EXECUTIVE SUMMARY

This report presents the results of a program of further research into the use of a combined approach of numerical and centrifuge modeling in assessing the stability of deep open pit mines.

The research has focused on assessing the use of the technique in assessing the stability and rock mass interaction arising from the development of an underground mine below an existing open pit.

The centrifuge models have provided a simplified understanding of the types of failure mechanisms associated with underground voids created below an existing open pit. In general, good agreement has been obtained between the numerical modeling of the centrifuge models and the results of the centrifuge modeling. Evaluations of the results suggest that the strain softening constitutive model provides an appropriate approximation of the centrifuge model result and the resulting numerical models could be used as a basis for preliminary design studies.

Some difficulties were experienced in the modeling of the displacements measured in the centrifuge models. The experimental displacements were observed to be erratic, making direct comparison with the predicted displacement arising from the numerical modeling difficult.

With respect to the numerical modeling of the Daye Mine, the continuum *FLAC* and *UDEC* models have produced results that differ in some significant ways, both with respect to the computed stability of crown pillars and the extent of yield induced in the adjacent pit slopes. They are broadly consistent in predicting that the crown pillar at the base of the pit is unlikely to be stable if it is less than 30 m in thickness, but are totally inconsistent in predicting the thickness required for stability.

There are a large number of differences in detail between the *FLAC* and *UDEC* models:

- the geological model used in UDEC is more simplified, as are the shapes of the pit and the initial stope;
- the assumed pit wall heights are somewhat greater in *UDEC* and *FLAC* far-field boundaries have been set closer;
- much finer zoning was used in the crown pillar in *UDEC*, whereas the FLAC zoning is fine in the walls of the orebody and relatively coarse in the crown pillar;
- the initial approximation to the in-plane in-situ stresses was computed using slightly different algorithms, and the out-of-plane stresses were much larger in most of the *UDEC* models;
- the internal treatment of plastic flow and artifical damping is not identical in the two programs, even though they are based on essentially the same explicit numerical method.

Work in earlier stages of this project (Swindells at al. 1995) demonstrated that, for the simpler centrifuge model systems that were studied then, the two programs produced very similar results, both for failure mechanisms and failure loads. It is therefore probable that some of the differences noted above have led to the different results that we have noted in these global models of section V-V' at Daye Mine. However, it would be a major undertaking to modify either the *FLAC* and/or the *UDEC* data file to resolve the various differences, and very little more would be learned from the exercise.

A physically more realistic response might be obtained in 2D models if the rock mass around the stope were to be allowed to being to relax by taking the numerical stepping only part way to equilibrium before cemented backfill was introduced into the stope. However, there is no rational way to determine how much relaxation should be allowed to occur to properly simulate the real 3D effects. The only reliable method of modeling the global response of the rock mass to the proposed underground mining would be to perform full 3D non-linear analyses. The quasi-3D elastic-plastic finite element analyses in Section 4.1 of the Chinese research team's report are a first step in that direction, but a much more extensive model that allowed representation of a sequence of mining and filling along strike would be needed to properly assess all of the likely 3D effects.

1.0 INTRODUCTION

1.1 OVERVIEW

As the open pit mines become uneconomical due to increasing depths, there is a trend to move into underground mining methods beneath existing open pits as shown in Figure 1.1. However, problems can arise when new underground excavations impact on the stability of the overlying open pit. This influence is usually difficult to predict, since currently there are no standard methods of analysis for these situations. Standard limit equilibrium methods are usually inaccurate when applied to such cases, because they fail to account for stress concentrations due to underground excavations.

The aim of this study is to investigate the interaction between open pits and underground excavations through physical model testing and to investigate the suitability of numerical codes such as *FLAC* (Itasca 1995, 1998) and *UDEC* (Itasca, 1996) for such purposes. In addition, one of the subsidiary objectives of the study was to extend the previous research into mixing physical and stress analysis modeling (ACG, 1995) into mining situations involving open pit and underground mine operations.

1.2 BACKGROUND

There is limited information dealing with the influence of underground excavations on open pit slope stability. The majority of existing literature describes studies of interaction between existing underground mines and new open pit mines, rather than the impact of new underground excavations on an existing open pit slope.

Walton and Taylor (1977) carried out an extensive analysis of the influence of existing underground excavations on the slope stability of open pit coal mines. The study was focussed on workings encountered within slopes and workings that occur beneath the level of surface mining. The authors identified the types of slope failures associated with old workings and classified them as:

- Translational slides – the first mode concerns the formation of bell pits, the second mode is a result of movement along bedding planes and the third mode is a result of open-jointed strata aggravating a plane or wedge-like slide.

- Toppling failures – excavation causes forward movement and collapse of in-fill. This leaves an unsupported overhanging beam of strata in the upper part of the slope, which fails by toppling.
- Span failures – caused by failure of the inner edge of a pillar at the toe of the slope. This causes the slope toe to collapse into the void.
- Slab sliding – leads to either the compaction of the arch infill or to the buckling of the roof strata which span the in-fill.

These modes were discussed in the context of void migration from underground excavations. Water was identified as the other factor that influences the stability of an excavated edge. It can be important both in terms of buoyancy and pore pressure, especially within discontinuities.

Morris and Clough (1986) highlighted the anticipated problems associated with mine layouts in old underground excavations on open pit slope stabilities. The authors conducted a probabilistic analysis on the highwall slope and investigated the effect of the direction of mining on slope stability due to working within slopes. They concluded that the principal effect of underground mining on slope stability appears to be the modification of existing structures or, alternatively, the development of new discontinuities which loosen the rock mass and may even alter the inclination of some critical surfaces. Highwall slope angles were recommended for areas of high and low probability of pillar failure.

Morris and Fourie (1986) studied some considerations regarding the stability of underground workings that are to be mined by opencast method in South African coal mines. The authors concluded that the stability of the underground workings has a great effect on the efficiency, safety, capital and working costs of the opencast mine that will be mined over underground workings. Finite element analysis was used to investigate the effects of:

- pit excavations on pillar stability, since the presence of open pit excavations changes the stress distribution in pillars adjacent to the highwall.
- complete failure of a single pillar on the stability of underground workings.

The authors also studied the effect of blasting vibrations on the stability of pillars, and recommended steps to be carried out by engineers when investigating such deposits.

Cotton and Matheson (1989) used a two dimensional, explicit formulation finite difference model that assumed Mohr-Coulomb elastic plastic rock behaviour to examine the effect of different stope sizes on slope stability in a gold mine located in the United States. They noted that stopes less than about 3 metres wide do not cause serious pit floor problems, but create rock fall instabilities in pit walls. The numerical modelling suggested that the change in stress field caused by excavation of relatively shallow opencast mines probably does not affect the stability of larger stopes.

Watters et al. (1989) conducted field and laboratory studies of the effects of backfilled stopes on pit stability. The research identified two possible ways the underground excavations affect the slope stability:

- backfill erosion from the stope due to slope excavations. This removes support from rock surrounding the backfilled stopes.
- presence of excavations undermines the slope, permitting rock displacement within individual benches, which over a period of time destroys slope integrity.

Watters et al. (1990) described field and analytical studies investigating the stability of slopes at a gold mine in Nevada being excavated through old underground workings. The computer modelling was performed using the *FLAC* and *STABL5* codes on the end-of-pit design with different numbers of openings. It was found that tensile stresses and shear stresses that developed around openings close to the slope face within the weak and fractured rock units may cause isolated bench failure, rock topples, and ravelling of slopes during excavation operations. However, if the fault or shear zones run roughly parallel to the slope face, and are located a distance less than 1/3 of the slope height behind the slope crest, they will control the slope instability, and not the presence of underground voids.

Singh and Singh (1991 and 1992) and Singh et al (1991) used physical models to predict ground movement in open cast mines above existing underground voids and monitor the behaviour of slopes during progressive excavations. Equivalent material modelling was used in the study, which is based on adequately scaling down the inherent properties of the rock mass. The authors also outlined the existing methods for slope monitoring in open cast mines.

Soukatchoff et al. (1993) defined a methodology for monitoring slopes influenced by underground workings in a French open pit mine. The authors suggested relevant instrumentation and presented sample outputs from the mine.

1.3 SCOPE OF STUDY

This study is part of an ongoing study into the effects of underground excavations on the stability of open pit slopes. The main objectives of the study are:

- to conduct extensive laboratory studies on artificial rock material suitable for centrifuge testing;
- to conduct centrifuge tests and collect relevant experimental data; and
- to conduct numerical modelling using computer codes such as *FLAC* and *UDEC*, and investigate their validity in predicting the mechanism of failure and failure load level.

In this project, two case studies were examined. The first case was of an underground mine planned to be constructed beneath an open pit at the Daye mine in China. This iron ore mine is situated near Huangshi City, Hubei Province as shown in Figure 1.2. It was the first open pit iron ore mine in China to use mechanised methods which were introduced at the end of the 19th Century. Today, it is the deepest iron ore mine in China with current maximum wall height of 372 m.

The second case study represents a typical Western Australian mine. Figure 1.3 illustrates an example where the ore body is partially extracted from an open pit, and underground stoping is employed to remove the remaining ore.

1.4 REPORT STRUCTURE

The report is presented in two parts. The first section presents the results and conclusions arising from the studies – largely centrifuge and numerical modeling – conducted by the Australian research team. The second section outlines the work conducted by the Chinese research team.