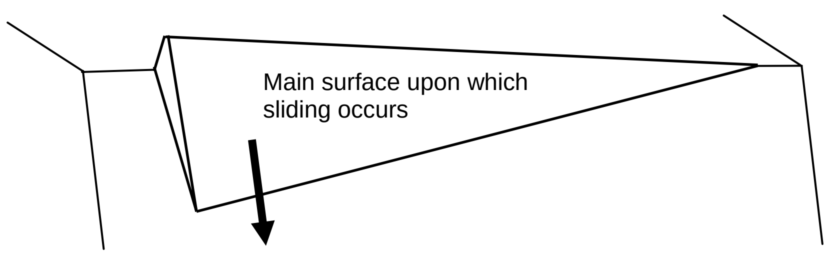


Figure 3: 3-D illustration of failure of a highly asymmetric wedge approximating planar failure

Table 1 shows the combinations of bench face angle, bench height and corresponding spill berm widths (SBW) considered in the analysis for each BSA. Examples of the different geometries can be seen in Figure 10.

Table 1: Bench face angle, bench height and SBW analysed for each BSA

BSA	Bench Height [m]	Spill Berm Width [m]			
		Bench Slope 65°	Bench Slope 75°	Bench Slope 85°	Bench Slope 90°
46°	16.7	10.01	13.98	17.60	19.35
	20	12.48	17.44	21.96	24.14
	25	16.65	23.26	29.27	32.19
52°	16.7	6.31	10.29	13.90	15.66
	20	7.87	12.83	17.34	19.53
	25	10.50	17.11	23.13	26.04
58°	16.7	3.18	7.15	10.77	12.52
	20	3.96	8.92	13.43	15.62
	25	5.29	11.90	17.91	20.83

As this is not a case study, a rock mass structural fabric has had to be defined. A data set of discontinuities that allow for a variety of different failure wedge geometries has been created. This data set provides for wedge geometries that will result in close to the maximum possible wedge failure volumes for individual bench faces. While such a rockmass structural fabric is unlikely in reality, the objective of the paper is to compare the performance of different slope geometries under the same set of discontinuities.

Failures affecting multiple benches or entire bench stacks are beyond the scope of this study.

The comparison between the geometries was done considering the following:

- Wedge failure analysis of the structural data set to identify the volumes of all possible wedge failures that will occur for a range of different bench heights each with a variation of bench face angles
- Rock fall analysis to assess the capacity of the different geometries to arrest individual rocks that have fallen over the edge of a berm and falling in to the ramp or geotechnical berm.

The results of analysis are therefore studied here so as to identify the geometry within each of a number of selected BSA's that will best allow for containment of all failed material for each of a range of set bench heights. The results are summarised in graphs and tables in order to have an easy understanding of the effect of different bench and berm geometries on the stability and safety of the slopes.

2 BENCH FAILURE ANALYSIS

2.1 The Input Data Set

2.1.1 Rationale for development of the data set

Joints sets were established that would generate wedge failures with lines of intersection for a wide range of steepness (from approximately 30º to 80º plunge), for a wide range of angles of intersection (25º to 155º) within the horizontal plane. Variations in the plunge of lines of intersection of wedges are illustrated in Figure 4. These sets therefore allow for the generation of a large number of generic wedges with suitable variation in symmetry, plunge of line of intersection and in width (shape) and thus suitable variation of the wedge volume.

As this data set of ideal joint orientations has been assumed in order to generate the generic wedges, the azimuth of the bench face is of no consequence, and has arbitrarily been chosen as 000º, with the joint orientations correspondingly chosen. In reality the azimuth of the bench face relative to the fixed orientations of the joint sets present is of paramount importance in determining wedge generation, shape and volume. Essentially the "worst case scenario" has been adopted for this study.

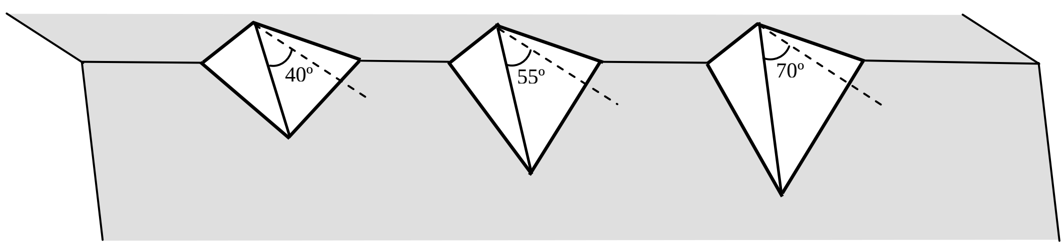


Figure 4: 3-D illustration to show variations in steepness of plunge of the line of intersection for joints sets forming wedges

2.1.2 Details of the input data set

The variations in dip and azimuth used to form a rockmass structural fabric of 140 joints sets are presented below. An example of the intersection of two of the sets to form a wedge is illustrated in Figure 5. All possible combinations of intersecting sets have been analysed for the wedge failure analysis in this study.

Dip angle (º)	35	40	45	50	55	63	70	75	80	85

Azimuth (dip direction)	020	030	040	050	060	070	080	285	295	305	315	325	335	345

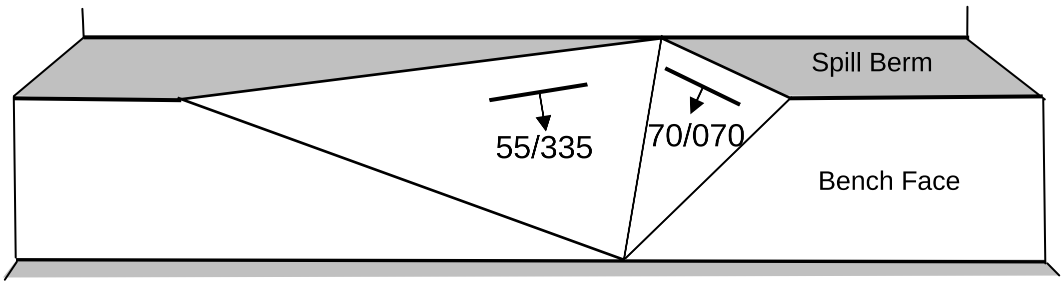


Figure 5: 3-D illustrative example of two joints of different dip/dip direction combinations forming a wedge

The various combinations of intersections of all of these joint sets form a large number of different wedge shapes and sizes, both symmetrical and asymmetrical - 9730 in total. The performance of each slope design configuration is therefore tested under a very large variety of wedge sizes and shapes.

2.2 Geometrical Factors Affecting Failure Volume

It must be understood that the wedge geometry is as important as the bench and berm geometry in determining the resultant failure sizes and volumes.

The first factor that controls wedge failure is the plunge of the line of intersection of the joints. If the line of intersection of two joint sets is steeper than the bench face angle, a wedge failure will not be generated (refer to Figure 6).

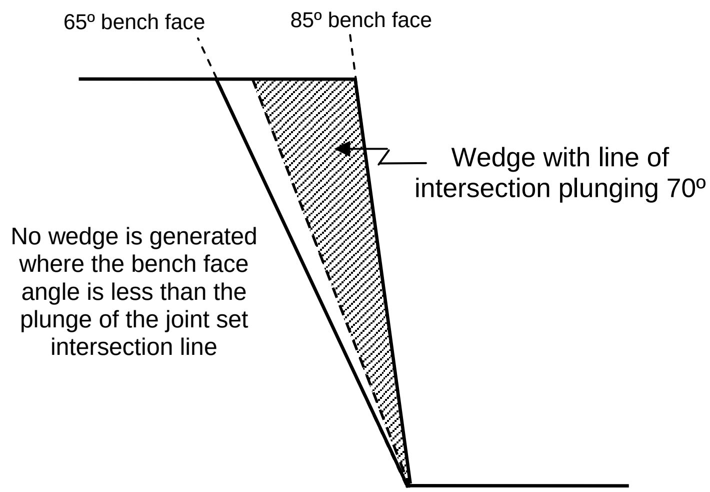


Figure 6: Sectional illustration of the importance of bench face geometry and joint line of intersection in wedge generation

The second factor that controls wedge failure is the bench face angle. The steepness of the bench face angle (for a given BSA) is important in defining the size of wedges that can be generated. Larger wedge failures are formed on steeper bench faces (refer to Figure 7) for a given BSA.

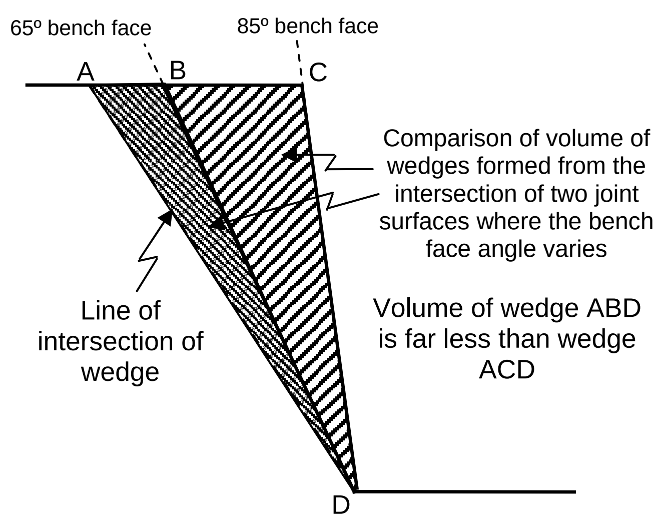


Figure 7: Sectional illustration of the importance of bench face geometry in determining wedge volume

The plunge of the line of intersection of a wedge also defines whether its size is controlled by the bench height or berm width. Where the wedge line of intersection is steep, the size of the wedge that can fail will be limited by the height of the bench. Where the wedge line of intersection is shallow, the width of the spill berm above the bench face will limit the size of the failure wedge (refer to Figure 8). If the wedge width is constant, the maximum wedge size that may be generated for any particular bench and berm geometry occurs where the line of intersection of the joint sets forming the wedge has the same plunge as the Inter Ramp Angle (IRA) of the bench stack. The IRA is the angle of the bench stack measured from bench crest to bench crest or bench toe to bench toe (refer to Figure 1).

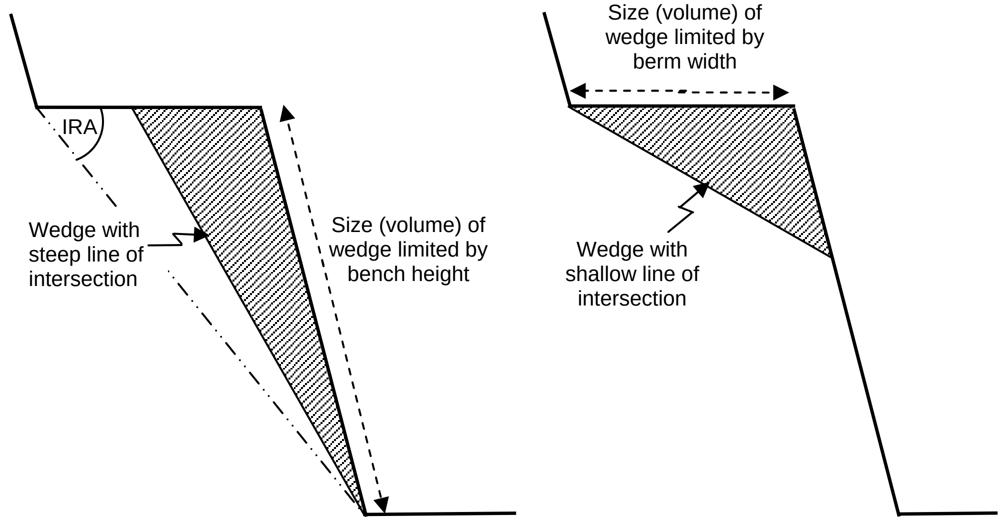


Figure 8: Sectional illustration of the limitations of bench height and berm geometry width on wedge size

It can be seen that the greater the length of the wedge for a given depth of failure, the greater the volume of failed material. However the failure material of a wedge of great length will be correspondingly more spread out along a spill berm (refer to Figure 9). This has important implications with regards to the required spill berm width.

2.3 Failure Analysis

2.3.1 Calculation of wedge failure volumes

The following data was entered into the programme MWedge (Gibson 2005), MWedge can analyze multiple combinations of wedges generated by a particular joint set. The data required for each analysis is as follows:

- The orientation (dip and dip direction) of all joint sets present
- The friction angle (ø) and cohesion (c) values for each joint set
- The bench height
- The bench face angle
- The berm width (all berms were assumed to be horizontal)

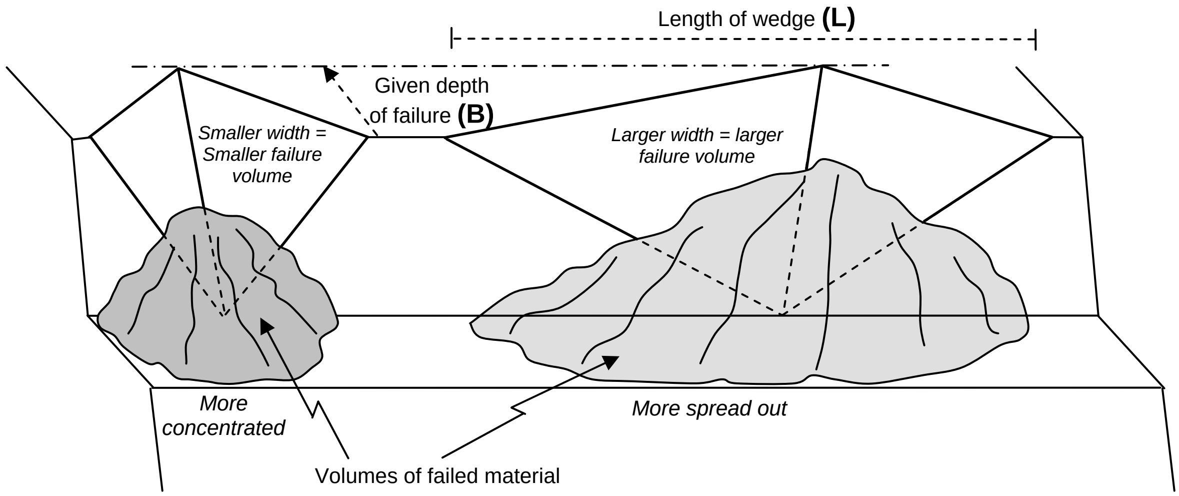


Figure 9: 3-D illustration of wedge shapes and distribution of failure volumes

A limit for continuity for each joint set can also be defined. Although this can often be a significant factor limiting the size of failure wedges that can develop, no limits for continuity were set for this study. As such, the performance of the different geometries was tested under very poor rockmass conditions where many highly continuous structures are present.

The programme MWedge calculates the volume and factor of safety of every possible geometry of failure wedge. At the same time the programme calculates the volume of material spilled to the next berm when the spill berm required to contain the wedge volume is larger than the spill berm defined in the geometry.

The friction angle and the cohesion of joint surfaces serve only to define the factor of safety (FoS) with regards to wedge failure (wedge geometry also plays a role in this). Where the FoS is less than 1, failure is indicated. In reality, the surface conditions on certain joint sets may preclude the failure of certain wedge geometries. For this study, a standard value of 28^o was used for friction for all joint sets. Twenty eight degrees was used because it is a realistic average which does not assume that the joint surface friction is very high. A value of zero for cohesion was entered for all joint sets. This is because, in the scale of individual benches and berms, blasting and slope displacements are assumed to have destroyed all natural cohesion within discontinuities.

For a fixed BSA the bench face angle, spill berm width and bench height are interdependent. Figure 10 illustrates different combinations of each for a fixed BSA. A reduction in the bench face angle will reduce wedge volumes but at the same time will reduce the width of the spill berms that retain the failed material.

Thus for each of three set BSA's of 46º, 52º and 58º, each with variations in bench height of 16.7m, 20m and 25m, the volumes of all possible wedge failures were calculated for bench face angles of 65º, 75º, 85º and 90º. The results of the analysis are presented in section 2.4.

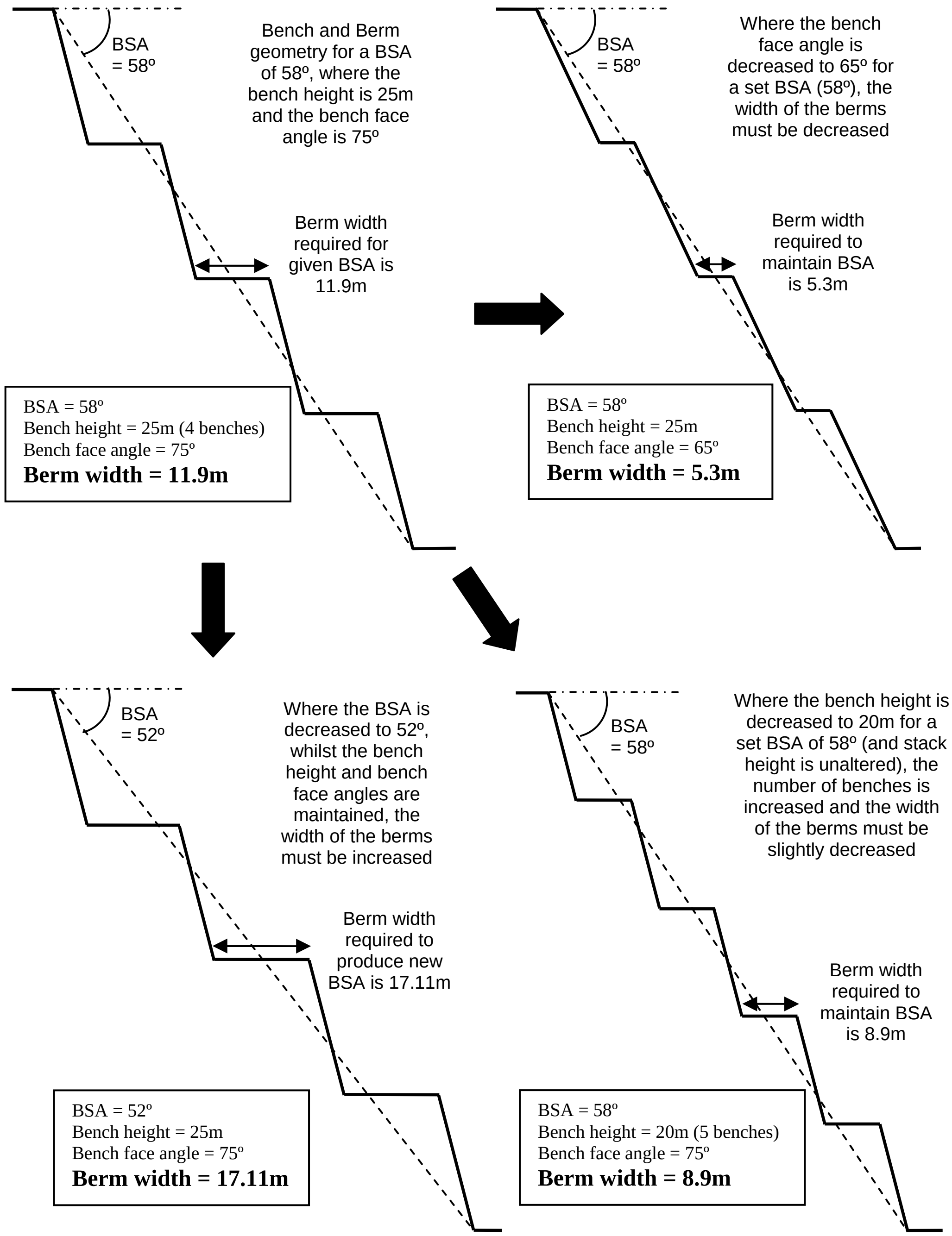


Figure 10: Effect of variation in bench height, bench face angle and BSA on the limiting spill berm width to be entered into wedge failure volume analysis

2.3.2 Calculation of volumes of wedge failure material

The first objective of this study is to assess the volume of material that may spill from berms as a result of individual wedge failures. In essence this is a difficult thing to accurately determine, as it is dependent not only on the maximum volumes of failure but also on the width and symmetry of the wedge.

A further complex consideration which is not studied in this paper is the actual mechanics of flow of failed material down off the discontinuity surfaces, depending on the attitude of the different surfaces and the direction of plunge of the line of intersection relative to the bench face. This essentially dictates the final disposition of the failed material along the berm.

Two methods of calculating the required spill berm width from the wedge failure volumes for a given bench and berm geometry have been derived for use in this study.

The first equation assumes that the failed material of the calculated volume is distributed on the berm in a symmetrically conical fashion (refer to Figure 11), with the section of the cone in the plane of the spill berm having radius R.

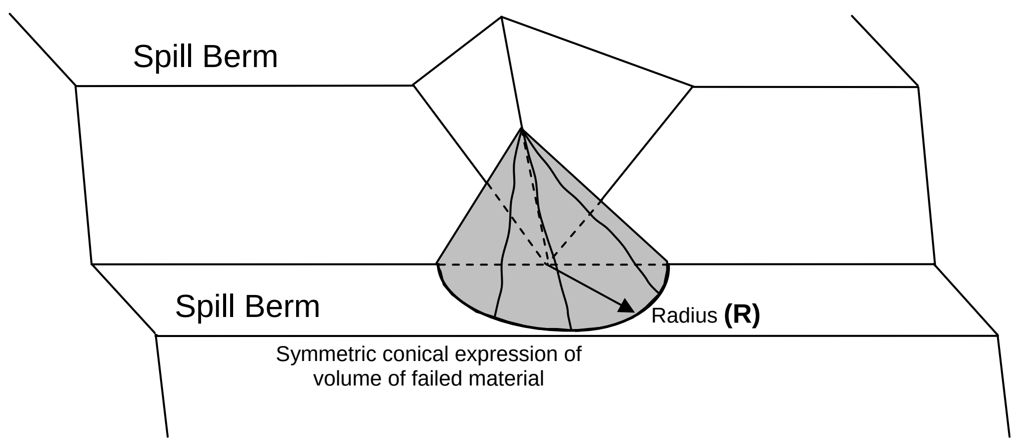


Figure 11: 3-D illustration of symmetric conical distribution of failed material on a spill berm

Where R is greater than the SBW, the failed material will not be contained by the berm and will spill onto the next berm below. The equation for determination of R may be expressed as:

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

Where *K = 1.5 swelling factor (assumed based on SRK practical experience)*
V = volume of failed material (m^3)
L = length of wedge (m)
α = bench face angle (◦)
ø = angle of repose of failed material (38◦) (typical value for granular material, Bowles, 1990)

The first method does not take into account the geometry of the wedge, whether it is wide or narrow, or whether it is symmetrical or asymmetrical. This equation may therefore tend to overestimate the spill berm widths required to contain failure material of wedges that have large volumes because of their large widths (refer back to Figure 9).

The second method takes the shape of the wedge into account and assumes that the failed material is distributed on the spill berm in the form of a pyramid (refer to Figure 12), with the section of the pyramid in the plane of the spill berm having width R. The symmetry of this pyramid reflects the symmetry of the wedge that has failed.

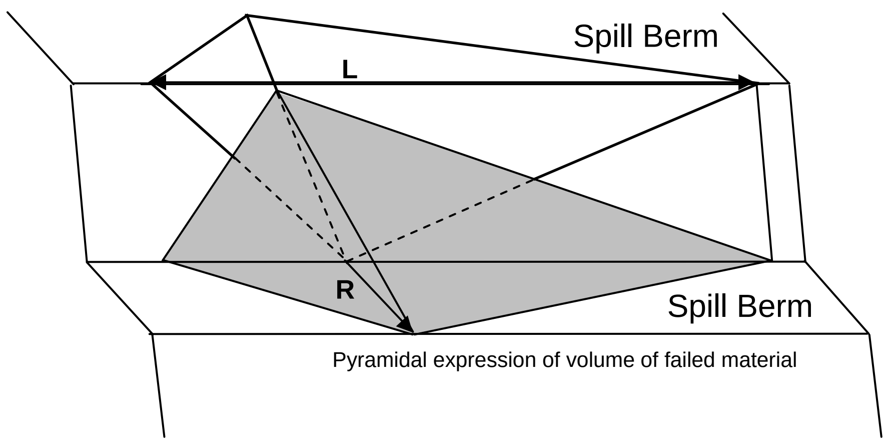


Figure 12: 3-D illustration of the pyramidal distribution of failed material on a spill berm

Where R is greater than the SBW, the failed material will not be contained by the berm and will spill onto the next berm below. The equation for determination of R may be expressed as:

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

Where *K =1.5 swelling factor*
V = volume of failed material (m^3)
L = length of wedge (m)
α = bench face angle (◦)
ø = angle of repose of failed material (38◦)

The second equation tends to overestimate the spill berm required when the length of the wedge (L) is small. Therefore the lesser of the two calculated values for R for that particular wedge geometry is deemed to be most realistic and is used to identify whether some failed material will spill from the berm, and what the volume of spilled material will be (according to the correspondingly assumed shape of distribution of failed material).

The results of the analysis are presented in section 2.4 below.

2.4 Results of Failure Analysis

The factor of safety (FoS) and volume of every possible wedge failure for each of the combinations of bench stack geometries has been calculated, and the following information has been summarised to compare the performances of each set of geometries:

- The total number of wedges with FoS less than 1.0.
- The total number of failed wedges with FoS less than 1.0 that will result in material overspilling the berm.
- The minimum volume of failed material generated from any single wedge failure that will result in spillage from the berm.
- The largest volume of failed material generated from any single wedge failure.
- The largest volume of material generated from any single wedge failure that will be spilled onto the bench below.
- The total volume of material from all wedge failures that will be spilled onto the bench below.

Table 2: Wedge Failure Analysis Results

Bench Stack Angle (BSA) (°)	Bench Height (m)	Number of benches in Stack	Bench Face Angle (°)	Spill Berm Width (SBW) (m)	Total no. of wedges formed	Number of wedges with FoS<1.0	Number of wedges with FoS<1.0 that result in spillage from berm	Minimum failure volume for spillage from berm [m3]	Maximum volume of any single wedge failure [m3]	Maximum volume of spillage from any single wedge failure [m3]	Average Spilled Volume per Wedge [m3]
46	16.7	6	65	10.01	6157	3455	1102	431	1784	540	180
			75	13.98	7045	4289	1087	944	3406	890	256
			85	17.60	7654	4837	1053	1598	5568	1150	335
			90	19.35	7813	4960	1040	1978	6734	1290	375
	20	5	65	12.48	6157	3455	1015	836	3352	1010	270
			75	17.44	7045	4289	964	1834	6533	1520	400
			85	21.96	7654	4837	921	3107	10078	1870	519
			90	24.14	7813	4960	896	3843	12348	2230	573
	25	4	65	16.65	6157	3455	894	1985	7464	1950	469
			75	23.26	7045	4289	795	4347	14122	2670	633
			85	29.27	7654	4837	718	7384	22741	3520	723
			90	32.19	7813	4960	684	9106	27648	3780	755
52	16.7	6	65	6.31	6157	3455	1948	108	708	470	136
			75	10.29	7045	4289	1898	376	1888	900	221
			85	13.90	7654	4837	1842	787	3421	1290	324
			90	15.66	7813	4960	1808	1048	4409	1400	377
	20	5	65	7.87	6157	3455	1888	209	1332	870	189
			75	12.83	7045	4289	1802	729	3540	1540	347
			85	17.34	7654	4837	1715	1529	6488	2190	514
			90	19.53	7813	4960	1661	2034	8212	2500	582
	25	4	65	10.50	6157	3455	1790	497	2943	1590	330
			75	17.11	7045	4289	1627	1730	7886	3000	574
			85	23.13	7654	4837	1494	3628	14395	4230	687
			90	26.04	7813	4960	1429	4822	18203	4800	739
58	16.7	6	65	3.18	6157	3455	2581	14	175	185	102
			75	7.15	7045	4289	2612	126	924	640	159
			85	10.77	7654	4837	2550	366	2088	1090	260
			90	12.52	7813	4960	2520	536	2830	1380	317
	20	5	65	3.96	6157	3455	2559	27	340	360	111
			75	8.92	7045	4289	2534	245	1706	1160	237
			85	13.43	7654	4837	2456	709	3878	1950	419
			90	15.62	7813	4960	2411	1040	5208	2460	502
	25	4	65	5.29	6157	3455	2525	64	741	770	148
			75	11.90	7047	4289	2423	582	3778	2470	427
			85	17.91	7654	4837	2283	1684	8668	4140	622
			90	20.83	7813	4960	2210	2469	11668	4960	675

From Table 2 it can be observed that the number of wedges with Factor of Safety (FoS) less than 1.0 increases when the bench face angle increases. The total number of wedges with FoS less than 1.0 is a function of the bench face angle only because a zero value for cohesion was used in the analysis. Therefore, changes in bench height change the scale of the wedge without changing the FoS.

From the results of the calculations performed for this study, it can be seen that that the most important criteria governing optimum open pit bench stack design all consider the material spilled from berms. These criteria are:

- The number of wedge failures with FoS<1 that will result in spillage from the berm
- The maximum volume of spillage from any single wedge failure (event)
- The average volume of spilled material per wedge failure (event)

2.4.1 Number of Wedge Failures resulting in spillage from the berm

For each bench stack geometry the number of wedge failures that will result in spillage of material from the berm of width defined by that particular design is shown in Figures 13, 14 and 15.

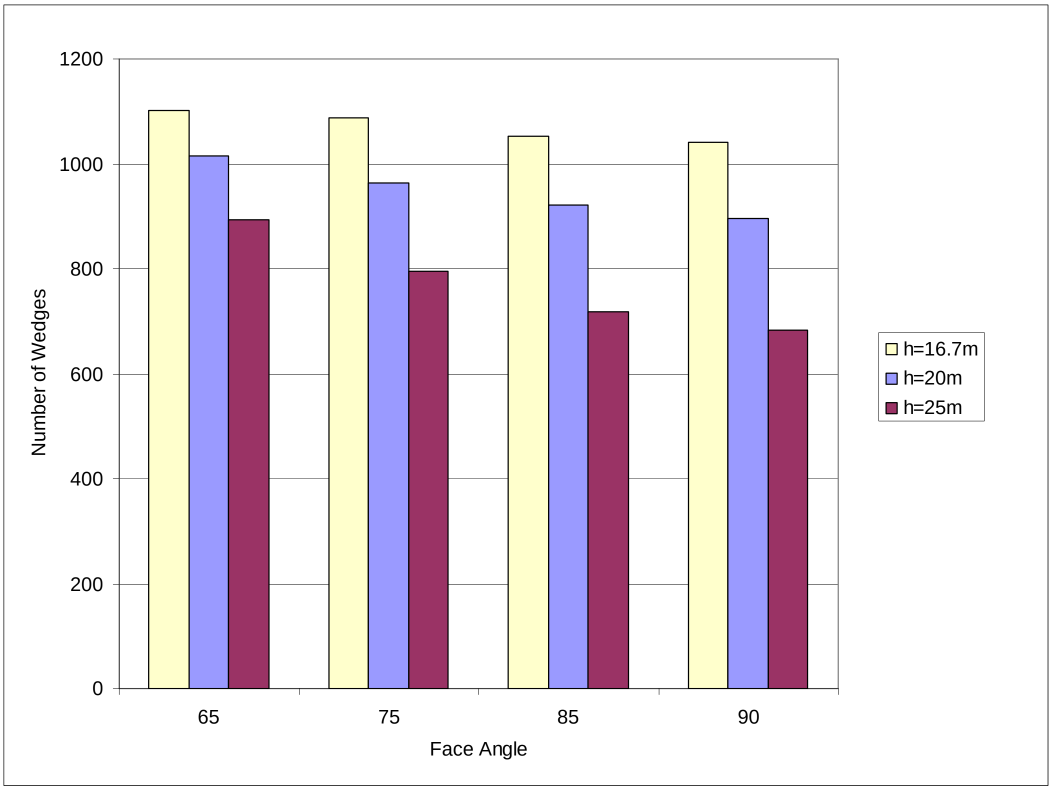


Figure 13: BSA = 46º. Number of wedge failures that will result in spillage of material from the berm

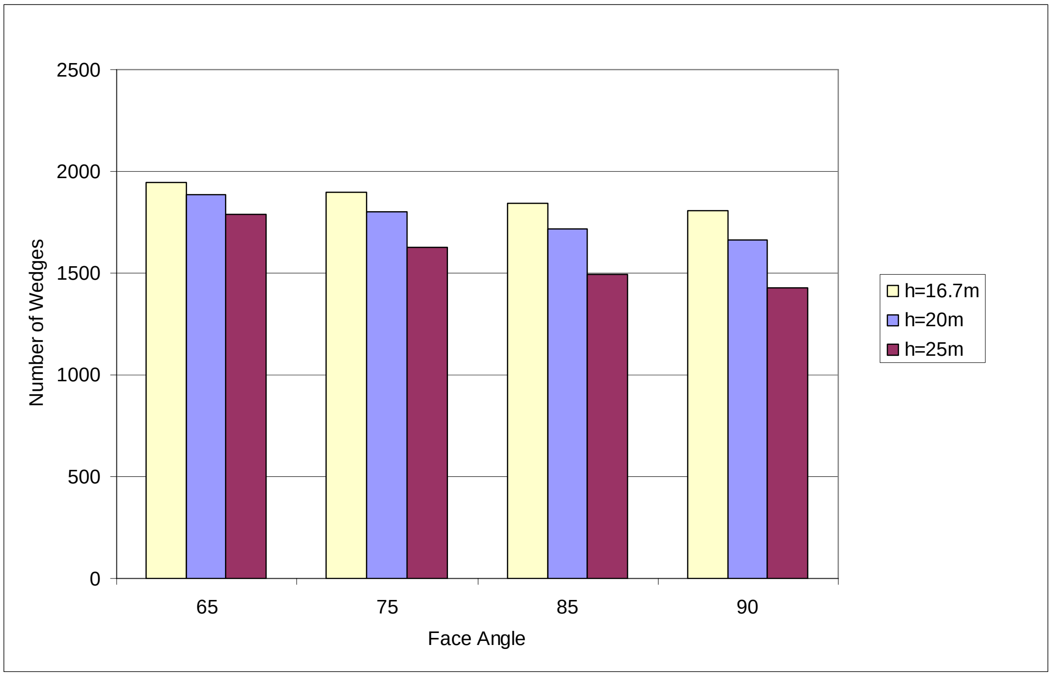


Figure 14: BSA = 52º. Number of wedge failures that will result in spillage of material from the berm

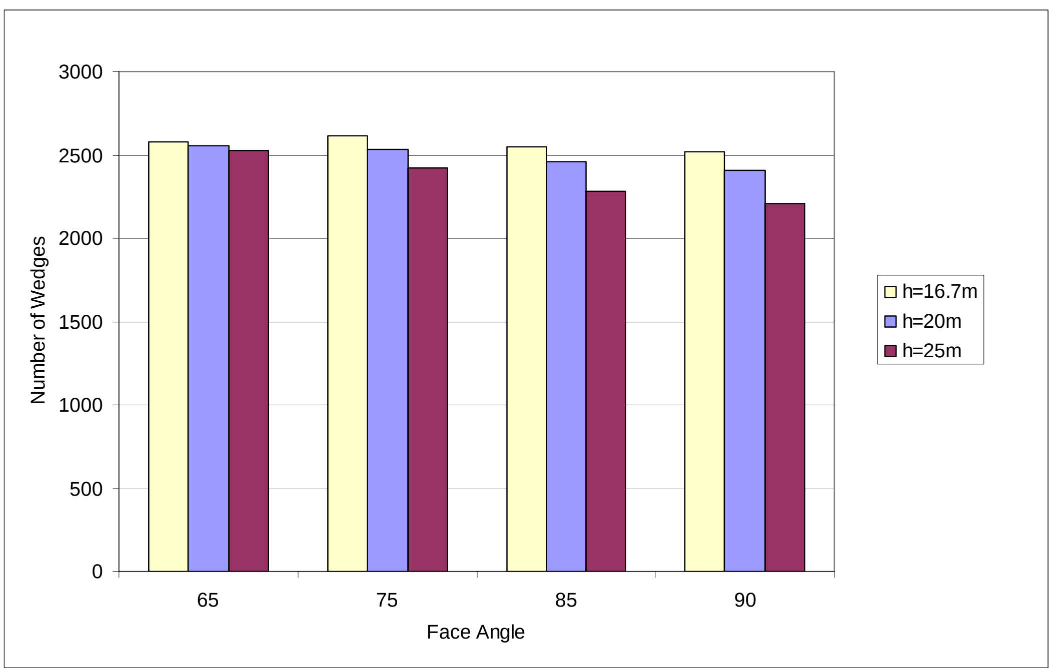


Figure 15: BSA = 58º. Number of wedge failures that will result in spillage of material from the berm

It can be seen that for a fixed bench face angle a greater bench height will reduce the number of wedges that will result in spillage of material to the next bench. This is because an increase in bench height introduces an increase in the SBW in order to maintain the same BSA. This increase in SBW reduces the chance of spillage. The same effect is observed if the bench height is kept constant and the bench face angle is increased. This reduction in number of wedges resulting in spillage of material is less pronounced for a steeper BSA than for a shallow BSA.

2.4.2 Volumes of spilled material

When the volumes of spilled material are compared for the different design geometries, it is useful to calculate the weighted average volume of spillage per wedge for each geometry analysed. The results are shown in Figures 16, 17 and 18.

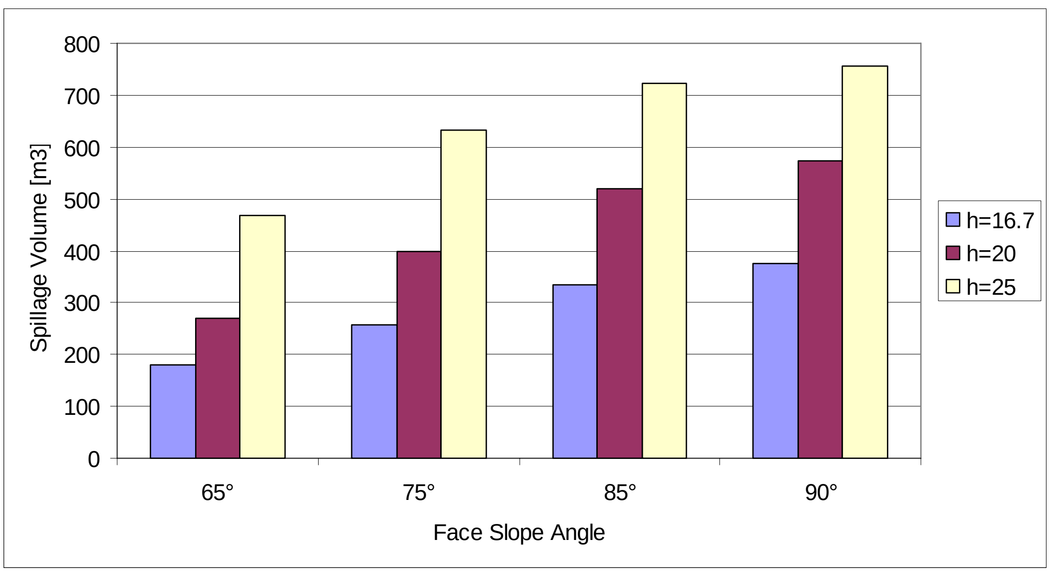


Figure 16: BSA=46°. Average spillage volume per wedge

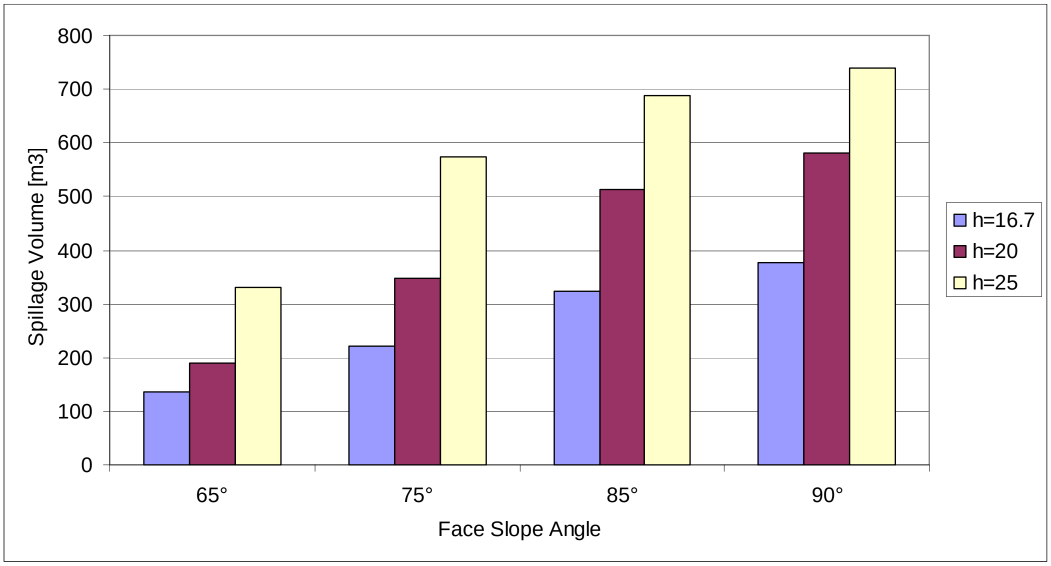


Figure 17: BSA=52°. Average spillage volume per wedge

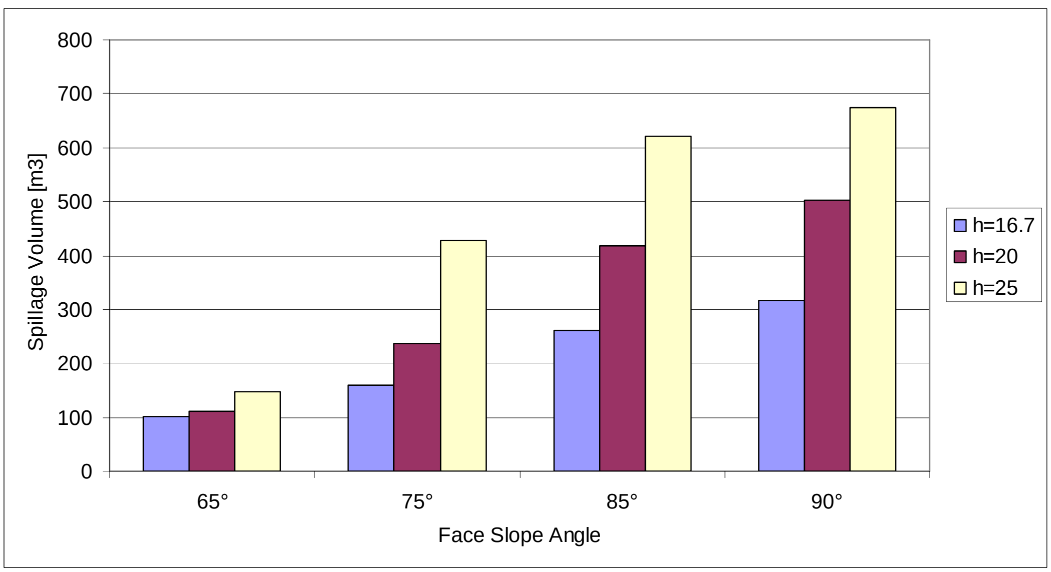


Figure 18: BSA=58°. Average spillage volume per wedge

It can be seen from the above plots and from Table 2 that both the average and the maximum volumes of spilled material increase when the bench face angle is increased or the bench height is increased. This is true even though the corresponding SBWs will also be increased in maintaining each fixed BSA.

3 ANALYSIS OF FALLING ROCK MOVEMENT

The second consideration in the assessment of the performances of different bench stack geometries is the nature of the downslope movement of individual falling rock fragments. In the preceding section, the volume and number of events of material spilled from berms has been considered. In this section, the analysis is focused on how far individual rock fragments might fall and whether they will eventually strike a geotechnical safety berm or pit ramp at the bottom of a bench stack.

Using the program RFall3D (Gibson, 2004) a comparison of the different bench stack geometries was made by modeling the trajectories of falling rocks from the bench faces near the top of a bench stack, and recording the percentage of rocks that reach the bottom of the stack (see Figure 19).

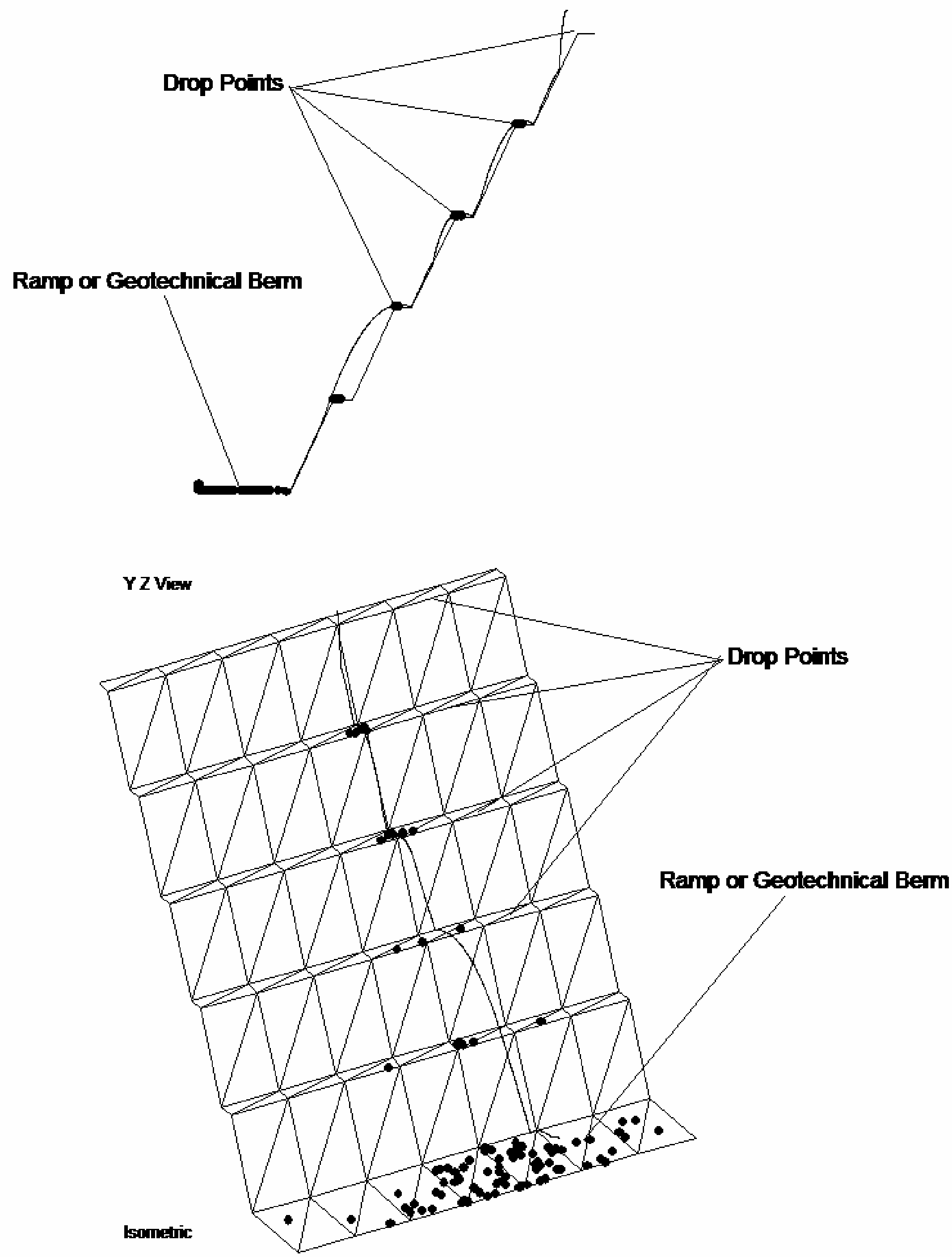


Figure 19: Typical rock fall analysis showing the drop points and the pit ramp or geotechnical safety berm

Figures 20, 21 and 22 show the results for the analyses in which the trajectories of 1000 falling rocks were analysed for each bench stack geometry under consideration. The graphs shows the percentage of falling rocks that reach the ramp or the geotechnical berm.

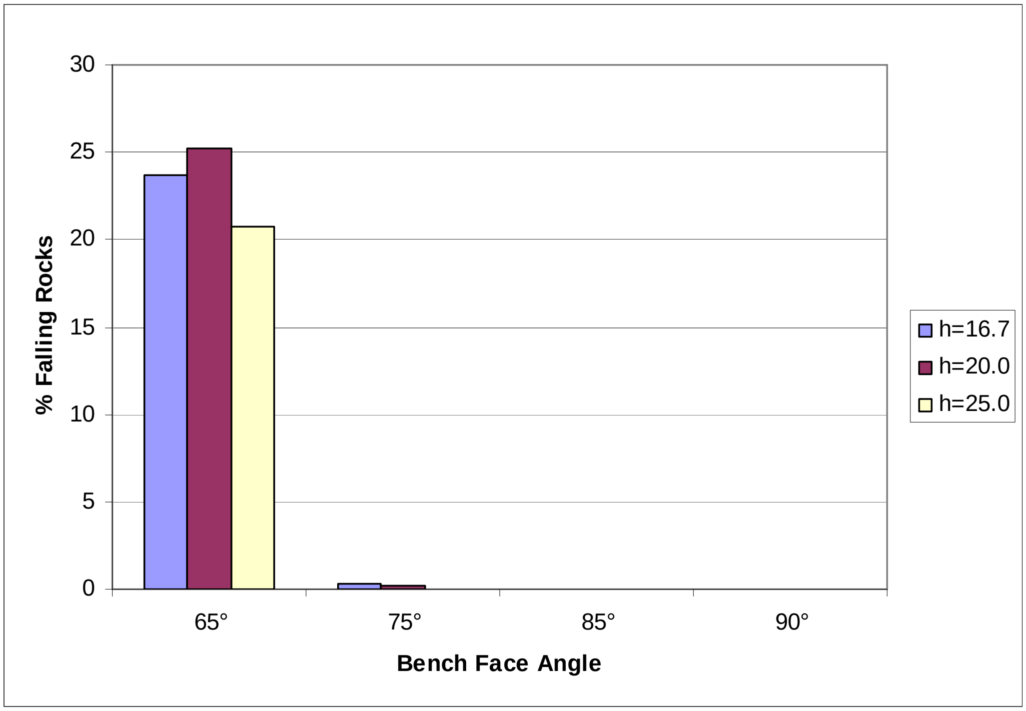


Figure 20: BSA=46°. Percentage of falling rocks that reach the base of the bench stack

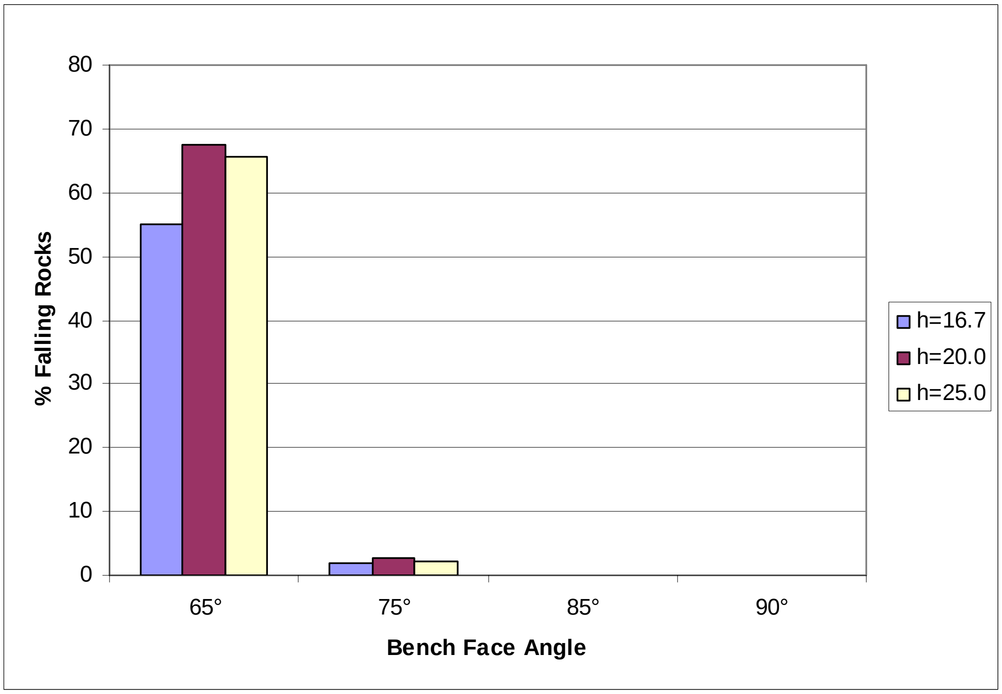


Figure 21: BSA=52°. Percentage of falling rocks that reach the base of the bench stack

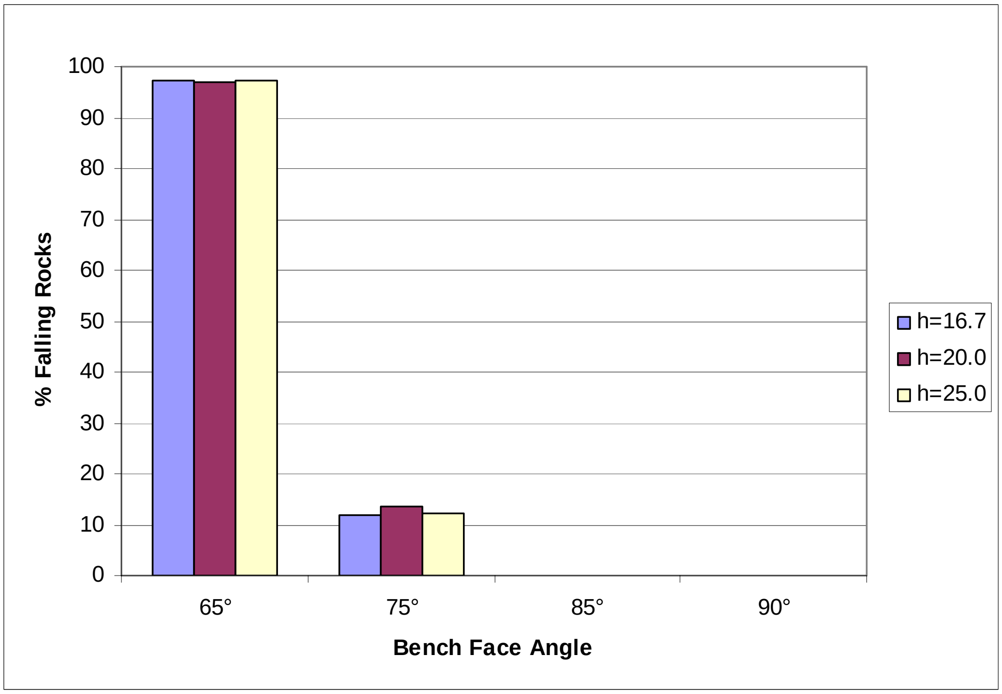


Figure 22: BSA=58°. Percentage of falling rocks that reach the base of the bench stack

From Figures 20, 21 and 22 it can be seen that the number of blocks that could reach the base of a bench stack with fixed BSA is reduced if the bench face angle is increased. It can also be seen that the steeper the bench stack, the more likely it is that falling rocks will reach the next ramp or geotechnical berm.

When the bench face angle is increased, the corresponding SBW is increased. This has two effects on the movement of falling rocks within the bench stack:

- A larger spill berm has a greater capacity to contain a rock falling from an upper bench.
- The falling rock has less likelihood of striking a bench face – which acts to increase its horizontal velocity. Striking a steeper bench face angle will produce a lesser component of horizontal velocity compared with striking a shallower bench face angle.

The results indicate that a very significant improvement is made in terms of the arrest of falling rocks where the bench face angle is increased from 65º to 75º. Only small improvement is made if the bench face angle is further steepened. It is apparent that bench face angle of 65° should be avoided if possible to minimise rock fall hazard.

4 SUMMARY AND CONCLUSIONS

The performances of a variety of different configurations for bench stack geometry have been analysed in the context of a large sets of joints that generate a large number of wedge failures of all shapes. Comparisons of performance must be done with consideration of both spillage of failed material from benches, and the movement of the falling material.

For each fixed BSA considered, the following has been observed:

- In order to minimise the <u>*number of wedges*</u> that might result in spillage of material from the berm, the bench height should be increased and the bench slope angle should be increased. It must be noted that the reduction in number of wedges will be less pronounced for a steeper BSA than for a shallower BSA.
- In order to minimise the <u>*volume*</u> of spilled of material from berms, the minimum practical bench height should be used with the minimum bench slope angle.
- To minimise the likelihood of <u>*rockfall*</u> reaching a pit ramp or geotechnical safety berm the bench face angle should be increased, and angles as low as

65° should be avoided. Changes in bench height do not have a major impact on rockfall considerations.

A general conclusion of these finding may be that in order to minimise the volumes of spilled material whilst simultaneously restricting the distance of movement falling rocks, a bench face angle in the order of 75º is optimal.

It must be borne in mind that this study has been designed to identify the volumes of spillage and analyse the movement of falling rocks for a range of bench stack geometries within a generic rockmass fabric designed to present a "worst case scenario", with no limits of joint persistence. The results are presented to allow different conclusions to be reached depending on which factors are considered most important.

Optimisation of pit slopes on actual mines can be considered in the overall context of these findings. However, local specific properties of the rockmass or operation restrictions are of great importance and must be factored in. These may relate to operational bench height requirements, characteristic persistence of joint sets, the presence of large faults or shears, and the presence of strong rockmass fabrics such as bedding and foliation of unfavourable orientation which may restrict the choice of bench face angles on walls of certain orientations within a pit.

5 REFERENCES

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