Slope Instability in Jointed Rock and Design of Ground Support

A.G. Thompson CRCMining/WA School of Mines, Curtin University, Kalgoorlie, Australia

Abstract

An important aspect controlling rock mass behaviour in jointed rock is the block assembly that exists prior to forming surface excavations. Block assemblies, formed using the parameters for discontinuity sets and fault planes, contain very large numbers of arbitrary shaped blocks that are fully and partly formed from the intersections of persistent and impersistent planes. The potential for progressive failure of a slope is assessed by examining the stability of individual blocks or aggregated blocks. Reinforcement designs for blocks assessed as being unstable may be proposed and then analysed for effectiveness. The functionality of the software is demonstrated by its application to a case study.

1 Introduction

Many rock masses in which excavations are to be formed consist of assemblies of partially and fully formed blocks. The sizes and shapes of these blocks have many implications for how the rock mass will behave following the exposure of the excavation faces. In particular, the stability of the block assembly influences the angles at which slopes can be formed in open pit mines and civil infrastructure excavations and the requirements for surface support and internal reinforcement.

2 Computer software

2.1 Background

A number of different items of software have been developed:

- Firstly, to analyse structural geological data.
- Secondly, to use these geological data to predict rock block assemblies and analyse for individual block stability.
- Thirdly, to analyse the stability of complex blocks formed from the aggregation of individual blocks.
- Finally, to analyse for the effects of reinforcement on individual or aggregated block stability.

The structural geological data analysis is achieved using software adapted from that developed by Villaescusa (1991). This software is not described herein. The following sections provide some of the recent developments associated with the various software modules used to predict block assemblies and their applications. More complete details of the various modules of the SAFEX software package have been published previously (e.g. Thompson 2002).

2.2 Block formation and analysis software

The main module used for creation of the block assembly is based on the work of Warburton (1985) and the resulting program known as BLOCKS. The program BLOCKS was originally developed to run in FORTRAN. The input to the original program required a tedious, time-consuming procedure. The writer’s contributions to making the software more efficient to use were firstly the creation of a number of “standard” excavation geometries for which basic information related to size and orientation could be input by the user. Secondly, the discontinuity planes were generated automatically within sets using only the orientation and spacing data. Previously, the data for each plane was required to be input manually into an input file. The most recent enhancement has been to introduce impersistent defects and the creation of rock bridges.
An important step in making BLOCKS more useful was the conversion of the FORTRAN code to VisualBasic. This has increased the capability from creating about 1,000 discrete blocks to being able to simulate assemblies with in excess of 250,000 blocks.

The second capability of BLOCKS was the ability to identify and assess the stability of blocks adjacent to excavations faces (Warburton 1981, 1993). The original program included the capability of removing some surface blocks to create new “free” faces and new potentially unstable blocks. The writer adapted the manual capability to automatically identify the unstable blocks and to progressively re-assess the stability of the block assembly. In this way progressive collapse of surface excavations may be simulated.

At about the same time as Warburton was developing BLOCKS, the writer was developing a program to analyse the stability of arbitrary shaped three-dimensional blocks with the effects of reinforcement included. An important difference from considering only translational block displacements, as assumed in BLOCKS and by the UNWEDGE program (Rocscience 2010), is the ability to include block rotations. This work was reported by Thompson (1989). The current software package has integrated the output from BLOCKS with the input requirements of the reinforced block stability assessment module.

2.2.1 Description of software interface and usage

The main user interface for the block assembly analysis software is shown in Figure 1. Block assemblies may be created and stability assessed for different geometries of underground and surface excavations (Thompson, 2010); with the latter, up to 5 separate benches may be defined with various berm widths and batter face slope angles and heights. The demonstration example involving a slope formed in jointed rock will provide more details on some of the other items in the menu bar.

![Figure 1. Types of excavations.](image)

2.3 Structural geological data

The structural geological data required for analysis and input to the various software modules may be obtained from boreholes, scanline and window mapping, digital photographic methods or combinations of these methods. For the purposes of simulation, the structural geological data are analysed into sets, using for example, DIPS (Rocscience 2010), for which the following basic parameters are obtained for each set:

- Orientation (dip and dip direction).
- Spacing parameters.
- Persistence parameters.
- Strength parameters (e.g. cohesion and friction angle).

It is also worth noting that the ubiquitous sets may need to be supplemented by discrete major structural features such as faults. Interestingly, the analysis of structural geological information attempts to achieve “order from chaos” while it will be seen that simulations of block assemblies attempt to recreate the “chaos from order”.
2.4 Discrete Fracture Network

The term Discrete Fracture Network (DFN) has become accepted to mean an arrangement of individual defects within a volume of simulated rock. Probably the most well known DFN package is FracMan (2010). Most DFN simulations involve defects (usually assumed to be circular in shape) at locations in three-dimensional space defined by the Poisson distribution based on the mean spacing values of the sets (e.g. Villaescusa 1991). The set spacing distributions are assumed to follow an exponential or log-normal distribution. The diameters of the circular defects may also be assumed to follow one of these distributions. The primary application of FRACMAN is for application to fluid flow problems by defining connectivity between the various defects.

An alternative “engineering approach” has been adopted by the writer for the purposes of assessing excavation stability. This engineering approach involves locating planes with various orientations in space with their spacing along a vector normal to the average plane orientation following either a uniform or exponential spacing distribution. These planes may then be assumed to be continuous defects (persistent) or comprise numbers of defects separated by rock bridges (impersistent). The centres of the defects are located on a variable spaced grid with the defect diameters generated from a probability density function such as exponential or log-normal. The writer has adopted this approach for a number of reasons. Primarily, the adopted approach enables reconciliation between the sum of the individual block volumes and the volume of simulation. This is considered particularly important when predicting block size distributions. Secondly, the approach enables detailed information to be retained for every generated block. In particular, the sets forming the generated block faces are defined and the blocks adjacent to simulated excavation faces can be assessed for their stability under gravity and seismic accelerations. Another perceived advantage of the approach adopted by the writer is that comparisons can be more readily made between block assemblies for which the different assumptions of persistent and impersistent defects are used.

Substantial developments have been made with regard to implementing limited persistence for planes within joint sets. It is known that limited persistence will improve the stability of excavations because fracture through rock bridges must occur for block release from the surrounding rock mass. Also, preliminary investigations have shown that limited persistence results in blocks with re-entrant corners with the stability of such blocks enhanced. The software modules described in the demonstration examples are able to form and analyse these complex shaped blocks.

As indicated previously, planes are generated as a number of discrete persistence circles with variable diameters. Figure 2 shows a plane with light coloured, fully formed block faces within persistence circles and dark coloured faces representing rock bridges on the plane while Figure 3 shows the intersection of one plane from each of three sets and one continuous fault plane. Firstly, convex shaped blocks are created by assuming the planes are fully persistent. The complex shaped blocks are formed from the convex blocks by eliminating the faces that correspond with rock bridges. This algorithm of “healing” block faces developed by Warburton (1983), and subsequently adapted by the writer, has been shown to be very robust and a single block can result with many thousands of faces and voids formed within it.

2.5 Stability assessment

The stability of benches in surface excavations may often be assessed using stereonets (e.g. Hoek and Bray 1981) or, in more recent times by computer software such as the program SWEDGE (Rocscience 2010). In both cases, the “wedge” is assumed to be formed by two discontinuities, the berm and slope face and, possibly, terminated by a tension crack. These simple analyses, as in this case study, may often lead to over simplified conclusions regarding stability. Warburton (1983) implied this when discussing “key block” theory developed and reported later by Goodman and Shi (1985). A key block may be identified adjacent to an excavation face for which reinforcement could be designed to make it stable. However, this so-called key block may actually form part of a larger block shape comprised of blocks that could rely on the key block stability but the reinforcement may be anchored within the bounding faces of a larger unstable block. Recent enhancements to the software allow for multiple unstable blocks to be combined and their stability re-assessed.
Figure 2. Plane showing fully formed block faces (lighter colours) and rock bridges (darker colours).

Figure 3. Intersection of one member each from three sets and a continuous fault (uniform colour).

3 Demonstration example

This example is designed to present practical uses of the software and is based on data collected and analysed as part of a consulting assignment involving stability assessment of a 15m high “east slope” with strike direction of 210° formed in jointed rock. In order to create the block assemblies, structural data may be specified as either, or both, sets and individual planes. The main difference between the input data is that the locations of the members of the sets are automatically generated in three-dimensional space while individual planes are specified in position by the user.
The structural geological data collected from oriented boreholes were analysed and found to contain 5 sets. The geological data used to create the block assembly is given in Figure 4. In this example, persistent discontinuities are initially assumed. An aspect of creation of block assemblies not presented herein is the ability to predict block size distributions for the initial assembly. Measured fracture frequencies within boreholes or along scan lines may be compared with sampling along the same orientations within the simulated block assembly and input data modified until reasonable agreement is achieved. A friction angle of 25° was assigned to all sets.

<table>
<thead>
<tr>
<th>Number</th>
<th>Orientation</th>
<th>Location</th>
<th>Limited Persistence</th>
<th>Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dip</td>
<td>Dip Dir</td>
<td>Nothing</td>
<td>Existing</td>
</tr>
<tr>
<td>1</td>
<td>67</td>
<td>120</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>35</td>
<td>292</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>81</td>
<td>90</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>367</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>5</td>
<td>45</td>
<td>220</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Figure 4. Structural geological data based on core collected from oriented boreholes.

Figure 5 shows the initial block assembly formed with a nominal berm width of 10m and a nominal 40m strike length; the light grey faces are associated with primary blocks that are predicted to fail by sliding. The preliminary assessment of the slope by others suggested that only minor failures could be expected. The example clearly distinguishes between single block instability and progressive instability in a block assembly adjacent to a surface excavation. The defined slope face is the only free surface towards which blocks may initially slide. However, if a primary block is unstable, it creates new free faces that may allow other blocks to either fall vertically following undercutting or slide sub-parallel to the excavation surface. In this particular case, as shown in Figure 6 and Figure 7, the primary block removal causes undercutting of the blocks above and failure is predicted to propagate upwards. Instability is also predicted to occur near the crest of the slope.

Figure 5. Initial block assembly showing a limited number of blocks (lighter grey) predicted to be unstable.
Figure 6. Block assembly after 20 steps of progressive removal of unstable blocks.

Figure 7. Block assembly after 40 steps of progressive removal of unstable blocks.

Figure 8 shows the slope outline together with the cumulative failure shape comprised of all the blocks that have been progressively removed from the stability analyses. The implications for this particular example are that the depth of failure at the initiation location near the toe of the bench face is relatively shallow and it is possible that the slope can be stabilised by relatively short lengths of reinforcement. In practice this would need to be checked using the capability described in the next section. It was demonstrated by the software that in this particular case, if the faces between blocks were replaced by rock bridges, the combined block was predicted to be stable.
4 Reinforced block stability

It has been indicated previously that the analysis of single blocks classed as key blocks may lead to the wrong conclusions regarding an overall excavation stability assessment. The use of surface support and internal reinforcement is sometimes used to stabilise otherwise unstable slopes formed in jointed rock. The use of ground support means that steeper, stable slopes may be formed. However, the use of reinforcement in mining is usually limited by economics. It was shown by Thompson and Windsor (1992) that the demands for length and force capacity of reinforcement increased with the height of slopes and the associated potential depths of failures. A case study reported by Thompson et al. (2005) involving instrumentation and monitoring of a reinforced pit slope showed that the ground support could not prevent failure but was able to slow the rate of movement to enable safe production prior to the failure.

4.1 Reinforcement demand

The results for stability assessment of the combined block equivalent to that shown in Figure 8 are given in Figure 9; the results indicate that the block will fail by sliding in the direction with plunge of 44° and azimuth of 303° with an “out-of-equilibrium” force of ~37,500kN. An option to reduce the slope angle from 70° was proposed but not considered due to other constraints. The out-of-equilibrium force divided by the nominal free face area of the block is equivalent to a “stability pressure” demand of about 60kPa. It is known that a pressure in excess of this value will stabilise the block and may be provided by reinforcement supplemented by surface support. For the purposes of design, reinforcement systems with force capacities of about 250-300kN located on a pattern of 1.8m by 2m result in a stabilising pressure in excess of 60kPa.
4.2 Reinforcement design and analysis

The software provides the capability of defining a database of reinforcement system properties. It is beyond the scope of this document to provide details of how the database is established. The software provides for the specification of reinforcement patterns with drill set up defined by a vertical distance above or below the reference level (usually the berm RL) and horizontal distances normal to and along the strike of the slope. The direction of the hole (plunge or inclination and azimuth) is also defined. The software then automatically calculates the actual collar position on the slope face. Simple and complex patterns can be easily specified in which the types of reinforcement system can be varied together with their total length. For example, Figure 10 shows the specification for seven rows of reinforcement with variable strike spacing. The upper 3 rows are 10m long, 250kN nominal capacity cable bolts, supplemented by 2 lower rows of 6m long cable bolts. The lowermost 2 rows are 3m long, 300kN nominal capacity, high strength steel bars. All the reinforcement systems are encapsulated with cement grout. The strike offset value allows for creation of either rectangular or oblique patterns. In this particular case, the offsets are different and result in the reinforcement pattern that is shown together with the unstable block in Figure 11.

The stability assessment for the reinforced block only relies on those reinforcement systems that intersect the block free face and pass beyond the failure surface by a distance to mobilise some resistance. The software performs all these calculations and uses the embedment lengths within the block and the remaining anchor length to predict axial and shear forces and displacements in response to block movements.

The summary of the results for the analysis of the reinforced block are shown in Figure 12. The analysis predicts stability with 123 reinforcement systems effectively intersecting the block. The block is predicted to translate 11.3mm in the same direction as the unreinforced block but is accompanied by small rotations; that is, in this case the reinforcement does not modify the translation direction but does prevent failure of the block. In other cases, the reinforcement often modifies the translation direction and can cause significant rotations of the block to enhance stability.
Figure 10. Specification of reinforcement.

Figure 11. Visualisation of aggregated block and generated reinforcement.
Figure 12. Results of stability assessment for the reinforced block.

The reaction forces provided by the underlying joints are detailed in Figure 13. It is worth noting that the shear forces resisting sliding are fully mobilised. This is usually the case for cases where “passive” reinforcement only provides reaction forces after movements in excess of those required to mobilise the discontinuity shear strength have been exceeded. For this reason, it is neither appropriate to calculate a factor of safety nor to assume that the reinforcement force capacities are fully utilised. It is better to consider by how much the combined reinforcement force exceeds the minimum force required to achieve equilibrium of the block. In this case, the axial and shear forces developed in the reinforcement systems are shown in Figure 14 as being mobilised to about 50% or less of their capacities. This would suggest that less reinforcement could be used by increasing the spacing between the collar locations. However, in many instances, the shear forces are approaching the allowable capacity.

4.3 Additional comments on ground support design

It was mentioned earlier that the software predicted some potential instability near the crest of the slope. Since it was critical to maintain the crest in the design position for surface infrastructure, 6m deep, vertical shear pins were designed to be installed approximately 1m back from the crest prior to excavation. The shear pins were nominally 100mm diameter hollow steel pipes, encapsulated inside and outside by cement grout. The effectiveness of shear pins for crest stabilisation was reported by Thompson et al. (2004). The shear pins were not included in the stability assessment since they did not penetrate below the underlying failure plane but contributed to maintaining the integrity of the rock mass. At this time, excavation has not commenced and no comments can be made regarding the performance and effectiveness of the design.
Figure 13. Statistics for faces on which sliding is predicted.

<table>
<thead>
<tr>
<th>Block Face</th>
<th>Contribution</th>
<th>Property Code</th>
<th>Cohesion</th>
<th>Friction</th>
<th>Closure</th>
<th>Shear Mod. Disp.</th>
<th>Normal Reaction</th>
<th>Shear Resistance</th>
<th>Mod. Factor</th>
<th>Slippage</th>
<th>Dip</th>
<th>Dip Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1.0</td>
<td>11423.5</td>
<td>4386.3</td>
<td>1.0</td>
<td>1.0</td>
<td>11.7</td>
<td>301</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.0</td>
<td>11423.5</td>
<td>4386.3</td>
<td>1.0</td>
<td>1.0</td>
<td>11.7</td>
<td>301</td>
</tr>
</tbody>
</table>

Figure 14. Summary of forces and displacements developed in reinforcement at six locations.
5 Concluding remarks

An integrated set of software modules has been developed based on the simulation of block assemblies and excavations formed in them. The uses of these modules have been demonstrated by applying them to a practical situation that is relevant to a surface excavation formed in jointed rock. The initial step was to take structural geological data and create an assembly of blocks. This block assembly was then analysed for instability of blocks exposed at the surfaces of the excavation. Instability was shown to progress away from the original intended excavation surfaces to create larger volumes of failed material than would have been anticipated by using simpler analysis methods. The software may be used to predict block size distributions in failed material. If the extent of failure and block size block distribution is amenable to “clean up”, then in mining failure may be allowed to occur. Otherwise, it was shown how reinforcement could be designed and the effectiveness checked by stability analysis for an aggregated block where it is assumed that surface support retains the smaller blocks between the locations of the discrete reinforcement systems.

6 Acknowledgements

The work described in this paper would not have been possible without the pioneering work of my former colleague Dr Peter Warburton. I am grateful for the financial assistance and support provided over many years by various organisations associated with the Australian mining industry and, in particular, AMIRA International and CRCMining. The writer wishes also to acknowledge the invaluable assistance and support of his colleagues and friends Ernesto Villaescusa, Chris Windsor and Glynn Cadby.

7 References