Rockfall hazard evaluation using probabilistic keyblock analysis
by G.S. Esterhuizen* and S.B. Streuders†

Introduction

Rock falls are the cause of approximately one half of all fatal accidents in South African mines, (Department of Mineral and Energy, 1997). Many of the rock falls occur during rock bursts when unstable fragments of rock are ejected into excavations in deep mines. The ground velocities associated with rock falls during a rockburst may be as low as 1mm/s, (van Aswegen & Butler, 1993). Almost all these rock fragments are delineated by pre-existing discontinuities in the rock. The discontinuities may be natural joints, stress fractures or blasting-induced fractures.

In mining operations, the rock surface which is exposed daily is intersected by numerous joints and other fractures, which contribute to the formation of unstable keyblocks. The objective of the support system is to stabilize as many of these keyblocks as possible. It is recognized that it is neither practical nor economical to attempt to support every occurrence of a keyblock. The support system attempts to reduce the probability of an injury occurring to an acceptable level.

In a producing mine, large rock surfaces are exposed daily and hundreds or thousands of new discontinuities are exposed, all of which may result in the formation of unstable keyblocks. It is impractical to attempt to map each discontinuity and carry out a stability analysis to identify potential keyblocks. The approach that is followed in mining operations is to design support in such a manner that sufficient keyblocks are supported so that an acceptable level of safety is achieved. Rock engineers therefore require a design tool which will allow them to evaluate the type and frequency of keyblocks that may be formed and the effect of support systems on the probability of failure of the keyblocks.

This paper describes a computer program, JBlock (Esterhuizen, 1996) in which a probabilistic approach is suitable for the evaluation of supports effectiveness in situations where large numbers of discontinuities or stress fractures are exposed in excavations.

Block generation method

Knowledge of the orientation, spacing and length characteristics of discontinuities makes it possible to simulate blocks in the hanging wall of an excavation. The JBlock program makes use of three discontinuity sets to generate blocks with between four and six faces. By applying the keyblock analysis method of Goodman & Shi (1985) each simulated block may be evaluated to determine whether it is removable from the surrounding rock mass. Once a keyblock has been identified and placed at random locations in a predefined excavation. The keyblocks are tested against the support to determine whether they fail the support, drop out between the support or are stable. By repeating the procedure several thousand times, statistics of the probability of failure of the keyblocks are obtained. This approach allows the relative hazard associated with different types of support or excavation orientations to be obtained. It is concluded that a probabilistic approach is suitable for the evaluation of supports effectiveness in situations where large numbers of discontinuities or stress fractures are exposed in excavations.

Synopsis

Gravity-driven rock falls account for a large proportion of all fatalities and injuries in underground mines. Potentially unstable blocks of rock are found in the hanging wall of excavations, which may be delineated by natural joints or stress fractures. These blocks, referred to as keyblocks, will fail if their weight exceeds the support capacity or if they are located between support units. This paper describes a computer program which simulates blocks in the hanging wall of an excavation based on measured properties of fractures and joints. Keyblocks are identified and placed at random locations in a predefined excavation. The keyblocks are tested against the support to determine whether they fail the support, drop out between the support or are stable. By repeating the procedure several thousand times, statistics of the probability of failure of the keyblocks are obtained. This approach allows the relative hazard associated with different types of support or excavation orientations to be obtained. It is concluded that a probabilistic approach is suitable for the evaluation of supports effectiveness in situations where large numbers of discontinuities or stress fractures are exposed in excavations.

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identified, it is a simple matter to establish whether it will be stabilized by the installed support.

The program makes use of joint length and orientation data to generate a given number of blocks. Each block is generated independently of previous or following blocks. It is assumed that a block may contain smaller blocks, resulting in large blocks which are limited in size only by the length of the joints. The procedure is as follows for the generation of each block.

**Selection of random joints**

It is assumed that joints from the two most frequent joint sets and the excavation surface intersect each other at the origin of an arbitrary coordinate system. The two planes (planes 1 and 2) are assigned random trace lengths and orientations taken from the trace length and orientation distributions of the joint sets. The intersection point of the two joint traces is assumed to lie at a random position along the joints from set 1 and set 2. This is the base corner of the block.

The program generates joints along these trace lengths, using the joint spacing data. Each generated joint plane is assigned a random length and located at random positions along their own length using the same procedures as for the first two planes. Joints are generated until the ends of the traces 1 and 2 are reached. An example of generated array of joints in the excavation plane is shown in Figure 1.

Joints traces are initially generated in the plane of the excavation. The result is a two-dimensional array of potential blocks. To provide the third dimension of the blocks, a single joint is generated along the intersection line of planes 1 and 2, which forms the upper cut off plane of the block. Only one joint is generated in the third dimension, since the analysis is only concerned with keyblocks; blocks which do not daylight into the excavation are not considered.

**Selection of blocks**

There are three blocks indicated in Figure 1. The program will consider only blocks or combined blocks with one corner at the intersection of the initial two planes. Blocks considered from this array will therefore be: Block A, Block A & C as a combined block and Block A, B & C as a combined block. The blocks B and C will not be considered as individual blocks since they do not have a corner at the intersection of the two original planes.

**Calculation of block corners and removability**

The program calculates all the corners of the blocks and determines whether they are removable using the keyblock method of Goodman & Shi (1985). The method of generation of blocks results in convex blocks being generated only. The program only considers those blocks which do not overlap the edges of the excavation. If they do, it is assumed that they are stabilized by the abutments.

The end result is a collection of blocks which may fall from the excavation if they are not supported.

**Evaluation of support effectiveness**

The collection of generated keyblocks is used to determine the effectiveness of a support system. The program selects each keyblock and places it at a random location in a predefined excavation with predefined supports. When placing the keyblock, its orientation is preserved. The location of the keyblock in the excavation determines whether it overlies a support element or not. If it overlies one or more support elements, their reaction forces are summed. The sliding direction and sliding force of the keyblock are determined, in

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**Figure 1**—Plan view showing block generation

**Figure 2**—Plan view of stope excavation with keyblocks placed at random positions

**Figure 3**—Example of results showing number of supports in a block versus frequency of occurrence
the absence of the support forces. The sliding force and support reaction forces are compared and if the support reaction is insufficient to counter the sliding force, the block is unstable. Blocks may also be unstable if the sliding direction is into the excavation and they do not overlie any support units. Figure 2 illustrates an example of an excavation with different support units and thirty keyblocks which were placed at random locations in the excavation.

The program counts the number of supports per keyblock and produces a graph showing the number of supports per keyblock versus the frequency of occurrence, as shown in Figure 3.

Blocks which are free to slide into the excavation or drop out of the hanging wall are counted as unstable blocks. The probability of failure of the blocks is expressed as a percentage of the unstable blocks over the total number of blocks tested. An example of the results are shown in Figure 4. Two types of failure are shown in the graph; blocks which fail by falling out between supports and blocks which fail the supports. It can be seen that larger blocks are less likely to fall out between supports but they are able to fail the support units.

Results may also be obtained showing the potential for keyblock failure at different locations in the excavation. The program counts unstable blocks at pre-defined grid points in the excavation. The probability of a block being unstable at any point in the grid is calculated as the number of unstable blocks overlying the grid point divided by the total number of blocks overlying the point. An example of the results for an area near a gold mine stope face is shown in Figure 5. The support is three rows of hydraulic props without headboards, spaced 1 m apart down the face. The first row of props is 3 m from the face. The back area support are matpacks spaced 3 m x 3 m apart. The supporting effect of the stope face is clearly shown, the probability of failure in the face area is lower near the face. However, the fact that the props are 3 m from the face results in a probability of failure of up to 40% in the face area. Between the rows of props the probability is generally less than 10%. Between the packs the probability of failure goes up to values of between 10% and 20%. The effect of the 2 m gap between the last row of props and the packs is shown to result in a probability of failure of between 10% and 20%.

These results show that the output is useful to develop an understanding of the interaction between the keyblocks and the support units.

**Example of an application**

An example is presented here in which the effect of reducing the spacing between mine pole supports is evaluated for a hypothetical gold mine problem. The effect of headboards is also evaluated. The input data for the analysis were chosen to model a typical deep gold mining situation in which stress fractures are parallel to the stope face and dip at about 70 degrees towards the direction of advance. The hanging wall is bedded and dips at 20 degrees to the south. In addition to the stress fractures, a vertical joint set exists, which strikes at right angles to the stope face. The face was assumed to be 20 degrees underhand. The joint and fracture input data, showing the variations in the parameters, are presented in Table I. Note that the joint set simulating the stress fractures was chosen so that it lies parallel to the face. The rock density was set to 2700 kg/m³.

Initially mine pole support was modelled in the stope excavation. The support was installed in rows parallel to the face in a square pattern. The spacing set between the supports varied between 1 m x 1 m, 2 m x 2 m and 3 m x 3 m. The distance of the first line of supports from the face was equal to the spacing between the rows of supports. The support units were assumed to have a breaking strength of 200 kN. The JBlock program was used to generate 1000 blocks using the provided joint data. The generated blocks were stored and were used to test all the different support options. The resulting size distribution of the blocks is shown in Figure 6, where it can be seen that a large proportion of the blocks are smaller than 1 m³, large blocks with volumes of up to 14 m³ are also indicated. Since the height of the blocks is limited by the bedding plane, the larger blocks could be up to 4 m x 3,5 m in plan.

The distribution of unstable blocks for the stope supported by mine poles with headboards, spaced 3 x 3 m apart is shown in Figure 7. The effect of the headboards on the probability of failure of blocks in their immediate vicinity is clearly shown, it is also clear that the probability of failure is lower between supports along dip than along strike. The
relatively low probability of failure near the face is also clear, owing to the supporting effect of the face.

The effect of changing the support type from poles with head boards, to poles without head boards, is shown by comparing the results in Figure 8. The density plots show that without the head boards, the probability of failure is increased considerably, the maximum value of failure probability in the stope is 81% whilst the maximum was 62% for the case with head boards.

An example of the probability of failure of the different sizes of blocks is shown in Figure 9 where it can be seen that the smaller blocks all fail by dropping out between supports. When the blocks are larger than 7 m³ the tendency to fail by dropping out between supports decreases and the probability of support failure increases.

The effect of reducing the support spacing on the probability of failure of blocks with a volume of less than 1 m³ is shown in Figure 10. The results show that there is a large increase in the probability of failure if the support spacing is increased from 1 m to 2 m. Increasing the spacing further to 3 m results in a smaller increase in the probability of failure. The results also show that mine poles would have to be spaced approximately 1 m apart to have the same effect as poles with headboards spaced 2 m apart.

The effect of the distance of the first row of support on the probability of failure of keyblocks in the face area is shown in Figure 11. The face area is defined as the area between the stope face and the first line of support. The support in this case was a row of sticks spaced 1 m apart on dip and the distance to the face was varied. The results show

![Keyblock size distribution](image)

**Figure 6—Size distribution of keyblocks used in gold mine example**

![Stope face and keyblocks](image)

**Figure 7—Plan view showing density plot of probability of failure of keyblocks in a portion of a stope supported by mine poles with headboards at 3 m centres**

![Probability of failure](image)

**Figure 8—Plan view showing density plot of probability of failure of keyblocks in a stope supported with mine poles spaced at 3 m centres**

![Probability of failure](image)

**Figure 9—Histogram showing probability of failure of keyblocks of indicated sizes in a stope supported by mine poles spaced at 3 m centres**

<table>
<thead>
<tr>
<th>Joint set</th>
<th>Dip</th>
<th>Dip direction</th>
<th>Scatter</th>
<th>Spacing</th>
<th>Minimum spacing</th>
<th>Maximum spacing</th>
<th>Length</th>
<th>Minimum length</th>
<th>Maximum length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress fractures</td>
<td>70.0</td>
<td>70.0</td>
<td>10.0</td>
<td>0.1</td>
<td>0.06</td>
<td>0.3</td>
<td>10.0</td>
<td>3.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Joints</td>
<td>90.0</td>
<td>340.0</td>
<td>5.0</td>
<td>3.0</td>
<td>1.0</td>
<td>5.0</td>
<td>7.0</td>
<td>2.0</td>
<td>12.0</td>
</tr>
<tr>
<td>Bedding</td>
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<td>180.0</td>
<td>2.0</td>
<td>1.0</td>
<td>0.8</td>
<td>1.3</td>
<td>40.0</td>
<td>20.0</td>
<td>50.0</td>
</tr>
</tbody>
</table>

**Table I—Input data used in gold mine example**
that the probability of failure increases with the square of the distance to the face, i.e. doubling the face to support distance quadruples the rock fall hazard in the face area. These results may not be true for all deep gold mine stopes, since the probability of failure depends on the jointing input parameters used.

Conclusions

Owing to the large number of discontinuities exposed daily in producing mining excavations, a probabilistic approach to evaluating the potential for keyblocks to fail is required. A computer program which uses joint or stress fracture orientation and spacing statistics was developed which allows rapid determination of the probability of failure of keyblocks for different support layouts.

The output of the program provides insight into interaction of support and keyblocks. The effect of changing support types, support layouts and excavation orientation may be evaluated. The potential for failure in varying geological conditions may be evaluated. Results of a typical gold mine layout presented in the paper show that the approach is able to provide useful results for practical mining situations. For the example studied, 75 cm long headboards were shown to result in a significant reduction in the probability of failure of keyblocks and that the stability of the face area was highly sensitive to the distance of the first row of support from the face.

Acknowledgements

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