PART I

SYNOPSIS

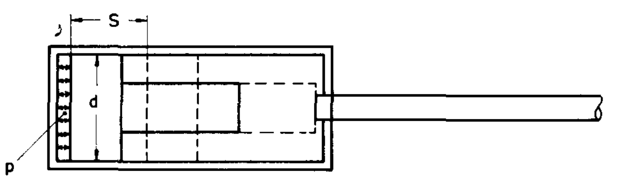
A theory is presented providing a concise mathematical description of the performance of a percussive rockdrill in terms of its principal mechanical dimensions. The theory defines the relationships between the values of thrust required to produce optimum rates of penetration at different throttle air pressures in terms of the piston areas and derives an equation for the prediction of these rates. An analysis of drillsteel life and bit wear is also made.

THE THEORY OF PERCUSSIVE ROCKDRILL OPERATION

As an aid to the interpretation of the experimental data, it is of interest to present the basic equations describing the operation of a percussive rockdrill. These equations, developed originally by Pfleider and Lacabanne,[1] will be presented in some detail.

Blow frequency

Consider the simplified percussive machine shown in Fig 1.



where S = piston stroke (ins)
d = piston diameter (ins)
p = applied air pressure (psi)

Fig 1 Diagram of a simplified percussive rockdrill

Assuming that (i) the piston is initially at rest when air at pressure p is admitted to the cylinder and that (ii) the pressure p remains constant during the stroke, the time t_1 required for the forward stroke becomes

$$t_1=\sqrt{\frac{SW}{6pAg}}, \qquad (1)$$

where W=weight of piston with rifle nut (lb)
A=area of piston head (in^2)
g=acceleration of gravity (ft/sec^2)
t_1=time of forward stroke (sec).

Assuming that the actual time taken for the piston to move from the front to the rear of the cylinder is K_1t_1 and that the time for which the piston is at rest is given by K_2t_1, the blow frequency f is given by

$$f=\frac{60}{1+K_1+K_2}\sqrt{\frac{6pAg}{SW}}, \qquad (2)$$

where f=blow frequency (blows/minute).

Pfleider and Lacabanne[1] assumed that K_2 is equal to zero, so that equation (2) becomes

$$f=\frac{60}{1+K_1}\sqrt{\frac{6pAg}{SW}}. \qquad (3)$$

From the stroke measurements made by Cheetham and Inett[2] it was found that the time required for the movement backwards is similar to that for the movement forward, so that equation (3) becomes

$$f=30\sqrt{\frac{6pAg}{SW}}. \qquad (4a)$$

Cheetham and Inett[2] found, however, that K_2 was not equal to zero as assumed by Pfleider and Lacabanne but rather that $K_2 \simeq 1$, so that equation (2) becomes

$$f=20\sqrt{\frac{6pAg}{SW}}. \qquad (4b)$$

The actual blow frequency $\bar{f}$ probably lies between these two values.

$$\bar{f}=K_o\sqrt{\frac{6pAg}{SW}}. \quad 20 \leqslant K_o \leqslant 30 \qquad (5)$$

Piston impact velocity and blow energy

Assuming that the pressure p remains constant over the entire stroke, the velocity at which the piston impacts the end of the drill steel is given by

$$V_s=\sqrt{\frac{SpAg}{6W}}, \qquad (6)$$

where V_s= piston impact velocity (ft/sec).

To allow for behaviour which departs from the above assumption, equation (6) should be written in the more general form

$$V_s=\beta_o\sqrt{\frac{SpAg}{6W}}, \qquad (6a)$$

where β_0=constant.

Combining equations (5) and (6a) gives

$$V_s=\frac{S\beta_o}{6K_o}\bar{f}. \qquad (7)$$

Ditson[3] found empirically that

$$V_s=\frac{S}{185}\bar{f}. \qquad (8)$$

The impact energy of the piston E_i is given by

$$E_i=\frac{1}{2}\,\frac{W}{g}V_s^2, \qquad (9)$$

where E_i=impact energy (ft/lb).

Combining equations (6a) and (9) gives

$$E_i=\frac{pAS\beta_o^2}{12}. \qquad (10)$$

Thrust requirements

Thus far in the discussion no mention has been made of the thrust requirements in rockdrilling. Recently Hustrulid[4] has shown that the thrust, F_t, required to ensure that the bit and rock are in contact when the impact wave arrives at their interface is given by

$$F_t=\frac{\bar{f}}{30}(1+\beta)\int_0^{\tau}\sigma_i\,dt\ , \qquad (11)$$

where σ_i=incident stress (longitudinal wave) as a function of time (psi)
τ=duration of incident wave (sec)
β=coefficient of momentum transfer from drill steel to piston, normally $0\leqslant\beta\leqslant.2$
F_t=minimum required thrust (lb)

This may be simplified to

$$F_t=\frac{\bar{f}}{30}(1+\beta)\frac{WV_s}{g}\ . \qquad (12)$$

The combination of equations (5), (6a) and (12) yields

$$F_t=\frac{K_o}{30}\beta_o(1+\beta)pA\ , \qquad (13)$$

which can be simplified to

$$F_t=\alpha pA\ , \qquad (14)$$

$$\text{where } \alpha=\frac{K_o\beta_o(1+\beta)}{30} \qquad (14a)$$

Prediction of penetration rate

It has been shown[6] that the penetration rate for a particular machine-bit-rock combination can be expressed approximately by

$$PR=\frac{12E_i\times\bar{f}\times T_R}{A_H\times E_V}\ , \qquad (15)$$

where T_R=coefficient of energy transfer from the drill steel to the rock
A_H=area of hole drilled (in^2)
E_V=specific energy value for the particular bit-rock combination (in lb/in^3).

Normally
$T_R\simeq 0{,}8$
$E_V\simeq C_0$ (uniaxial compressive strength of the rock), and these approximations will be used for the purposes of further analysis.

Combining equations (5), (10) and (15) shows the dependence of penetration rate on machine geometry.

$$PR=\frac{K_o\times T_R}{A_H\times E_V}\left[\frac{6Sg}{W}(PA)^3\right]^{\frac{1}{2}}\beta_o{}^2\ . \qquad (16)$$

Equations (14) and (16) can now be used to predict and compare penetration rates with the thrusts required, as shown in the following examples.

Example 1:

A comparison between the rates of penetration and the required thrusts for drills operating at the same air pressure in the same rock.

Penetration rate ratio:

$$\frac{PR_1}{PR_2}=\left(\frac{S_1}{S_2}\,\frac{W_2}{W_1}\right)^{\frac{1}{2}}\left(\frac{A_1}{A_2}\right)^{\frac{3}{2}}$$

Thrust ratio:

$$\frac{F_{t1}}{F_{t2}}=\frac{A_1}{A_2}$$

It has been assumed that the same values of the constants K_o, T_R and E_V apply to both machines.

Example 2:

Penetration rates and the required thrusts, when using identical machines to drill in two different rock types.

Penetration rate ratio:

$$\frac{PR_1}{PR_2}=\frac{E_{V2}}{E_{V1}}\simeq\frac{C_{o2}}{C_{o1}}\ .$$

Thrust ratio:

$$\frac{F_{t1}}{F_{t2}}=\left(\frac{1+\beta_1}{1+\beta_2}\right)\simeq 1\ .$$

Example 3:

Penetration rates and the required thrusts when using the same machine to drill the same rock with two different bit diameter.

Penetration rate ratio:

$$\frac{PR_1}{PR_2}=\frac{A_{H2}}{A_{H1}}$$

Thrust ratio:

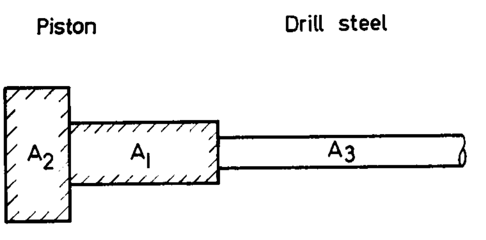
$$\frac{F_{t1}}{F_{t2}}=\frac{(1+\beta_1)}{(1+\beta_2)}\simeq 1\ .$$

It has been assumed that the values of T_R, β and E_V remain unchanged.

An important result that should be emphasized is that the thrust required for optimum drilling depends upon the particular drill and is essentially independent of rock type and bit diameter.

Drill steel life

The life of the drill steel depends on many factors. The most important of these are care in handling, drill



where A_1 = piston shank area (in^2)
A_2 = piston head area (in^2)
A_3 = drill steel cross-sectional area (in^2)
E_1 = Young's modulus of piston (psi)
E_2 = Young's modulus of drill steel (psi)
C_1 = Wave velocity in piston (in/sec)
C_2 = Wave velocity in drill steel (in/sec)
V_s = striking velocity of piston (ft/sec)

Fig 2 Diagram of a simplified piston and drill steel

steel material properties, percussive machine operation and peak magnitude of the stresses generated.

The first two factors are housekeeping and manufacturing responsibilities, and this paper will not be concerned with them. The latter two, however, will be discussed in some detail.

Consider the simplified diagram of a piston and drill steel shown in Fig 2.

The peak longitudinal stress generated in the drill steel by impact, assuming plane wave behaviour, can be shown to be given by

$$\sigma_p=\sigma_i\left[1+\frac{2}{\frac{A_3}{A_1}+\frac{E_1}{E_2}\frac{C}{C_1}}\left(\frac{A_2-A_1}{A_1+A_2}\right)\left(\frac{A_3}{A_1}\right)\right] \quad (17)$$

where

$$\sigma_i=\frac{12V_s}{C_1A_3/E_1A_1+C_2/E_2}, \quad (18)$$

σ_p=peak stress (psi).

Normally, however,

$C_1=C_2=C=2\times10^5$ in/sec (steel),

$E_1=E_2=E=30\times10^6$ lb/in^2 (steel).

Introducing these simplifications, equations (17) and (18) become

$$\sigma_p=\sigma_i\left[1+\frac{2A_3}{A_3+A_1}\left(\frac{A_2-A_1}{A_1+A_2}\right)\right], \quad (19)$$

$$\sigma_i=12\frac{E}{C}\left(\frac{A_1}{A_1+A_3}\right)\left(V_s\right). \quad (20)$$

The peak stress as a function of the piston impact velocity is presented for three pistons in Table 1 below.

TABLE 1

PEAK STRESSES CALCULATED FOR THREE DIFFERENT PISTONS

1. Impacting a 1in hexagonal drill steel

Rock-drill type	A_1 (in^2)	A_2 (in^2)	A_3* (in^2)	Peak stress lb/in^2
A	3,06	7,07	0,83	σ_p =1 658,88 V_s
B	1,77	6,49	0,83	σ_p =1 674,72 V_s
C	1,93	5,42	0,83	σ_p =1 615,68 V_s

*Corrected for water hole.

2. Impacting a 7/8 in hexagonal drill steel.

Rock-drill Type	A_1 (in^2)	A_2 (in^2)	A_3* (in^2)	Peak stress lb/in^2
A	3,06	7,07	0,55	σ_p =1 713,60 V_s
B	1,77	6,49	0,55	σ_p =1 748,16 V_s
C	1,93	5,42	0,55	σ_p =1 699,20 V_s

*Corrected for water hole.

Paul and Fu[5] presented the following relationship between drill steel life and the stress amplitude,

$$N=N_o e^{-\left(\frac{G_o\sigma}{E}\right)}, \quad \sigma_o\leqslant\sigma\leqslant\sigma_u, \quad (21)$$

where

N=fatigue life of drill steel (No of cycles)

N_o=material constant of drill steel (cycles)

G_o=non-dimensional material constant of drill steel

σ=stress amplitude in drill steel (lb/in^2)

σ_o=fatigue limit (lb/in^2), at which the fatigue life is indefinitely long

σ_u=ultimate strength of drill steel (psi).

Constants for two types of drill steel materials are given in the following table[5]:

TABLE 2

Material	G_o	N_o (10^6 cycles)
1 080 steel	1 420	60,7
Ni-Cr-Mo steel	2 300	22,2

When a piston impacts the end of the drill steel an incident wave having a certain amplitude travels towards the bit-rock interface. The shape and amplitude of the wave that is reflected back down the drill steel (away from the interface) depends on conditions at the interface. If bit and rock are not in contact when the wave arrives, a free-end reflection will result, as is shown in Fig 3. Successive incident and reflected waves will

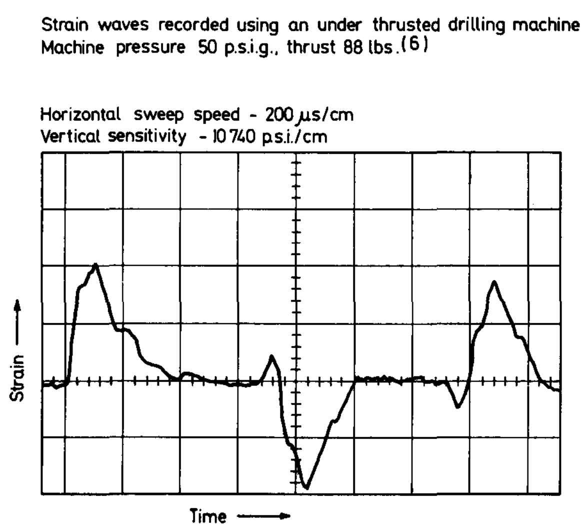


Fig 3 Strain waves recorded using an under-thrusted drilling machine

continue to be of nearly the same amplitude as the initial incident wave, decreasing only by hysteresis losses and dispersion, until bit-rock contact is established when quite rapid decrease in amplitude occurs. If bit and rock are in contact when the first incident wave arrives, the amplitude of the reflected wave will be much smaller that that of the incident wave, Fig 4. Because the fatigue life decreases exponentially with increasing peak-to-peak stress amplitude, it is important to keep the number of high-level stress reversals per blow to a minimum. As has been indicated, this minimum occurs when bit and rock are in contact each time a new blow

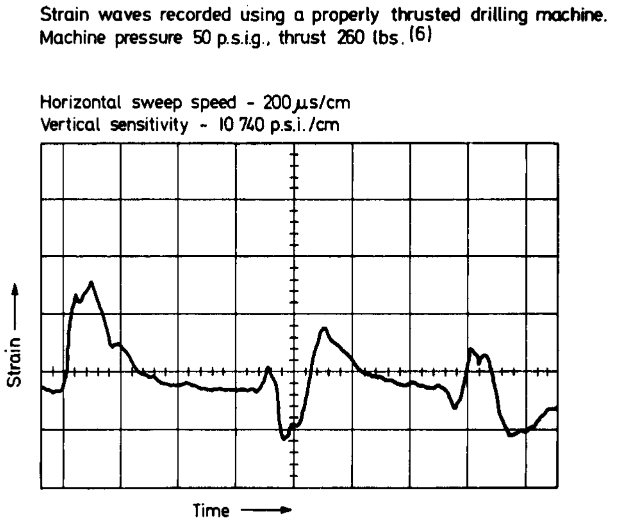


Fig 4 Strain waves recorded using a properly-thrusted drilling machine

arrives at their interface. The thrust force F_t necessary to ensure contact was presented earlier, equation (11). A typical curve for penetration rate as a function of thrust at a given machine pressure is shown in Fig 5.

If the applied thrust is F_1 rather than F_t, the penetration rate is approximately half that at optimum thrust. The machine, however, delivers the same amount of energy to the drillsteel irrespective of the thrust.

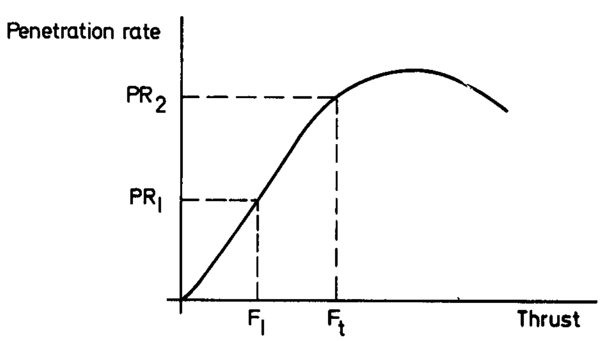


Fig 5 A typical thrust-penetration rate curve for a percussive rockdrill

This implies that when the thrust is too small the energy not then absorbed in penetration must be dissipated as heat through hysteresis losses in the drillsteel, requiring a large number of cycles of stress reversal. Assume that n of these cycles occur at high stress levels while under optimum conditions only one occurs per blow. For a system operating at half the required thrust, the average number of high level stress reversal cycles per blow is

$$N_1=\frac{n+1}{2}\,.$$

The life of a drill steel used at proper thrust is therefore $\frac{n+1}{2}$ times longer than when used at half the proper thrust. A typical value of n might be 5, which would suggest a decrease in drillsteel life by a factor of 3 when operated at half the optimum thrust. However, Paul and Fu[5] found that when drilling was conducted under corrosive conditions, such as when using mine water as a flushing medium, $\sigma_o=0$. In this case all stress cycles reduce the life of the drillsteel and the above analysis provides only guidance in this respect.

Drill steel life in terms of footage drilled is given by

$$T.F.=\frac{N\times PR}{12N_1\times\bar{f}}\,, \qquad (22)$$

where

$T.F.$ = drill steel life (ft)
PR = average penetration rate (in/min)
$\bar{f}$ = blow frequency (BPM)
N_1 = number of high stress level cycles per blow.

Bit wear

In the preceding analysis the question of bit wear has not been considered. The effect of bit wear is primarily to change the values of E_V, T_R and β. For any analysis of bit wear it must be assumed that wear takes place by abrasion rather than by chipping. In addition, it will be assumed that the volume of bit material removed is directly proportional to the volume of rock removed.

$$\frac{V_c}{V_{rock}}=\gamma \qquad (23)$$

where

V_c = volume bit material removed (in³)
V_{rock} = volume of rock removed (in³)
γ = constant.

The value of γ will be determined, firstly, by the properties of the bit material and the rock and, secondly, the bit configuration.

Rewriting equation (23) and differentiating with respect to time gives

$$\frac{dV_c}{dt}=\gamma\frac{dV_{rock}}{dt}\,. \qquad (24)$$

But,

$$V_{rock}=A_H\times L\,. \qquad (25)$$

where

A_H = hole area (in²)
L = total length of hole drilled (in).

Substituting equation (25) in equation (24) yields

$$\frac{dV_c}{dt}=\gamma A_H\times PR\,, \qquad (26)$$

where

$\frac{dV_c}{dt}$ = rate at which bit material wears (in³/min).

The total amount of bit material removed during the drilling of a hole of depth L is

$$V_c=\gamma A_H L. \qquad (27)$$

If a chisel bit having an included angle of 2θ degrees as shown in Fig 6 is used, the flat width, W_o, in terms of total length of hole drilled is

$$W_o=(\gamma\pi d_h L\tan\theta)^{\frac{1}{2}}, \qquad (28)$$

where

d_h = hole diameter.

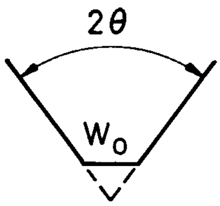


Fig 6 Chisel bit configuration

Sufficient information in not presently available to describe the changes in the values of E_V, T_R and β which occur as a result of this wear.

Gauge wear of bits is a very important consideration in percussion drilling. An analysis similar to that suggested for tip wear can be used. Rewriting equation (23) gives

$$V_c=\gamma V_{edge} \quad \ldots \ldots \ldots \ldots \quad (29)$$

Now the volume of rock removed is contained in a circular ring having a triangular cross-section around the bottom edge of the hole, Fig 7a.

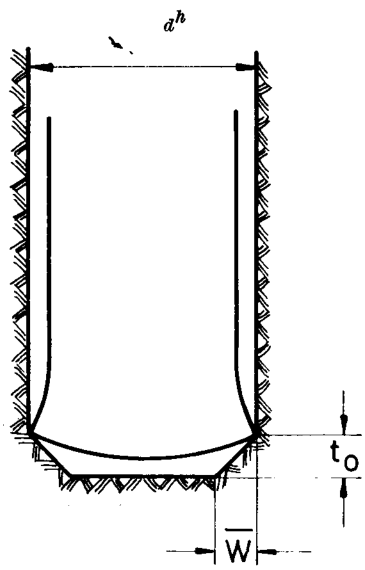


Fig 7a Diagram showing the effects of gauge wear of a bit leaving a ring of rock with a triangular cross-section, $\overline{w}\times t_o$

More energy is required to remove this rock than that near the centre of the hole, because of the confining effect of the rock surrounding the edge of the hole. Before the entire bit contacts the hole bottom, the bit edges must cut through this ring of rock. From experiment it has been observed that the width and length of the triangular cross-section are very similar, $\overline{W}\approx t_o$. Further $\overline{W}$ is found to be both nearly independent of hole size and related to the penetration depth per blow.

Assume that the bit edge makes an angle of ϕ with the axis of the drillsteel, as shown in Fig 7b.

The volume of bit material removed as a function of one half of the decrease in gauge, $\overline{d}$, is given by

$$V_c=\frac{1}{2}\,\frac{d^{-3}\tan\theta}{\cos\phi\sin^2\theta} \quad \ldots \ldots \ldots \ldots \quad (30)$$

The percentage of the total volume of the hole that must be removed by the bit edges is given by

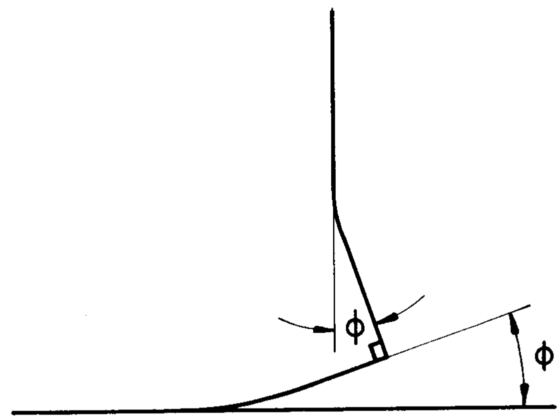


Fig 7b Diagram showing the angles between the edge of the bit and axis of the drillsteel and the bottom of the hole

$$\frac{V_{edge}}{V_{hole}}=(d_h\overline{W}-\overline{W}^2)/d_h^{\,2}\,, \quad \ldots \ldots \ldots \ldots \quad (31)$$

because

$$V_{hole}=\frac{\pi d_h^{\,2} L}{4}$$

and

$$V_{edge}=\pi(d_h\overline{W}-\overline{W}^2)\,L\,. \quad \ldots \ldots \ldots \ldots \quad (32)$$

Equations (29), (30) and (32) give

$$\frac{\overline{d}^3\tan\theta}{\cos\phi\sin^2\phi}=\gamma\pi(d_h\overline{W}-\overline{W}^2)\,L\,, \quad \ldots \ldots \quad (33)$$

which can be rewritten as

$$\overline{d}=\left[2\pi\gamma\frac{\cos\phi\sin^2\phi}{\tan\theta}(d_h\overline{W}-\overline{W}^2)\right]^{\frac{1}{3}}(L)^{\frac{1}{3}} \quad \ldots \quad (34)$$

The bit gauge as a function of L becomes

$$\text{bit gauge}=d_h-4\left[\frac{\pi\gamma\cos\phi\sin^2\phi}{\tan\theta}(d_h\overline{W}-\overline{W}^2)\right]^{\frac{1}{3}}L^{\frac{1}{3}} \quad \ldots \ldots \quad (35)$$

Equation (35) can be rewritten as

$$\text{bit gauge}=d_h-K'\,L^{\frac{1}{3}}, \quad \ldots \ldots \ldots \ldots \quad (36)$$

where

$$K'=4\left[\frac{\pi\gamma\cos\phi\sin^2\phi}{\tan\theta}(d_h\overline{W}-\overline{W}^2)\right]^{\frac{1}{3}}\,.$$

Work by Cook, Joughin and Wiebols 6 has shown that for tungsten carbide cutting quartzite the value of γ is $\gamma=4\times10^{-5}$.

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