Geotechnical Computing for Mount Isa Mines: Problems and some Solutions

G. BEER
Department of Civil Engineering, University of Queensland

1. INTRODUCTION

The Civil Engineering Department of the University of Queensland has had a long association with the mining industry and in particular with Mount Isa Mines. Dr. J.L. Meek seems to have been one of the first to apply the Finite Element method to the analysis of mining excavations. He has been consultant to various mining companies including Mount Isa Mines for the past 15 years.

The Author joined the Department in 1978 to work on a research project with the aim of investigating parameters influencing the ground behaviour at Mount Isa, and assisting mine design and other sections of the Mount Isa Mine.

The paper attempts to summarise the work done in the last 4 years. This work was carried out in close liaison with the staff of the Mining Research Section at Mount Isa, particularly Mr. R. Cowling, Senior Research Engineer. A great deal of time was spent becoming familiar with the highly complex mining operation at Mount Isa, and the Author has made numerous underground visits to examine the general structure as well as specific problem areas. At regular intervals, seminars and discussions have been held with personnel involved in the planning and operation of the mine.

Before the problem at Mount Isa can be discussed, a short description of the mine layout and the scale of operations follows. A more detailed description is given in (1). Because this paper addresses geotechnical engineers as well as mining engineers, some of the terminology used in mining will be introduced. The description given here is the Author’s interpretation as a civil engineer (who had no background in mining engineering 4 years ago) of the explanation given to him by mining engineers.

The mining operation at Mount Isa can be divided into two main areas: the lead-silver-zinc and the copper ore bodies. Herein we shall concentrate on the Northern Mine area containing the lead-silver-zinc ore which is deposited in long narrow lenses inclined at about 65 degrees to the horizontal. Fig. 1 shows and idealised cross-section of this area. The thickness of the lenses ranges between 5m and 50m, and the dimensions in the direction normal to the figure is in the range 500m to 1,000m.

The method of extraction of ore in the lead-silver-zinc ore bodies is either by open stoping or by cut and fill. In the open stoping method, the ore is blasted in vertical slices creating large openings (termed stopes). These stopes can be as large as 100m x 30m x 30m. The broken ore is drawn from the base of the stope which, when empty, is backfilled with mill tailings suspended in water (hydraulic backfill). In the direction inclined 65 degrees to the horizontal (up dip), ore is left behind between stopes and is termed a "crown pillar". In the direction along the lenses (along strike) ore is left in vertical pillars between the stopes. The basic strategy of mining is to excavate a series of stopes along the strike leaving vertical pillars, to backfill the open stopes, and finally to recover the pillars (Fig. 2). This is, however, a somewhat simplistic view. The actual mining operation is more complicated. The main aim is to extract as much ore as possible, i.e. recover all pillars because they contain valuable ore, and this is the reason for backfilling the stopes.

![Fig. 1. Cross-section of Northern Mine Area Mount Isa.](image-url)
It is appropriate, at this stage, to discuss the porperties of the host rock. Most of the ore is in shale which has a distinct bedding in planes parallel to the ore bodies. Some of the bedding planes are particularly smooth and graphitic, and exhibit an angle of friction which has been measured to be about 10° with a very small cohesion. Thus the bedding is obviously a major feature of the rock. In addition, there are many other geological features such as major joints (or "shears" as they are called by geologists) and dominant fracture directions such as "steep east dippers" etc., which have been surveyed and well documented.

To complicate matters, there are large silica dolomite intrusions into the shale in certain locations. The silica dolomite is a fairly competent rock with a measured angle of internal friction of 50° and a cohesion of 20MPa. The intact rock has an elastic modulus of about 800GPa and a Poisson’s Ratio of 0.3.

Several measurements have been made to determine the stress field that exists before any excavation takes place (i.e. "virgin" stress field). From this, formulae have been worked out which describe the virgin stress in terms of the depth below surface, D. The major principal stress , is perpendicular to the bedding planes (i.e. at -25° from the horizontal). The formulae due to Malcolm Bridges of the Mining Research Section are:-

\[
\sigma_1 = 10 + 0.028D + 10\text{MPa}
\]

\[
\sigma_2 = \sigma_3 = 6 + 0.016D + 5\text{MPa}
\]

As can be seen, there is a wide tolerance in the equations indicating a fair degree of uncertainty. However, anybody associated with rock mechanics or mining will appreciate the difficulty of obtaining good stress measurements in virgin ground.

2. PROBLEMS

In the course of the project, Mining Research personnel highlighted problem areas for which a better understanding could be sought using numerical models. Some of the major areas of interest which have been investigated during the past 4 years will be summarised here.

The first problem is the behaviour of crown pillars in an open stope situation. Fig. 4 depicts a typical cross-section where the top stope has been excavated and backfilled after the ore has been extracted. Then the bottom stope is excavated. The questions of interest are:-

- What effect has a decrease in the thickness, d, on the behaviour of the crown pillar? At what dimensions will the pillar fail?

- Will the presence of fill in the top stope affect pillar behaviour?

The second problem relates to the interaction between ore bodies as they are excavated in a certain sequence. Measurements and observations made underground have revealed that significant slip on weak bedding planes takes place in some locations for certain excavation sequences. Obviously, two factors are of major importance:-
3. NUMERICAL MODELS

In this section we will discuss the numerical modelling techniques used to obtain solutions to the problems discussed previously. Methods which can be applied to rock mechanics can be summarised under three headings:

1. Domain methods such as Finite Element and Finite Difference

2. Boundary methods such as Boundary Element and Displacement Discontinuity

3. Blocky Models (e.g. Cundall’s Distinct Element Method).

At the commencement of this project, a number of Finite Element programmes written by J.L. Meek such as, VISPLAS and TVIS were available. In addition, the Author has developed a Finite Element code over a number of years and applied it together among other things, analysis of lined tunnels. Thus, the obvious choice was to use the Finite Element method, especially since it seemed capable of modelling the Mount Isa situation. However, some deficiencies of the existing computer programs obvious very early in the project, and therefore a major proportion of the time was spent in improvement of these codes.

One of the shortcomings relates to the fact that in the Finite Element method, the whole domain has to be discretised (i.e. divided into finite regions). This poses obvious problems with underground excavations where no distinct boundary exists except on the surface. The strategy used by analysts with F.E.M. in such a situation has been to extend the mesh of finite elements to some (arbitrary) large distance away from the openings and to apply an artificial zero displacement or constant stress condition. This has led to very large meshes and “wastage” of discretisation effort just to model the infinite domain. Examples of such meshes can be seen in some reports dealing with Finite Element analysis in mining excavations.

This problem has been solved by developing special Finite Elements which have an infinite extension in one direction and, more recently, by coupling of the Finite and Boundary Element methods. The theory of the Infinite Elements and the coupling of the Boundary and Finite Elements has been published and will not be discussed here.

Fig. 5 may be used to demonstrate the effort required in the discretisation of the crown pillar problem using three methods:

1. Finite Element only

2. Finite and Infinite Elements

3. Finite and Boundary Elements

By parameter studies, it has been found that, for a Finite Element mesh, the distance of an artificial zero displacement boundary from the centre of the opening has to be at least five times greater than the largest dimension of the opening in order to give results which are acceptable. When Infinite Elements are used, this distance can be reduced to one times the dimension for the same accuracy. The coupled Boundary–Finite Element mesh does, in this case, need no discretisation of the domain, except...
for the pillar area. The Author's Finite Element program has thus been extended in recent years and now features Infinite Element as well as Boundary Elements.

plastic volume change. Two models have been used for this type of material: The "cap" model, and the Critical State model developed in Cambridge. The "cap" model was implemented for the modelling of backfill behaviour.

A further development of the program has been made recently. It has been found that, for the deformation of hanging walls in well bedded rock, a discontinuous model is needed. This is because it has been observed that, when an excavation is made, the hanging wall rock parts at weak bedding planes and forms a series of plates. To be able to make predictions about the behaviour of hanging walls, the parting and formation of these plates has to be modelled. Special contact elements were developed similar to the ones used in the Blocky model. These contact elements have a large stiffness when in compression and are assigned zero stiffness when tensile forces develop across the element interface. In addition, they possess Mohr-Coulomb frictional properties.

Other features implemented include a facility to handle sequential excavation and backfilling. Here elements are either deactivated or activated, and the excavation forces are computed automatically. The pre-processors have also been extended, and now include mesh generation and other facilities which minimise the input required for a specific problem. Extensive plotting routines have been added which plot contours of stress and slip on bedding planes, displaced shape, visco-plastic zones etc. These can be plotted either on the Department's own Hewlett Packard plotter or on the GIGI colour graphics terminal.

Fig. 5. Mesh for crown pillar problem using:
(a) Finite Elements; (b) Finite and Infinite Elements; (c) Finite and Boundary Elements.

Another deficiency in the program at the commencement of the project related to material models. To model the Mount Isa conditions, the following material models were needed:

1. A direction-dependent yield condition to model the weak bedding planes of the shale rock.
2. A material model for hydraulic backfill.

A direction dependent material law was available in VISPLAS but had not been applied to practical problems. The Author had experimented with the multilaminate model by Zienkiewicz and Pande and successfully applied it to the analysis of lined and unlined tunnels in jointed rock. In this model, a number of planes can be defined with associated frictional properties. This model therefore allows one to consider anisotropic plastic straining. In addition, a non-associative flow law may be specified which enables the control of dilation.

Tests on hydraulic backfill have shown that the material models developed for rock cannot be used. The fill exhibits strain-hardening plastic behaviour when compressed, with a large amount of
In this section only a few solutions to the problems discussed previously will be presented. Further details have been presented in internal reports to Mount Isa Mines.

Fig. 6 shows the mesh used for problem 1. The top stope is excavated first by specifying the corresponding elements to be inactive. The equivalent out-of-balance nodal point forces on the excavation boundary are then computed automatically for the field after excavation, and the stress field is then obtained from the analysis. Next the elements which have been removed are replaced. Now they have properties of fill ("cap" model). The bottom stope is excavated next using the same procedure as for the top stope. Fig. 7a shows a plot of yielded zones in the pillar region for a pillar dimension of 12m. For this dimension the pillar still has an elastic core. The problem was then re-analysed for different dimensions of d. For d = 9m, the whole pillar is plastic and can be considered as having failed (Fig. 7b).

Further runs were made for the case with no fill in the top stope. No detectable changes in the pillar stresses or extent of yielded zones was found. The reason for this is that the fill has to undergo a great amount of consolidation before its modulus reaches the same order of magnitude as that of the pillar rock. The following may be inferred from these results:-

1. The pillar will fail when its dimension is between 9m and 12m.
2. The presence of fill will not influence the stress levels in the pillar or the failure of the pillar.

This does not mean, however, that the fill is ineffective in ground support. It simply indicates that the fill will not prevent pillar failure. The major role of the fill is to stabilise hanging and footwalls and to prevent their collapse. In the confined situation of a stope, the fill will become more and more effective as it becomes more consolidated. The analyses done so far assumes plane strain conditions and are therefore only valid if the dimension of the stope normal to the figure is large.

For the second problem, the whole Northern Mine area is considered. The Finite Element mesh is shown in Fig. 8 and the number of orebodies has been reduced to three in the Racecourse area by combining two or more orebodies in close proximity and not including some smaller ones. For the purpose of the analysis, the shapes of the Black Star orebodies have also been idealised. This problem looks at the extraction of ore below level 15, which has been commenced recently. The sequence of excavation is indicated on the top of the figure. Before the excavation below level 15 is considered, the stopes above this level have been excavated to obtain the correct pre-mining stress field.

**Fig. 8. Finite Element Mesh of Northern Mine Area (with infinite elements).**

Fig. 9 shows some of the results of the analysis. Here contours of the magnitude of slip (mm) on weak bedding planes ($\phi = 10^\circ$, $c = 1\text{MPa}$) are shown for different excavation geometries (i.e. crown pillar sizes). As expected, the amount of slip increases as the crown pillar dimensions decrease. This is because the major principal stress (perpendicular to bedding) has to undergo a more severe direction change. Also, the most critical areas with respect to movement on bedding planes are on the left side (hanging wall) of the top of the first excavation and of the second excavation in Fig. 9d. This result seems consistent with the observations made underground, and may have some effect on the deformation of hanging walls.

This brings us to the last problem. In the study currently being undertaken, the behaviour of hanging walls is being investigated in more detail. The programme of work consists essentially of two phases.

- Phase one examines what has been termed "primary failure". That is, the initiation and propagation of cracks, and the formation of plates. This phase involves small displacements only.
- Phase two is concerned with the stability of the hanging wall, and this involves large displacements.

A result of phase 1 is shown in Fig. 10. Here, an idealised hanging wall has been analysed, using both Finite Elements and the contact elements discussed previously. The figure shows the displaced shape for a spacing of 2m of weak bedding planes (tensile strength = 0, angle of friction = 10\(^\circ\), cohesion = 0).
Fig. 9. Plots of contours of slip on bedding planes for different geometry of crown pillar at Level 15.

Fig. 10. Result of hanging wall parameter study: Displaced shape for frequency of weak bedding planes of one per 2m.
Many of these analyses (with different spacing and orientation of fractures and virgin stress fields) have been made. It is planned to report the results of these analyses, and their conclusions at the I.S.R.M. Congress in Melbourne in April, 1983.

5. CONCLUSIONS

An attempt has been made to summaries work done for Mount Isa Mines on numerical modelling of mining excavations. During the study, it was necessary to modify and improve existing software to be able to tackle the challenging and complex problems encountered at Mount Isa. Many of the developments (such as Infinite Elements, coupling of Boundary and Finite Elements, and the Contact Elements) are novel, and have been reported in international journals. Without these developments, however, the difficult job could not have been done efficiently. During the study, the Author has found invaluable the liaison with Mining Research, Mine Planning and other staff at Mount Isa. The large amount of monitoring, observation and measurement data available was of great assistance in the verification of new models or procedures. It is hoped that Mount Isa will continue its support for research in geometrical computing at the Civil Engineering Department of the University of Queensland.

6. ACKNOWLEDGEMENTS

The author would like to acknowledge the initiative of Dr. J.L. Meek in starting the current project and his stimulating ideas. The continuous support and encouragement of Mount Isa Mines staff is also gratefully acknowledged. In particular, the Author would like to thank R. Cowling for his introduction to mining problems, and his expert technical assistance with their solution.

7. REFERENCES