EXECUTIVE SUMMARY

This report presents the results of a three-year program of research studies funded by the WA-China Economic and Technical Research Fund. The main focus of the research study has been to investigate and validate techniques for modelling the stability of deep open pit mines, based on the use of combined numerical and physical modelling techniques using the geotechnical centrifuge.

The scope of the studies has included the following:

- a review of a number of slope failures in open pit metalliferous mines in Western Australia to identify predominant failure mechanisms as a basis for the modelling studies
- evaluation and development of the centrifuge modelling techniques using a series of simple models of homogeneous slopes
- introductory numerical and centrifuge modelling aimed at investigating the mechanics influencing open pit and underground mine interaction
- detailed evaluation of numerical and physical modelling of flexural toppling failure
- review of the stability of part of the Daye Open Pit mine in Central China as a basis for validating the modelling techniques developed in the studies.

A review of stability conditions from a large number of slope failures in open pit metalliferous mines in Western Australia has shown that the majority are toppling failures in hanging wall slopes.

Summary experience curves were derived from a number of the case histories of pit wall failure and these represent empirically derived stability curves. The envelopes define ranges of apparently stable and unstable wall geometries that can be used for preliminary evaluation of overall wall stability.

The use of rock mass classification systems in characterising pit stability conditions was also evaluated. Whilst they show some distinction between the stable and unstable slopes from the case histories, with poor quality rock mass ratings or classes being associated with higher frequencies of wall failure, the rock mass ratings do not show enough distinction when presented as wall height versus slope angle relationships for various rock quality class.

More extensive evaluation of rock mass classifications over smaller, more specific areas, is warranted to evaluate their use in developing further empirically derived stability curves for rock slope stability analysis.

The material property requirements for the modelling studies were such that the model rock materials were required to behave in a similar way to rock materials in terms of general strength and deformation properties without attempting to model any specific rock types. A large number of alternative material mixes were evaluated during the studies, centred around varying the main constituents of the model rock materials, the composition of the cementing agent and filler. Preparation and compaction procedures were developed to provide the types of samples required for the centrifuge testing program, particularly the toppling models which required discrete cast plates to be produced.

Centrifuge modelling is applicable to those slope stability applications particularly where failure is initiated by yielding of the rock mass or shearing along discontinuities purely or non-dilational. The models were tested by increasing the gravity level until failure occurred. Subsequent analysis of the centrifuge testing using numerical models permitted not only the confirmation of the results of the centrifuge tests but also examination of other constraints such as changed geometry and sequential excavation.

Centrifuge and numerical analysis was conducted on model homogeneous slopes to examine some of the technical issues related to accurate slope stability assessments using stress analyses. It was found that the size of the finite difference grid had a significant effect on predicted failure level. The orientation of the grid also influences the location of shear bands which will develop along the path of least resistance - orientation of the finite difference grid may also affect collapse load prediction.

Other factors to influence the results of stress analysis modelling were:

- variations in strength - random variations in strength throughout the mesh can lead to significant differences in predicted collapse level
- the inclusion of dilation angle in the stress analysis altered the location of the predicted failure paths and increased the predicted collapse level; measurements of dilation angle are seldom available, however, from geotechnical studies of open pit stability
- post-peak softening can influence predicted collapse level, and strain softening is dependant upon the length of the failure path as well as the ratio $c/\tan \varphi$.

The studies highlighted a number of issues that need to be taken account of in the numerical model, but also validated the generalised approach of coupled centrifuge and numerical modelling studies of slope stability.

The introductory models aimed at investigating the mechanisms influencing open pit and underground mine interaction showed that not only did the centrifuge models quantitatively reproduce observed field behaviour, the numerical models also yielded good correlation between the failure levels and overall mechanisms of failure. However the following important features were also highlighted during the studies:

- an accurate representation of strain softening response is important if a good prediction of collapse level as to be achieved
- shear bands tend to develop parallel to the first difference grid in FLAC that influence the shape and location of the failure mechanism and the collapse levels for different grids
- care is needed in defining break boundaries in UDEC where relatively small voids within a rock body are being modelled
- slope failure generated by compression of backfill below the toe was modelled well with FLAC.

The flexural toppling mechanism of instability was examined in some detail during the studies with a number of centrifuge and numerical models being undertaken. The most successful models of flexural toppling were developed using heavy mineral - gypsum materials with the actual models being built from a series of incrementally cast plates of model rock material

Centrifuge testing of the models of flexural toppling showed that in general, failures resulted in the development of a reasonably consistent basal failure surface. The failure surface appears to initiate at the toe of the slope of the model and progress towards the crest of the model. The basal surface was oriented at between 10° and 20° above a line normal to the modelled joint set.

Numerical modelling of the centrifuge testing was carried out using a variety of techniques comprising a modified limit equilibrium analyses, finite difference analysis and wall or stress analysis using FLAC and UDEC. The analyses showed the following:

- good agreement on the geometry of the failure surface in the centrifuge models was achieved using the computer program FLEX developed by Adhikary (1995) as part of an associated study
- using the computer code FLEX a series of charts was prepared that could be used as the basis for preliminary slope design for slopes susceptible to flexural toppling failure; reasonable correlation was obtained between the design charts and field case histories
- UDEC modelling accurately reproduced the general mechanism of failure seen in the centrifuge models and also the overall levels of displacement
- comparison of FLAC, UDEC and FLEX show that FLEX appears to overestimate the calculated factor of safety against flexural toppling.

Generally good agreement was also obtained with regard to the overall toppling failure mechanism in a detailed back analysis of a case history. However, a detailed evaluation of the case history using the methods of analysis developed during the study were limited by the lack of available detailed geotechnical information.

As a basis for validating the methods of analysis developed during the studies, the stability of a part of Area A of the Daye Open Pit mine was reviewed. The review was based on detailed geological, geotechnical and groundwater studies carried out by the Chinese research team. All conclusions in respect of the stability assessments are based on the geological interpretations finalised by the Chinese research team in November 1993.

Rock mechanics studies conducted by the Chinese research team have identified the development of slope instability in Area A since 1990. Wall monitoring data suggest that in the upper part of the wall movement has been occurring sub-parallel to the strike of Fault F9, with movements in the lower part of the slope being consistent with movement along Fault F9 and also sub-parallel to Fault F9 and normal to the strike of the north-east joints.

The monitoring data show significant increases in the rate of slope displacement between 1991 and 1994 coupled with an increase in the magnitude of the measured displacement over the same time period. The measured displacements appear to be consistent with a pattern of near-surface cracks that has been mapped in the pit walls.

Centrifuge and numerical models conducted using the geological information provided by the Chinese research team show the following:

- confirmation of the important role that Fault F9, the north-east joints, the presence of the strongly altered diopside diorite, and groundwater play in influencing the stability of Area A

- the mechanism of slope instability predicted by the centrifuge models comprises:

  - active slip and separation along Fault F9

  - active slip along the north-east joints

  - toppling of blocks defined by the north-east joints

  - active yield through the strongly altered diopside diorite at the toe of the slope.

The mechanism of instability is consistent with the field observations and the monitoring information which suggests that toppling is occurring, controlled by the north-east joints. The failure mechanism is, however, extremely complex, strongly influenced by both geological structure, rock strength and groundwater and is also three-dimensional in nature.

Whilst there are some discrepancies in relation to the detail of the centrifuge and numerical models compared to actual observed field behaviour, it is clear that:

- the combined centrifuge - numerical models have provided a significant insight into the mechanisms of wall instability in Area A
- the overall modelled mechanisms of slip and separation along fault F9, toppling controlled by the north-east joints and yield at the toe of the slope is in accord with the observed behaviour of the slope
- important factors in the future behaviour of the slope have been demonstrated by the modelling to be:
    - the accuracy of the geological model; in particular the detailed location and nature of fault F9; the persistence of the north-east joints and the degree of alteration of the strongly altered diopside diorite
    - the material properties of both the main rock types and the fault infill materials; the estimated shear strength of the strongly altered diorite is a major controlling factor
    - the influence of groundwater - the numerical modelling indicates that it will be essential to ensure that the slopes below RL0 are effectively dewatered and depressurised.

It is strongly recommended that the following ongoing geotechnical and rock mechanics studies are implemented to further evaluate and manage the operating safety of Area A of the Daye open pit:

a) An ongoing program of pit wall monitoring must be maintained - the existing program of pit wall monitoring must be confirmed, and the network of monitoring points extended to the west and east of Fault F9, as well as below RL-60 as the pit deepens. Additional extensometers and inclinometers should be installed particularly in the area below RL0 in the area of maximum predicted deformations. The frequency of surface and other monitoring should be based on regular review of movement trends.

b) Additional geological, geotechnical and hydrogeological studies are required to:

- confirm the current geological interpretation, particularly the geometry of Fault F9, the continuity of the persistent north-east joints, and the extent and nature of the strongly altered diopside diorite:
- confirm the geometry of Fault F9 at depth below RL-60
- accurately define the regional groundwater table and assess likely groundwater inflows in the lower part of the pit below RL-60.

c) Further evaluation, including testing of the rock mass shear strength should be carried out for the strongly altered diopside diorite

d) Should the additional geological and geotechnical studies show that there are changes in the geological interpretation, then further detailed analysis of the stability of Area A should be carried out.

1. INTRODUCTION

1.1 BACKGROUND

This report presents the results of a program of collaborative research in slope stability conducted by research teams in Australia and China. The overall program of research studies was conducted in accordance with a research proposal approved for funding by the Western Australia - China Economic and Technical Research Fund in September 1992.

The studies comprised a staged program of research covering the following stages :

- Stage 1 - an initial visit to China by members of the Australian research team.
- Stage 2 - a review of the operational performance of artificially reinforced open pit mines in Western Australia; the review studies were completed in October 1992.
- Stage 3 - a visit to Western Australia in November 1992 by members of the Chinese research team.
- Stage 4 - a program of geological and geotechnical studies conducted at the Daye iron ore mine in Central China by members of the Chinese research team.
- Stage 5 - a program of centrifuge and numerical modelling studies of various aspects of open pit slope stability, carried out by both the Australian and Chinese research teams.

The members of the various research teams in Australia and China were as follows:-

Australian Research Team

- Dr C F Swindells (Golder Associates Pty Ltd - formerly of the Department of Minerals and Energy, Western Australia).
- Dr D P Stewart (Department of Minerals and Energy, Western Australia).
- Dr M A Coulthard (M A Coulthard and Associates Pty Ltd - formerly Division of Geomechanics, CSIRO, Australia).
- Members of the Engineering Geology Section, Department of Minerals and Energy, Western Australia and the Geomechanics Group at the University of Western Australia.

Chinese Research Team

- Mr Wang Guofa - Wuhan Iron and Steel Corporation.
- Mr Sun Zainan - Wuhan Iron and Steel Corporation.
- Mr Niu Jingkao - Metallurgical Ministry of the Peoples' Republic of China.
- Professor Xiong Chuanzhi - Changsha Research Institute of Mining and Metallurgy.
- Prof Lu Shizong - North Eastern University.
- Members of the Mine Research Institute at the Wuhan Iron and Steel Corporation and the Changsha Research Institute of Mining and Metallurgy.

The program of research studies commenced in October 1992, preceded by an initial visit of members of the Australian research team to China in February 1992. The main three year program of studies was completed on schedule in June 1995.

1.2 Scope of Study

The main program of research studies was undertaken in Stages 3 to 5, generally comprising studies carried out concurrently in Australia and China. The three main stages comprised the following activities :-

- Stage 3 - a technical visit by representatives of the Chinese research groups to Western Australia; the visit was undertaken in November 1992.
- Stage 4 - study and review of the geological and rock mechanics properties of the Daye mine, evaluation of modelling techniques and preliminary design of the physical models, and assessment of the numerical codes.
- Stage 5 - physical and numerical modelling studies and development of a calibrated approach to the analysis of the stability of deep open pit mines; assessment of alternative wall and reinforcement designs for the Daye pit and selected open pit mines in Western Australia.

The details of the work program for each of these stages is presented below:

Stage 3 - Technical visit to Western Australia by Chinese research groups

The technical visit to Western Australia by representatives of the Chinese research groups in November 1992 included the following :

- visits to Western Australian open pit mines that have adopted steep walled and/or reinforced wall designs;
- technical presentations on the numerical codes to be evaluated during Stage 4 of the research program;
- examples of the application of the centrifuge to mining geotechnical problems;
- a one-day presentation on Australian experience of optimising open pit blasting techniques to ensure slope stability.

Following the technical visit during Stage 3, the final scope of Stages 4 and 5 of the program was reviewed and finalised.

Stage 4 - Geological and rock mechanics studies to be performed at the Daye mine

To ensure that the subsequent numerical and physical models of the Daye pit were based on realistic representations of the geology and rock mechanics of the mine, a comprehensive review of those aspects was undertaken by members of the Chinese research team; all of the studies were carried out in the People's Republic of China.

This stage of the program comprised :

(i) Further geological mapping, borehole drilling and a thorough review of the geological model of the Daye iron ore mine.

(ii) Review of existing shear strength, back-analysis, groundwater and rock property data.

At the completion of the fieldwork by the Chinese research groups, a visit was made to the Daye mine in November 1993 by key members of the Australian research team who carried out the following :-

(i) Collaborative review of the existing and revised geological, rock mechanics and groundwater information for the Daye mine, in conjunction with the Chinese research team.

(ii) Agreement on the geometry and parameters for the design of the lower part of the Daye mine for use in the physical and numerical modelling to be carried out in Stage 5 of the studies.

It was originally intended to collect samples of groundwater, rock and currently installed reinforcement at Daye for subsequent testing in Australia. This was, however, not undertaken due to cost and time constraints as well as technical difficulties in obtaining reinforcement samples.

Stage 5 - Physical and Numerical Modelling studies

Stage 5 of the research program comprised the core of the research activities. Work performed during this stage of the program was carried out concurrently in both the People's Republic of China and Australia, as follows :

People's Republic of China :

- geological modelling;
- numerical modelling of slope stability;
- investigation of optimum methods of open pit reinforcement;
- development of a calibrated numerical code for the design of stable mine slopes.

Australia :

- geological modelling;
- design and performance of the program of physical testing using the centrifuge;
- numerical modelling of slope stability;
- development of a calibrated numerical code for the design of stable mine slopes.

At the conclusion of the physical and numerical modelling programs, the results of the numerical modelling studies carried out independently by the Chinese and Australian research groups have been compared with the results of the centrifuge modelling. The comparison has then been used as a basis for :-

- assessing the most effective method of two-dimensional and three-dimensional numerical analysis;
- development of the coupled centrifuge numerical method of slope stability analysis;
- assessment of the proposed design for the lower part of the Daye iron ore mine with particular attention being paid to Area A and the potential for steepening the currently planned wall design below RL-60m.

The following visits were undertaken for this phase of the studies :-

(a) A visit by 3 members of the Chinese research team to Australia during the performance of the centrifuge modelling program to observe the performance of this phase of work; this visit was carried out in December 1994.

(b) A visit to the People's Republic of China by 3 members of the Australian research team at the conclusion of the physical and numerical modelling. The purpose of this visit undertaken in June 1995 was to perform the collaborative comparison of the modelling results carried out by both research teams, and to finalise the assessment of the coupled centrifuge numerical modelling of slope stability.

1.3 Scope of the Report

During the visit to China by members of the Australian research team in June 1995, the format of the final report was agreed, along with the responsibilities for the completion of the report as follows :

- preparation of Chapters 1 to 8 and Chapter 10 were the responsibility of the Australian research team;
- preparation of Chapter 9 was the responsibility of the Chinese research team, and there has been no input to this work by members of the Australian research team.
- a back analysis of Area A would be performed by the Australian research team based on the following proposals by the Chinese research team :
  - the analysis would be conducted on section line I-I;
  - the shear strength parameters for the strongly altered diopside diorite will be varied;
  - material properties of F9 and the other structural features and rock types will remain fixed;
  - analyses are to be conducted for both a dry slope and the groundwater surface defined by WISCO;
  - the analyses are to include reinforcement;
  - the analyses are to consider the results of the slope monitoring data.

Most of the analyses would be performed using a limit equilibrium method for non-circular slip surfaces, with UDEC stress analyses being used to confirm the stability analysis results. A factor of safety = 1.0 is to be assumed.