DEVELOPING NEW APPROACHES TO ROCK SLOPE STABILITY ANALYSES

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ABSTRACT

This paper describes mining industry funded research that is being undertaken to address the critical gaps and uncertainties in our knowledge so that we can develop new approaches and create more effective ways for predicting the reliability of rock slopes in large open pit mines. It is envisaged that this research will not only lead to more effective pit slope design but further reduce the potential for unforseen geotechnical risks by enabling the geotechnician to communicate the risks more effectively with management and to optimise site specific control measures.

To achieve this, several research tasks are in hand. The first is to accurately represent the structured rock mass with a 3D computer model (Siromodel) that creates polyhedral blocks from structural distribution data characterised by position, orientation and persistence. Siromodel is being coupled with particle flow and other numerical codes to evaluate how the structured rock mass deforms in the stress environment of an open pit and how a candidate failure surface may propagate through the dilating rock mass along the path of the least shear and/or tension resistance. A beta version of the Siromodel software has been distributed to 20 Sponsor mine sites for technical evaluation. The end state is to develop methods of analysis that characterise the reliability of a described candidate surface, and the probability of the candidate surface propagating to failure, recognising that the rock mass strength may well be defined in a different way than before.

Introduction

Over the years the slope design process in large open pit mines has been hampered by critical gaps in our knowledge and understanding of the relationships between the strength and deformability of rock masses and the likely mechanisms of failure. As practitioners we have not yet mastered particular complications associated with rock masses that are neither homogenous nor isotropic in low stress regimes that encourage large deformations. We usually manoeuvre around these difficulties by smearing the whole system with 'average' rock mass strength properties, calibrating its likely performance using existing slope movement data, and then performing parametric studies to isolate what we judge to be the more unlikely events. Although this is accepted practice, it has some distinct disadvantages. Notably, by approximating the behaviour of the whole system in the design phase we may have inadvertently masked a critical variation in the geotechnical model and potentially either underestimated or overestimated the geotechnical risk to the operation. Additionally, current procedures do not overcome the fundamental issue of accounting for anisotropy and large

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deformations. Last but not least, by calibrating against a known event we may also be inadvertently increasing production costs and, in fact, be limiting our chances of reliably predicting a future failure event.

Collectively, these anomalies have generated a need to step outside the box and reassess the fundamentals of rock mass strength and slope failure mechanisms from first principles. With financial support from a number of international mining companies with interests in open pit mining, CSIRO Exploration & Mining has initiated a research project to achieve this objective. The project was developed during 2004 and officially commenced following an inaugural technical meeting between the Sponsors, a number of senior industry practitioners and researchers, and CSIRO in Santiago, Chile, in April 2005. The purpose of this meeting was to be as inclusive of industry opinions as possible, consolidate the research plan, and finalise its direction.

The project is also supporting parallel streams that seek to bring into the public domain the outcomes of the research, together with all current knowledge about geotechnical data collection and manipulation, uncertainty analysis, slope stability analysis, and risk management via updated pit slope design and risk management manuals. Existing manuals such as that produced by CANMET almost thirty years ago remain as valuable literature references, but the time has come for a new generation of manuals that detail accepted practice for today’s practitioners. The forum provided by this conference is also seen as an opportunity to gather opinions as to the value-adding potential of this project and to seek comments on industry’s research needs in rock slope stability analyses.

Technical Requirements

A reliable geotechnical model is the cornerstone of all slope design. Advanced methods of rapid, non-contact data collection are now available and any number of three-dimensional modelling tools that enable sophisticated visualisation of the resulting lithological, structural, geotechnical and groundwater information are available in the market place. Similarly, a number of extremely sophisticated two- and three-dimensional numerical modelling software packages are also available to the practitioner. How is it then, that when we appear to have the tools at hand to produce good models and perform sophisticated analyses our record at predicting slope performance is so patchy? Invariably there are animated discussions of likely failure mechanisms, often backed up by excellently presented case histories, but rarely do we agree on how failures actually propagate through the rock mass.

The fundamental issues to be addressed in predicting slope failures can be grouped into three categories (Read, 2003).

1. Knowledge of the strength, geological structure and deformability of the potentially unstable rock mass, including:

    - the orientation, spacing and continuity of the joints that intersect the rock mass;
    - the location and orientation of the larger faults or weak zones that may subdivide the jointed rock mass into separate zones or domains; and
    - the quality of the rock mass in each domain.

2. Knowledge and understanding of failure mechanisms.

3. Knowledge of how to analyse these failure mechanisms for stability.

Additionally, experience has demonstrated that the very low stress and dilatational environment in slopes virtually guarantees that existing or incipient structures that cut through a rock mass are exploited before a through-going failure surface develops, and this must be accounted for. It is necessary also to recognise that failure is three-dimensional, there is no such thing as a two-dimensional failure, and that all of our methods of slope stability analysis assume Mohr-Coulomb failure, which requires the input of the frictional parameters phi and cohesion. However, as the low stress environment of an open pit is created and the structured rock mass dilates, the individual particles or blocks of rock may be free to move apart and start moving about. Under these circumstances, the stability of the slope is potentially a function of particle interlock rather than particle friction (phi and cohesion), and the use of the Mohr-Coulomb failure criterion may not be appropriate.

Research Objectives

Due consideration of the technical requirements for research generated four main objectives.

1. Production of a 3D computer model (Siromodel) that accounts for the spacing, orientation and continuity data for the structures and weak zones that intersect the rock mass and predicts how candidate failure surfaces propagate through the rock mass. The purpose of the model is to:

    - visualise candidate 3D failure surfaces propagating through the jointed rock mass along the path of least shear and/or tension resistance;

    - determine the proportion of the candidate 3D surface which is entirely along incipient structures or through a combination of incipient structures, rock bridges and/or weak rock; and

    - identify where rock bridges/weak rocks occur and where they need to break to in order for the surface to continue propagating.

2. Provision of data handling systems that interface real data with the 3D model.

3. Description and setting of criteria for the different failure mechanisms that may be associated with or attached to the predicted candidate surfaces recognising that, as the rock mass dilates and deforms;

    - existing and incipient structures will open up,

    - individual rock particles and/or rock bridges will move about,

    - large deformations may occur as the particles/bridges move about,

- the in situ stress conditions may change locally as the pit deepens, and
- stability may be controlled by particle interlock or some other energy form other than particle friction (Mohr-Coulomb).

4. Developing methods of analysis that examine the reliability of the described candidate failure surface. This incorporates the statistical analysis of determining the probability of the candidate surface propagating to failure, whilst recognising that the rock mass strength may well be defined in a different way than before.

Research Tasks

The research objectives are being progressed within the framework of the following seven tasks.

1. Preparation of Siromodel in a beta version that can be interfaced with real data and trialled at sponsor-company mines.
2. Use of Siromodel to visualise and evaluate likely pathways for candidate failure surfaces along or through a combination of incipient structures, rock bridges and/or weak rock in the structured 3D rock mass.
3. Use of particle flow codes and/or other numerical codes together with Siromodel to evaluate how the structured rock mass deforms in the stress environment of an open pit and how the identified candidate failure surfaces may propagate through the dilating rock mass along the path of least shear and/or tension resistance.
4. Evaluation of the rock mass characterisation data and recognition/definition of attributes that control the strength of the structured rock mass as it deforms and the candidate failure surfaces propagate. The possibility that the strength of a dilated rock mass comprised of individual particles or blocks of rock that may be free to separate and move about is a function of particle interlock or some other energy function rather than particle friction (phi and cohesion) as dictated by the Mohr-Coulomb failure criterion will be critically assessed, as will the question of whether or not we need to define a rock mass strength at all. For example, for a structure or set of unfavourably oriented structures of given shear strength and persistence, combined with the intact rock strength, pore pressure and stress, it may be possible to determine the likelihood of a slope failing without having to estimate rock mass strength at all.
5. Evaluation of the potential for decay and loss of rock mass strength with time, which may vary significantly from rock mass to rock mass.
6. Description and setting of criteria for the different failure mechanisms that may be associated with or attached to the propagating candidate failure surfaces.
7. Development of methods of analysis that examine the reliability of the described candidate failure surfaces.

Progress of Research

The beta version of Siromodel (research task 1) has been distributed to 20 Sponsor mine sites for technical evaluation, and to ensure that the data input and procedural instructions are reasonable and user friendly. Essentially, structures submitted to Siromodel are modelled as polyhedra and thus consist of polygonal facets. The polygons are defined in terms of their vertices in 3D space with the open pit polyhedron constituting the so-called ‘bounding volume’ of the simulation. The bounding volume consists of polygons representing the pit benches and the base, back and sides of the simulation volume (Poropat & Elmouttie, 2006).

Several sets of joints, faults or bedding planes can be introduced into the model, each with their own orientation and distribution characteristics. The general procedure for block detection firstly involves detecting the vertices corresponding to the intersection of the polygons with the simulation volume and each other. The discontinuities created by these intersections are then regularised such that only those that can contribute to block formation are retained. Once this is complete, the block faces can be identified as closed polygons created by these remaining discontinuities. Finally, blocks themselves can be identified as closed polyhedra formed by the faces. Blocks located at the open pit face of the simulation volume can be tested for movability by examining contact edges and surfaces of each block for possible sliding directions. Blocks are deemed to be kinematically free if they are movable and their weight will cause them to overcome the specified friction along the available sliding directions (Poropat & Elmouttie, 2006).

A simple example with joints, faults and bedding planes is illustrated in Figure 1 (Poropat & Elmouttie, 2006). Blocks free to move at the surface are coloured red. A unique feature of the realisation is that curved or undulating surfaces can be simulated, which is vital in assessing the freedom of a polygon to move and the direction in which it can slide. Also, the back of the bounding volume can be extended any reasonable distance behind the benches, so that when blocks free to move at the surface have been identified it is possible to continue the process inwards, identifying how far a candidate failure surface can propagate before it hits an immovable rock bridge. Currently, research task 2 is progressing this attribute as a means of visualising and evaluating likely pathways for candidate failure surfaces along or through a combination of incipient structures and rock bridges.

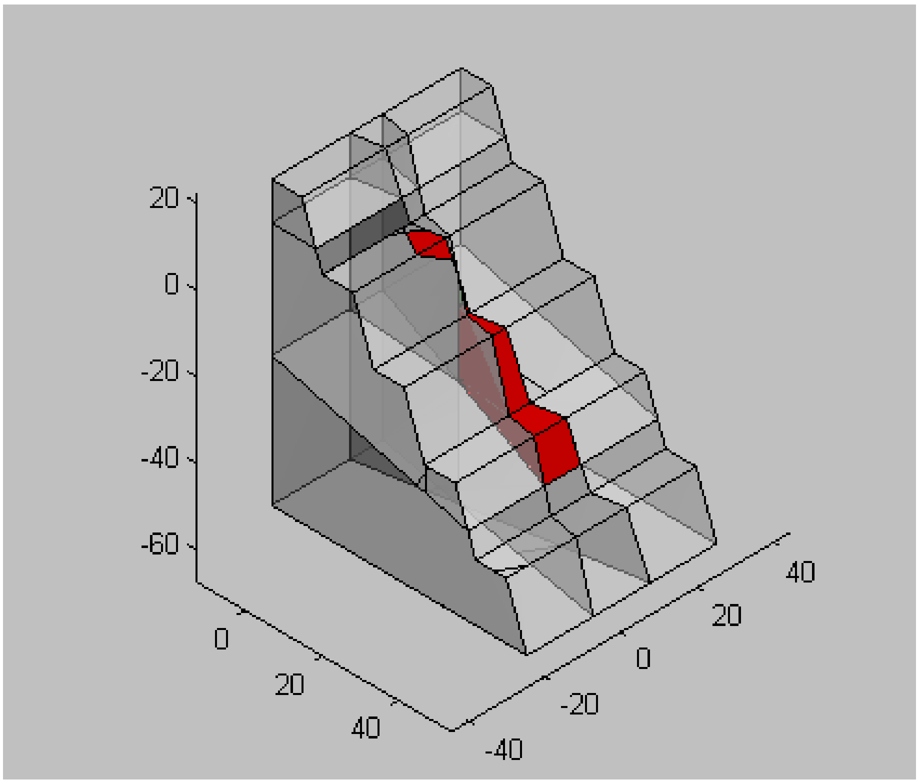

Figure 1: White blocks represent those bound to the simulation volume, red represent free blocks

Work linking numerical codes with Siromodel to evaluate how the structured rock mass deforms in the stress environment of an open pit (research task 3) commenced early in 2006 and will continue through 2006 in concert with research tasks 4, 5 and 6. Work on research tasks 6 and 7 is expected to flow over into 2007.

Preparation of the Pit Slope Design and Risk Management manuals is being progressed in parallel with the pit slope design studies, and preliminary drafts have been prepared. Sponsor-approved final copies are expected by the end of the year after which they will be released as web-based documents in the public domain. It is anticipated that detailed accounts of the results of the research will be published at the planned International Symposium on the Stability of Rock Slopes in Open Pit Mining and Civil Engineering Situations, Perth, Western Australia, 12-14 September 2007.

Conclusion

The development of the 3D beta version of Siromodel has initiated the process of our quest in identifying new approaches to rock slope stability analysis. The beta version currently under trial by sponsors creates polyhedral blocks from structurally distributed data characterised by position, orientation and persistence. It has the ability to simulate kinematically free blocks on curved or undulating surfaces, identify potential direction of failure and determine the extent of a propagating candidate surface to a rock bridge. Research is progressing towards coupling Siromodel with particle flow and other numerical codes to evaluate how the structured rock mass deforms in the stress environment of an open pit and how a candidate failure surface may propagate through the dilating rock mass along the path of the least shear and/or tension resistance.

By stepping outside the box and reassessing the fundamentals of rock mass strength and slope failure mechanisms from first principles we can start to address the critical gaps and uncertainties in our knowledge relating to issues such as slope failure propagation mechanisms, change in stress regimes, isotropic variation, groundwater effects, rock mass homogeneity, calibration errors, and averaging rock strength data, we can create more effective ways than now in predicting the reliability of rock slopes in large open pit mines.

With financial support from a number of international mining companies it is envisaged that this CSIRO Exploration & Mining led research project, coupled with parallel streams in pit slope design and risk management, will not only improve pit slope design methodology but further reduce the potential for unforseen geotechnical risks by enabling the geotechnician to communicate the risks more effectively with management and to optimise site specific control measures. Our end state is to develop methods of analysis that characterise the reliability of a described candidate surface, and the probability of the candidate surface propagating to failure, whilst recognising that the rock mass strength may well be defined in a different way than before.

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