Mechanical Rock cutting-4th section

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Mechanical Rock cutting- Button cutters

Button Cutting

- Button cutters consist of cylindrical or conical tool bodies inset with tungsten carbide buttons.
- The tool is mounted in a bearing in the same way as disk cutters or roller cutters and is free to roll in response to applied forces acting parallel to the rock surface.
- Tools deploying buttons are the most robust form of cutting mechanism so far devised and can be operated effectively in types of rock that would quickly demolish other forms of cutter.
- Although being the most robust form of cutter, they are intrinsically the least energy efficient.

Button rolling button cutter used on a raise boring reamer

WD 4-LKG 1

WD 5-LKG 1

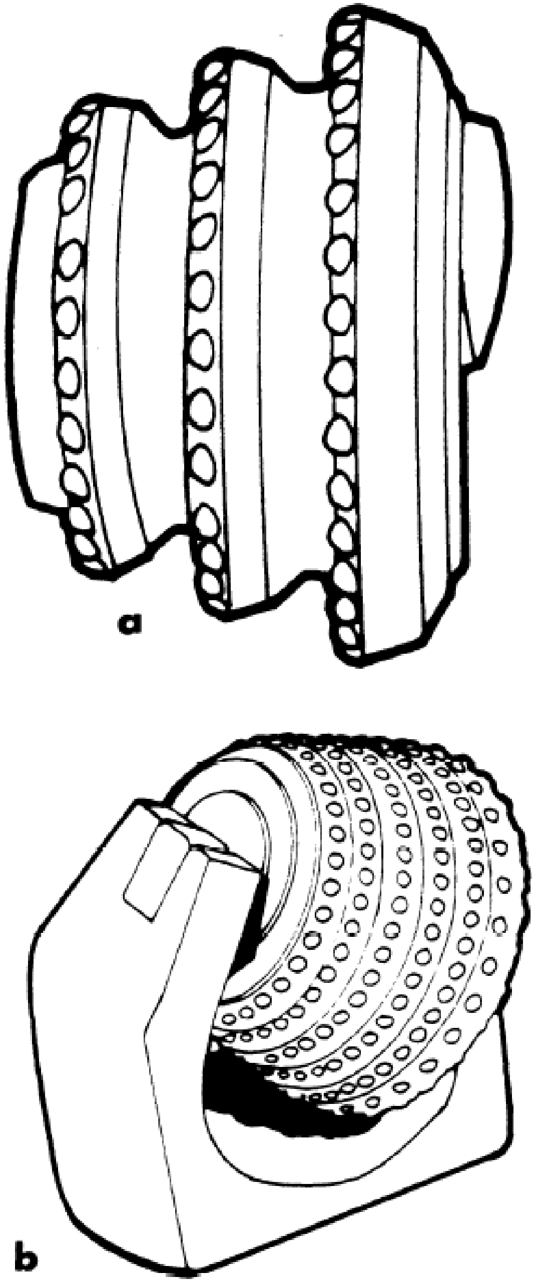
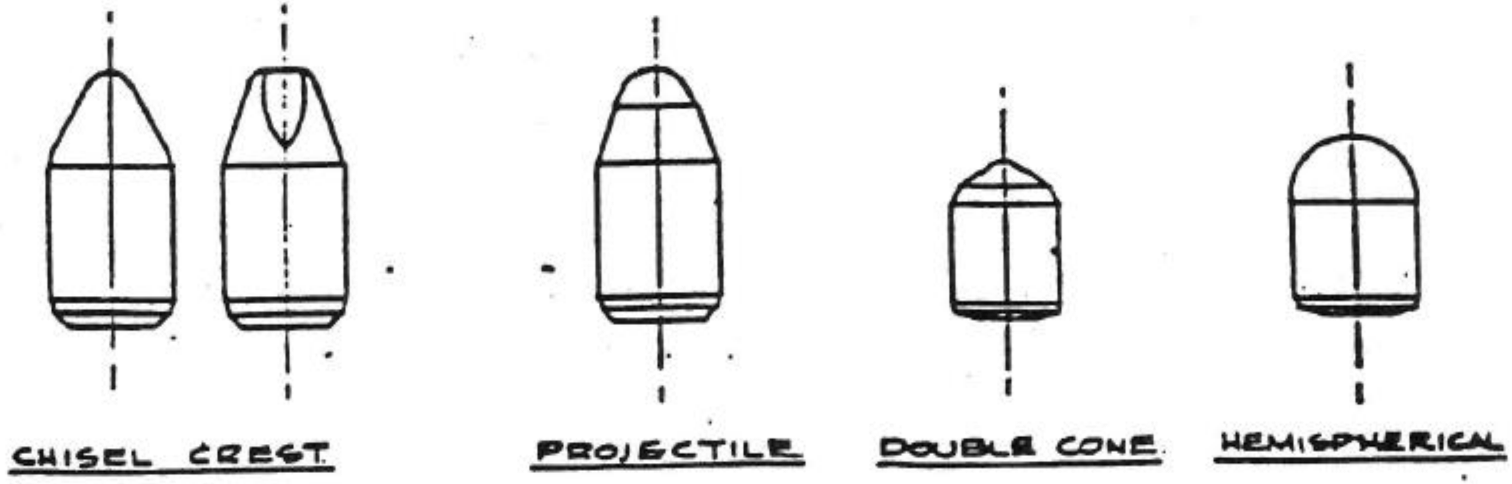


Fig. 9.1.54. (a) Kerf cutter (b) Pineapple cutter.

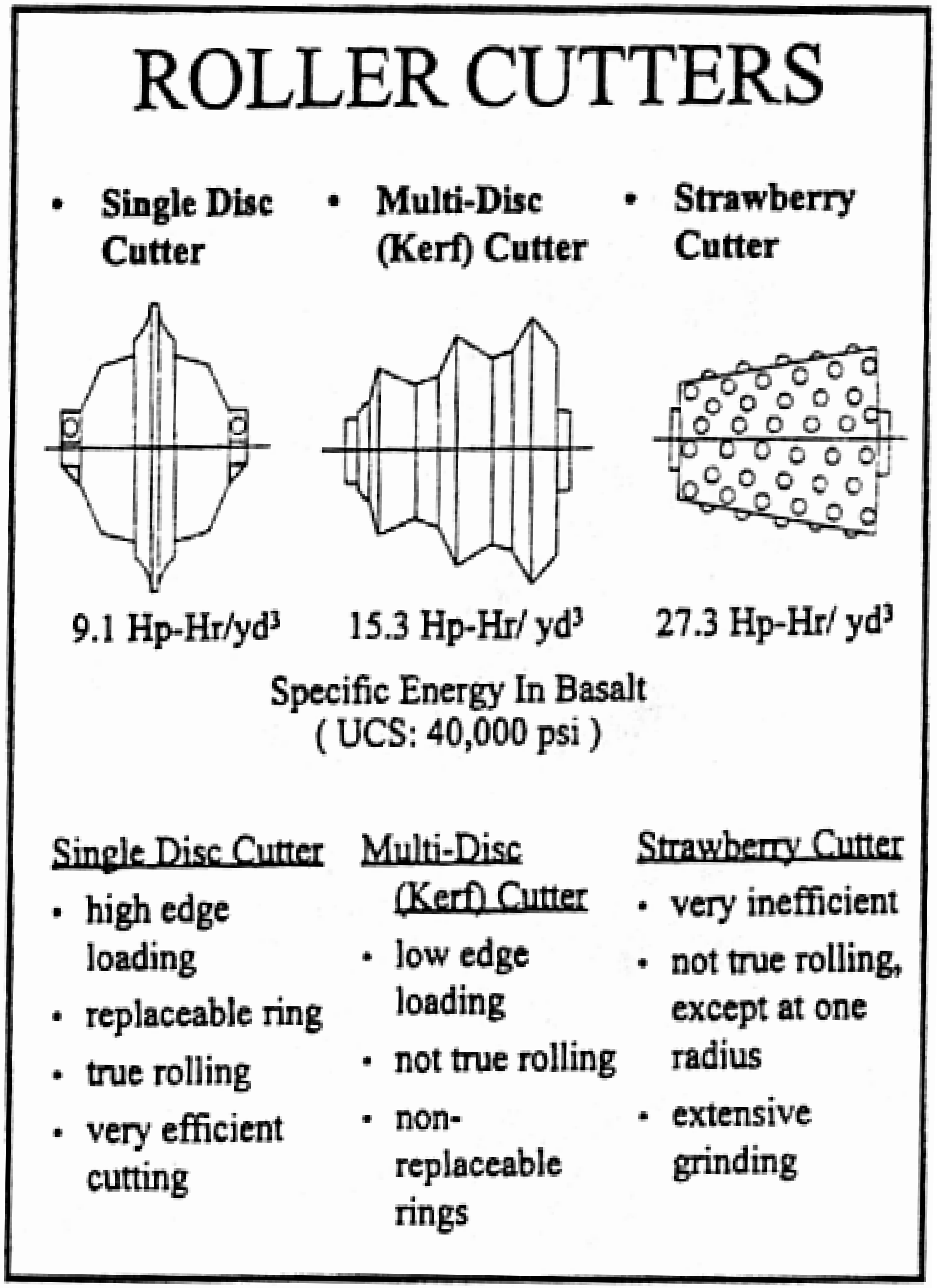
Button insert shapes



Button Cutting

- Thrust forces cause high stress concentrations beneath each button as they roll across the rock surface, resulting in local failure and pulverization of the rock.
- The area of influence of each button is small and results in a fine-grained product. Because the product size is small, specific energy requirements are high.
- Button cutting is used in applications in which high rock strength and abrasivity preclude the use of other methods.
- These cutters also find application as reaming cutters used for final profiling on RBMs and TBM.

Comparison of different free roller cutters



ROLLER CUTTERS

- **Single Disc Cutter**
- **Multi-Disc (Kerf) Cutter**
- **Strawberry Cutter**

9.1 Hp-Hr/yd^3 15.3 Hp-Hr/ yd^3 27.3 Hp-Hr/ yd^3

Specific Energy In Basalt
(UCS: 40,000 psi)

Single Disc Cutter

- high edge loading
- replaceable ring
- true rolling
- very efficient cutting

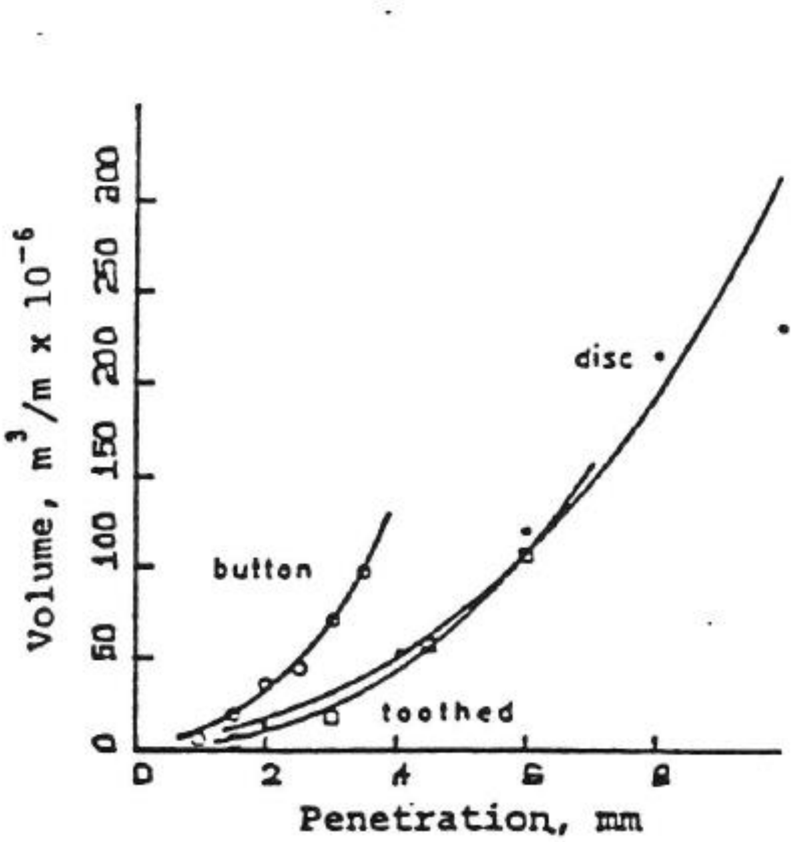
Multi-Disc (Kerf) Cutter

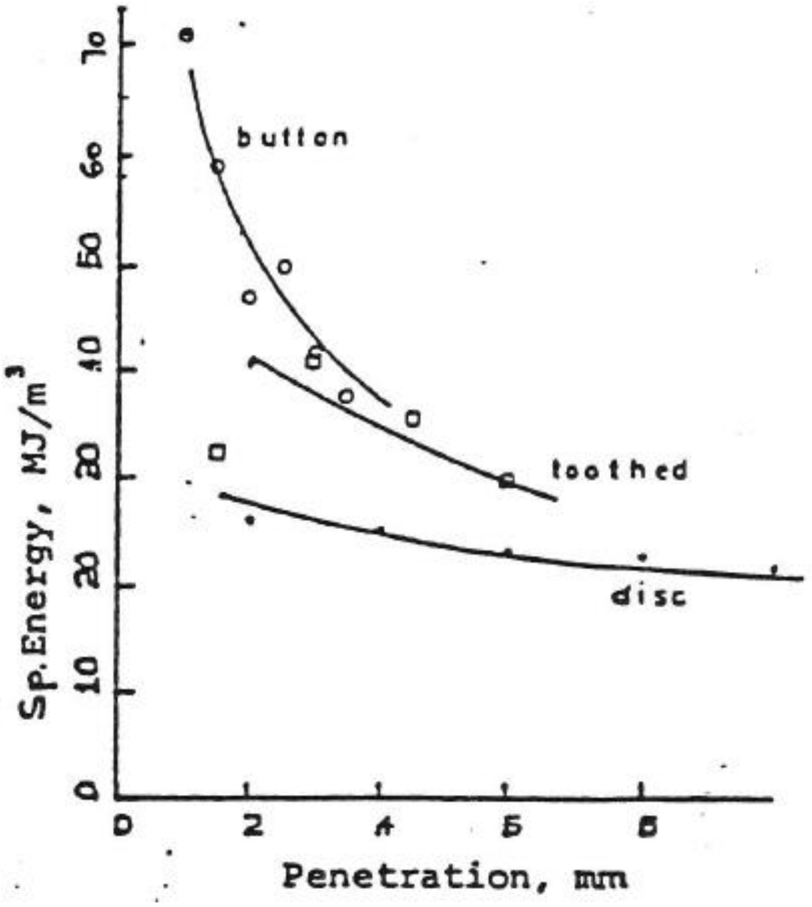
- low edge loading
- not true rolling
- non-replaceable rings

Strawberry Cutter

- very inefficient
- not true rolling, except at one radius
- extensive grinding

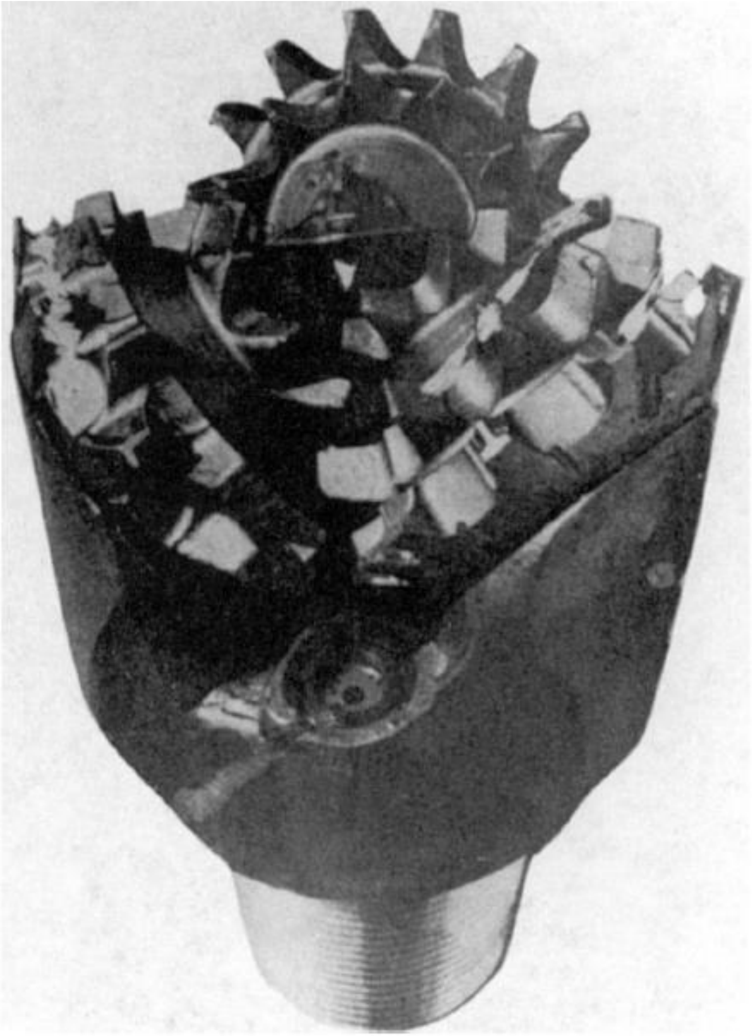
Comparison of different free roller cutters



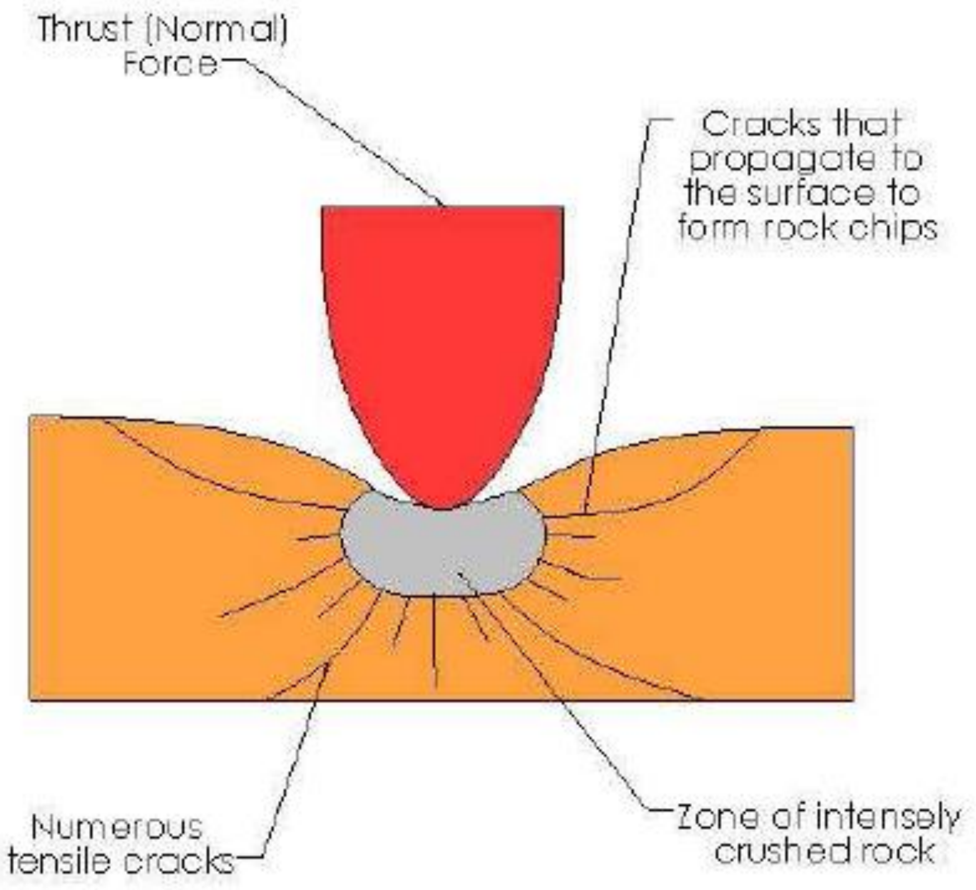


Roller or Mill Tooth Cutting

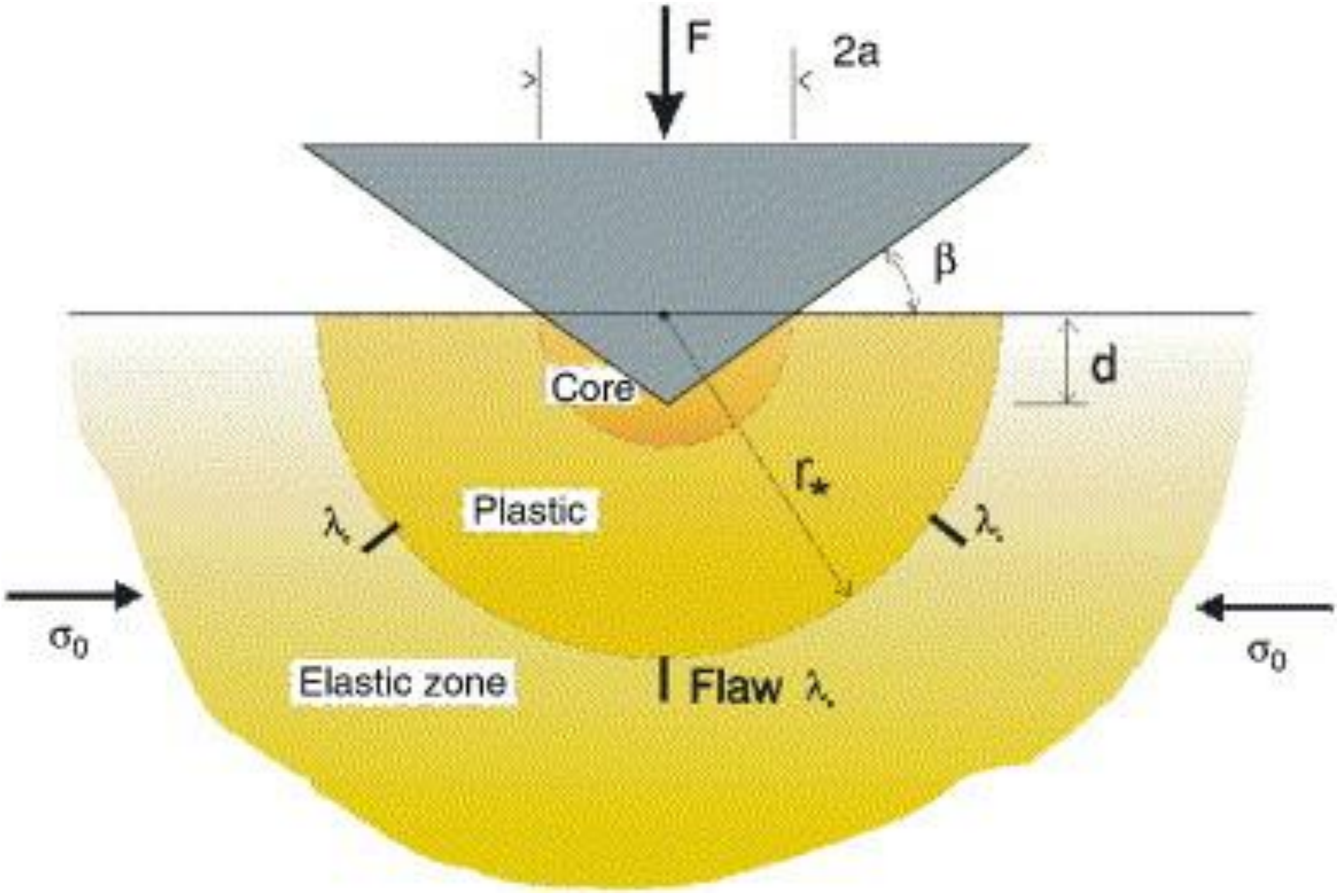
- Roller or mill-tooth cutting is similar to disk cutting except that instead of a tapered disc edge, the tool is equipped with circumferential teeth.
- As the cutter moves in response to rolling forces, each tooth in turn is pushed into the rock, acting like a wedge, and causing local failure.



Breakage action of indenter



Failure mechanisms under the cutter edge



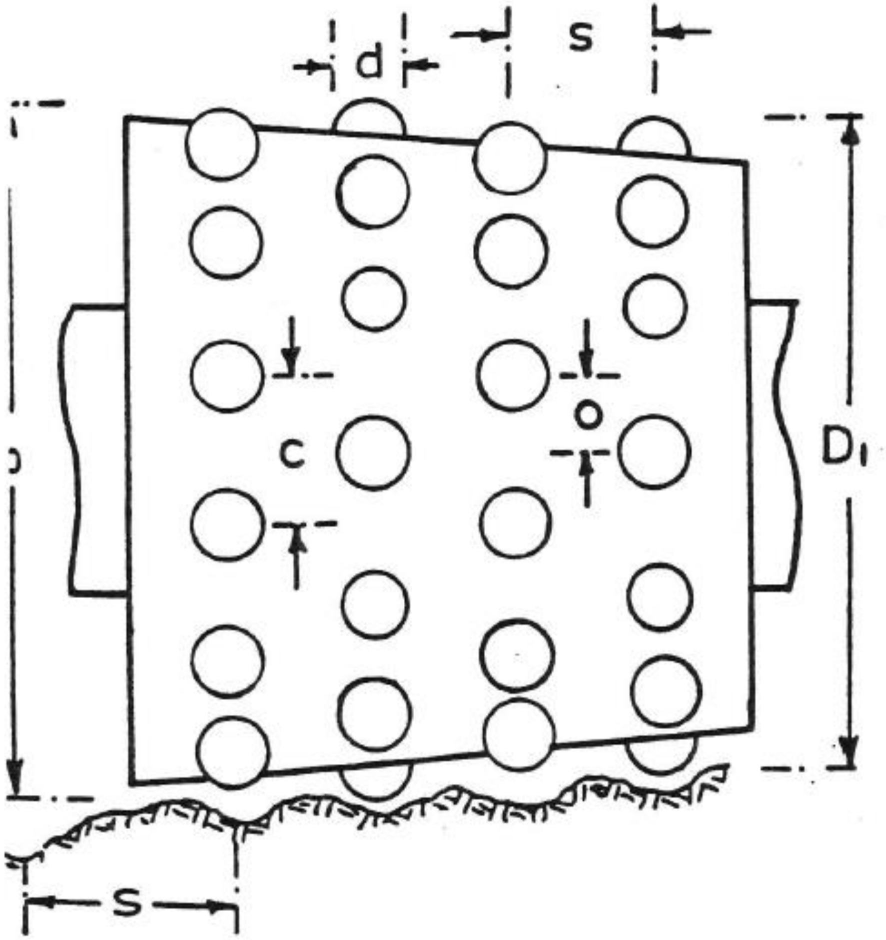
Button cutter variables

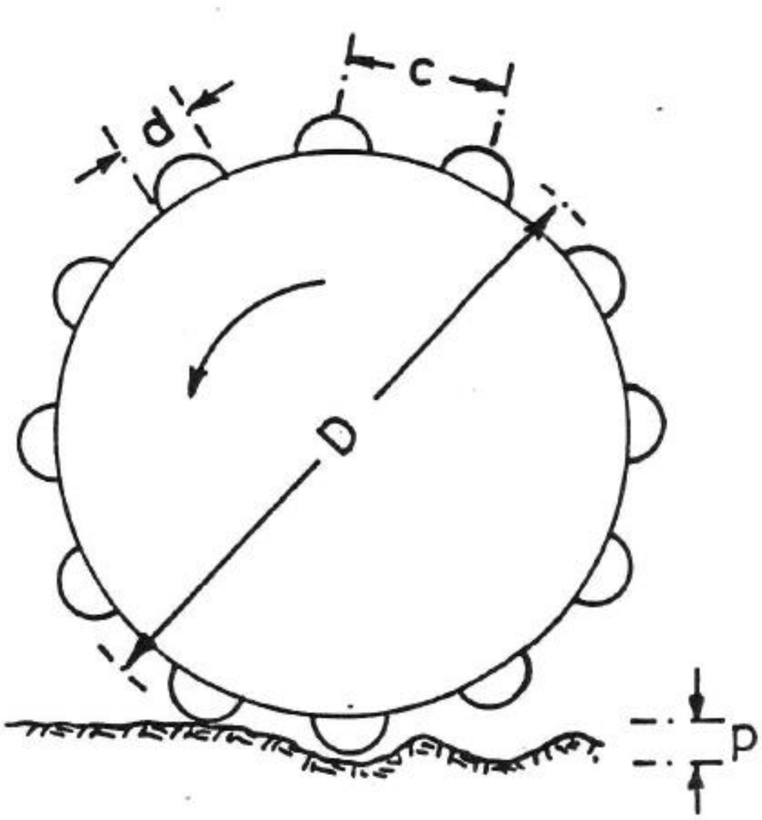
- Cutter diameter (D)
- Button diameter (d), including button shape
- Pitch (c), the separation of buttons in the same row.
- Spacing (s), the separation of adjacent rows of buttons
- Offset (o), the displacement of individual buttons between adjacent rows.

Also:

- Depth of penetration (p)
- Rock strength
- Cutting speed (v)

Button cutter variables





Contact geometry

- The number of buttons engaging the rock face at any instant varies according to the relative radial positions on the cutter of the buttons making contact, also button diameter, cutter diameter, pitch and depth of penetration.

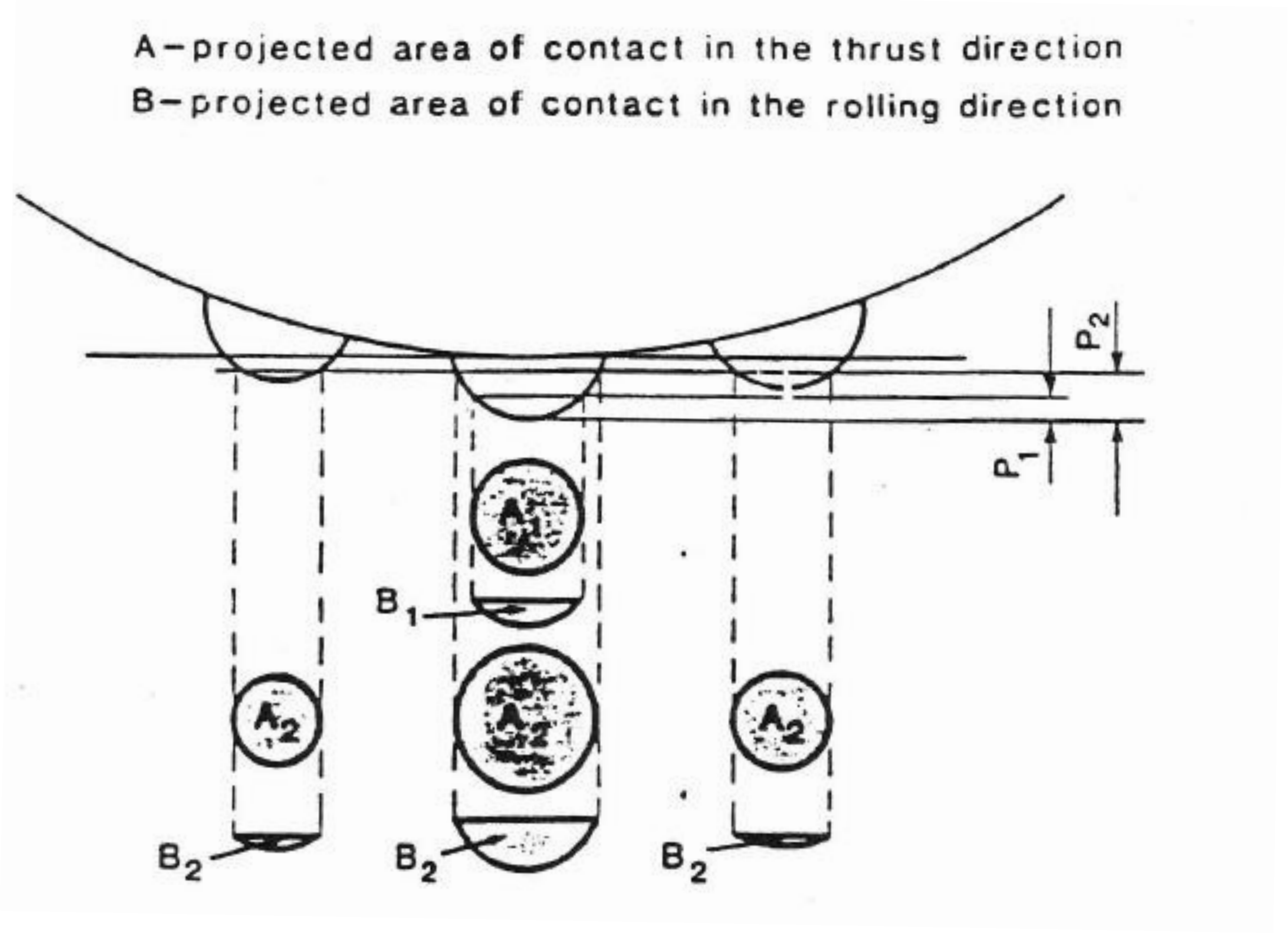
- As the cutter rolls across the rock surface, its buttons sequentially and progressively move into the rock surface, reach maximum penetration and then exit.

Contact geometry

- This leads to a periodicity in the forces generated by a button cutter. A uniform cyclic pattern in the tractive (i.e. rolling) force diagram has been observed for a button cutter.

- It was found that its frequency matched the pitch of the buttons and also the periodicity to decline when the pitch was reduced (more buttons coming into simultaneous contact with the rock).

Contact geometry



A – projected area of contact in the thrust direction

B – projected area of contact in the rolling direction

Notes

- Few systematic research has been undertaken on button cutters. Other than modelling the penetration of indenters into a rock surface, no cohesive theoretical description has been found to describe the behaviour of button cutters.
- Given the complex interaction of variables at play, it is a system that is very difficult, if not impossible, to parallel in mathematical terms.
- The development of button cutters has remained very much the province of the equipment manufacturers and most of the information gained by them from laboratory testing and field trails with new designs and different materials remains confidential.

Lab studies with button cutters

- Maximum penetration (p_1), being the depth immediately beneath of each button, increases with thrust force at all values of pitch.

$$F_T \propto p_1^{\,a}$$

- Where: $a>1.0$

Lab studies with button cutters

(Takaoka 1973)

- For a given thrust force (F_T), maximum penetration reduces with increasing button pitch.
- Minimum penetration (p_0), occurs midway between adjacent buttons (at half pitch), also increases with thrust force.

$$F_T \propto p_0^{\,b}$$

- Where: b<1.0

Thrust force-penetration curve

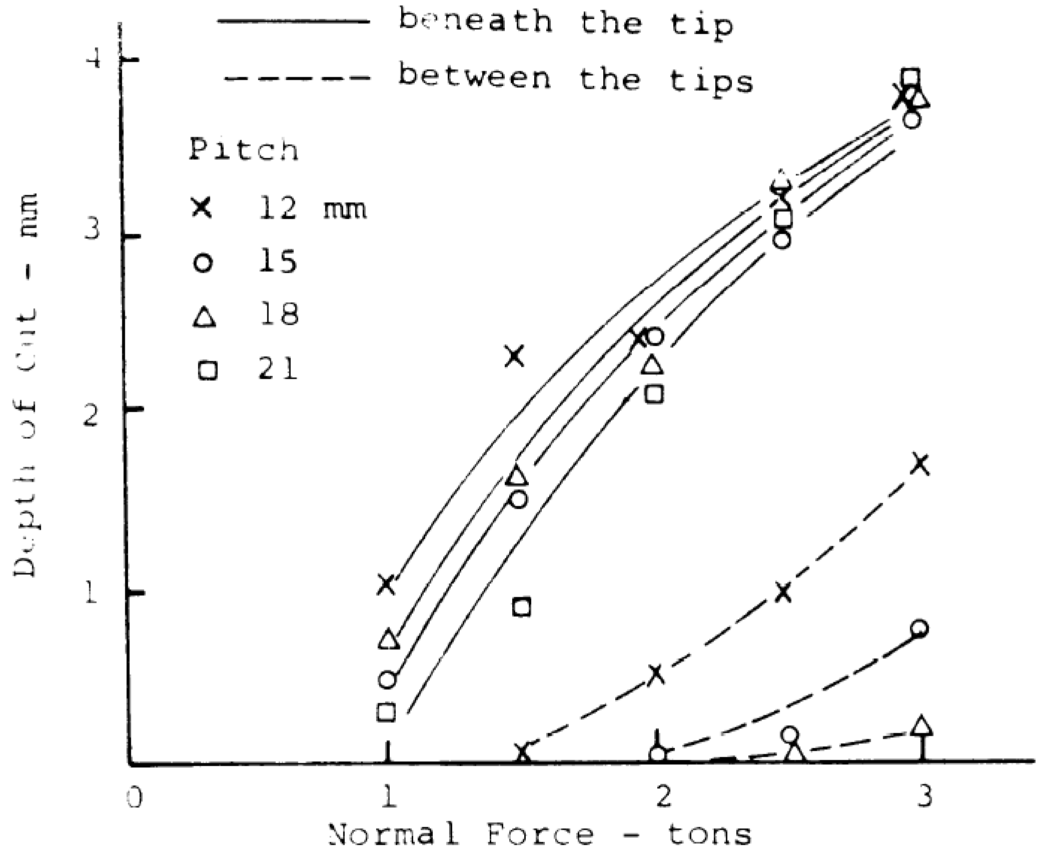


Fig. 9.1.38. Relation between thrust force and groove depth (after Takaoka et al., 1973).

Lab studies with button cutters

- It can be deduced from some data that there is no interaction between adjacent buttons when the pitch/penetration ratio exceeds about 6.

- Takaoka (1973) made corresponding measurements of crater width (w) produced by the buttons. The results suggest that:
    1. Maximum width w_1 *increases with thrust force* F_T *is* similar fashion to maximum depth p_1.
    2. For a given thrust force, maximum width appears to increase only marginally with decreasing button pitch
    3. Minimum width w_0 *increases with thrust force in similar* fashion to minimum depth and is clearly affected by button pitch

Lab studies with button cutters

- Groove width was found to be linearly related to penetration depth and to independent of button pitch. Therefore:

$$Q \propto p^{2}$$

Where: Q is volume of cut groove

p is the depth of cut groove

- Then

$$Q \propto F_T^{2}$$

Rolling force vs. Normal force

- Takaoka and his co-workers also report values for rolling force F_R, which increase linearly with thrust force F_T. The peak F_R/F_T ratio ranges from about 1/15 to 1/10 according to thrust force and pitch and, thereby, according to penetration.

Rolling force vs. Normal force

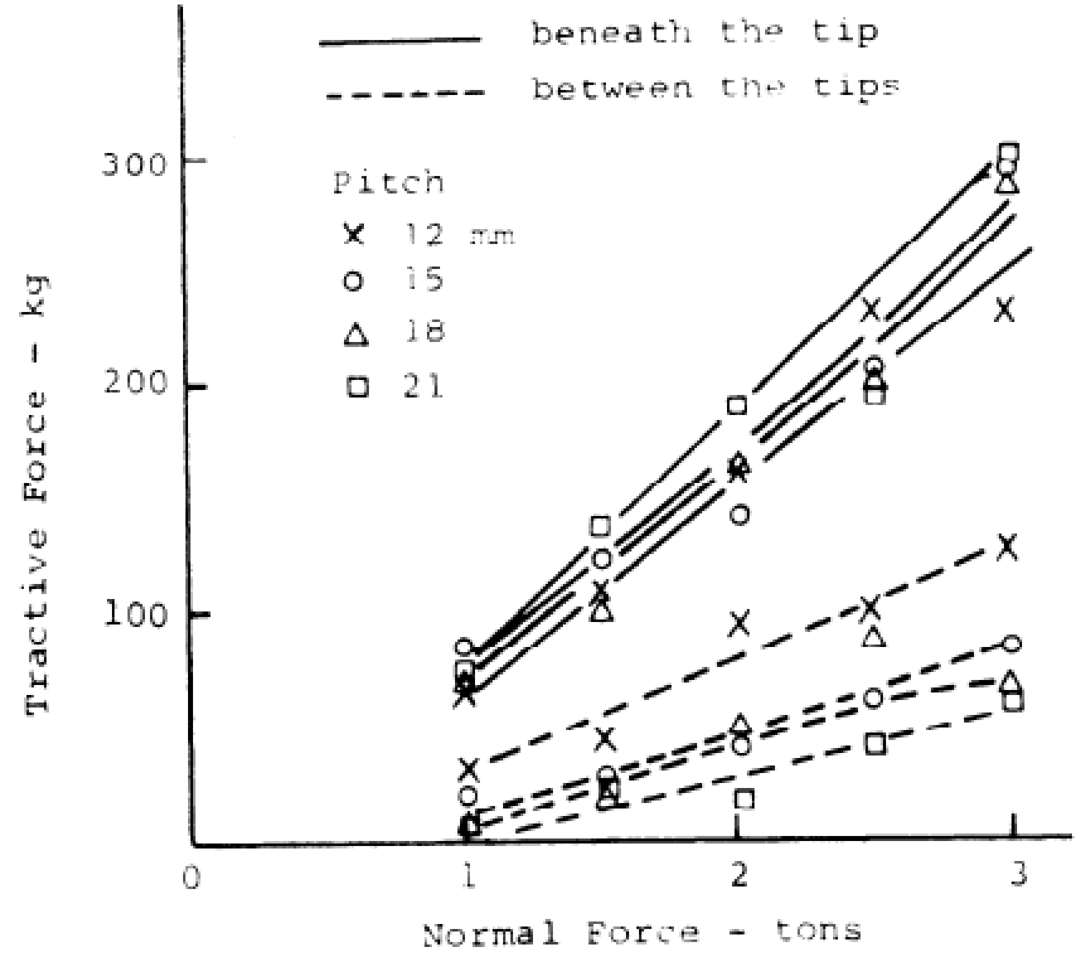


Fig. 9.1.39. Relation between normal and tractive forces (after Takaoka et al., 1973).

Effect of penetration depth

- Thrust force (F_T) for all cutters in each rock, increased with penetration (p) according to the relation

$$F_T = A + Bp^a$$

- Where the value of the constants A and B depend on the rock type and cutter geometry and the exponent a>1.0

Effect of penetration depth

- The corresponding rolling force (F_R) increased with penetration (p) according to the relation

$$F_R = Cp^b$$

Where constant C depends on the rock type and cutter geometry.

Effect of penetration depth

- Rock strength has a major effect on force levels. Both F_T and F_R to increase roughly in proportion to any of the basic measures of rock strength.
- The ratio of F_R/F_T to increase sharply with increasing penetration in each rock types. The trend is similar to that found with discs and toothed cutters.
- Rock yield increases with penetration (p)

$$Q = Ap^2$$

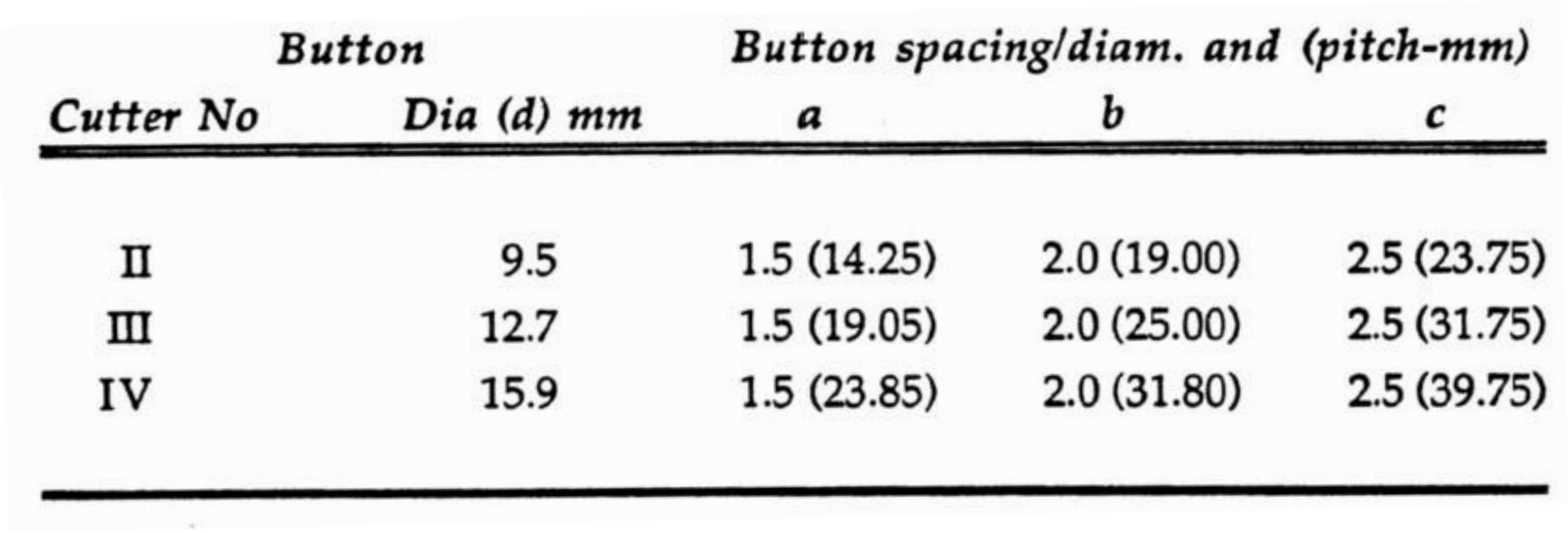
Effect of penetration depth

- The relation between specific energy (SE) and penetration (p) can be inferred by last two equations. Thus:

$$SE = \frac{F_R \cdot L}{Q \cdot L} = \frac{C \cdot p^b}{A \cdot p^2} = \frac{C \cdot p^{b-2}}{A}$$

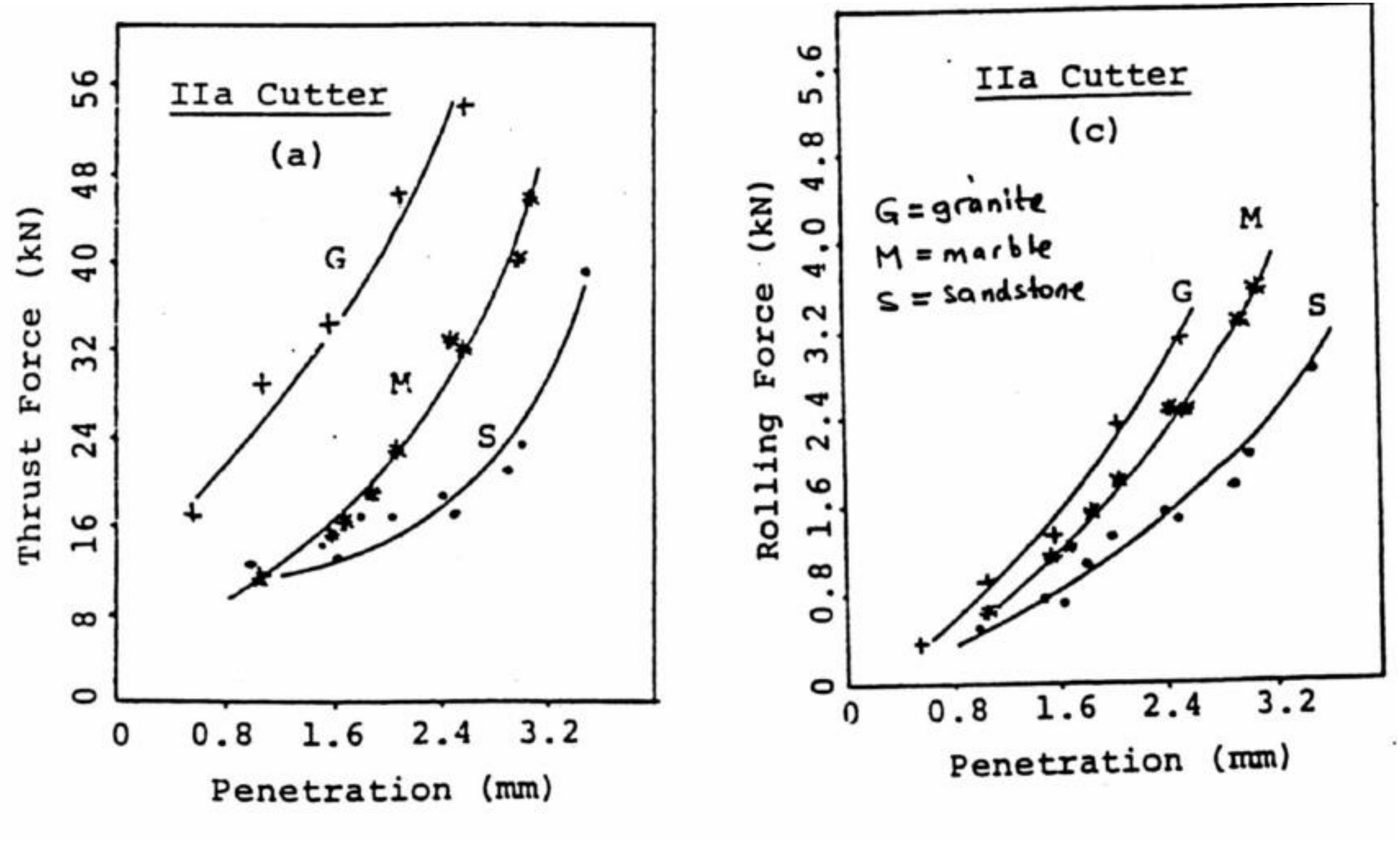
- If ‘b’ is 2, SE will not vary with penetration but all other physically admissible values for ‘b’ imply a reduction in specific energy with increasing depth.

Cutters geometry

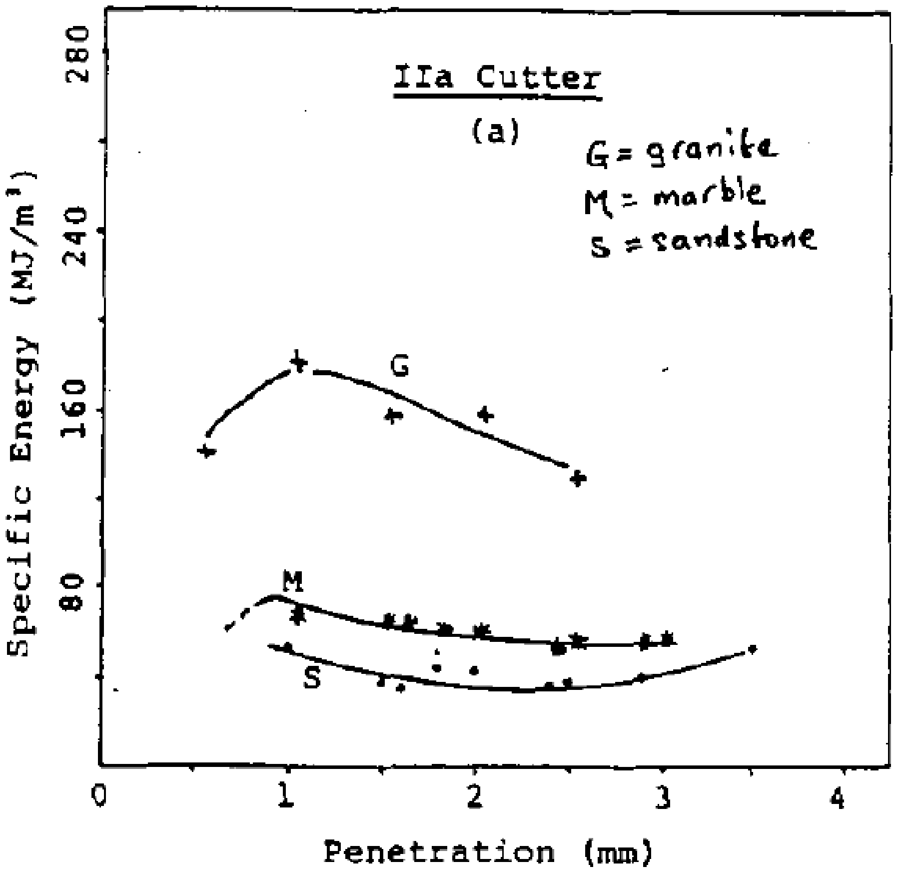


	Button	Button spacing/diam. and (pitch-mm)		
Cutter No	Dia (d) mm	a	b	c
II	9.5	1.5 (14.25)	2.0 (19.00)	2.5 (23.75)
III	12.7	1.5 (19.05)	2.0 (25.00)	2.5 (31.75)
IV	15.9	1.5 (23.85)	2.0 (31.80)	2.5 (39.75)

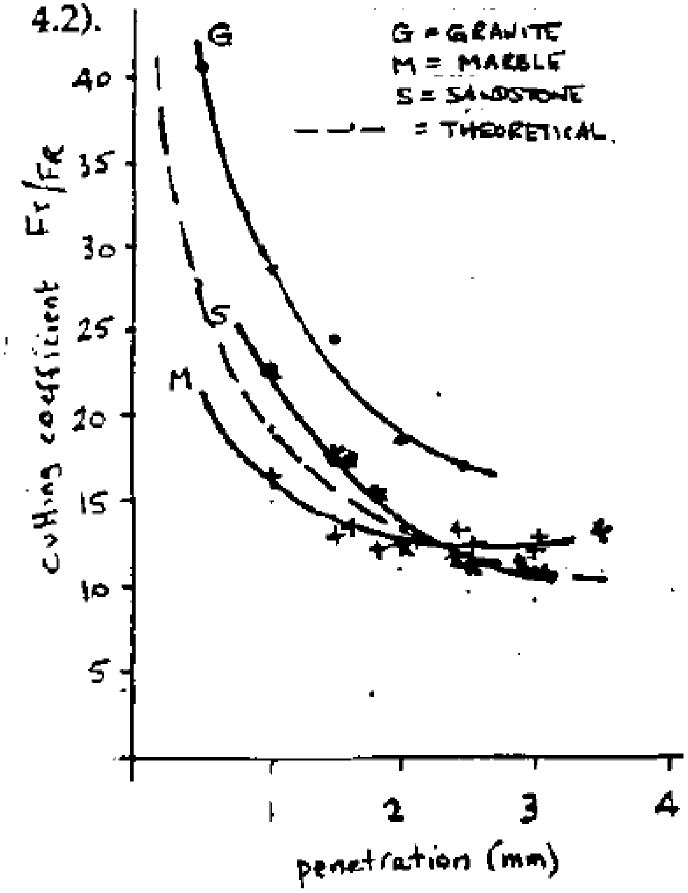
Effect of penetration on thrust and rolling forces

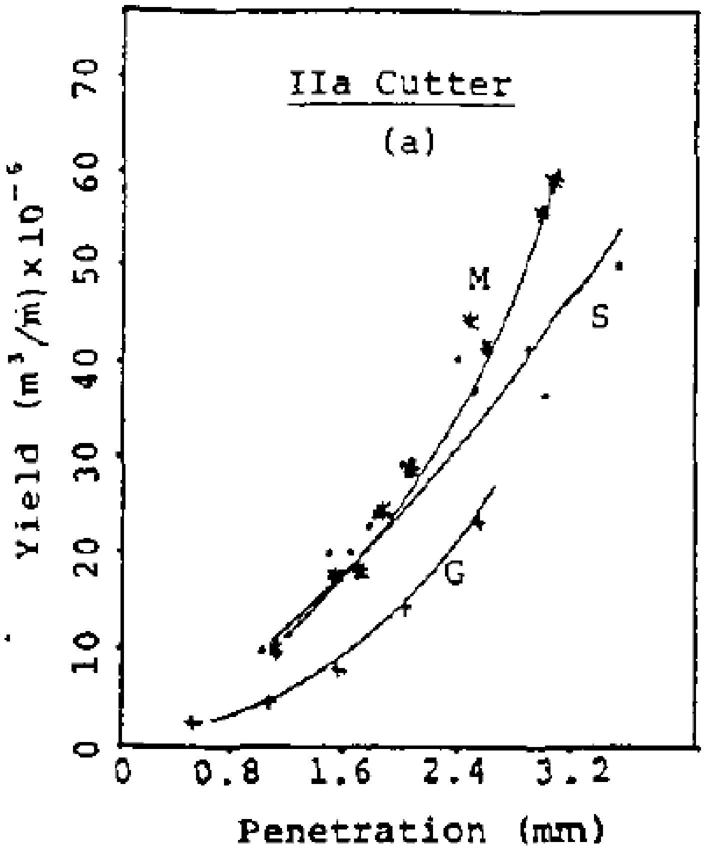


Variation in specific energy with penetration

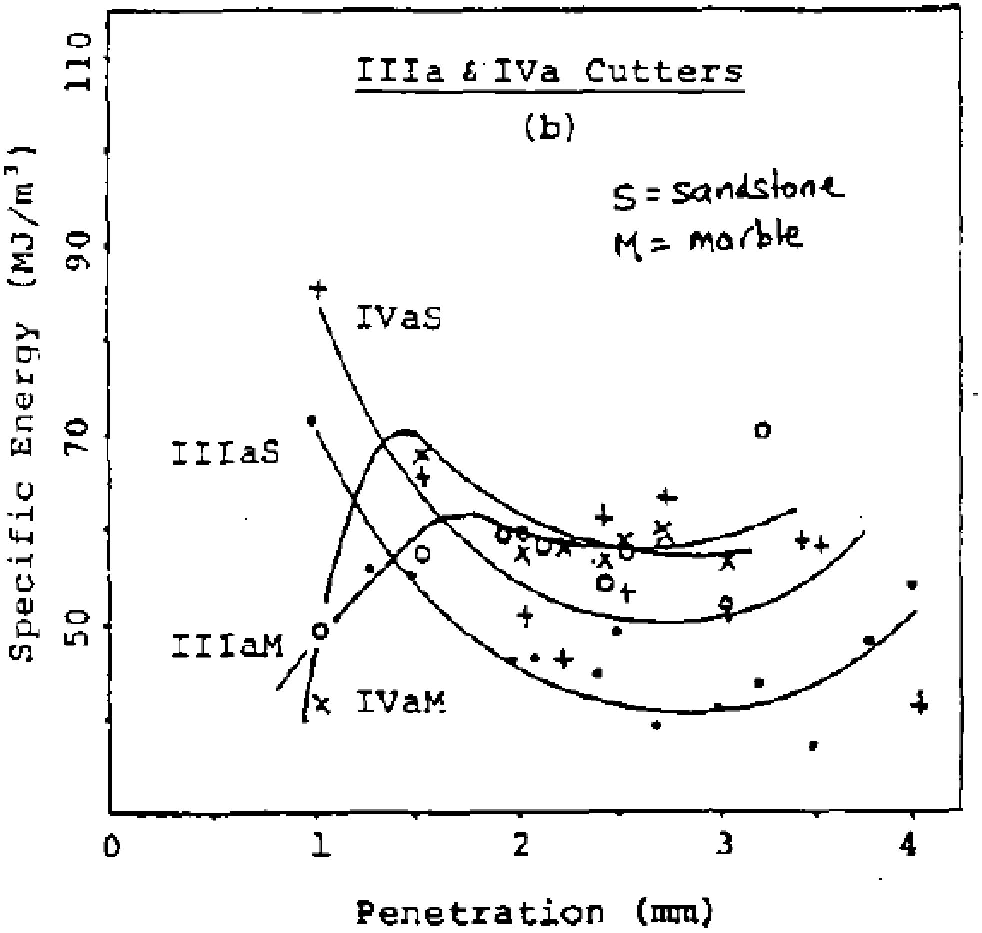


Effect of penetration on Ft/Fr and rock yield

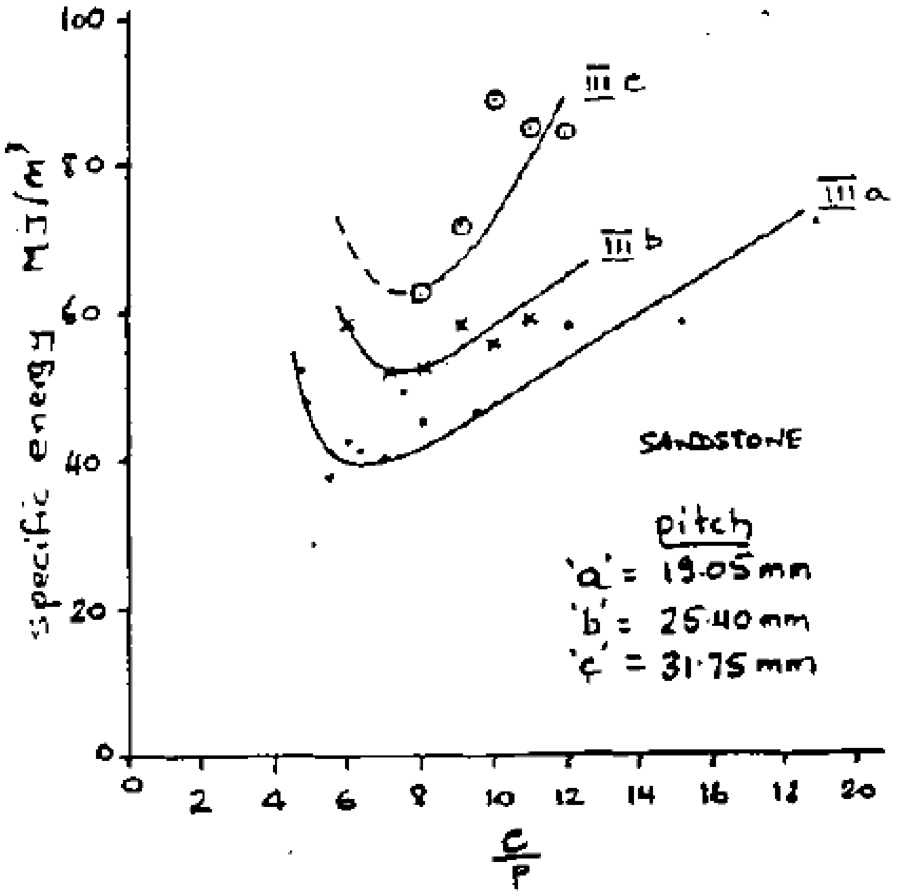




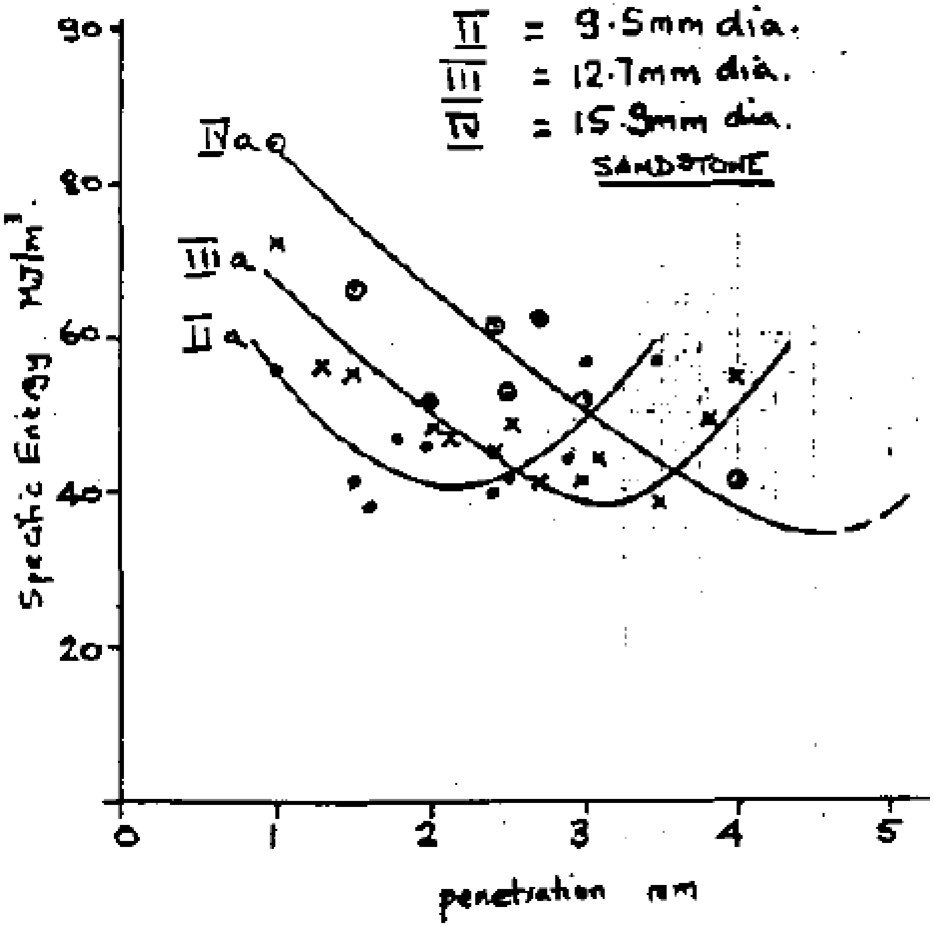
Effect of penetration on specific energy



Effect of pitch-penetration ratio on specific energy



Effect of button diameter on specific energy



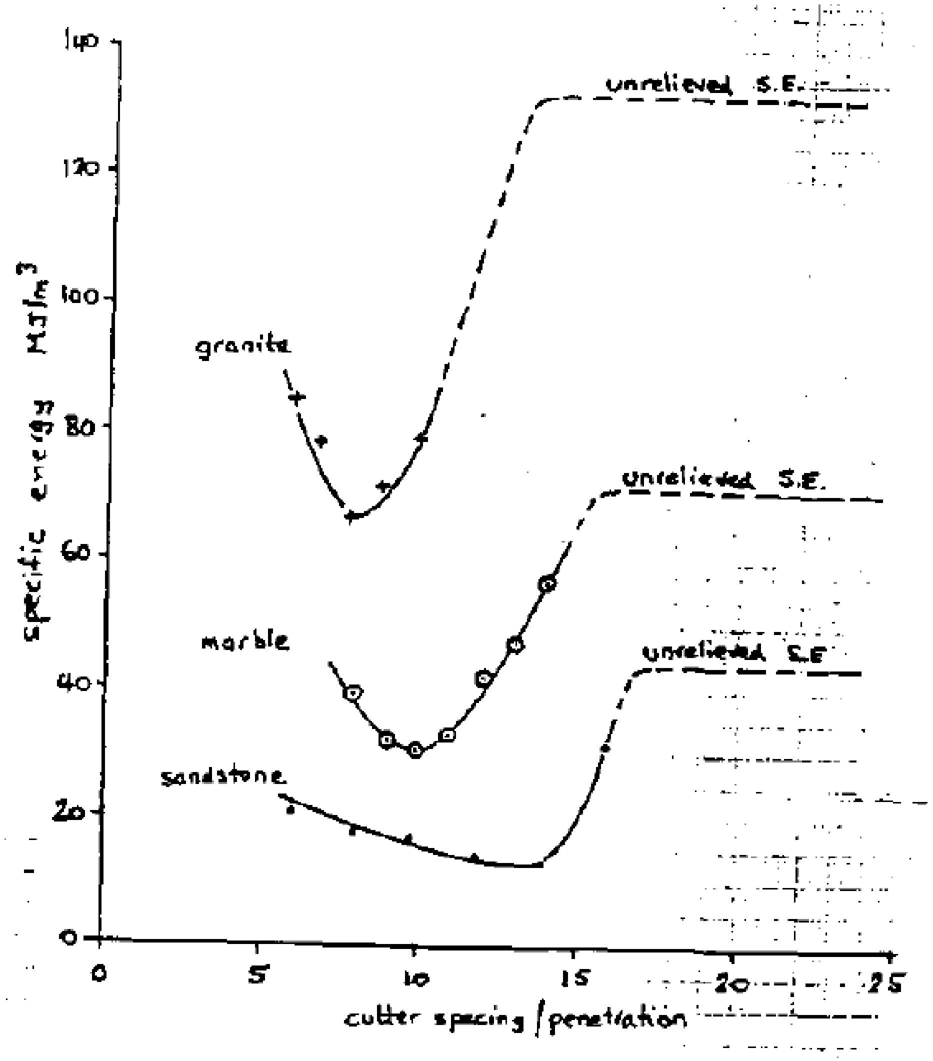
Effect of Button cutter design variables

- There is a depth of penetration at which specific energy is minimized at each button diameter.
- This optimum penetration increases with button diameter.
- Below optimum penetrations, larger button involve higher specific energy. But the minimum specific energy might reduce with increasing button diameter.

The spacing of parallel cutters

- The results of effect of cutter spacing clearly show an identifiable minimum specific energy. At higher s/p ratios, specific energy increases and is presumed to plateau at value equal to the corresponding unrelieved specific energy.

Effect of cutter spacing on specific energy



Multiple pass cutting

- In general, the level of both F_T and F_R to achieve a given penetration depth, increases with incremental size.
- The efficiency of the groove deepening process depends on the increment size and cutter spacing. If the same total volume of rock was cut in each case, the most efficient way would be the use of wider cutter spacing and the largest increment size.

Multiple pass cutting

- The cutting speed has no effect on either the forces involved in cutting with buttons, or in the specific energy requirements (consistent with other mechanical cutter).
- The presence of crushed rock in the groove will reduce around 15 to 20 % of cutter forces and about 25 % of the specific energy.
- In this mode, button cutters appear to be only marginally less efficient than discs.

Field experiments with button cutters (Fenn et al.,1981)(Robbins 61R raise borer)

- The forces on individual cutters are high and fluctuate widely.
- Average peak forces are typically 2 times the mean but single peaks are from 3-4 times the mean.
- Gauge cutters can be subject to extremely large dynamic forces with single peak values occasionally reaching 10 times the mean.

Field experiments with button cutters (Fenn et al.,1981)(Robbins 61R raise borer)

- The magnitude of the thrust and rolling forces with discs and button cutters are very much the same. Also their respective peak-mean force ratios (dynamic factor) are of the same order.
- Thrust and rolling forces for both types of cutter were found to vary with radial position of the cutter head. Thrust force decreases approximately linearly with cutter radial position. Conversely, rolling force increase linearly with cutter radial position.

Summary of button cutter performance

- Button cutters are intrinsically less efficient than other forms of free rolling cutter such as disc.
- The principal forces acting on a button cutter increase roughly in proportion to rock strength.
- Both thrust force, F_T, and rolling force, F_R , increase with depth of penetration (p), the general relationship being of the form:

$$F_T = A + Bp^{a} \qquad F_R = C + Dp^{b}$$

Where A, B, C and D are constants and exponents a and b>1.

Summary of button cutter performance

- The cutting coefficient for button cutters increases with increasing penetration depth in similar fashion to disc cutters. As with disc cutters, there is no evidence that the average Cc ratio is or should be affected by any variable other than cutter diameter D and penetration P.
- The dynamic factor (peak/mean force ratio) can be high, with values commonly in the range 2-4 and occasionally reaching 10. There is strong evidence to suggest that the dynamic factor reduces with increasing penetration.

Summary of button cutter performance

- Cutting speed, within reasonable practical ranges, evidently has no effect on the forces and energies involved with button cutters.
- This absence of speed effect is the same as is commonly found with other forms of mechanical cutter.
- The volume of rock produced by a button cutter increases approximately as the square of penetration depth.

Summary of button cutter performance

- The effect of penetration depth on button cutter efficiency (specific energy) is less clear than with other types of cutter. There is consistent evidence of a general reduction in specific energy with increasing penetration.
- But there is additional evidence that penetration depth may be reached beyond which specific energy increase. This behaviour is consistent with the existence of an optimum depth for button interaction.

Summary of button cutter performance

- There is an optimum pitch–penetration ratio for button interaction which for a small range of rocks has been found to vary from 4 to 10.
- Thrust and rolling forces increase with button diameter. For geometrically similar cutters, the penetration needed for button interaction increases with button diameter. Such proportionately larger scales of cutting involve much higher cutter forces but overall may be more energy efficient.

Summary of button cutter performance

- The lateral spacing for effective interaction between a row of buttons and an adjacent precut groove can be high. The spacing/penetration ratio for maximum lateral interaction is up two times the ratio for interaction between adjacent buttons that are being simultaneously loaded. Lateral interactions have been found to occur at spacing–penetration ratios up to 14.

Summary of button cutter performance

- Widely spaced cutter tracks requiring repeated passes of a cutter to achieve interaction is at least as energy efficient as more closely spaced single pass interactive cutting and may be significantly more efficient depending on the extent of rock debris recomapction.
- About 20 percent of the energy input in button cutting is expended in the recompaction of fine broken material under the cutter. A further 10 percent or thereabouts is dissipated as elastic energy.