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ROTARY PERCUSSION FORCES AFFECTING A DRILLING RATE OF BIT FOR ROCK MASS

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The drilling rate of rotary percussion drill bit depends on the revolving energy and the impact energy of drifter as well as the characteristics of rock mass. The rotary percussion drill tests were executed in-situ for 13 kinds of rock mass using 12 actual drill machines to clarify the interrelations between them. As the results, the drilling rate has been expressed as the function of the revolving energy, the impact energy, the bit diameter, the coefficient of crack of rock mass and the Shore hardness or the amount of Los Angeles abrasion or the radial compressive strength of rock specimen. On the other hand, the rock mass properties could be determined by measuring the drilling rate of a standard rotary percussion drill machine.
Keywords : drilling rate, bit, rotary percussion, rock mass

1. INTRODUCTION

Nowadays, various kinds of rotary percussion drill machine are used mainly to drill holes into rock mass by means of the impact load and the torque acting simultaneously on the bit under the thrust.

The mechanism of rock failure due to rotary drilling is considered as shear or tensile failure of rock material due to the revolving excavation of drill bit, and the drilling rate of bit depends on the revolving work i.e. the product of rotation speed and torque. On the other hand, the mechanism of rock fracture due to percussion drilling is the dynamic shear or tensile failure due to the impact action of drill bit, and the amount of rock failure depends on the impact energy and the interval of blow. For the rotary percussion drilling machine supplying thrust, impact load and torque, the mechanism of rock fracture is the dynamic shear or tensile failure due to the impact action and the revolving excavation of drill bit, and the drilling rate depends on the impact and revolving energy under some interval of blow which is calculated from the rotation speed and the blow number per minute. Sofar, Tanaka et al.[1),2)] made a drop hammer test apparatus of maximum impact energy 19.1 Nm with maximum thrust 2.94 kN to test the influence of impact energy, thrust and interval of blow on the drilling rate and the efficiency of tungsten-carbide curb bit of $2\pi/3$ apex angle, 18 mm bit gauge. As results, they showed that the drilling rate of bit for limestone increases linearly in accordance with the thrust at rotary percussion drilling and it increases parabollically with 1.5 to 2.0

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powers of the impact energy, but it decreases with the increment of interval of blow i.e. rotation angle for each blow.

To increase the drilling rate of bit, large supply of impact energy would be more effective than increasing thrust or torque. At the same time, an optimum combination of blow number and rotation speed should be selected to get a small interval of blow which increases an impact energy per revolution, a torque and a rotation energy under a high thrust. Furthermore, to decrease a penetration energy per unit drilling length and to increase an efficiency of drilling, an optimum selection of thrust and interval of blow should be made under a constant drilling rate and an impact energy per one blow. From their drilling tests to limestone or sandstone, they also proposed that the interval of blow should be increased by decreasing the number of blow per revolution under the high thrust to get the maximum efficiency of drilling.

Here, 15 kinds of rotary percussion drill test were executed in-situ for the different combinations of rock mass and actual drill machine respectively to measure the drilling rate, the blow number per minute and the rotation speed of bit, and the thrust, the torque and the impact energy of drifter. To clarify the main factors affecting the drilling rate, the interrelations between revolving energy, impact energy, bit diameter, coefficient of crack of rock mass and some rock properties have been analysed. After that, an optimum combination of thrust and impact energy have been presented to get a maximum efficiency of drilling.

Furthermore, some methods to investigate the properties of rock mass would be proposed by measuring the drilling rate of bit of a standard rotary percussion drill machine.

2. ROCK AND ROCK MASS PROPERTIES

All rotary percussion drill tests were executed at several rock mass excavating sites, quarrying sites and stone pits. As the main physical properties of rock sampled at each site and

Table 1 Physical properties of rock sample and rock mass.

Site	Rock	* G	** H_s	*** V_1 (m/s)	† U(%)	†† σ_{co} (MPa)	††† σ_t (MPa)	△ V_2(m/s)	△△ C_r
A	Sandstone	2.59±0.01	84.9± 3.1	3201± 148	15.2	304.7 ±30.9	10.5± 1.8	560± 74	0.969
B	Shale	2.68±0.02	77.8± 3.1	3737± 150	23.0	164.6 ±16.3	8.6± 1.5	1934± 251	0.732
C	Limestone	2.70±0.01	63.6± 1.1	5773± 185	25.5	140.9 ±17.0	6.5± 0.7	1357± 294	0.945
D	Limestone	2.68±0.01	55.5± 1.7	5681± 154	25.5	85.8 ±20.0	7.2± 0.8	491± 120	0.993
E	Quartzite	2.56±0.02	90.3± 5.1	4011± 227	23.9	119.8 ±39.7	11.3± 3.7	738± 154	0.966
F	Granite	2.61±0.03	71.9± 4.1	2785± 392	40.9	39.7 ± 5.9	3.1± 1.8	394± 120	0.980
G	Andesite	2.57±0.01	74.0± 4.0	4041± 80	14.2	141.4 ±19.6	11.6± 1.5	3061± 920	0.426
H	Sandstone	2.61±0.01	84.0± 3.8	4271± 72	17.4	187.6 ±66.6	15.7± 1.9	1679± 530	0.845
I	Sandstone	2.62±0.01	76.9± 3.5	4982± 212	17.3	175.7 ±30.7	13.5± 1.3	2594± 225	0.729
J	Sandstone	2.62±0.03	82.4± 4.4	4737± 162	14.7	254.6 ±46.3	14.6± 2.4	1352± 204	0.919
K	Diabase	3.04±0.01	73.6± 5.1	6015± 204	21.0	186.5 ±34.1	15.8± 2.8	1964± 27	0.893
L	Sandstone	2.59±0.01	75.6± 3.1	4381± 99	26.2	179.3 ±21.6	8.8± 1.4	571± 92	0.983
M	Green schist	2.95±0.02	63.9± 3.1	4265± 173	28.3	122.3 ±43.5	19.3± 5.1	1084± 81	0.935

* Apparent specific gravity
** Shore hardness
*** Wave velocity for rock
† Abrasion
†† Compressive strength
††† Tensile strength
△ Wave velocity for rock mass
△△ Crack coefficient

the characteristics of rock mass, the apparent specific gravity G, the Shore hardness H_s, the longitudinal elastic wave velocity of non-fissured sample V_1, the amount of Los Angeles abrasion U, the uniaxial compressive strength σ_{co}, the radial compressive strength σ_t, the longitudinal elastic wave velocity of rock mass V_2 and the coefficient of crack of rock mass C_r are presented in **Table 1**.

13 kinds of rock mass from site A to site M are divided into sandstone, shale, limestone, quartzite, granite, andesite, diabase and green schist. On each site, several longitudinal elastic wave velocities were measured for different directions. And then, the average coefficient of crack of rock mass C_r has been calculated by use of the average longitudinal elastic wave velocity of rock mass V_2 and that of non-fissured rock sample V_1 as

$$C_r=1-\left(\frac{V_2}{V_1}\right)^2 \quad (1)$$

3. ACTUAL ROTARY PERCUSSION DRILL TEST

(1) Specification

Several drill tests were executed for 9 kinds of rock mass by use of various rotary percussion drill machines supplied with air pressure and for 4 kinds of rock mass by use of those supplied with oil pressure. **Table 2** shows the specifications of each drill machine and drill bit. Here, the impact energy per one blow of drifter supplied with air pressure has been calculated to be the product of cross section area of cylinder, piston stroke and air pressure[3]. The torque and the rotation speed were measured directly in-situ. For rotary percussion drill machine supplied with air pressure, the average ratios of air consumption used for impaction, rotation and air blow are 58, 21 and 21%.

(2) Drilling rate and rotary percussion forces

Among several drillabilities of rotary percussion drill machine, the most important drilling rate depends mainly on the thrust, the impact load and the torque which are supplied from drifter to drill bit.

Table 2 Specifications of rotary percussion drill machine.

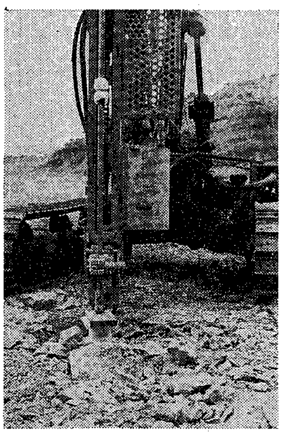
Site	Type of pressure	Cylinder diameter (cm)	Piston stroke (cm)	Air pressure (KPa)	Air consumption (m³/min)	Impact energy (Nm/blow)	Blow number N (blows/min)	Rotation speed R (r.p.m.)	Torque Q (Nm)	Drill bit D (mm)
A	Air	12.0	9.0	490	13.5	498.8	1600	0 ~ 180	———	Cross 65 φ
B	Air	9.5	9.0	490	6.4	312.6	1500	0 ~ 230	———	Curb 38 φ
C	Air	12.06	9.5	539 ~ 588	15 ~ 17	611.5	1400	0 ~ 250	———	Cross 60 φ
D	Oil	———	———	———	———	343.0	2300 ~ 2500	0 ~ 350	< 529.2	Cross 70 φ
E	Oil	———	———	———	———	343.0	2300 ~ 2500	0 ~ 350	< 529.2	Cross 70 φ
F	Air	13.0	10.0	490 ~ 588	20.0	715.4	1300	0 ~ 140	———	Cross 65 φ
G	Oil	———	———	———	———	294.0 ~ 333.2	2550 ~ 2850	0 ~ 300	< 431.2	Cross 65 φ
H	Air	12.06	9.5	490 ~ 588	13.5	584.9	1450	0 ~ 200	———	Cross 75 φ
I	Air	12.0	9.0	490	13.0	498.8	1300	———	———	Cross 65 φ
J	Air	12.0	8.9	490	13.5	493.2	1600	0 ~ 180	38.7 ± 4.4 *	Cross 65 φ
K	Air	10.2	8.5	490	10.0	340.3	1600	165 ± 20 *	75.5 ± 8.8 *	Cross 65 φ
L	Air	12.06	9.5	548.8	15.0	595.6	1400	137 *	63.2 ± 12.3 *	Cross 65 φ
M	Oil	———	———	———	———	343.0	2300 ~ 2500	162 ± 12 *	80.0 ± 16.5 *	Button 70 φ

* Measured value

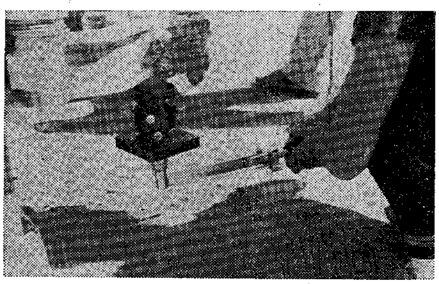
Here, the thrust and the impact load were measured at 9 kinds of rock mass drilling as the axial loads appling on the hexagon rod on which 2 semiconductor strain gauges were stuck at 1 m height. For the calibration, a load cell of 500 kN capacity were set under the drill bit to measure the relation between axial load and strain. In the same way, the torque appling on the hexagon rod was measured at 4 kinds of rock mass respectively by use of 4 semiconductor strain gauges. For the calibration, a torque cell of 100 Nm capacity were set on the drill bit. **Photo 1** shows the general view of calibration of axial load and torque. As an example, **Fig. 1** shows the variation of thrust, impact load and torque measured at site M. The thrust decreases at initial collaring and increases to be some value at the complete drilling state of the hole. The impact load supplied from drifter should be considered as the amplitude of incident and reflected strain waves propagated in the rod[4]. But it is not measured accurately because of the lack of following capacity of recorder. As results, the thrust and the torque at the completely stable drilling state under air blowing were measured respectively to be 9.51 ± 1.18 kN and 80.0 ± 16.5 Nm. As the rotation speed was measured to be 162 ± 12 r.p.m., the rotation work was calculated to be $(8.14 \pm 1.78) \times 10^4$ Nm/min. The nominal impact energy was calculated to be $(8.23 \pm 0.34) \times 10^5$ Nm/min. The drilling time was measured 5 times for 3 m length of drilling, and the drilling rate was calculated to be 223 ± 13 cm/min. **Table 3** shows the drilling rate, the thrust, the impact energy per minute and the rotation work per minute measured at each site. The thrust is controllable due to air pressure. So, the drilling rate at site A was verified to increase with the increment of thrust. Another drilling rates were measured under the usual air pressure. **Photo 2** (a), (b) shows a cross bit used here, and a general view of measurement of a drilling rate and rotary percussion forces acting on a drill bit.

(3) Considerations

First of all, the mechanism of rock fracture due to rotary percussion drilling should be considered. The drilling rate of bit due to pure rotary drill machine depends not only on the rock material, the



(a) Axial load



(b) Torque

Photo 1 A general view of calibration of axial load and torque.

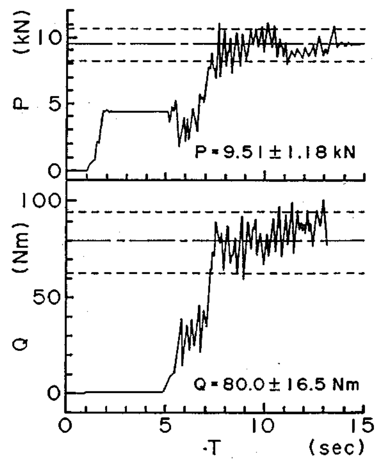
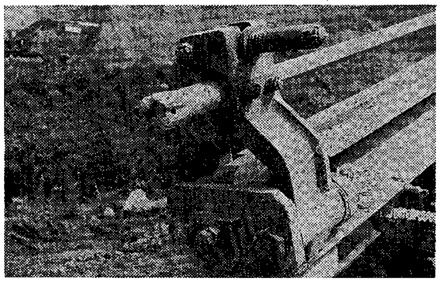


Fig. 1 Variations of axial load P (thrust and impact load) and torque Q applying on drill bit with time T. (Site M)

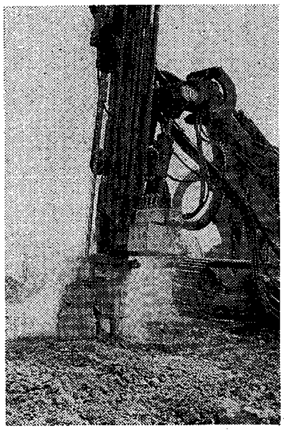
Table 3 Drilling rate and rotary percussion forces.

Site	Drilling rate V (cm/min)	Thrust P_a (kN)	Impact energy * E_d (Nm/min) ×10^5	Rotation work E_r (Nm/min) ×10^5
A	139.7 ± 5.3	4.57	7.09	——
	176.9 ±37.4	5.13		
	186.7 ±28.5	6.77		
B	90.9 ± 7.2	——	4.69	——
C	40.4 ± 8.4	——	8.56	——
D	76.3 ± 7.8	——	7.89 ~ 8.58	5.821 *
E	96.9 ± 9.2	——	7.89 ~ 8.58	5.821 *
F	97.6 ± 7.9	5.69	9.30	——
G	135.4 ± 3.9	9.80	7.55 ~ 9.51	4.067 *
H	46.8 ± 6.5	3.89	8.48	——
I	68.8 ±17.8	7.02	6.48	——
J	196.3 ±19.0	13.87	7.89	——
K	34.2 ± 0.6	10.51	5.45	0.783 ± 0.132
L	76.0 ± 7.9	7.25	8.34	0.544 ± 0.106
M	223.0 ±13.1	9.51	7.89 ~ 8.58	0.814 ± 0.178

* nominal catalogue data



(a) Cross bit



(b) Drilling

Photo 2 Cross bit, and measurement of drilling rate and rotary percussion forces.

bit shape, but also on the thrust and the rotation speed[5]. On the other hand, the amount of rock fracture due to percussion drilling depends on the impact load and the interval of blow. There is some optimum interval of blow to maximize the amount of rock fracture under an impact load, and it is necessary to supply an appropriate thrust on drill bit to increase an efficiency of percussion[6]. Therefore, for the rotary percussion drill machine supplying thrust, impact load and torque, the drilling rate of bit could be expressed as the function of the thrust, the impact energy and the rotation work per minute, and the interval of blow which is calculated from the rotation speed and the blow number per minute.

Here, it is necessary to consider the required energy per one revolution of bit and that per unit length of drilling under some interval of blow in rotary percussion drilling. **Fig. 2** shows a schematic model of bit locus for one revolution. Tanaka et al.[2] clarified that the drilling length d per one revolution decreases with the increment of interval of blow $2\pi R/N$ (Revolution speed R r.p.m. and number of blow N blows/min) for various thrusts. **Fig. 3**

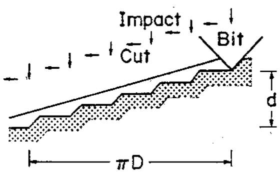


Fig. 2 Mechanism of rotary percussion drilling. (d : drilling length per one revolution, D : bit diameter)

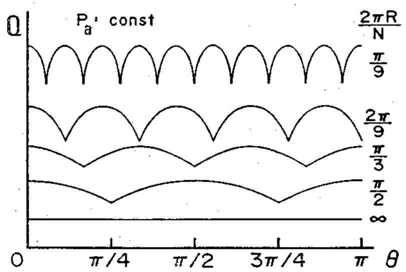


Fig. 3 Typical relations between torque Q acting on a bit and revolution angle θ for various interval of blow $2\pi R/N$ under a constant thrust P.

shows the typical variations of torque with revolution angle for various intervals of blow. The smaller interval of blow, the larger revolving work per one revolution which is calculated as an integration of the torque-revolving angle curve could be obtained. This revolving work consists of an energy which is required to shear a crater occurred after percussion, and a constant energy due to a static rotary cutting under a thrust. On the other hand, an impact energy per one revolution (Number of blow : N/R) is in inverse proportion to an interval of blow. Therefore, the energy "e" required per one revolution of bit under a constant thrust P_a decreases with the increment of interval of blow $2\pi R/N$, as shown in **Fig. 4**.

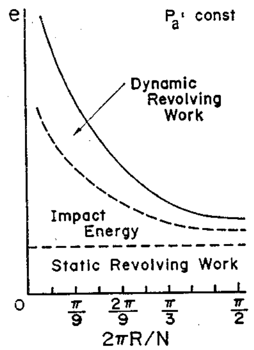


Fig. 4 Relation between energy e required per one revolution of bit and interval of blow $2\pi R/N$ under a constant thrust P.

Now, the required energy for R revolution per minute "R·e" is assumed to be expressed as a function of the maximum nominal impact energy E_d (Nm/min) and the revolving energy E_r (Nm/min);

$$R \cdot e = \alpha E_d^{\beta} E_r^{\gamma} \quad (2)$$

E_d is the product of impact energy per one blow and blow number N of bit during R revolutions and E_r is expressed as $2\pi RQ$ for the torque Q applying on bit. As shown in **Fig. 1**, the torque Q could be assumed to be proportional to the product of axial load P and bit diameter D. The coefficient of proportion μ is determined for the angle of shear resistance of a given rock material. Therefore, the revolving energy E_r could be expressed as,

$$E_r = 2\pi\mu RPD \quad (3)$$

Here, E_r means the total revolving energy including the static and dynamic revolving work. The larger thrust, the larger total revolving work could be obtained due to a high efficiency of propagation of impact energy, and the drilling rate would be increased[6]. To fracture the rock materials effectively, there is some optimum interval of blow, in which the required energy per unit drilling length Re/v reaches a minimum value. Tanaka et al. clarified that Re/v could be expressed as a parabolic function of $2\pi R/N$[2].

Generally, the drilling rate V' for some rock mass could be expressed as a function of the number of blow per one revolution N/R, the maximum nominal impact energy E_d supplied from drifter and the revolving energy E_r as follows;

$$V' = \frac{\alpha}{f(2\pi R/N)} E_d^{\beta} E_r^{\gamma} \quad (4)$$

Here, the interval of blow which minimizes this parabolic function $f(2\pi R/N)$ varies with the kind of rock mass. The exponents β and γ could be determined from actual rotary percussion drill test results by means of multi-regression analysis because E_d and E_r are independent variables each other.

And the influences of rock mass characteristics on the drilling rate of bit of actual rotary percussion drill machine are assumed to be presented as a function of coefficient of crack of rock mass, Shore hardness, amount of Los Angeles abrasion and radial compressive strength of rock specimens as reported previously[7],[8].

Considering the efficiency of propagation K of impact energy and revolving work, the drilling rate V of bit of actual rotary percussion drill machine could be expressed as,

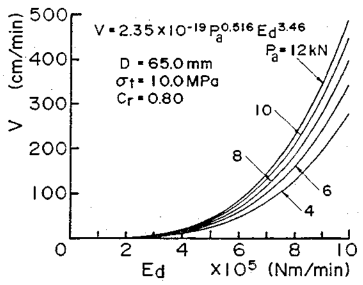


Fig. 5 Relations between drilling rate V and nominal impact energy E_d for various thrust P_a.

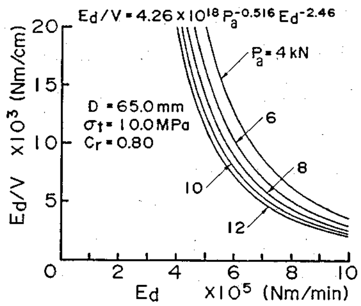


Fig. 6 Relations between required energy per unit drilling length E_d/V and nominal impact energy E_d for various thrust P_a.

$$V=K\cdot\frac{1}{f(2\pi R/N)}E_d^{\beta}E_r^{\gamma}(1+1.25\,C_r^{2.32})\times\begin{Bmatrix}H_s^{-0.483}\\U^{0.225}\\\sigma_t^{-0.477}\end{Bmatrix}D^{-1.82}\cdots\cdots(5)$$

As results of multiple regression analysis concerning with E_d and E_r,

$$V=5.56\times10^{-12}\,E_d^{2.80}E_r^{0.276}(1+1.25\,C_r^{2.32})H_s^{-0.483}D^{-2.10}\quad(R_m=0.707)\cdots\cdots(6)$$

$$V=1.95\times10^{-14}\,E_d^{2.98}E_r^{0.834}(1+1.25\,C_r^{2.32})U^{0.225}D^{-2.15}\quad(R_m=0.734)\cdots\cdots(7)$$

$$V=5.39\times10^{-17}\,E_d^{3.46}E_r^{0.516}(1+1.25\,C_r^{2.32})\sigma_t^{-0.477}D^{-2.34}\quad(R_m=0.841)\cdots\cdots(8)$$

could be obtained. Here, R_m means the coefficient of multiple correlation and the dimensions are V : cm/min, E_d : Nm/min, E_r : Nm/min, σ_t : MPa and D : mm.

From these results, it is clarified that the influence of impact energy on the drilling rate is more effective rather than the revolving energy.

As an example, **Fig. 5** shows the relations between the drilling rate of 65 mm diameter bit and the nominal impact energy for various thrust against some rock mass of coefficient of crack C_r : 0.80, radial compressive strength σ_t : 10.0 MPa, μ : 0.2 and rotation speed : 150 r.p.m. Also, **Fig. 6** shows the relations between the required energy per unit drilling length and the nominal impact energy for various thrust under the same conditions. The lower required energy per unit drilling length, the higher drilling efficiency could be obtained. Therefore, both the drilling rate and the drilling efficiency increases as the nominal impact energy is largely supplied under the higher thrust.

In actual cases, the optimum combination of thrust and impact energy should be determined under some drilling rate or some drilling efficiency, considering the wear life of drill bit.

4. CONCLUSION

To clarify the relations between the drilling rate of bit, the impact energy and thrust supplied from drifter, and the characteristics of rock mass, a series of rotary percussion drill machine tests were executed in-situ at various rock masses. As resuls, the drilling rate of actual rotary percussion drill bit could be expressed with a high coefficient of multiple correlation in Eq. (6), (7) and (8) as the function of the nominal impact energy and the revolving energy supplied from drifter, the diameter of drill bit, and the rock mass properties C_r, H_s, U or σ_t respectively. And it is clarified that both the drilling rate and the efficiency of drilling increases with the increment of nominal impact energy under the higher thrust.

Also the drilling rate of a given rotary percussion drill bit could be estimated for various rock masses. On the other hand, the properties of rock mass could also be investigated simultaneously by measuring the drilling rate of bit in-situ by use of a standard rotary percussion drill machine.

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