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TECHNICAL SESSION No. 2—UNDERGROUND WORKS

"Stresses Induced by Mining Operations at Mount Charlotte", by W.E. Bamford.

"A Rock Mechanics Survey and its Use in an Underground Stability Analysis at Kambalda, W.A.", by L.A. Dyson.

"Horizontal Pillar Extraction at Mt. Isa Mines Limited - Some Rock Mechanics Aspects", by D.B. Edwards.

"A Comparative Theoretical Study of the Effects of Inclination and Progressive Mining on Stope Behaviour", by C.M. Gerrard & W. Jill Harrison.

"The Gravity Flow of Material in the Sub-Level Caving Mining System", by G.D. Just & G.D. Free.

"The Establishment of Optimized Design Parameters for a New Gypsum Mine", by I. Weir-Jones.

GENERAL REPORTER - Dr. A.J. HARGRAVES:

A group of only six papers classified as Underground Works necessarily falls short of a full cross-section of geomechanics problems in underground works. Nevertheless they form a spread of problems across the cross-section, and the problems are approached with a sophistication of design virtually unknown in underground works twenty years ago. An apology is due from the coal mining industry, which is not represented at all. Another obvious absence is the tunnelling industries which have such advantages in comparative simplicity of analytical approach and generally with geometric openings in rocks more grossly homogeneous, more isotropic and less disturbed than are found in mining environments.

The paper by Bamford on stresses at Mount Charlotte profits from an unintended pillar failure which provides the opportunity for deduction of failure stresses, the checking of stability of remaining pillars and the use of the deduced data in future design. It is a more positive approach than the first attempt eight years ago at scientific design in rock mechanics at Mount Charlotte. This ended with the arbitrary practical over-riding of the designs, and their substitution by a virtually traditional empirical design method long established in the mining industry.

Several points in the paper could be explained more fully:

1. The apparent anomaly in the use of S.M.A. stress determinations indicating no change in stress between depths of 300 and 500 ft. and in the use of Hast's relationship clearly showing significant increase in stresses with depth to extrapolate stresses at greater depth. The data for the extrapolation were the similar stress values at 300 and 500 ft. depth and the mean depth.
2. A survey of a blasted excavation is necessarily approximate, and a selected cross-section is necessarily a sample which is intended to approximate the average or the worst condition. The selection of the best fitting geometric shape to represent a chosen cross-section is a further approximation. Has allowance been made for all of these factors?
3. The estimation of stress concentrations was based on elastic theory which probably is feasible as long as the limitations are understood. In a two-dimensional solution this should be

satisfactory for a stope block of limited extent. Undoubtedly there are some end effects which are ignored.

4. Nobody wants a support pillar to fail but capital has been made from this (unintentional) pillar failure to use it as a large-scale in-situ test. On this basis the likely strengths of other crown pillars in the same region have been determined. But at the same time factors of safety for the remaining pillars were determined using Mohr's envelopes. What part of the Mohr's circle was used to determine this mathematical expression of factor of safety?

5. What were the results of the finite element study mentioned - has sufficient progress been made to allow the hoped-for comparison to be made? Bamford's concluding remark modestly hoped for greater precision in the future finite element investigation at Mount Charlotte compared with the deduction method of the paper.

The paper by Gerrard and Harrison studies theoretically the effects of progressive mining on stope behaviour. The aim is similar to that of Dyson - to study sequential mining by the finite element technique. Two stopes at Cobar are the examples taken. Firstly, a crack-tip theory is employed on the premise that the theory can be extrapolated to a large orebody of mine dimensions. The Griffith crack theory is an extremely general one, and this extrapolation is open to question.

Secondly, an extremely general approach is made to the finite element technique in the stoping model. Some might question the inference that this work could be extended to other areas for progressive mining of stoping areas because it is rather more specific to Cobar than a general rock mechanics study. There is a caution regarding edge effects when using the finite element technique.

Whether specific or general, a most intensive and thorough study of the problem has been made, giving encouragement for work in similar problems elsewhere. Nevertheless, several matters would be improved by classification:

1. Is the finite element technique really suited to long, thin excavations?
2. It is stated that stresses were independent of

modulus effects, but displacements were inversely proportional to modulus. Elsewhere both stresses and displacements have been found to be dependent upon modulus.

3. It would be interesting to have field results to correlate with theory. Has this work progressed to a stage where it is possible to compare theory with measurement?

4. What would be the effect of different initial stress fields?

5. As every mining situation is unique, how can a useful general theory be created from finite element work?

6. The solution to this study not only depends on stress and deformation in two-stope systems — it also depends on the strength of structure, the rock mass. It appears that whereas this is stated in the conclusions, these considerations appear to be overlooked in the work done. Does the crack-tip theory allow for any of these things?

The paper by Just and Free has a strong theoretical and practical basis. It is important for a university project to have clear practical application, yet a high degree of theoretical content and whilst being academic, have good prospects of a successful conclusion.

The previous examples of drawing of broken ore have been more a documentation of experiences than an investigation of the mechanics of movement of the broken ore. However, sufficient qualitative material existed to provide a description of the movement patterns.

The authors have made an intensive background study before embarking deeply into a study of the factors underlying gravity flow. However, whilst the development is thorough, there are several points which should be raised:

1. At several points in the text, an expression is presented, largely without introduction, and usually without deduction or reference. Whilst the expressions appear logical and their mode of development is probably empirical, are they based on the authors' analysis or the work of others?

2. It is admitted that the model suffers the limitation of a two-dimensional approach to a three-dimensional situation. But more specific detail is required about the general extrapolation from two- to three-dimensional results.

3. Regarding the effect of overburden pressure, after a statistical analysis a linear regression expression is developed between the eccentricity factor and the height of overburden, indicating very little change due to the height of overburden. The qualitative assessment that an increase of overburden pressure might be expected to decrease eccentricity does not appear obvious nor the grounds for the inference. From the regression analysis it appears that overburden pressure might not be mathematically significant in any case.

4. In the longitudinal model of draw through the chute gate with variation of the parametric angles, the independence of the three angles does not appear to be clear either in the diagram or the text.

5. The two-dimensional limitations stated require some three-dimensional work to test the extrapolations made. In the conclusion the imminence of three-dimensional work was mentioned. Have these progressed to the stage of confirmation of the extrapolation?

A point of interest in summing up the papers of the session is that several authors have employed the finite element technique, apparently with varied success. Perhaps time could be taken to review what has happened — how far the method has advanced. Quite a considerable capital outlay has been made on these investigations of finite element — what has been gained?

In general, there have been some valuable investigations made of strength etc. properties in the laboratory and geological, geometric, failure and safe design situations in the field. The general situation of the geomechanics design in mining and its successful application in the field has been brought closer by the valuable papers presented in this session.

Paper by W.E. BAMFORD:

The Author in Reply:

1. Because of the limited number of stress determination results available, and the fact that these did not, as noted, show any increasing trend with depth, it was decided to average the stress values and also to average the depths below surface at which they were obtained. The vertical distance between stress determination sites — 200 ft. — was small by comparison with the depth to which these figures were to be extrapolated. This led to assumptions of the stresses at a depth of 400 ft. below the surface. It was felt reasonable to assume that the stresses would increase with increasing depth below surface, and as the horizontal stresses fell close to Hast's relationship a modified form of this was used to predict virgin field stresses at greater depths in the mine.

2. For the purposes of the approximate calculations, as outlined in the paper, representative cross-sections were selected. It is conceded that errors may arise due to the approximations involved. For the more detailed analysis, which is continuing, East-West cross-sections are selected for analysis at 5 or 10 ft. intervals; this should reduce approximation errors; it should also be noted that failure was found to have occurred due to concentration of the easterly field stresses, so a closer spacing of East-West than of North-South cross-sections is indicated. A survey error of as much as one foot should lead to only insignificant changes in axis ratios of the 100-200 ft. wide holes, and so of the stress concentration factors associated with the holes.

3. The fact that three-dimensional openings were being modelled in two dimensions was regarded seriously.

While a modelled slice normal to the axis of a long tunnel can obviously be regarded as leading to a fairly close analogy to the stresses in the field prototype, the dimensions of the stopes at Mount Charlotte meant that the dimension normal to the plane of each cross-section could not be regarded as infinitely large. However, the position of the most critically-stressed unit (Rib Pillar B2, from 500 to 600 ft.) was close enough to the centre, measured in a northerly direction, for the stresses calculated in an East-West section to be reasonably valid. The stresses in North-South sections were adjusted, in an attempt to allow for the small length of openings normal to the section. The diminution of stresses near the ends of the stopes was also allowed for.

4. If shear failure was observed to have occurred in the pillars, the factor of safety of other pillars could be expressed by

(i) Finding the point on the circle at which the normal distance to the failure envelope was a minimum.

(ii) Measuring the value of shear stress at this point (S_c) and also at the point on the failure envelope (S_e) corresponding to the same normal stress ($N_c = N_e$).

(iii) Factor of safety = $\frac{S_e}{S_c}$

If, as was the case here, the pillar failure was by axial cleavage, the factor of safety is obtained by measuring the radius of the Mohr stress circle (R_c) and the minimum radial distance, measured normally to the failure envelope, between the centre of the Mohr circle and the failure envelope (R_e).

Then factor of safety = $\frac{R_e}{R_c}$

5. Unfortunately, the final results of the Mount Charlotte stress study can still not yet be presented. It can, however, be stated that the finite element method is producing results in acceptable agreement with the approximate elastic stress concentration method first adopted.

Paper by C.M. GERRARD and W. Jill HARRISON:

The Authors in Reply:

(a) Crack-tip theory can be extrapolated to a large orebody of mine dimensions under the assumptions made in the paper. Provided the rock mass is assumed to be linearly elastic, and that the mine opening is geometrically similar to a crack (that is, breadth of the opening is less than about 1/10 of its length), it is only a question of changing the units of length.

(b) Finite element technique can be applied to long thin openings provided care is taken with stress concentrations around the ends of the opening. To obtain accuracy of solution in these regions, a high concentration of triangles was used around

the stope backs. About a quarter of the 380 nodal points used in the mesh were in the pillar region and within 50 ft. of the back of the upper stope.

A detailed comparison of the crack-tip and finite element results was carried out round the back of the upper stope and the two results agreed quantitatively. This indicates that the finite element mesh used can cope with the high stress gradients near the ends of the long thin stopes.

(c) From the graph presented in the papers by Mr. Bamford and Mr. Dyson of the world-wide stress results, our assumption that the initial stress field falls off linearly with depth from the value measured at the 1200 ft. level to zero at the surface is suspect and will probably need revision when more information regarding the initial stress field is available. If the initial stress field were to decrease at a slower rate with depth, stresses above the upper stope would be increased. There would be a slight increase as well in the stresses in the pillar region.

Another possible initial stress field based on some earlier stress measurements of Carrard and Alexander has principal stresses parallel to the N-S, E-W and vertical directions. This would decrease considerably the 'shear' component of initial stress parallel to the stope walls. Hence the resultant stress field would be more like the 'compressible' stress field shown in Fig. 6(a) of the paper.

The solution to this study not only depends on stress and deformation in two-stope systems— it also depends on the strength and structure of the rock mass. Detailed consideration of these matters is not given in the paper because of the very limited amount of available data relating to the strength of the rock. The only strength tests results available to date are ones carried out by Stephenson at the 1200 ft. level. Stephenson found for tests on samples, a uniaxial compressive strength from 8000 p.s.i. to 25,000 p.s.i. with an average of 16,000 p.s.i.

On the basis of this very limited data, values of cohesion of 4000 p.s.i. and an angle of internal cohesion of 34° were assumed for the rock mass. For the case of two fully-developed stopes with a pillar width of 50 ft. (as shown in Fig. 11(d), contours of excess stress were plotted for the finite element results. 'Excess stress' is defined as the maximum value at a given point of

$$|\tau| - \mu\sigma - c$$

where μ is the coefficient of friction, and c is the cohesion. If the excess stress is positive the failure criterion for the rock mass has been violated at that point. The contour plots indicated that this occurred in the pillar region in regions of high compressive stress.

Also from the values of maximum tensile stress shown in Fig. 7(b) for the pillar, tensile failure is likely on the other side of the pillar region.

However these results are only preliminary and only apply to the fully-developed 600 ft. stopes. They are also heavily dependent on the assumed initial stress field.

Paper by G.D. JUST and G.D. FREE:

The Authors in Reply:

The mode of development of the expressions presented in the paper is largely of a theoretical nature. The majority of the expressions are derived from a study of plane geometry and calculus and have been developed by the authors. A limited number of the expressions presented have been developed by Professor Janelid (1966).

The model studies presented in the paper were solely of two-dimensional systems in which the flowing

particle size was greater than one-third of the third dimension. No attempt was made to extrapolate any results obtained from the two-dimensional models to a three-dimensional flow system. Small-scale model tests have been conducted recently by Bishop (1971) at the University of Queensland. The limited number of these three-dimensional tests so far completed indicated that an elliptical draw shape definitely exists.

References:

- D1. BISHOP, G.A. - Report to A.M.I.R.A. on Sub-level Caving Project. - Department of Mining and Metallurgical Engineering, University of Queensland, October, 1971.
- D2. JANELID, I. and KVOPII, R. - Sub-level Caving Int. Jour. Rock Mech. Min. Sci., Vol. 3, 1966, pp. 129-153.

TECHNICAL SESSION No. 3 — CREEP AND CONSOLIDATION

- "Non-Linear Consolidation and the Effect of Layer Depth", by E.H. Davis.
- "Recompression Characteristics of Perth Overconsolidated Clays", by R.J. Frost, L.K. Walker & I.K. Nixon.
- "Aspects of the Consolidation of Morwell Brown Coal", by D.C. Green.
- "The Primary/Secondary Transition during the Consolidation of Clay", by J.G. Hawley.
- "An Investigation of the Three-Dimensional Creep Properties of a Clay", by P.L. Newland.
- "Application of Rate Analysis to Settlement Problems Involving Creep", by A.K. Parkin.
- "Deformation of Walls Retaining Soft Clay Backfills", by G.K. Spencer & P.J. Moore.

GENERAL REPORTER - Prof. I.K. LEE:

Introduction:

Although time has not diminished the importance of Terzaghi's original contributions to the prediction of the magnitude and the rate of primary consolidation, it is clear that the applicability of this "conventional" one-dimensional theory has to be examined rather carefully. Terzaghi did, of course, state the basic assumptions and was aware of some of the limitations of the theory, but as time elapses there is a tendency to ignore the limitations and to concentrate on the application of the analytical solutions of the conventional equation without sufficient thought being given to the applicability of the theory. Fortunately, the continued research on the topic of consolidation and the progressive publication of these studies has provided the opport-

unity to review the limitations of the conventional concepts and to study the developments of theories which are no longer restricted to a one-dimensional strain state.

Certain of these developments, concepts, and applications of the consolidation theories are given in the papers which form the present session. Of the seven papers, three concentrate on different aspects of secondary consolidation or creep (Newland, Parkin, Spencer and Moore) and the need for clearly defining what is meant by primary and secondary consolidation is evidenced by some of the apparent conflicts of concept. For example, the paper by Hawley proposes an interpretation of secondary consolidation based on strain rate which is vastly different from the commonly accepted interpretation.