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AUSTRALIAN GEOMECHANICS SOCIETY

RAISE AND TUNNEL BORING IN AUSTRALIA

UNIVERSITY OF MELBOURNE

1970

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SYMPOSIUM ON RAISE AND TUNNEL BORING

August 14-15, 1970

AUSTRALIAN GEOMECHANICS SOCIETY

VICTORIAN GROUP

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AUSTRALIAN GEOMECHANICS SOCIETY

SYMPOSIUM ON RAISE AND TUNNEL BORING

AUGUST 14 - 15, 1970

PROGRAMME

August 14th, 1970 - 2.15 p.m.

Public Lecture Theatre, Old Arts Building
University of Melbourne

OPENING - Professor D.H.Trollope, National Committee Chairman, Australian Geomechanics Society.

INTRODUCTORY ADDRESS - Mr. A.G.Robertson, Engineer in Chief, Melbourne and Metropolitan Board of Works.

SESSION A - Chairman - Mr. F.G.Taylor

"Tunnel Boring in Fractured and Weathered Sedimentary Rock".

Part 1: Selection of Boring Machine, Associated Plant, and Ground Support - A.J.Neyland.

Part 2: Interim Report on Operating Experience - R.F.Murrell.

Part 3: Modification of the Original Boring Machine - F.G.Watson.

Part 4: Interim Report on Cutter Experience - A.J.Cusworth.

"Soft Ground Tunnelling by Machine"

Part 1: Introduction - N.B.Smith.

Part 2: Factors Influencing the Selection of the Soft Ground Tunnelling Machine - P.R.Callow.

Part 3: Support Requirements for Machine Excavated Soft Ground Openings - A.A.Nelsen.

SESSION B - Chairman - Mr.W.E.Bamford

Part 1: Machine Boring and the Mechanical Properties of Hard Rock" - H.J.Handewith (presented by G.A.Smith).

Part 2: Drillability and Wear Prediction by Laboratory Techniques and Correlations with Operating Experience - R.M.Lightfoot.

Part 3: The Design and Application of Rolling Cutters for Raise and Tunnel Boring - R.L.Dixon and E.P.Worden (presented by A.Jacobs).

Part 4: The Application Raise Boring to Vertical Development at Mount Isa Mines - A.W.Howe and R.J.Boyd.

Part 5: Raise Boring Performance and Costs at Cobar Mines - A.Finucane.

Part 6: Raise Drilling at Kambalda - A.Palmer.

SESSION C - Chairman Dr. C.M.Gerrard

Part 1: Economic Factors in Tunnel Boring - R.J.Robbins, (presented by C.C.Wilson)

Part 2: Tunnel Boring in Hard Rock as Applied to the Thomson-Yarra Tunnel - R.P.Aschenbrenner.

Part 3: The Behaviour of a Closely Jointed Rock Mass around a Machine-Bored Tunnel - A.G.Bennet and W.A.Peck.

Part 4: Stress Failures in Fisher Tunnel, Tasmania - J.M.Maddox.

Part 5: Development of Continuous Excavation Techniques for Hard Rock - V.Satyanarayana.

AUSTRALIAN GEOMECHANICS SOCIETY

SYMPOSIUM ON RAISE AND TUNNEL BORING

August 14 and 15, 1970

Drillability and Wear Prediction by Laboratory Techniques and Correlation with Operating Experience.

by

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M.Eng.Sci. Candidate Mining Department
University of Melbourne

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ABSTRACT

The use of a Security Model 480 Raise Drill in the development of its mine at Kambalda W.A., by the Western Mining Corporation provided an opportunity to compare methods of predicting penetration rates of this machine in different rock types.

Kambalda basalt, porphyry and serpentinite were test drilled by a Goodrich 3/8" x 3/8" x 3/32", 90^{o} chisel edged tungsten carbide drag bit, drilling vertically upwards at 150 R.P.M. for 150 revolutions under a thrust of 40 lbs. The depth of penetration was measured by a vernier depth gauge and the width of wear flat by a calibrated traversing binocular microscope. Wear was plotted against penetration and this divided the test rocks into groups of equal drillability.

In an effort to simulate the basic bit penetration mechanism, the Morris method of determining drillability was used. This consisted of hydraulically pressing a 1/8 inch radiused, hemispherical ended conical tungsten carbide compact into the rock surface until chipping occurred. The crater depth divided by the ram load gave the drillability index (P/E). Using this index, the bit type and thrust, penetration rate and bit life can be estimated. The predicted penetration rates were comparable to the field results.

The raise-head cutter efficiency was determined from the log plotting of the Somerton non-dimensional drilling parameters, $\frac{R}{ND}$ versus $\frac{Th}{D^2Sc}$.
This allows the cutters to be compared on their advance per revolution for different thrusts and rock strengths.

INTRODUCTION

Drillability is the resistance of rock to penetration by a drilling technique operating at standard conditions.

The first determinations of drillability were based on the rocks' physical properties. This proved to be ineffective. Hartley (1926), classified rocks by determining the input energy required to cut a unit volume of rock. The rock requiring the greatest amount of energy was classified as A+, while that requiring the least was D-.

Continuing the determination of percussive drillability Shepherd (1950), attempted to correlate the experimentally determined drillability to the tested material's physical properties and concluded that Shore hardness was not an acceptable measure of drillability. Sievers (1950), Wells (1950) and Head (1950) have investigated drillability by standardising testing to determine the rate of penetration and wear.

At Drilling Research Inc., Simons (1953, 54 and 56) carried out fundamental studies of rock failure mechanisms for percussive drilling. He has made a significant contribution by relating penetration rate to drilling parameters.

$$R = \frac{2.4\,(P - Pt)}{D^2 S}$$

R = Penetration Rate in/min.
P = Mechanical Power in lb/min.
Pt = Threshold Mechanical Power in lb/min.
D = Hole diameter in.
S = Drilling Strength lb/in^2.

Extending Simon's work, Hartman (1959), conducted dynamic wedge indentation tests at varying energies and index distances, noting the difference in crater volumes.

$$S = \frac{V\,B\,W}{A}$$

S = Penetration Rate ft/min.
V = Single Blow Crater Volume ft^3
B = Blow frequency cycles/min.
W = No. of Bit wings.
A = X-Section of the Hole ft^2.

In an attempt to correlate laboratory to field results for drag bit drilling, Goodrich (1956) designed and built a 3/8" x 3/8" x 3/32", 90^{o} chisel edged tungsten carbide drag bit (Fig. 1). This bit was rotated vertically by the drilling machine at 150 R.P.M. for 150 revolutions, the sample being drilled under a constant thrust of 40 lb. (Fig. 2). The Goodrich drillability index "J" was the depth drilled in inches multiplied by 254. Using a binocular microscope (Fig. 3), the wear flat occuring in drilling was measured in millimeters (mm.). This gave the degree of abrasiveness of the rock.

Diamond bit drillability was studied by Paone and Bruce (1963). Using two AX - sized diamond coring bits at different thrusts and rotation speeds, they concluded that the bit performance was directly related to the drilling strength of the rock.

$$d = \frac{2\,(T - VF_v r)}{SA - F_v}$$

d = Penetration per Rev in.
T = Applied Torque in lb.
V = Coefficient of Resistance
Fv = Applied Thrust lb/in^2.
S = Drilling Resistance lb/in^2.
A = X-Sectional Area in^2.
r = Bit radius in.

The last decade has seen drillability predicted for roller cutters. Medlock (1961) and Rollow (1962) used 1¼" diameter roller bits to predict drillability. These laboratory results were correlated to field results for the same material and successful field wear predictions were made.

Morris (1968) investigated the basic penetration mechanism of roller cone drilling and concluded that by indentation of a 1/8" radiused, hemispherical ended cone of tungsten carbide into rock (Fig. 4), the crater depth (P') inches, divided by the ram load (E) in lbs. gave a drillability index (P'/E). The values obtained from laboratory tests were related to the field drilling by the empirical formula,

$$R = C\,N\,\frac{(P')}{(E)}\,\frac{W}{C} \qquad \text{Appendix (1)}$$

R = Penetration Rate ft/hr.
C = Constant
N = Revolution Speed R.P.M.
P' = Crater Depth in.
E = Threshold Strength lbs.
W = Effective Drilling Weight lbs.
C = Total No. Bit Elements

Dissatisfied with the work that had been done to relate drillability to the drilling systems, White (1969) used the systems of Rotary, Rotary Percussive and Percussive drilling and based his drillability index on the time required to drill a 3/4 inch diameter hole to a depth of 3 inches. Using regressional analysis on these results, it was concluded that the uniaxial compressive strength was related to drillability.

LABORATORY METHODS USED TO PREDICT PENETRATION RATES OF A RAISE DRILL

Goodrich Method

In 1967 the Mining Department of the University of Melbourne built a drillability testing machine similar to that designed by Goodrich of Joy Manufacturing Co. In his studies of drillability and the physical properties of rock, Singh (1968), used this machine to test Australian rock types, standardising this machine with the same rock as Goodrich.

The machine has been used to test rocks from the Western Mining Corporation mines at Kambalda W.A. to predict the penetration rate of that company's Security Model 480, 6' - 0" diameter raise - drill. The high strength basalts proved the most difficult to drill, closely followed by porphyry and talc-carbonate serpentinite being the easiest. By plotting depth drilled versus wear flat width, the more difficult to drill wore rapidly, however, rocks with high silica contents produced the greatest wear flat width (Fig. 5).

Although the drilling mechanism is not the same as the rotary cone drilling, this method enables the degree of abrasivess of the formation to be determined. Since there is considerable frictional contact between the rock and the tungsten carbide compacts in the field drilling, the Goodrich method of predicting wear and drillability may be used to determine penetration rates for the raise drill.

Morris's Method

The method of predicting drillability proposed by Morris (1968) has proved the most satisfactory of the published techniques commercially used. The method used to predict penetration rate and bit life is based on an empirical relationship and does not rely solely on prediction from a knowledge of field performances and the material's uniaxial compressive strength.

The experimental apparatus used was easily adapted to the equipment already in use in the department's rock mechanics laboratory (Fig. 6), and the tungsten carbide compacts were supplied by courtesy of the Oil and Mining Division of Dresser Industries. These tungsten carbide compacts were pressed into an adaptor plate which was fixed to the cross-head of the department's

Avery transverse testing machine. This machine was able to supply a load of up to 12,000 lbs. with the scale graduated in 50 lb. divisions.

The depth of indentation of the compact to produce the first chip was measured continuously from the beginning of loading, by two averaging Linearly Variable Differential Transformers (L.V.D.T.'s) and amplifier. The outputs from the L.V.D.T.'s were recorded on one channel of a four channel pen recorder, while a second channel recorded the load. The output voltage difference of the L.V.D.T.'s between initial contact and final depth to produce the first chip was converted to a depth of penetration in thousandths of an inch from a prepared voltage - depth calibration chart for the amplification used.

To obtain the drillability index the depth of penetration in inches was divided by the load in lbs. This gave the Morris factor of (P'/E).

On testing Kambalda and other rocks, the penetration rates predicted agreed with those obtained by Dresser Industries for the same material (Fig. 7). This method of predicting penetration rate and bit life is only as reliable as the sampling and relies on the raise-drill penetration rate to give the degree of variation in results, Table 1.

Somerton Non-Dimensional Relationship

A theoretical method of predicting wear was suggested by Somerton (1959) in his non-dimensional studies of rock drilling. He stated that by plotting of the log $\frac{(R)}{ND}$ vs. log $\frac{(F)}{D^2SC}$ a series of parallel sloping lines at $\alpha = Z$ would result

R = Penetration rate ft/hr.
N = Revolution Speed rev/hr.
D = Diameter in ft.
F = Thrust in lbs.
Sc = Drilling Strength lb/sqft.

The experimental confirmation of this method was conducted on a bicone bit whose wear was easily measured and when plotted the non-dimensional relationship gave the predicted parallel lines of decreasing $\frac{R}{ND}$ as the wear increased.

As the relationship is non-dimensional, it may be used for more complex drill bits.

On plotting these relationships for Kambalda basalts (the toughest and most abrasive to drill) (Fig. 8), there was too much variation in operating conditions and rock properties to determine wear. As it was impossible to determine rock strength at every foot drilled, an average value of strength was taken from the uniaxial compression test conducted on similar material. Similarly, the operating speed of the raise-drill was assumed constant although stalling has occurred in drilling.

The value of $\frac{R}{ND}$ was greatest for the high profile cutters operating at 14 r.p.m. for both raise-drill hole 1 and 6 (RD1 and RD6). In RD6 the rotation speed was increased and the advance per revolution was found to be less. Similarly, low profile cutters operating at 14 and 20 r.p.m. were used in RD6. These gave results similar to those of high profile cutters operating at 20 r.p.m.

To predict wear from the parallel lines at a slope of α, assumes that the wear is even. This was not found to be the case as it does not allow for the leading cutter affect (one or two cutters taking a greater load even though the cutters are attached at set levels). Wear is also increased by skidding of the cutters (all the cutters are of the same profile, and since they are at different radii, cannot rotate at their natural radius of rotation).

RESULTS

The methods outlined by Morris (1968) predicted penetration rates to a deviation of less than 25 per cent of the actual field rates, but his method does not allow for variation in jointing, faulting or intrusions. To predict penetration rates accurately it is necessary to sample widely to account for the rocks variability.

There is good correlation between the predicted and actual values of penetration rates for the Kambalda rock types, Table 1. The predicted values were determined in a similar manner to Morris, while the actual values were calculated from the recorder results of the raise-drill. To ensure the prediction of accurate penetra[tion] rates, well documented field results are necessary.

The Goodrich method of drillability prediction allowed the Kambalda rocks to be divided into groups of decreasing difficulty to drill. The high strength basalts proved the hardest to drill in terms of penetration per revolution; they were closely followed by the more abrasive porphyrys and the talc-carbonate serpentinites drilled rapidly producing a small wear flat. These material groups can be assigned an average value of penetration rate allowing the broad determination of penetration rates for other materials to be found.

The non-dimensional plotting of the raise-drill results for basalt being drilled with different types of cutters at two speeds, allowed a comparison to be made of the relative efficiency of these cutters. Basalt was chosen as the test material as it caused the greatest amount of wear to the cutters and was the most expensive rock to drill.

Using a log-log plot of $\frac{R}{ND}$ vs. $\frac{Th}{D^2Sc}$ showed that there was too much variation in the results to predict the average wear of the raise-head cutters. However, it showed that high profile cutters operating at 14 R.P.M. gave the greatest advance per revolution while the low profile cutters operating at 20 R.P.M. gave the least.

CONCLUSIONS

The Morris method for predicting penetration rates of large hole drilling machines proved to be accurate within the limit of sampling. It gave likely field penetration rates and estimated the bit life from a quick and simple laboratory test.

Predictions from Goodrich testing could only give average rates for a material type, but it was sufficient to divide materials into an order of hardest to easiest to drill. It gave the materials' relative drillability and width of wear flat.

The performance results of new cutter designs operating in different rocks and rotation speeds can be easily compared from the Somerton non-dimensionsal plot.

This plot allows the cutters' advance per revolution to be used to compare their efficiency, but cannot predict average wear if there is a large variation in test results.

The methods discussed gave different aspects of drillability and when used together were able to predict drillability accurately.

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APPENDIX (1)

This index was determined from the force penetration plotted for a 90^{o} conical tungsten carbide compact, with a 1/8" radius at the apex (Fig. 4).

The penetration is a direct function of load up to the threshold force (E). The crater depth (P') and threshold force (E) was thought to be a direct measure of roller-cone drillability. For this reason the ratio (P'/E) appears to be the more definitive index.

By multiplying the static threshold force (E) by the average number of bit elements working (I) we should get the effective drilling weight (W).

$$W = EI \qquad (1)$$

Observation and study reveal that I = 0.08c, where C = the total number of bit elements.

$$W = 0.08\ EC \qquad (1a)$$

The roller cone penetration rate may be expressed as:-

$$R = Np \qquad (2)$$

R = Penetration Rate

N = Rotation Speed

P = Penetration per rev.

Assuming that a direct relationship exists between actual penetration per revolution (P) and (P') from test results.

$$P = Kp'$$

$$R = NKP' \qquad (2a)$$

similarly

$$P' = \frac{P'}{E} E$$

substituting E from (1)

$$P' = \frac{P'}{E} \frac{W}{I}$$

then

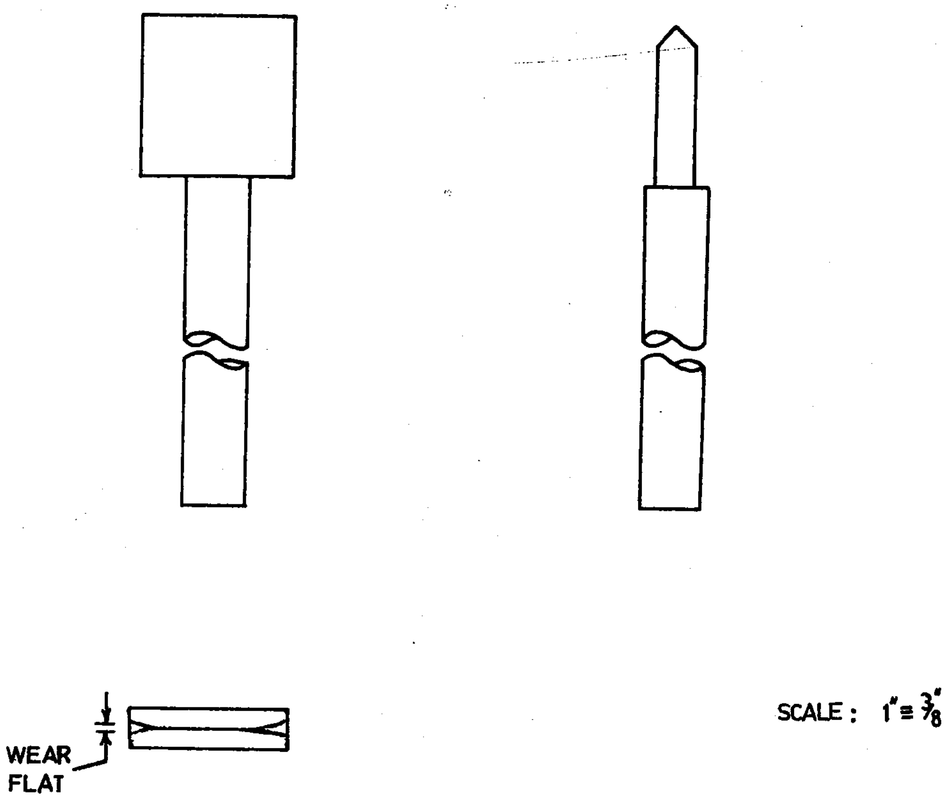
$$R = NK \frac{P'}{E} \frac{W}{I} \qquad (2b)$$

It has been found that the constant K varies with the drilling conditions. The bit penetration rate equation has been empirically modified to:-

$$R = 56\ N \frac{P'}{E} \frac{W}{C} \qquad (3)$$

The estimates of bit life have been based on field drilling in similar materials.

$$L = 5 \left(\frac{P'}{E}\right)^2 \times 10^{12}\ \text{(feet)} \qquad (4)$$



Goodrich Drag Bit ($\frac{3}{8}" \times \frac{3}{8}" \times \frac{3}{32}"$)

Fig 1

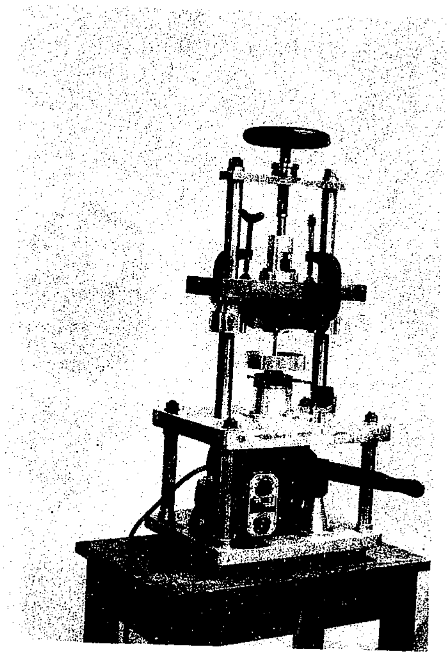


FIGURE 2

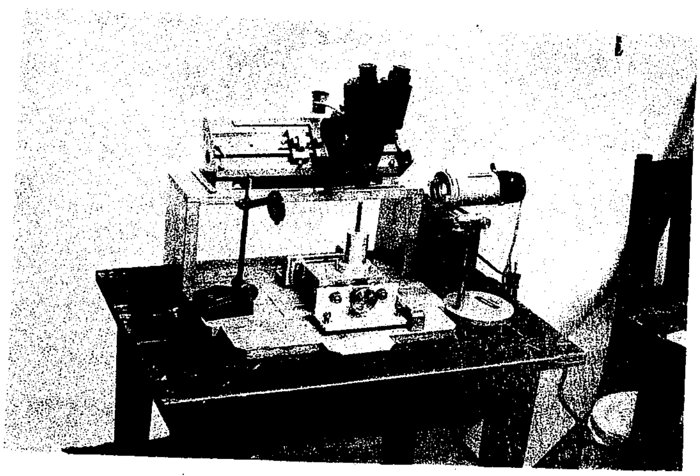
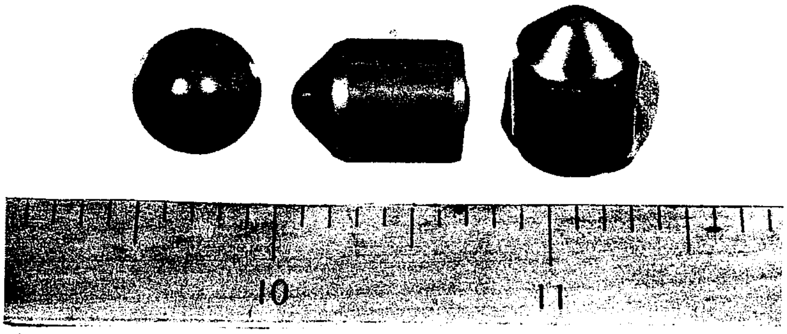


FIGURE 3



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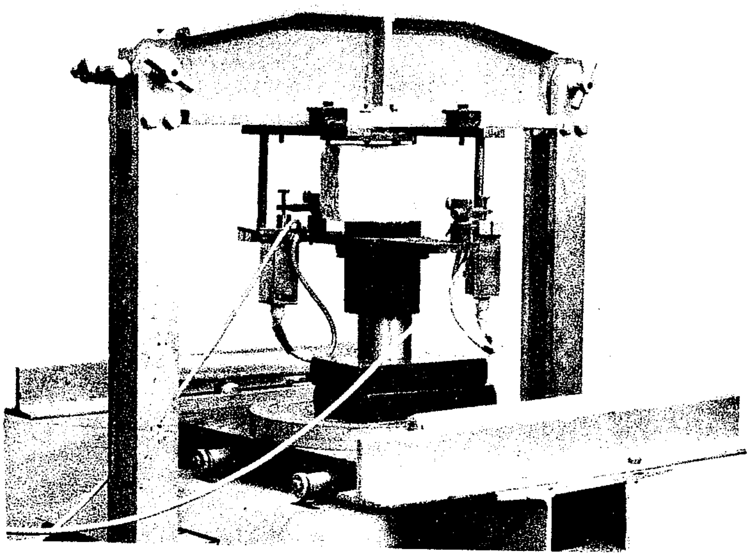

FIGURE 6

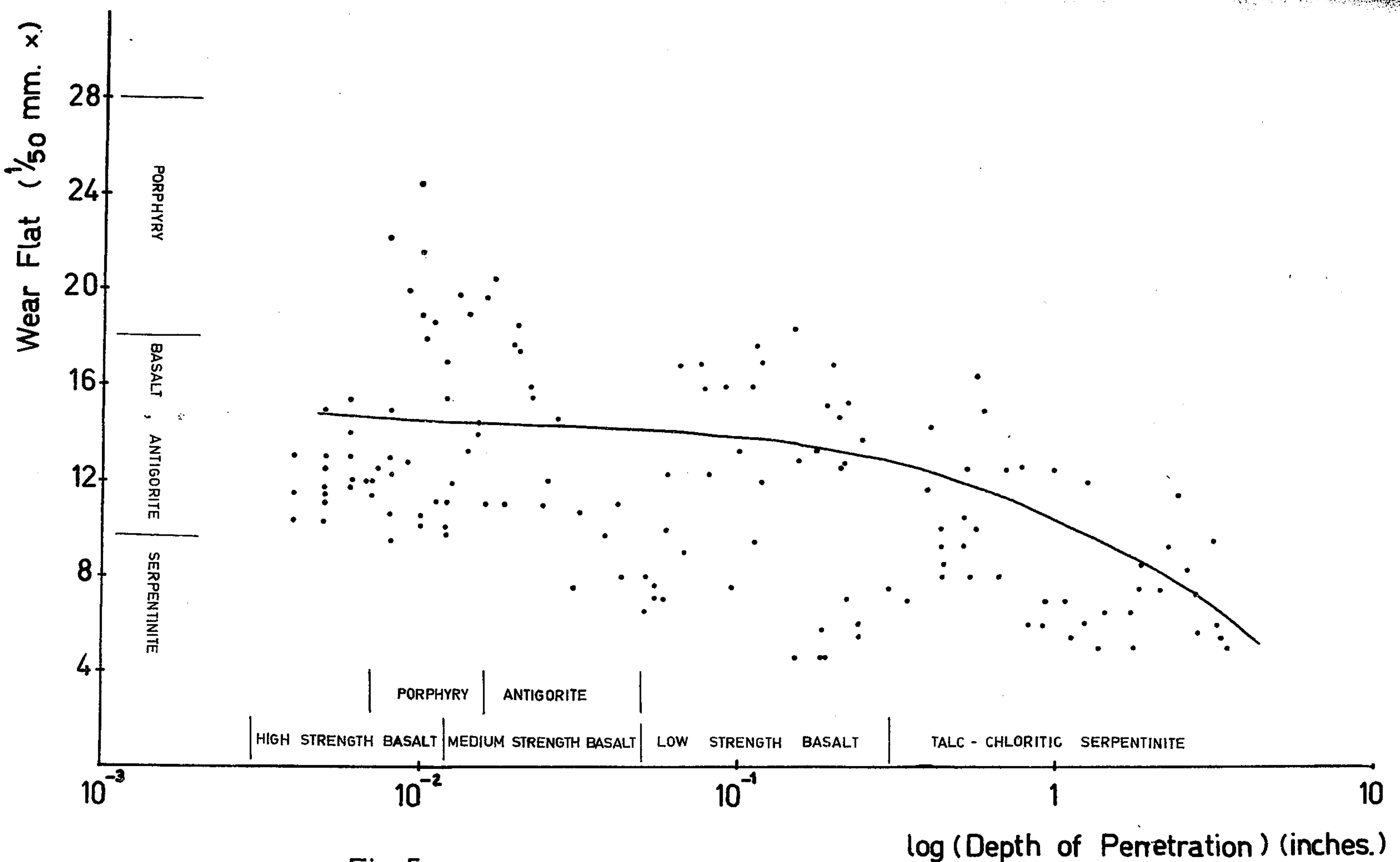
Wear Flat ($^1/_{50}$ mm. x)
28
24
20
16
12
8
4
PORPHYRY
BASALT , ANTIGORITE
SERPENTINITE
PORPHYRY
ANTIGORITE
HIGH STRENGTH BASALT
MEDIUM STRENGTH BASALT
LOW STRENGTH BASALT
TALC - CHLORITIC SERPENTINITE
10^{-3}
10^{-2}
10^{-1}
1
10
log (Depth of Penetration) (inches.)

Fig 5

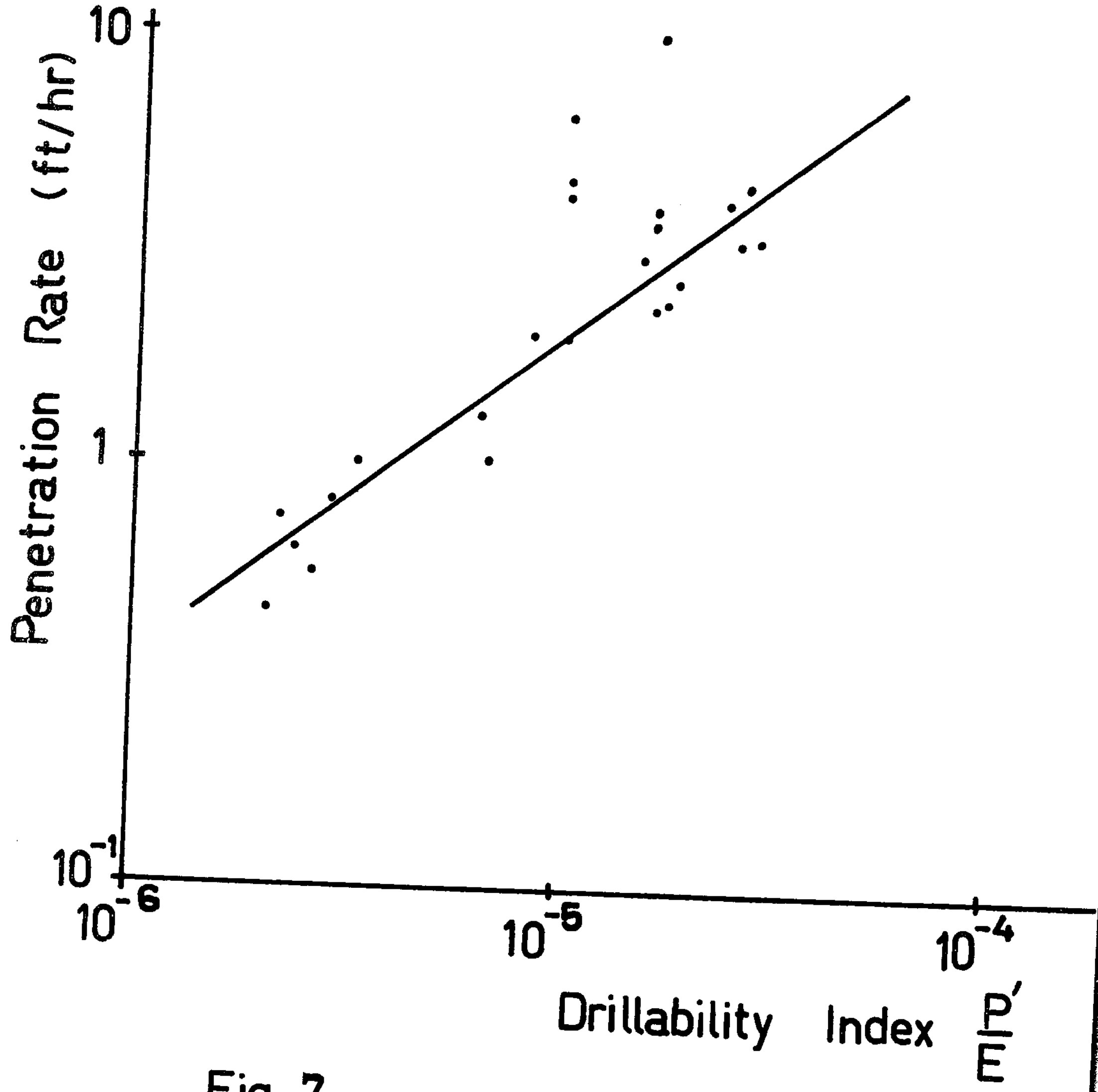
10
1
10⁻¹
Penetration Rate (ft/hr)
10⁻⁶
10⁻⁵
10⁻⁴
Drillability Index P′/E

Fig 7

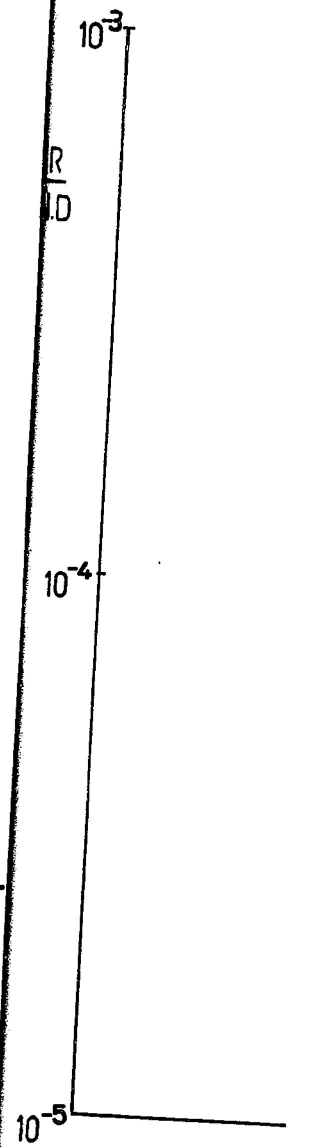
10⁻³
10⁻⁴
10⁻⁵

Fig 8

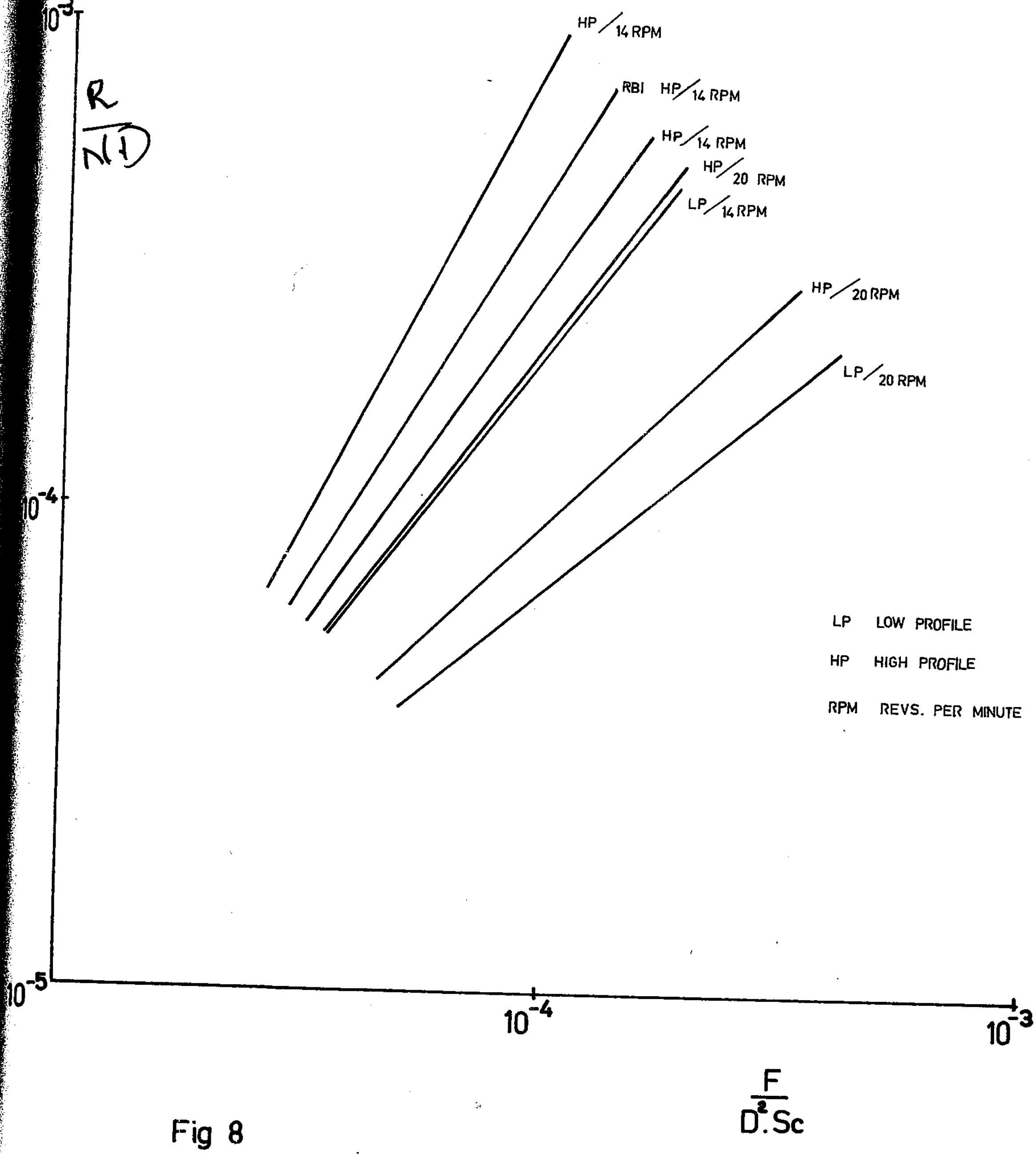
10^{-3}
10^{-4}
10^{-5}
R / n(t)
HP/14 RPM
RBI HP/14 RPM
HP/14 RPM
HP/20 RPM
LP/14 RPM
HP/20 RPM
LP/20 RPM
LP LOW PROFILE
HP HIGH PROFILE
RPM REVS. PER MINUTE
10^{-4}
10^{-3}
$\frac{F}{D^2.Sc}$

Fig 8