Some fundamental aspects of the use of disc cutters in hard-rock excavation

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SYNOPSIS

Some important aspects of the design of rock-cutting systems remain relatively unexplored. Two areas of practical significance in this context form the subject of this paper: cutting in jointed or fissured rock, and groove-deepening.

A series of controlled laboratory experiments on the performance of disc cutters in jointed rock showed that the spatial and geometrical configuration of jointed rock masses needs to be taken into consideration in the design of mechanized rock-excavating systems. One series of experiments showed that, under favourable geometric conditions, the energy required to cut in a jointed rock mass is at least half that required to cut otherwise intact rock.

Groove-deepening—the progressive deepening of a groove by successive passes of a cutter—is a potential operational feature with most mechanized rock-excavating systems. Laboratory experiments revealed an important fundamental cycle of events associated with disc cutters when progressively deepening a groove in intact rock. Furthermore, in contrast to pick cutting, groove-deepening by discs is shown to be an efficient operation and one that should not necessarily be avoided. This can be directly attributed to increased interaction between the disc cutters as the result of an increase in magnitude of the lateral forces generated as a groove is deepened.

SAMEVATTING

'n Paar belangrike aspekte van die ontwerp van snystelsels is nog betreklik onbekend. Twee terreine van praktiese belang in hierdie verband vorm die onderwerp van hierdie referaat: snywerk in rots met nate en splete, en groefverdieping.

'n Reeks beheerde laboratoriumeksperimente in verband met die werkverrigting van skyfsnyers in rots met nate het getoon dat die ruimtelike en geometriese konfigurasie van rotsmassas met nate in aanmerking geneem moet word by die ontwerp van gemeganiseerde rotsgraafstelsels. Een reeks eksperimente het getoon dat die energie wat nodig is om, onder gunstige geometriese toestande, in 'n rotsmassa met nate te sny, minstens die helfte is van wat nodig is om andersins ongeskonde rots te sny.

Groefverdieping—die progressiewe verdieping van 'n groef deur agtereenvolgende lope van 'n snyer—is 'n moontlike gebruiksaspek met die meeste gemeganiseerde rotsgraafstelsels. Laboratoriumeksperimente het 'n belangrike fundamentele siklus van gebeurtenisse in verband met skyfsnyers wanneer hulle 'n groef in ongeskonde rots progressief verdiep, aan die lig gebring. Verder word daar getoon dat groefverdieping met skywe, in teenstelling met piksnywerk, 'n doeltreffende bewerking is wat nie noodwendig vermy moet word nie. Dit kan regstreeks toegeskryf word aan die groter wisselwerking tussen die skyfsnyers as gevolg van 'n toename in die grootte van die sydelingse kragte wat ontwikkel word namate die groef verdiep word.

Introduction

The performance of rock-cutting tools and tunnelling machines has been studied extensively during the past ten years. The mechanisms of rock breakage associated with each of the principal rock-cutting tools (picks, discs, cutters with button and toothed rollers) are now reasonably well understood. However, one important aspect of the rock-excavating process that has been relatively unexplored is the effect of changes in rock structure or geometry on the performance of the cutting tool or machine. This aspect of rock cutting can be visualized as a rock-excavating machine operating in a variety of rock structures, some more heavily jointed than others.

This aspect of tunnelling-machine performance was studied in an investigation into the behaviour of disc cutters in simulated jointed rock. Composite blocks of simulated jointed rock were assembled, the geometry of the assembly was varied, and the performance of single-disc cutters during the excavating process was monitored.

Groove-deepening, an operational feature of most rock-excavating systems, refers to the progressive deepening of a groove where breakthrough between adjacent grooves does not occur until the optimum ratio of spacing to penetration is reached. *Prima facie*, this process is inefficient, and can lead to the rapid wear of cutting tools. The experiments detailed in this paper not only examine the energy requirements of the groove-

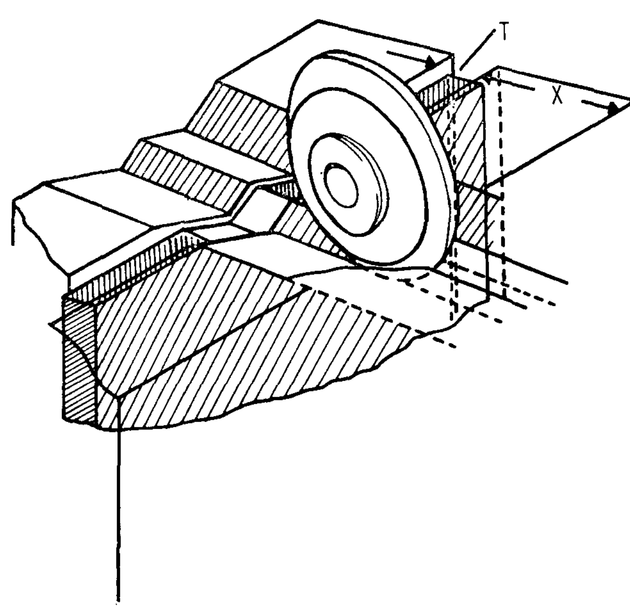

Fig. 1—A disc cutting in a jointed rock assembly. X = width of block (spacing of joints), T = width of joint. The angle of attack, i.e. the angle of the joint plane relative to the line of action of the disc cutter, is 90°. An angle of 90° is defined as the disc cuts normal to the direction of the joint planes.

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deepening process but also provide a useful comparison with other types of rock-cutting tools operating in groove-deepening situations.

The instrumentation and method of experimentation have been described in detail elsewhere[1,2].

Excavation in Jointed Rock

A diagram of the jointed rock assembly is shown in Fig. 1. To establish the effect of jointed rock on the performance of the disc cutters, identical experiments were undertaken in samples of intact rock taken from the same quarry location. Standard tests of physical and mechanical rock properties were undertaken to ensure that the quality of the various test blocks was reasonably consistent.

The experimental programme was conducted in Gosford Summersby Sandstone, which has the measured properties detailed in Table I.

TABLE I

PROPERTIES OF GOSFORD SUMMERSBY SANDSTONE

Property	Value
Grain size, mm	0,2 – 0,8
Quartz content, %	63 ± 5
Unconfined compressive strength, MPa	42,3 ± 2,56*
Unconfined tensile strength, MPa	2,84 ± 0,36*
Unconfined shear strength, MPa	14,5 ± 1,62*
Static Young's modulus, GPa	9,62 ± 2,47*
Schmidt rebound number	47,4 ± 6,43*
Dry mass density, kg/m³	2200 ± 61

* Mean value of property in two directions, one at right angles to the other.

Experiments were undertaken on the effect of the angle of cutting attack on the major rock-cutting parameters, the angle of attack being varied from 30 to 90° in increments of 15°. Although one hundred individual experiments were undertaken, it was found that the angle of attack did not have a significant (based on rigorous statistical criteria) effect on any of the major rock-cutting parameters[2].

The experiments detailed later in this paper were all undertaken with the angle of cutting attack equal to 90°. The graph in Fig. 2 shows how thrust and rolling forces varied with disc penetration for both jointed and intact rock. Here, the joints were 1,5 mm wide (T) and at a spacing (X) of 60 mm (see Fig. 1).

As might reasonably be expected, the jointed rock assembly has a lower excavation resistance than a similar block of intact rock. The difference at high penetration is considerable. For example, at a penetration of 10 mm, both thrust and rolling forces are reduced by between 35 and 40 per cent as a result of the jointing.

To explain this difference it is useful to consider possible mechanisms of disc-cutter penetration in a jointed rock mass. A simple, but perhaps plausible, explanation for the reduction in disc forces in jointed rock is the decrease in projected disc surface area in contact with the rock, as shown in Fig. 3.

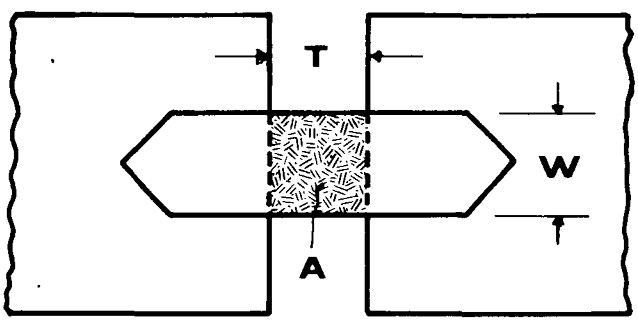

Fig. 3—Projected area of disc contact with jointed rock.

The projected area of disc contact over one open joint is given by

$$A = W \cdot T, \qquad (1)$$

where T = width of joint

W = width of disc contact at penetration P.

From the geometry of disc penetration given in an analysis by Roxborough and Phillips[3],

$$W = 2P \tan \frac{\phi}{2}, \qquad (2)$$

where P = penetration

ϕ = included disc-edge angle.

The combined equations (1) and (2) give

$$A = 2 \cdot P \cdot T \cdot \tan \frac{\phi}{2}, \qquad (3)$$

which is the projected area of disc contact over one open joint. The combination of equation (3) with the thrust force equation (4) proposed by Roxborough and Phillips[3],

$$F_T = \sigma_c \, 4 \tan \frac{\phi}{2} \sqrt{DP^3 - P^4}, \qquad (4)$$

gives a revised thrust force requirement for a disc penetrating across a centrally disposed open joint of width T, thus:

$$F_T = \sigma_c \, 2 \tan \frac{\phi}{2}\left(2\sqrt{DP^3 - P^4} - PT\right). \qquad (5)$$

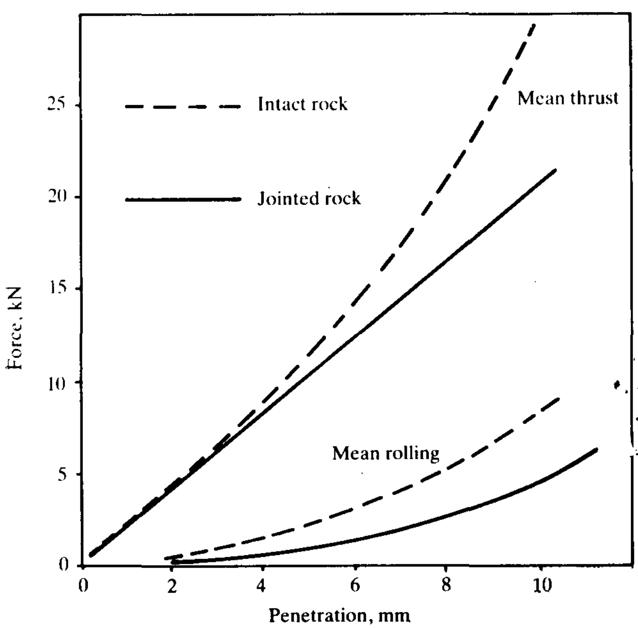

Fig. 2—Effect of penetration on disc forces in intact and jointed rock. Disc-edge angle = 60°, disc diameter = 100 mm.

It should be noted that the derivation of equation (5) is for the special case where the disc cuts across one joint with its centre lying over the centre of the joint. This probably represents an extreme situation of joint effect and furthermore enhances the mathematical simplicity.

By the substitution of values of ϕ, D, and T from the experimental conditions into equation (5) and for $P = 10$ mm, the reduction in thrust force due to the joint on the basis of this model is predicted as 2,5 per cent. This is much less than the observed reduction of 35 per cent.

It is evident that the reduction in thrust force required to excavate the jointed rock cannot be attributed to any appreciable extent to the reduction in the projected area of disc contact with the rock. Since equations (4) and (5) assume that the rock is broken under the action of compressive forces, and equation (4) is found consistently to be a reliable model for intact rock, it is necessary to look for some other failure mechanism for discs in jointed rock. It is probable, when a disc penetrates a jointed rock mass, that the material between adjacent joints expands or dilates normal to the direction of the applied stress (the Poisson effect). Consequently, high tensile strains are likely to be generated by the disc and, because of the jointing, such strain will be unconfined. It follows that tensile failure of the rock would occur at a much lower strain level than it would in the confined status of intact rock[4].

The lower forces involved in the cutting of jointed rock are further demonstrated by Fig. 4. This graph shows the effect of the disc-edge angle on the cutting forces. The difference between the forces for jointed rock and those for intact rock is considerable. At an edge angle of 90°, for example, the mean thrust force is 45 per cent, and the mean rolling force is 50 per cent lower than the equivalent values in intact rock. (The experimental conditions of this experiment were identical to those for the experiment described earlier.)

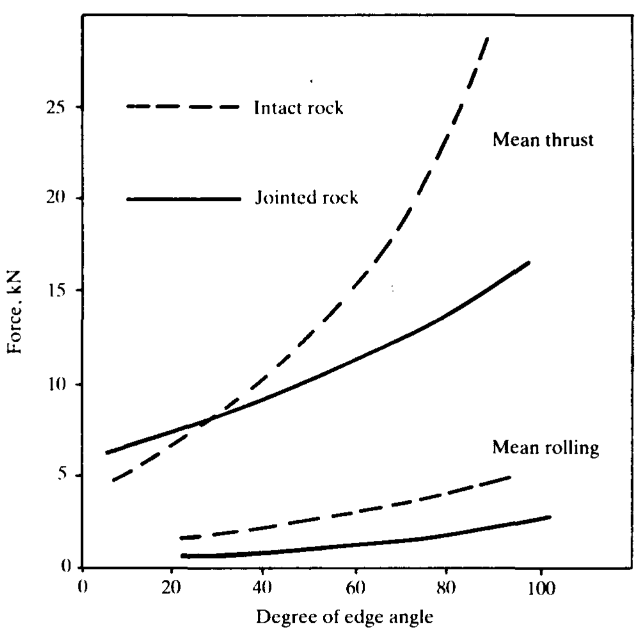

Fig. 4—Effect of disc angle on disc forces (P = 6 mm).

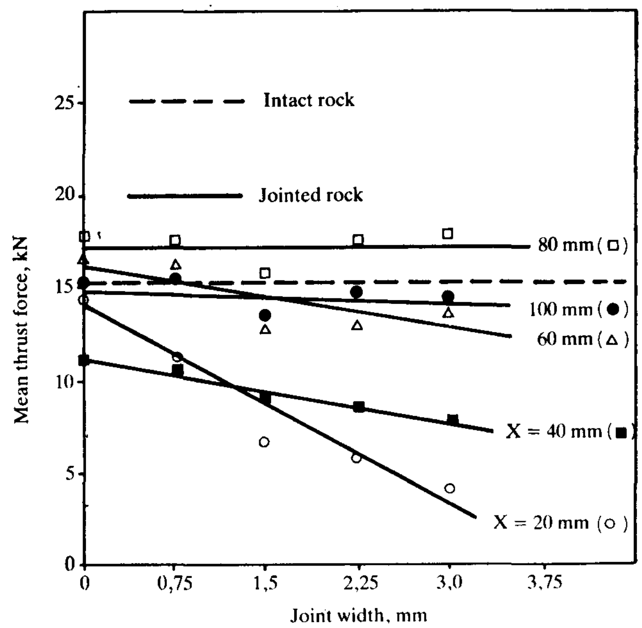

Fig. 5—Effect of joint width on mean thrust force (P = 6 mm, ϕ = 60°, x = joint spacing).

Two of the most significant variables to be considered in the cutting of jointed rock masses are the width of the joints (T) and the width of the blocks (see Fig. 1). The effect of joint width on mean thrust force is shown in Fig. 5. This graph shows the combined effects of joint and block width on disc force. For example, a widening of joint spacing from 20 to 80 mm involves a larger than threefold increase in the thrust force. This is at a penetration of 6 mm in joints 3 mm wide. Evidently the effect of joint spacing on disc performance is very significant.

It is also evident that, when the joint spacing is large, the joint width has little effect on the magnitude of the disc forces.

Fig. 5 also indicates that, at a high joint spacing (80 to 100 mm), the disc forces are of similar magnitude to those found in intact rock, regardless of the joint width. It is also seen that, at certain values of joint spacing and width, discs perform much the same as they do in otherwise similar intact rock. At a joint width of zero (closed joints), it was observed that all the disc performance criteria approximated values obtained for intact rock; this was not unexpected.

As shown in Fig. 6, if disc forces are presented as a function of the ratio of block width to joint width, the point at which the disc forces approximate those in intact rock is given by

$$X/T = 80 \quad \ldots\ldots\ldots\ldots\ldots \quad (6)$$

over the range of variables tested. At this ratio, jointed rock responds similarly to intact rock in terms of the disc forces required to excavate it.

Equation (6) indicates that, at a joint width of zero (closed joint), the joint spacing at which the rock mass approximates a continuous mass is also zero. Clearly, this is unacceptable. A modified empirical equation based on the relationships given in Fig. 5 is proposed in order to describe the behaviour more realistically, thus:

$$X = 60 + 20\,T, \quad \ldots\ldots\ldots\ldots \quad (7)$$

where X = block width (mm) and T = joint width (mm). This means the block width at which the jointed rock mass approximates intact rock is 60 mm when the joint width is zero, and 120 mm when the joint width is 3,0 mm. These values are in close agreement with the measured values as presented in Fig 5.

Some wider implications of equation (7) are presented graphically in Fig. 7. If a combination of joint width and spacing falls within region A, for all practical purposes the disc cutter can be considered to be excavating intact rock. If, however, the joint widths and spacing combinations fall in region B, some benefit will accrue. It should be noted that this relationship may not hold for levels of variables outside this experimental range and is based on a relatively small number of tests in one type of rock.

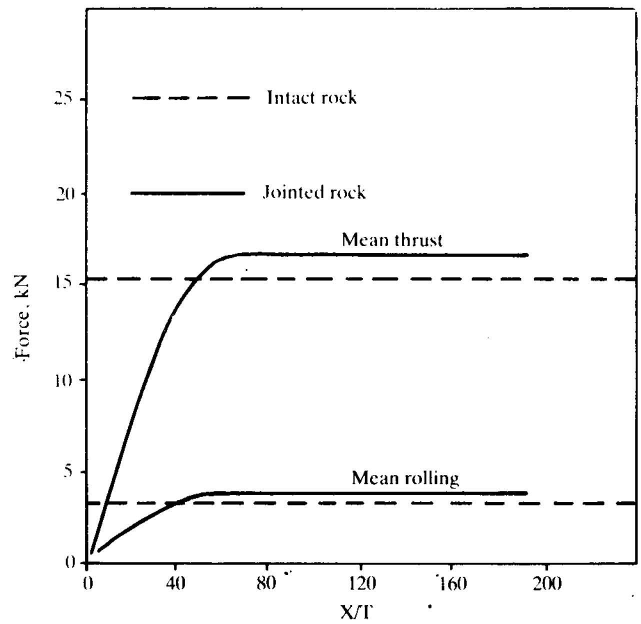

Fig. 6—Effect of X/T on disc forces. Each data point represents the mean value of four individual tests.

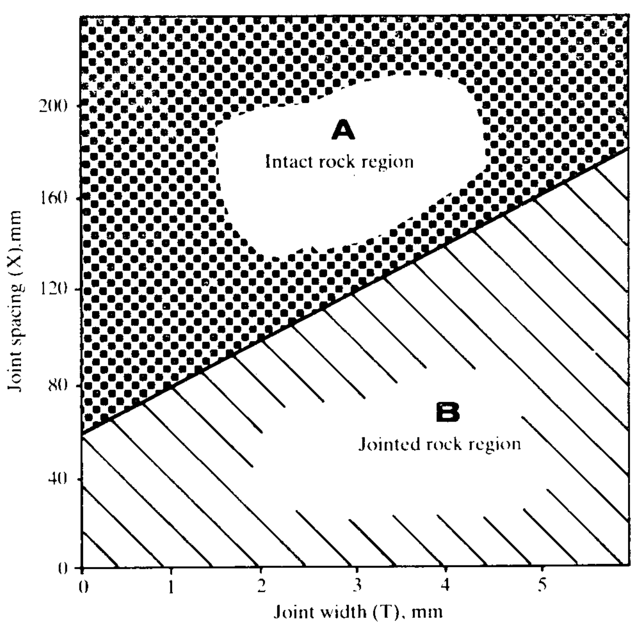

Fig. 7—Definition of intact and jointed rock regions based on levels of joint and block width.

Groove-Deepening

'In practice, the spacing between adjacent cutting tools in array is sometimes too great for the depth of cut taken during each revolution of the cutter head to allow the rock rib between adjacent tools to breakthrough'[5]. If this occurs, the groove is progressively deepened by successive passes of the tool until breakthrough occurs. Breakthrough will occur when the optimum ratio of spacing to penetration is reached for that particular tool.

Groove-deepening is an operating feature of most mechanized rock-excavating systems that use free-rolling cutters since optimum ratios of spacing to penetration cannot be achieved in one revolution of a cutting head. This is due to the geometric and physical constraints imposed by the large size of the cutter housings and the relatively small penetrations that can be employed.

Details of the instrumentation and method of experimentation used for the groove-deepening experiments have been given by Howarth[2].

Groove-deepening experiments provide a more realistic assessment of the field performance of cutting tools since they model the incremental cutting of tools operating in concert, rather than in isolation as is the case with single-pass, single-disc rock-cutting experiments.

A cycle of events associated with a pair of incrementally deepened adjacent grooves in intact rock as typified by Fig. 8 can be summarized as follows.

Stage 1. The first cut is on a fresh rock surface; the forces required to cut the rock are small, and no breakthrough occurs. Hence, the rock yield is small.

Stage 2. Successive passes of the tool deepen the grooves, and the disc forces increase as the contact area between tool and rock increases. The disc forces reach a maximum before breakthrough. At this stage no breakthrough occurs, and the yield remains small.

Stage 3. With the next pass of the tool, the ridge between adjacent grooves is sheared through (see Fig. 8). Hence, the rock yield is at a maximum.

After breakthrough, the disc is effectively cutting on a new surface, and hence the cycle will be repeated.

It is to be expected that cutting tools in a groove-deepening situation will wear more quickly than a corresponding tool cutting in an optimally relieved situation. This is due to the increased rubbing area between tool and rock (Fig. 8, Stage 2) and the increased forces on the disc.

Work undertaken by Roxborough and Phillips[5] showed that groove-deepening using chisel picks is an extremely inefficient operation in terms of the specific energy required. A similar analytical procedure to that of Roxborough and Phillips was used to provide a comparison of groove-deepening by disc cutter and chisel pick.

The basis for comparison is the use of the overall specific energy required to produce a groove by incremental

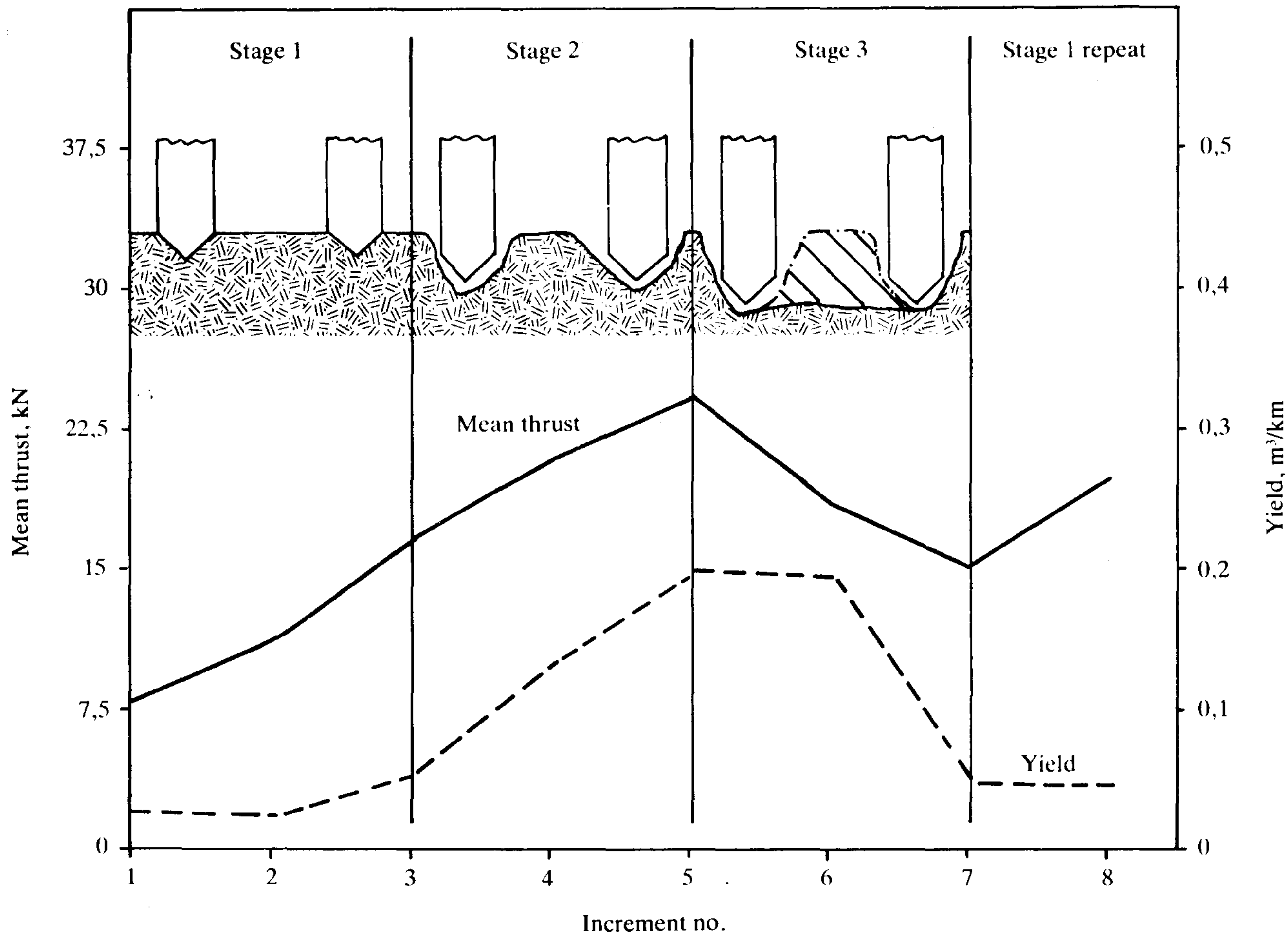

Fig. 8—The effect of groove-deepening on mean thrust force and rock yield.

cutting. The concept of overall specific energy is explained in detail by Roxborough and Phillips[5]. It can, however, be summarized by the following equation:

$$SE_{tot} = \frac{(\bar{F}_{R1}\times l_1)+(\bar{F}_{R2}\times l_2)+\ \ldots\ (\bar{F}_{Rn}\times l_n)}{(Q_1\times l_1)+(Q_2\times l_2)+\ \ \ldots\ )Q_n\times l_n)} \quad (8)$$

where SE tot = total specific energy required to produce a groove by incremental cutting in the number of steps indicated

$\bar{F}_R$ = mean rolling force of an individual cut

Q = rock yield of an individual cut

$l_1, l_2 \ldots l_n$ = lengths of cut

n = total number of increments of cutting.

Fig. 9 gives a comparison of total specific energies for a disc cutter (edge angle = 60°, diameter = 150 mm) and a chisel pick (rake = +10°, width = 10 mm). The graph shows the disc to be far more efficient than the chisel pick when operating in a groove-deepening situation.

The significance of curves A and B in Fig. 9 requires further explanation. Table II gives a summary of the data on which curves A and B are based. From the data for the chisel pick, it can be seen that, when the cutting force and the yield both reach relatively constant values, the total specific energy continues to increase. These data describe a condition known as coring.

Coring, which is shown diagrammatically in Fig. 10a, occurs when the volumes cut and swept by a pick are the same and there is no breakthrough between adjacent grooves. Under these conditions, the yield and the cutting force remain constant until the tool holder fouls the rock surface. Consequently, this process is highly inefficient, as indicated by the increasing total specific energy required.

The data for the disc cutter show (Table II) that, when the rolling force attains a relatively constant value, the yield increases, reaches a maximum at breakthrough, and then decreases, following the sequence of events described earlier (Fig. 8). The net effect is to produce a gradual decrease in the total specific energy required, as shown by curve B in Fig. 9. The reason for this cyclic rise and fall in yield is the interaction between adjacent discs caused by the favourably disposed flanks of the cutter, giving rise to high lateral forces, which ultimately cause the rib of rock between grooves to shear off. Such breakthrough between adjacent discs is shown in Fig. 10(b).

Conclusions

The principal conclusions drawn from this investiga-

TABLE II

DATA FOR FIG. 9

Chisel pick—curve A, Fig. 9 (Data from Roxborough and Phillips[5]).								
Groove depth, mm	3	6	9	12	15	18		
Cutting force, kN	0,6	0,85	1,03	1,11	1,2	1,18		
Yield, m^3/km	0,046	0,052	0,035	0,035	0,035	0,033		
Total SE, MJ/m^3	13,04	14,80	18,65	21,37	23,60	25,30		
Disc cutter—curve B, Fig. 9								
Groove depth, mm	2,5	5,0	7,5	10,0	12,5	15,0	17,5	20,0
Rolling force, kN	0,57	0,90	1,15	1,19	1,48	1,59	1,31	1,51
Yield, m^3/km	0,022	0,052	0,081	0,076	0,123	0,276	0,197	0,091
Total SE, MJ/m^3	25,91	19,86	16,90	16,50	14,94	10,92	9,90	10,57

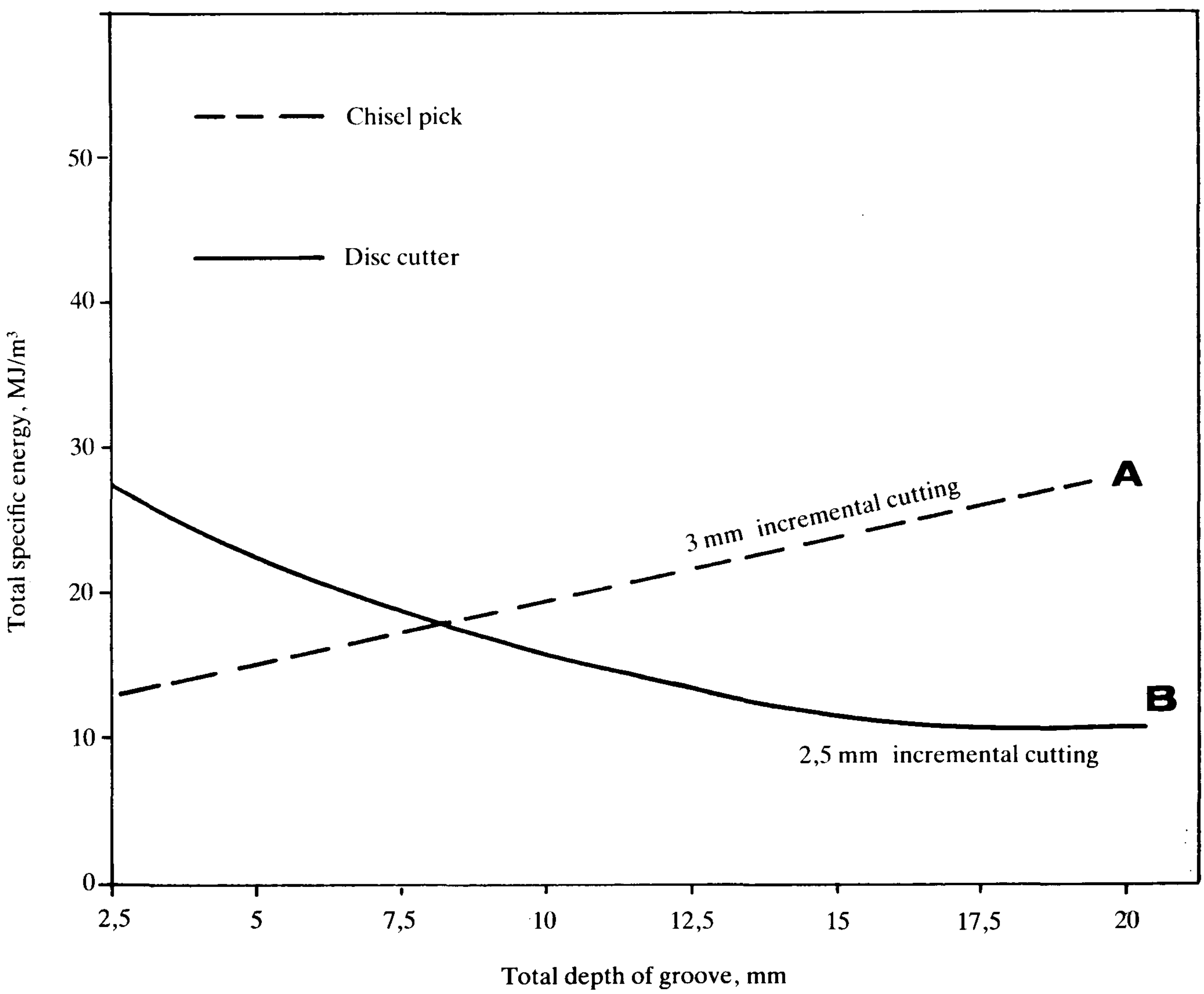

Fig. 9—A comparison of the total specific energy required for a chisel pick and a disc cutter in a groove-deepening situation.

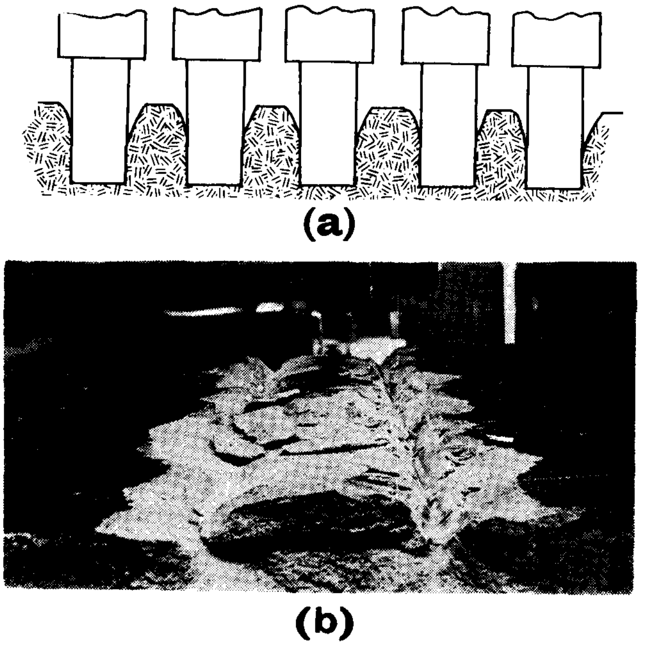

Fig. 10—(a) Coring by chisel pick.
(b) Groove-deepening by disc cutter.

tion can be summarized as follows.

(i) The forces required to excavate jointed rock with disc cutters are up to 50 per cent lower than those required to excavate an otherwise similar intact rock.

(ii) The difference between these forces for jointed and intact rock increases with increasing penetration and disc-edge angle.

(iii) Under certain conditions of block and joint width, jointed rock appears to exhibit behaviour similar to that of intact rock.

(iv) Groove-deepening experiments with disc cutters indicate a sequence or cycle of events associated with a progressively deepened groove. The cycle of events manifested in curves of disc-performance criteria is directly attributable to the gradual deepening of the groove and subsequent breakthrough of the rib of rock between adjacent cuts.

(v) On the basis of the total or overall specific energy required in incremental groove-deepening, disc cutters are far more efficient than chisel picks.

Acknowledgements

The research described in this paper forms part of an investigation into fundamental aspects of the mechanical excavation of hard rock with free-rolling cutters. This investigation is currently being undertaken in the School of Mining Engineering at the University of New South Wales. The project is supported financially by the Australian Research Grants Committee, whose generous assistance is gratefully acknowledged.

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