TECHNICAL SESSION No. 5—DRILLING AND BLASTING

"Application of Oriented Drill Core in Structural Geology at Mount Isa", by M.C. Bridges & E.J. Best.

"Damage Induced in a Smooth Work Piece by a Sliding Diamond - an Approach to Hard Rock Drilling", by J. Graham.

"Some Basic Aspects of Diamond Drilling", by D. Rowlands.

"Reduced Soil Strength and Stiffness at the Top of Tube Samples", by J.G. Lang.

"Model Studies of Fragmentation of Explosives", by G.D. Just & D.S. Henderson.

GENERAL REPORTER - Mr. M.D. HUGHES:

It is good to note that Geomechanics is being used to see what can be done to make drilling and also blasting more efficient. This is the main contribution from the work described in the papers at this session. Drilling and blasting are expensive mining operations. Drilling is expanding its scope as it embraces raise and tunnel boring. The field is a large, complex and exciting one requiring work in several aspects.

Drilling is also a tool of the structural investigator and our session also covers this aspect mainly in the first paper, which is about oriented core at Mt. Isa.

Before we go looking through the microscope at the papers, let us first look through the telescope at the field.

1. Classification. - Usually if there is a drilling problem ahead, whether for a diamond drill contractor quoting a job or an engineer appraising likely cutter costs for a raise borer, the first question is "show me a typical piece of rock". At present this question is meaningless, but the problem is capable of analysis. Whether it is worth it for the sake of the odd drilling contractor is another matter. Some means of classifying rock on the basis of its drillability by various methods is desirable.

2. Structure. - Now, even if there is a completely uniform rock-type in a mine, it will not necessarily drill or blast uniformly because of the effect of structural weaknesses, such as joints that might give short runs to a diamond driller or which might allow easy fracturing by a raise borer or might give excellent fragmentation to a blast. I wonder if the structural work done for other purposes may help drillers and blasters.

3. Drillability. - Now, knowing what the workpiece is, how do we drill it efficiently, quickly, straight enough and with minimum cutter cost or maximum cutter life by various methods, either filing with diamonds, chipping with jack hammers, gouging with button bits, etc? Can we use additives equivalent to a steel turner's soluble oil to increase our efficiency?

4. Blasting. - If the holes are blast holes, should there be a lot of thin ones or a few wider ones? What pattern is right? How full should they be of explosive? What is the best explosive?

5. Scale of Tests. - All testing can be done in a workshop, on a tombstone size block or an actual drilling or blasting situation. Correlations between the three techniques are desirable.

So much for our look through the telescope. Let us see what our authors have done.-

1. The Mt. Isa paper tells us how an application of drilling helps structural investigators.

2. The paper about a sliding diamond takes us right back to fundamentals.

3. The paper on basic aspects takes over somewhere about where the previous one leaves off and gives some interesting summaries on diamond drilling theory and describes how penetration rate, torque and specific energy varied during some tests.

4. The paper about samples tackles a specific and relatively simple problem and leads to a definite answer to it.

5. The blasting paper was based on being able to predict the size distribution of blasted rock.

So the papers range widely in their subjects and their scope.

Some of the papers spark off many conjectures and questions, as well as comments. Others treated a limited field and do not lead to much extension beyond themselves.

Now let us look briefly at the papers and their implications:

The paper by Bridges and Best comes from Australia's largest underground mine and it is only fitting that they should be our leaders in structural underground examinations. The authors say that they drill core and orient it and lay it out as oriented and then make many measurements of structural defects, their extent, frequency, continuity, cohesions, etc.

This provides a tremendous amount of data which they classify and analyse on stereograms, etc.

They give examples of an investigation of a crusher station excavation and a stope wall to illustrate how they applied their techniques.

They conclude with a statement which all mine structural men might do well to heed. One of their examples "demonstrates the necessity for probing the rock mass rather than only mapping nearby development and assuming rock conditions will be the same. In this instance, the distribution of defects in the rock mass changes markedly four times within 220 ft."

Questions on this paper range more over the whole problem of analysing the structure of a large mine rather than following the paper too closely.

Here are some ...

(a) Is it necessary to examine the structure of all potential stope walls at Mt. Isa and all major openings? If so, is a pattern emerging which simplifies the task with time?

(b) Is the appraisal a continuing task like mineral drilling?

(c) For stopes, can general figures be quoted indicating how many tons of ore are proved by each foot of mineral drilling and how many tons of ore are structurally investigated by each foot of structural drilling?

(d) What is the order of the additional cost of oriented core compared to mineral core?

(e) Is there a future in examining mineral holes with cameras or periscopes?

(f) What steps were taken to ensure the stability of crusher excavation and the stope wall quoted as examples?

Mr. Graham aimed to extend previous work in this field to embrace the effects of various lubricants

of diamond radius
of different loads on soda glass, silica glass and quartz.

He concluded that even from such a simple fundamental test as this, no broad generalities could be established. He noted that bentonite as an additive seemed to induce more fracturing than other additives. This is odd, because bentonite is used to avoid scouring rather than to improve cutting.

Diamond drillers talk of a maximum figure of 12 lb. per diamond point as its working load, regardless of radius or diamond size, although such diamonds have a diameter of 1 to 2 mm. Some called "hard core" or "processed material" are rounded like river gravel and are something like spherical. Hard core diamonds are claimed to be thoroughly polished in addition.

Here are some questions ...

(a) Once the apparatus has been prepared can this method give quick, inexpensive results?

(b) Why did the author choose two kinds of glass for study rather than natural material?

(c) Would the author comment on the early part of Mr. Rowlands' paper including Fig. 1. - the theory of how a diamond cuts, diamond exposure and size, bit thrust, etc?

(d) Why did the author use spherical diamonds? Rowlands refers to the sharp points of octohedrons.

(e) Did the author observe the blunting of the diamond?

(f) What happens as the load on a diamond is increased?

(g) What mechanism is responsible for pulling apart the fragments of Fig. 8. and getting them away?

(h) Can the author see why soluble oil or other "hardness reducers" might be effective?

Turning now to the paper by Rowlands, a diamond driller cannot move too many ways to improve his penetration. He can vary -

the cutting tool,
lubricant (soluble oil, etc),
bit speed,
axial thrust,
rate of flow of circulating fluid.

As he does this, the rate of penetration, size of cuttings, torque and specific energy and blunting of the bit will vary.

After examining some basic diamond drilling beliefs, the author carried out a series of tests to show what happens.

Bit Speed. - Tests showed that with other things constant, penetration rate is directly proportional to bit speed and that torque, and hence specific energy, are independent of bit speed. This fortunately eliminates bit speed as a complicating factor. By the same token, it indicates that the faster we spin the faster we advance. There must be some factors to guide us in the upper limit to this. The author might comment as to what they are.

Axial Thrust. - Then the tests showed that as axial thrust is increased drilling becomes more efficient than we might at first expect. This may be because there is a minimum thrust below which only elastic deformation occurs. A graph of penetration rate vs. thrust at constant r.p.m. (say 1,000) would illustrate this and it would be good if the author would draw it.

Specific Energy. - The figuring showed that specific energy is proportional to $\frac{\text{bit speed}}{\text{penetration rate}}$ which is a term which can be expressed in turns per inch.

Underground diamond drillers often use screw-feed machines in which bits advance a set number of turns per inch and they usually have a choice of four feed gears fitted to the head; so these feed gears set the specific energy.

Incidentally, the gears in a drill are commonly 200, 300, 400 and 500 turns per inch for drilling rock. It is noted on Fig. 4 that at a thrust of 404 lb. the feed rate was about 35 turns per inch which is an almost unheard-of feed in igneous rock.

Bit Wear. - The author refers to wear on bits and his method of correcting it. Could he draw a graph of penetration rate under standard conditions vs. total drilling done by bit to show us how blunting affected drilling? Did he make any observations of flats on the diamonds? We would hope that efficient drilling with low specific energy goes hand-in-hand with reduced blunting. Is there evidence of this? Is the author's correction to sharp bit performance likely to provide a set of information which holds for the special case of a new bit but not for the more general case of a bit somewhere between new and blunt?

Practical Results. - Much EX drilling in mines is done at bit speed around 1,000 r.p.m.

Torques up to 50 lb. ft.	(Paper around 10)
Thrusts to 3,000 lb.	(Paper around 450)
Feeds around 300 turns/inch	(Paper around 30)
Machine H.P. around 16	(Paper 2 H.P.)

These seem to be very different.

Hardness Reducers. - Has the author done work on the effects of hardness reducers?

The paper by Lang is the case of an investigator with a specific and limited problem to which he got a conclusive answer, but which did not open readily into wider fields.

The author noted that when he used a 3-in. auger soil sampler and took runs either $1\frac{1}{2}$ or 2 ft. long, he got consistently different results from the top half of the samples from those from the bottom half. So he set out to see why and which half was right. He did sets of readings taking long samples and compared results to sets of readings with short samples.

He got much more conclusive agreement than common when analysing the earth. He showed that the bottom half of the long sample was close to the strength and stiffness of the short sample and that the top half was weaker.

When a sample of this nature is taken, not much force is needed initially but the force to penetrate further increases with extra length of sample, so that the bottom half of the sample is taken with quite a high force which might be expected to disturb things and give a false reading.

The author said that it did disturb something - the zone immediately below it. This formed the top of the next sample and this was weakened by the disturbance from the preceding sample.

The author aimed to check his conclusion by taking a long sample and then taking steps to clear away any material which it disturbed and then taking another sample.

We only have one paper on the complex operation of blasting which has all sorts of variables and which is subject to changes as we use jumbo drills, large carrying vehicles and ANFO instead of air legs, chutes and gelignite. The paper by Just and Henderson tackles an interesting aspect in that it aims to give data to predict the size distribution resulting from a blast.

The authors used models and they worked in dimensionless constants proportional to the optimum depth, i.e. the depth of charge which yields the largest crater.

They achieved some neat relationships between some of the blasting variables which ought to help simplify design of blasting. Here are some examples ...

The authors found logarithmic size distributions for different depths of charges and they illustrated this in Fig. 2. The slopes of the lines in Fig.2 are called "fragmentation gradients". Then they plotted the fragmentation gradients against depth ratios (the ratio of charge depth to the optimum depth) to log scales and got a straight line.

The work was done with both concentrated and linear charges using concrete and sandstone blocks. In due course, full-scale tests will be carried out.

Here are some questions ...

(a) Whatever breaking is not done by the explosion will have to be done by the primary crusher. What are the relative costs of breaking 4-ft. blocks into, say, 6-in. blocks by the two methods?

(b) The paper treats the toughest job for an explosion, in that it does not include breaking due to falling, or for collisions of rocks from adjoining blasts or of structural weaknesses in the rock.
Can the authors give some examples on the effect of those factors on size distribution?

(c) Is the rock close to a concentrated charge shattered more than rock which is close to the free face?

(d) Would blocks have to be significantly bigger to get meaningful results from model tests with ANFO?

(e) Is this work fairly fast, giving plenty of results for a day's work?

Paper by M.C. BRIDGES and E.J. BEST:

The Authors in Reply:

(a) The geological structure of the rocks around our bedded lead-zinc orebodies is believed to be strata controlled, that is, relatively uniform along strike or down dip but variable across dip. Each orebody is relatively uniform in structure but each is different from others. Ideally, it is only necessary to drill into each orebody at several points in a stoping block to establish this uniformity. Special features, such as folds, need to be individually investigated.

Copper orebodies are enclosed within a massive rock whose structure is fairly uniform throughout. A few thousand feet of drill core can be applicable to a large area such as a 1000 ft. cube.

In all cases sufficient drilling is done to establish uniformity or regular variation of structure.

(b) Yes it is. As new mining areas are opened up along strike and down dip, structural geology investigations, including diamond drilling, are undertaken. However, as more becomes known of an area, both structural and mining, the intensity of structural investigation decreases. New techniques of drilling and of analysis and presentation of data are continually being investigated.

(c) For a stoping block the percentage of exploratory drill core which is structurally logged depends on whether there has been mining experience in this rock and whether there are development openings in the area.

At the proposed Hilton mine, about 14 miles north of Mount Isa, there are no development openings as yet. In an initial mining block about 33% of exploratory diamond drilling was structurally logged, so that, overall, each foot of logged core investigated about 15,000 tons of ore.

In another orebody with no exposures we logged about 39% of exploratory drill core. A third area has been mined up dip and there are some exposures in the exploratory block and we plan to log about 15% of core. In an operating copper orebody, with many exposures, the amount is less than 1%.

(d) Oriented drill core of good quality costs approximately double that of usual exploratory core. It also costs more to log and process the data.

(e) In most underground mining situations the core provides all the information that is required from the drill hole. Borehole cameras and periscopes are not thought worthwhile at Mount Isa. There may be a future for down-the-hole geophysical surveys. In special cases, where there are thought to be open cracks, then these down-the-hole devices may be worthwhile. However, there is no substitute for the recovery of good quality core.

(f) The planned orientation of the crusher excavations was such that the principal set of fractures would be parallel to the largest walls. During excavation there would tend to be slabbing from these walls and support would be costly. As a result of the exploratory programme, the excavations were turned through an angle of 20° to lessen the possible slabbing. The investigation enabled an effective rock bolting pattern to be drawn up. The structural information was incorporated in a plaster model which was constructed and tested at the Australian Coal Industry Research Laboratory at Wollongong.

Production has been deferred in the stope whose hanging wall was investigated.

Paper by J. GRAHAM:

The Author in Reply:

Experiments and theory applicable to drilling range from the friction results of Bowden and his school, through the static indenter described in Rowlands' paper, the low-load single diamond work of Schlössin (Ref. D1) and of Tabor et al (Ref. D2), and the "ploughing" experiments of Appl et al (Ref. D3) to attempted instrumentation of a complete drilling bit in the manner described by Rowlands.

The present work was intended to be a bridge between the 1 mm dia. slider used by Schlössin at loads of 2-5 kg (1 or 2 lb), and that of Appl et al, who used a normal force of 1 to 60 lb. to cut limestone.

The optical technique used in the present paper limits the material to glass, or transparent crystals such as quartz or feldspar, and limits the load on a 1 mm diameter diamond to about 10-12 kg (5 lb.). This is a severe restriction, but this range could be more sensitive to variations in the conditions than the more heavily loaded ranges, and the technique has enabled the gathering of new information.

At light loads, Schlössin has interpreted his results on the basis of elastic Herzian fracture; the forward component of stress due to the movement of the diamond prevents the crack opening ahead of the indenter, and a series of semi-circular cracks like those of Fig. 3 (e) is left behind. Tabor et al predicted that plastic behaviour would result in cracks forming in front of the diamond, and this may be the reason for the reverse cracks shown in Figs. 8 and 9. Thus increased normal loads give greater plastic behaviour, inverse cracking, and greater depth of damage. Extending this even further, Appl et al ploughed a furrow in limestone under very heavy loads, and interpreted the mechanism as a plastic deformation, followed by fracture to produce the debris, somewhat like metal turning.

An obvious extension of the present work would be to include higher loads more akin to the loads used in practice. We hope to do this when a technique for evaluating the debris has been developed. In this case, the technique would also be suitable for polycrystalline samples of natural hard rocks, so that the extra variable of intergranular failure can be evaluated.

The apparatus used is simple and inexpensive, and the experiments may be carried out quickly and easily. However, some limitations have already been pointed out, and these make the application to field work very difficult. Spherical diamonds were used so that comparison could be made with previous work and with hardness theory, and because the diamonds used in drill bits are usually rounded as indicated by Mr. Hughes. Absolutely spherical diamonds, however, are not used in drilling as they require higher than normal loads.

The low loads used in our experiments had important effects both on diamond wear and on removal of material from the work piece.

The effect of wear in a bit is not understood, although it is known that wear and fracture of the diamond are extremely important in affecting the efficiency of drilling. According to one theory, wear is associated with the temperature of the interface, high temperatures resulting in graphitisation. A flat worn underneath a diamond will affect the depth of cut, by reducing the local pressure there.

To obtain removal of material with our low loads, it is necessary to make multiple passes. Schlössin believes this to be a real mechanism for drilling, but if most material is removed by a ploughing action, its effect will be minimal. Even in this case, however, a deep cracking network may form below the fracture surface, which will make the work of the next diamond easier.

Various possible explanations have been advanced for the effect of soluble oils and lubricants. Joris and McLaren (Ref. D4) suggest that the primary function of the lubricant is to keep the diamond cool. Polishing and nickel plating of the diamond have also been attempted to accomplish the same end. Other possible effects of the lubricant are to lower the surface energy of the rock, thus decreasing the energy required to break it; to lubricate all the components of the drill string, and to remove particles as quickly as possible. Another effect sometimes advanced is that of chemical corrosion of the rock near the drill bit, although this seems very unlikely to the present writer in view of the time available. Joris and McLaren say that soluble oils improve all these functions. In view of the excellent results achieved by Rowlands in his paper, I would tend to rate particle removal ahead of the other effects.

We have found almost any lubricant to be effective in drilling glass, and suggest that only where a large volume of work is done would turps or bentonite have any advantage. This would need to be evaluated in the workshop.

I am not competent to comment in detail on Mr. Rowlands' theory, although I think that the shape of the diamond and the presence of a tangential force will profoundly modify the ideas expressed. One theoretical treatment of a diamond bit which takes these points into account is given by Hamilton and Goodman (Ref. D5). Most of the Herzian theory applies to lighter than practical loads, as mentioned in my previous remarks, but one very elegant experiment shows the difference between a normal and inclined force atthis level (Ref. D6). A ball bearing is dropped from a height onto a flat surface and the crack shape is observed as a function of the inclination of the surface.

Equation (1) of Rowlands' paper is only meaningful to me if P is the mean penetration per revolution, and this is not simply related to the embedment of the diamonds. The exact mode of cutting of a multi - diamond bit has not been established in detail, and even the number of diamonds contacting the rock is in doubt. In some of his experiments, Rowlands achieved a penetration rate of $\frac{3}{4}$ mm per revolution, and this must mean a very appreciable diamond embedment in the rock.

References:

D1. SCHLÖSSIN, H.H. - Crack-Slip in the Abrasion of Quartz by Diamond. Reports No. 14, 18 and 30 of the Department of Physics, University Witwatersrand, 1962, 1963 and 1968.

D2. BILLINGHURST, P.R., BROOKES, C.A., and TABOR, D.- The Sliding Process as a Fracture-Inducing Mechanism. Proc. Conf. on the Physical Basis of Yield and Fracture, Ser. No. 1, Oxford, Sept., 1966, Inst. Physics & Physical Soc., pp. 253-258.

D3. APPL, F.C., ROWLEY, D.S., and BRIDWELL, H.C. - Theoretical Analysis of Cutting and Wear of Surface Set Diamond Cutting Tools. Report of Christensen Diamond Products Company, Salt Lake City, Utah, 1967.

D4. JORIS, A.C.T., and McLAREN, G. - Additives to Coolants used in Diamond Drilling and Sawing in Australia. Proc. of the Int. Industrial Diamond Conf., Oxford, 1966, Vol.2.

D5. HAMILTON, G.M., and GOODMAN, L.E. - The Stress Field Created by a Circular Sliding Contact Trans. A.S.M.E. (Jour Appl. Mech.), Vol. 33, June, 1966, pp. 371-376.

D6. LAWN, B.R. - Partial Cone Crack Formation in a Brittle Material Loaded with a Sliding Spherical Indenter. Proc. Roy. Soc., Series A., Vol. 299, 1967, pp. 307-316.

Paper by D. ROWLANDS:

The Author in Reply:

Bit Speed. - The upper limit of bit speed is probably governed by the rate of heat dissipation and/or cuttings removal.

Axial Thrust. - Any vertical line through Fig. 4 will give a graph of penetration rate vs. thrust at constant r.p.m.

Specific Energy. - The gear feed rates will indicate the specific energy if the thrust remains constant.

Bit Wear. - Bit wear, in the form of flat areas, was observed on the leading diamonds but it was not measured.

Equation (6) gives a curve of penetration rate against depth drilled for 200 inches of drilling; from such a curve one can standardise for any depth of drilling.

Work on Hardness Reducers is currently being undertaken.

Paper by G.D. JUST and D.S. HENDERSON:

The Authors in Reply:

The relative costs of breaking rock by blasting and crushing will depend upon the nature of the operation. Although these costs are important other unit costs such as drilling, loading and haulage costs should be considered. Very little information is available from Companies on such costs. However, in one large underground mining operation the following relative unit costs have been found to apply— drilling 33%, blasting 8%, loading 32%, haulage 19% and crushing 8%.

With regard to shattering near the hole, it is generally accepted that most of the very fine particles are produced from this region. The larger particles are produced from the region near the collar of the hole. It is recognised that structural weakness planes will have a significant effect upon the degree of fragmentation. Model tests have been planned to investigate this phenomenon in detail.

Model testing is a slow process and field testing on even a moderate scale is even more costly and time-consuming. However larger-scale tests are essential due to the lack of knowledge regarding scaling factors as applied to size distributions. A limited number of such tests have been conducted.

In conclusion it should be noted that the prediction of size distributions from blasting may also be relevant to Civil Engineering operations where a particular grade of rock fill is required.

TECHNICAL SESSION No. 6—FOUNDATIONS

"An Analysis of Pile Loading Tests in a Stiff Clay", S.B. Bromham & J.R. Styles.

"Model Tests on Piles in Clay", N.S. Mattes & H.G. Poulos.

"A High Capacity Load Test for Deep Bored Piles", J.D. Moss.

"Analysis of the Movements of Battered Piles", H.G. Poulos & M.R. Madhav.

"The Bearing Capacity of Strip Footings from the Standpoint of Plasticity Theory", E.H. Davis & J.R. Booker.

"Uplift Testing of Prototype Transmission Tower Footings", R.J. McKenzie.

"Stresses Beneath Granular Embankments", I.K. Lee & J.R. Herington.

GENERAL REPORTER - Prof. P.W. TAYLOR:

Of the seven papers presented at this session, five are concerned with piles, one with spread footings and one with embankment stresses. Your Reporter considers that this emphasis on piled foundations is desirable for, despite the fact that civil engineers have employed piled foundations for centuries, estimates of load deflection relationships and ultimate bearing capacities are still subject to a wide margin of error. For this reason, high 'factors of safety' are commonly used. More exact knowledge will undoubtedly lead to more economic design. The three papers dealing with full-scale loading tests will be considered first.

That by Bromham and Styles is of considerable interest as it attempts to compare three methods of estimating ultimate bearing capacity with results of field loading tests. Concerning field and laboratory soil tests, it would be of interest if the authors could give the liquid limits for the soils tested and a definition of 'friction ratio' for the penetrometer. Perhaps the authors could state also whether or not 'N-values' were corrected for vertical effective stress (Ref. D1) and whether lubricated end platens were used for the triaxial tests on samples with a height/diameter ratio of unity. Referring to Fig. 5, showing time-dependent deflection under constant load, it is difficult to accept the statement that "secondary consolidation effects begin after about 30 minutes". One would expect the start of secondary consolidation to be indicated by a reverse curvature, as shown in Mattes and Poulos' paper (Fig. 2) for model piles.

In the pile loading test at 38 ft. depth, failure is clearly defined but, for that at 76ft., the load was still increasing rapidly at 0.35 in. deflection and while the elastic limit may have been passed,