# INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

# Rock Mechanics Investigations for a Large Open Cut at Mount Isa

By
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SUMMARY.- As part of a feasibility study of open cutting the outcropping portions of the Black Star lead orebodies at Mount Isa, a rock mechanics investigation into the stability of the proposed western batter has been carried out. Detailed structural measurements were made on oriented diamond drill core to determine the pattern of jointing in the area. Laboratory sliding tests were conducted on typical joint surfaces to provide data on frictional characteristics. Slope stability analyses, based on equilibrium of blocks and wedges formed by the joint systems, indicate that quite steep overall batter slopes are possible.

## I.- INTRODUCTION

The Black Star lead orebody was one of the original outcrops discovered at Mount Isa in 1923. It proved to be very large, although of rather low grade, and mining commenced in 1931. The upper carbonate ore was mined by glory-holing to a depth of 100 ft. Below this depth the sulphide ore was mined by open stoping although the stopes were subsequently filled, mainly with surface overburden.

There is sufficient high grade ore remaining in pillars and lower grade ore not considered payable in the early mining to make open cut mining an economic proposition, using modern excavation techniques.

The orebody is tabular in shape, some 200 ft wide, striking north-south and dipping 65° west. The proposed open cut is fairly rigidly defined by existing surface structures and would be 2200 ft long x 1400 ft wide on the surface. It would be 550 ft deep and total excavation of ore plus waste would exceed 30 million tons.

Because of the major nature of this open cut it was considered essential to include a rock mechanics study of batter stability in the feasibility study. The only other large open cut operation at Mount Isa was situated in the Black Rock secondary copper orebody (Ref. 1). This open cut was completed some 40 ft short of its planned depth of 520 ft owing to instability of the western batter (Ref. 2).

The preliminary study was restricted to the western or hanging wall batter for the following reasons.

(i) In-stability of the western batter had caused premature closure of the Black Rock open cut some 2000 ft further south.

(ii) The longer sides of the open cut were more likely to show instability than the shorter sides, which gain support from their arch shape.

(iii) The eastern batter was unlikely to present a major problem, since the bench slope would coincide with the average bedding dip.

Since it is well established that the stability of slopes in hard unweathered rock is controlled principally by the distribution of structural defects in the rock (Ref. 3), the rock mechanics investigation was concerned primarily with the geology and structure of the rocks in the batter area.

## II.- NOTATION

| | |
|---|---|
| $\alpha$ | Angle of joint plane to horizontal |
| $\beta$ | Angle of slope to horizontal |
| $\delta$ | Angle formed by stepped failure surface |
| $\gamma$ | Unit weight of rock |
| H | Vertical height of slope |
| Z | Depth below surface of secondary failure plane |
| F | Factor of safety |
| c | Cohesion parameter for sliding on joint |
| $\phi$ | Friction parameter for sliding on joint |

## III.- GEOLOGY AND STRUCTURAL ANALYSIS

None of the mine openings penetrated the area and only meagre information was available from the logs of diamond drill holes put down some 40 years earlier. Further exploration was required and diamond drilling was selected as the most economical method. Since the bedding orientation in the Urquhart Shale and Spear Siltstone appeared reasonably uniform in the area, it was hoped that the diamond drill core could be oriented to give maximum information on structural defects.

To explore the structure in three dimensions, three mutually perpendicular drill holes are, ideally, required. There are, however, certain limitations on the drill hole orientations to ensure favourable intersections with bedding planes for core orientation purposes. After possible drilling sites had been considered, two intersecting horizontal holes, denoted A and B were drilled from No. 4 level development (350 ft below surface) and a hole dipping east, denoted C, was drilled from the surface (Figs. 1 and 2). Each hole was approximately 800 ft long and drilled NMLC size with a triple tube core barrel and hydraulic feed drilling machine; this equipment is essential for successful structural drilling (Ref. 4). High core recovery was obtained and most of the core was ultimately oriented.

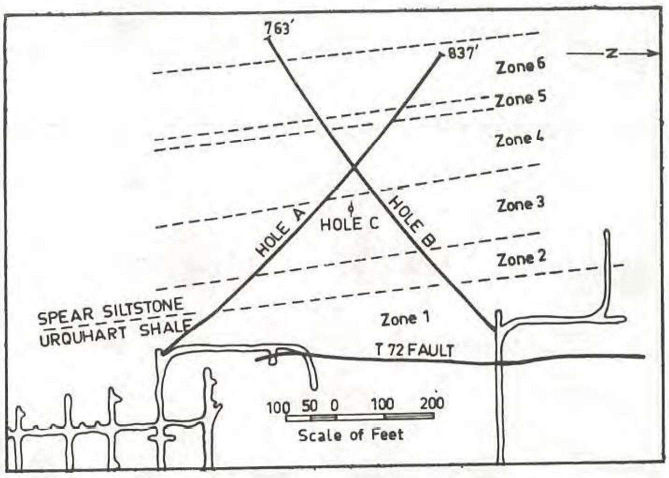

Fig. 1 Plan of No. 4 level horizon showing drill holes A and B and rock zones.

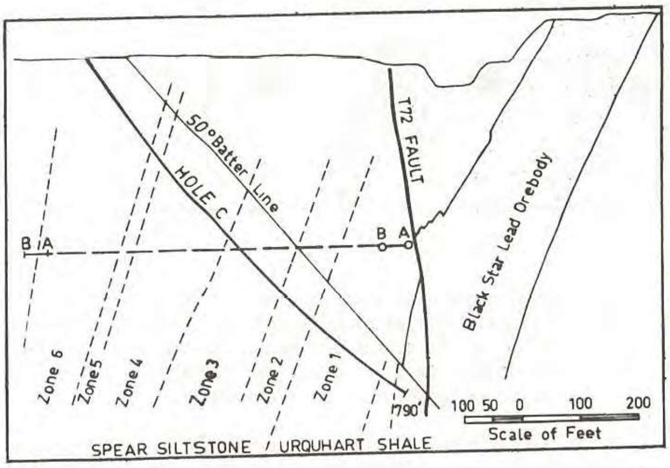

Fig. 2 Cross-section showing drill hole C and rock zones.

Six different rock zones were delineated by correlations of tuff marker beds and changes in rock type in the three holes. Briefly, these were

1. thin bedded Urquhart Shale with two sub-zones, one highly pyritic and the other non-pyritic;
2. coarse bedded dolomitic siltstone;
3. bedded gradation of siltstone, mudstone and slate;
4. intensely sheared black slate;
5. thin zone of sedimentary breccia;
6. thin bedded light grey slate.

All except zone 1 are part of the Spear Siltstone formation (Ref. 5).

The core was fitted together and a reference line drawn along it. The orientation of bedding planes and any breaks was measured relative to the core by two angles.

(i) angle between feature and core axis

(ii) angle between major axis of elliptical trace of the feature and the reference line, measured on the circumference of the core.

Breaks were classified as bedding or joints, and artificial breaks obviously caused by drilling were not counted (Ref. 6).

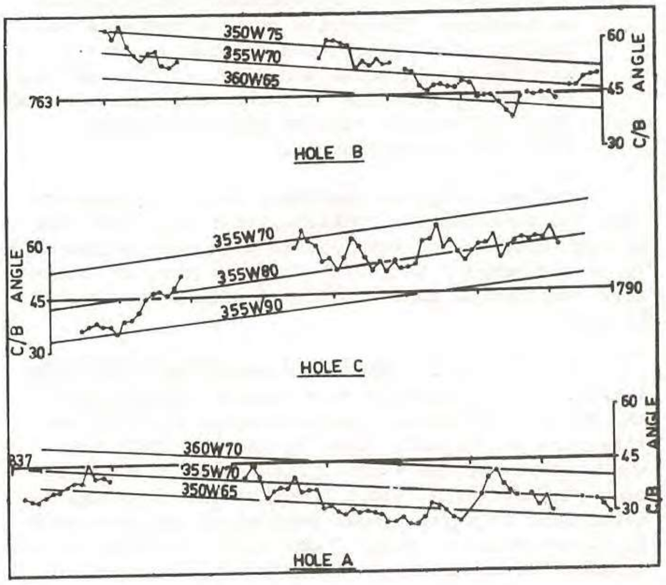

Fig. 3 Variation of the 10 ft average core bedding angle in the three exploratory holes.

The core bedding angle, defined as the angle between bedding trace and core axis was measured at 3 in. intervals, where possible. 10 ft average values are shown in Fig. 3 and there is only a relatively small scatter about the average 335° strike and W70° dip defined by the rock zone boundaries shown in Figs. 1 and 2. This proved that the bedding orientation is reasonably constant and that there is no major folding; thus the core orientation procedure should be successful.

The core was oriented in 10 ft sections by calculating the most likely bedding orientation from the average core bedding angle and rotating the core axis and bedding orientation to their true positions in space on a stereographic projection. The orientation of joints and other structural features in the core was then determined. A computer program was developed which plotted contoured equal area projections of the joint poles and which automatically weighted the readings to compensate for the effect of drill hole orientation using the method of Terzaghi (Ref. 7).

Contoured equal area projections of the weakness plane orientations in the various zones are shown in Fig. 4. Three joint sets are evident.

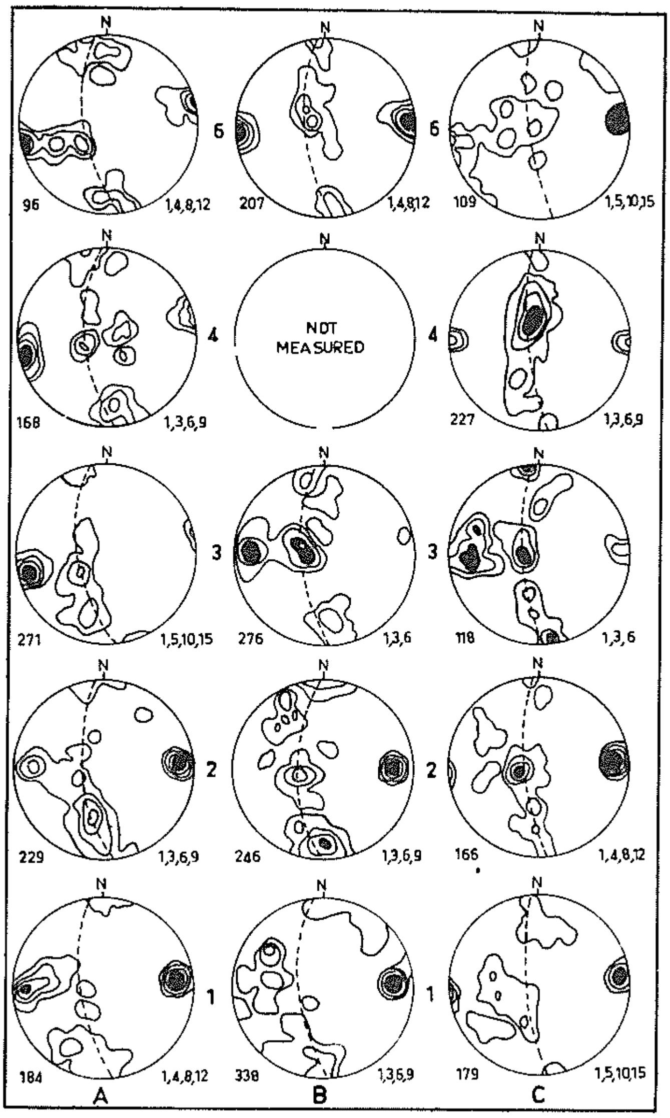

Fig. 4 Contoured equal area lower hemisphere projections showing weakness plane orientations as determined from oriented drill core. Numerals denote number of readings and contour intervals respectively.

(i) Bedding joints, striking north south and dipping 70° west are prominent in zones 1 and 2. Bedding is present, but is not a major weakness plane, in zones 3 to 6.

(ii) Microfaults, parallel to the cleavage in the slates, striking north south and dipping 70° to 80° east are most prominent in zones 3 to 6. Although shear features, these are typically discontinuous and are mainly breaks on chlorite filled veins.

(iii) In all zones there is a family of joints whose poles lie in a girdle containing the bedding plane; the joints are therefore perpendicular to bedding. The girdle usually contains two maxima defining joints described as set 1, striking north south and dipping 20° - 30° east, and set 2, striking east-west and near vertical. These joints are tension features and are typically discontinuous.

Analysis of joint spacings, including corrections for borehole inclinations, indicates that the average spacing for each set in each zone is generally in the range 1 to 2 ft. The rock mass is therefore composed of approximately equidimensional unit blocks.

No major fault zones were encountered although drill core cannot easily distinguish between minor and major structures. The pattern of faulting in this part of the mine (Ref. 5) is such that only north-south and east-west striking faults, both with near vertical dips, would be expected. Both types, determined from geological mapping of the mine workings, are shown in Figs. 1 and 2, but neither is oriented unfavourably with respect to the open cut batter.

## IV.- STRENGTH PROPERTIES OF JOINTS

Sliding friction tests were conducted on typical specimens of the various joint sets using a modified triaxial cell which permitted large displacements on the joint plane (Ref. 6). Despite wide variations in surface roughness and surface coatings the frictional properties fell within a relatively narrow range. In nearly all cases the shear stress - normal stress plot gave a linear relation with an angle of friction $\phi$ in the range 25° - 35° and a cohesion intercept, c, in the range 50 - 200 lb/in.$^2$. Furthermore, these values were not significantly altered by pore pressure in the joint, provided that the results were calculated in terms of effective stresses.

## V.- SLOPE STABILITY ANALYSIS

Because of the well defined bedding and jointing in the rock forming the batter, it was considered that limit equilibrium analysis of blocks sliding on these weakness planes was the most appropriate method of stability analysis for a preliminary study. The three major weakness planes determined by the structural analysis influence the stability as follows.

(i) The bedding planes cannot be primary surfaces of failure since they dip into the batter. They can, however, be important secondary failure planes which separate blocks tending to slide on other planes.

(ii) The microfaults dip in general, from 70° east to vertical. Therefore they cannot be primary surfaces of failure, but will again be important secondary failure planes.

(iii) The joints normal to bedding are likely to be the most important primary failure planes in the batter. The east dipping joints will provide single planar failure surfaces. In addition, the wide range of orientation of the joints means that tetrahedral blocks of a variety of shapes will have questionable stability.

(a) Plane Failure

The simplest case of plane failure is that of a slope of height H and inclination $\beta$, containing a continuous joint plane with inclination $\alpha$ passing through the toe (Fig. 5(a)). The factor of safety (F), defined as the ratio of resultant available resisting force to the resultant force tending to cause collapse, is given by

$$F = \frac{\tan\phi}{\tan\alpha} + \frac{2c\sin\beta}{\gamma H \sin\alpha \sin(\beta-\alpha)} \qquad (1)$$

Therefore, for given values of $\alpha$, c and $\phi$ the factor of safety is a function both of the height H and inclination $\beta$ of the slope. For c = 0 the slope will be stable only if $\alpha < \phi$

The presence of bedding planes and microfaults makes this mode of failure, termed case A, rather unlikely. More likely failure modes are shown in Fig. 5(b) and 5(c) with secondary failure on bedding (case B) and microfaults (case C), respectively. However for both these cases the expression for factor of safety is identical with equation (1). Since the factor of safety is inversely proportional to H, the height of the sliding block, for any given slope the most likely sliding plane is that passing through the toe of the slope.

A more critical condition is shown in Fig. 5(d) where the secondary failure plane is located behind the top of the slope (case D). This is analagous to the case of a tension crack in slope stability analysis and the factor of safety is given by

$$F = \frac{\tan\phi}{\tan\alpha} + \frac{2c(1-Z/H)}{\gamma H \sin^2\alpha\,(\cot\alpha - \cot\beta - (Z/H)^2\cot\alpha)} \qquad (2)$$

where Z is the depth below surface of the secondary failure plane. The factor of safety in this case is a minimum when the secondary failure plane is approximately midway between the top of slope and trace of the primary failure plane.

TABLE I

VALUES OF COHESION NECESSARY TO MAINTAIN STABILITY

| Slope angle degrees | Cases A,B,C lb/in.$^2$ | Case D lb/in.$^2$ |
|---|---|---|
| 40 | 8 | 9 |
| 45 | 15 | 16 |
| 50 | 20 | 23 |
| 55 | 24 | 30 |

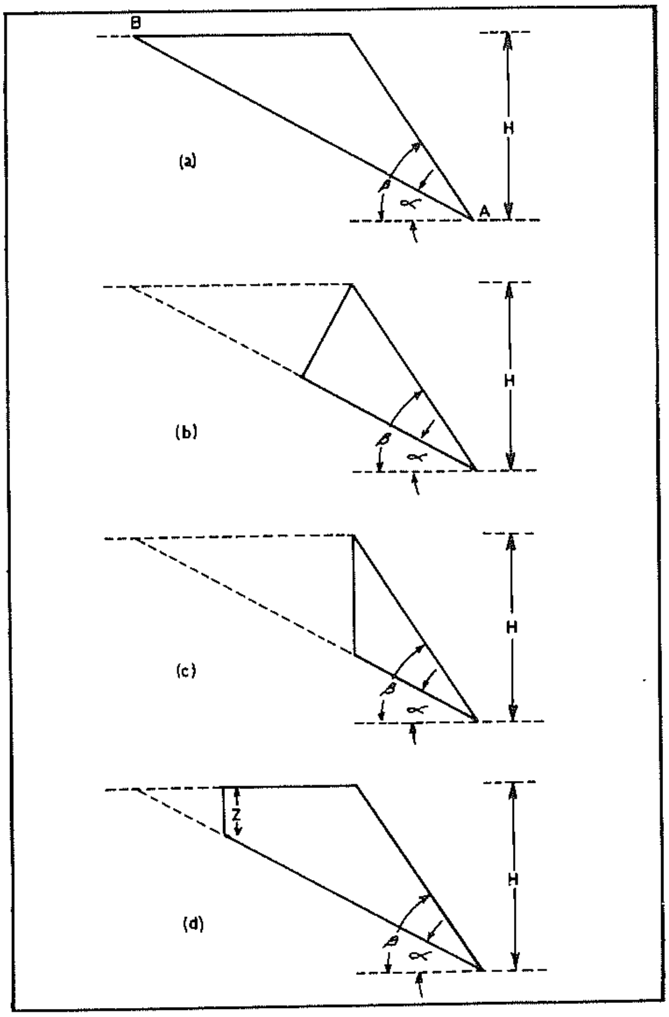

Fig. 5 Four possible cases of plane failure on east-dipping joints.

The joints are statistically normal to bedding which dips west 60° to 80° and the angle $\alpha$ is generally in the range 30° to 10°. Since $\phi$ normally lies between 25° and 35°, in most cases stability can be maintained by friction alone. Under certain circumstances, however, a joint with high angle may have low friction angle $\phi$. The worst combination likely to occur is $\alpha = 35°$ and $\phi = 25°$. For H = 550 ft and $\gamma = 165$ lb/ft$^3$ the values of cohesion c, required to maintain stability (F = 1.0) are set out in Table I.

These cohesion values are small compared with those measured in laboratory sliding friction tests on joints, which were in the range 50 to 200 lb/in.$^2$. Moreover the analysis is conservative, since the joints are characteristically discontinuous, and for failure to occur material bridges must be sheared or, alternatively, a continuous but stepped failure plane formed. In the latter case (Fig. 6) the stable slope for c = 0 is $(\alpha + \delta)$ where the angle $\delta$ is a function of the shape of the unit blocks formed by the joint sets. For equidimensional blocks, which approximate the present situation, $\delta = 26°$ and the stable slope for $\alpha = 30^\circ$ is $56^\circ$.

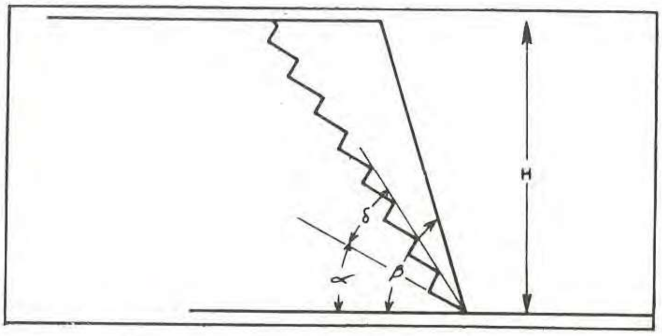

Fig. 6 Stepped failure surface resulting from a discontinuous joint set.

An additional factor which must be considered is the stability of individual bench faces, which would normally be designed with height approximately 70 ft and slope approximately $70^\circ$. Blocks formed by microfaults with dips less than $70^\circ$ east will be inherently unstable, since very high cohesion values would be required to maintain stability. However, as shown in Fig. 4 the microfaults are normally steeply dipping and this situation would arise only in isolated cases.

Analysis of sliding on east dipping joints is identical with that given in equations 1 and 2. Cohesion values equivalent to those given in Table I for a 70 ft high $70^\circ$ bench slope are 5 lb/sq.in. and 7 lb/sq.in. for cases A, B, C and case D, respectively. It is clear therefore that individual bench slopes should be generally stable with respect to the east dipping joints.

### (b) Wedge Failure

The wide range of orientations of joints normal to bedding, makes it probable that in many cases the mode of failure will be by sliding of a tetrahedral wedge on two inclined joints. A typical situation is shown in Fig. 7(a); partial block failures, as in Figs. 5(b), (c) and (d) are similarly possible.

If contact is maintained on both joint faces during sliding, there is only one possible slip direction, which is the line of intersection of the two planes. Since the joint poles lie in a great circle girdle, the line of intersection of any combination of joints must be the pole of the plane containing the joint poles, which in this case is the pole of the bedding plane (Fig. 7(b)).

The analysis of stability of such a wedge follows exactly that given above for plane failure, except that the geometry is more complex. However, a method developed by John (Ref. 9) permits a rapid graphical appraisal of the situation. Considering frictional resistance only when the wedge is on the point of sliding, the resultant force on the wedge from each joint plane must lie in a plane containing the pole of the joint plane and the slip direction. When friction is fully mobilised the resultant forces, $R_1$ and $R_2$, must be located at $\phi$ degrees along the great circles from the respective poles of the joint planes in the correct sense (Fig. 8 (a)). For equilibrium to be maintained, the plane containing the resultant forces $R_1$ and $R_2$ must also contain the direction of the resultant disturbing force on the wedge. If gravity is the only disturbing force, $R_1$ and $R_2$ must lie in a vertical plane. The case of different coefficients of friction on the two planes is easily included.

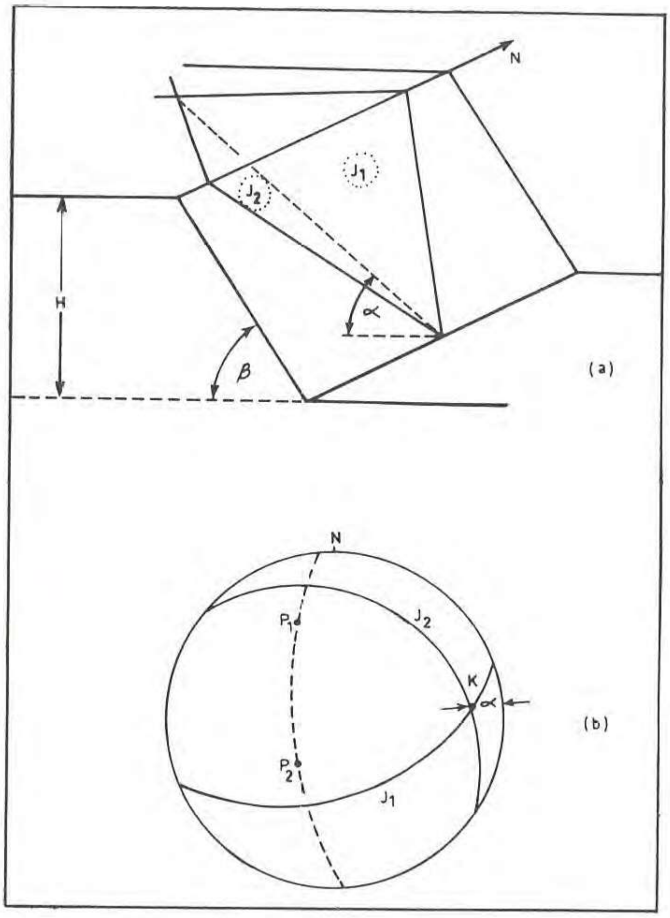

Fig. 7 Wedge failure on two incline joints with stereographic projection showing slip direction.

An example is shown in Fig. 8(b) for two joints intersecting to give $\alpha = 30^\circ$. In this case, the angle of friction mobilised on each joint plane to preserve stability is $22^\circ$. For a given value of $\alpha$ it can be shown that the angle of friction mobilised increases from zero to a maximum as the two joint poles move from the primitive of the projection (corresponding to two parallel east-west vertical planes) towards coincidence in a vertical plane normal to the batter (corresponding to a single failure surface shown in Fig. 5(a)). Therefore, wedge failure is not as critical as plane failure in this situation where the joints are normal to bedding. This is not necessarily so in the general case where there are no restraints on the orientation of the joint planes.

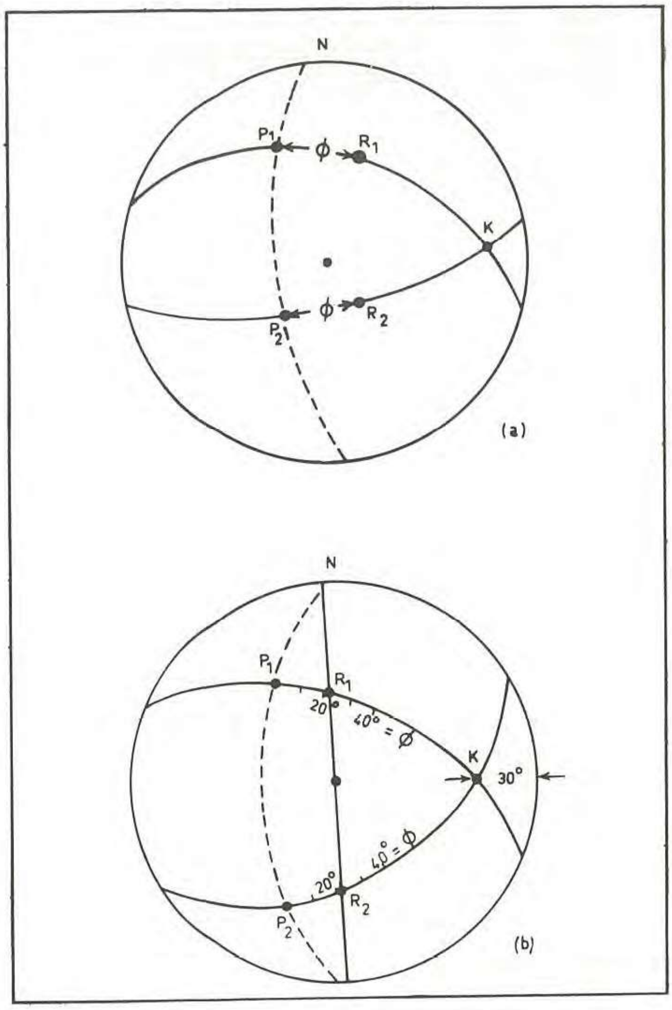

Fig. 8 Stereographic projections illustrating resultant forces on sliding wedge.

(c) Effect of Water Pressure

The whole of the above analysis has assumed that the slope is fully drained. In the present case this is a reasonable assumption since the slope directly overlies the worked out stopes of the 650 copper orebody (Ref. 1) and the water table in the area is likely to be well below the bottom of the open cut. In fact, considerable trouble was experienced with loss of water circulation during the drilling of the structural holes described in Section III.

However, high rates of precipitation occur in the Mount Isa area during the wet season and it is possible that significant transient cleft water pressures may occur under these circumstances. Since the stability of the batter is dependent primarily on frictional resistance of the joints, it is essential that the phreatic surface for seepage through the batter should be kept below the potential slip planes through the toe at each stage of open cut development. Adequate drainage provision and field piezometer installations will therefore be an integral part of open cut design and operation.

## VI.- CONCLUSIONS

The simple calculations show that major sliding can occur only on the east dipping joints and that in the worst case stability can be maintained by small values of joint cohesion. Quite steep batter slopes are therefore theoretically possible. However since the various assumptions are largely untested on a large scale, an overall slope of $50^\circ$ is considered optimum for initial design, provided adequate drainage measures are included; this represents an increase of at least $5^\circ$ on what could be proposed from experience in the Black Rock open cut. In any case, a slope of this order will be near the maximum on geometrical grounds, allowing for minimum width berms and a spiral haul road.

Rock mechanics investigations will not cease at the conclusion of the feasibility study. The open cut will be continuously monitored during operation and the further information on structure and other variables obtained as excavation proceeds will permit progressive amendments to the design to suit the particulár circumstances.

## VII.- ACKNOWLEDGMENTS

The major part of this work was carried out between 1966 and 1968 during the tenure of a Research Scholarship at the Australian National University. The author is grateful to Professor J.C. Jaeger for his guidance and encouragement during this period.

The author wishes to thank Mount Isa Mines Limited for permission to publish this paper and Mr. K.E. Mathews, Mining Research Engineer, for his helpful assistance.

## REFERENCES

1. DAVIES, E. - Mining Practice at Mount Isa Mines Limited, Australia. Trans. Instn. Min. Metall. (Sect. A: Min. industry), vol. 76, 1967, pp. A14-40.

2. EDWARDS, D.B. - Ground Stability Problems Associated with the Black Rock Open Cut at Mount Isa. Proc. Aust. Inst. Min. Met., No. 226, pt. 2, 1968, pp. 61-72.

3. TERZAGHI, K. - Stability of Steep Slopes on Hard Unweathered Rock. Geotechnique, Vol. 12, No. 4, December 1962, pp. 251-270.

4. MOYE, D.G. - Diamond Drilling for Foundation Exploration. Civ. Engg. Trans. I.E. Aust., Vol. CE9, 1965, pp. 95-100.

5. BENNETT, E.M. - Lead-Zinc-Silver and Copper Deposits of Mount Isa. Geology of Australian Ore Deposits, 2nd edition (ed. J. McAndrew) Melbourne, Eighth Comm. Min. Met. Congr., 1965, pp. 233-246.

6. ROSENGREN, K.J. - Diamond Drilling for Structural Purposes at Mount Isa. Aust. Diamond Drilling Assoc. Symp., Surfers Paradise, November 1969.

7. TERZAGHI, R.D. - Sources of Error in Joint Surveys. Geotechnique, Vol. 15, No. 3, Sept.,

1965, pp. 287-304.

8. ROSENGREN, K.J. - Measurement of Rock Friction in the Triaxial Apparatus. To be published, 1971.

9. JOHN, K.W. - Graphical Stability Analysis of Slopes in Jointed Rock. Journ. Soil Mech. Found. Div., A.S.C.E., Vol. 94, No. SM2, Proc. Paper 5865, March, 1968, pp. 497-526.