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SHOCK WAVE THEORY OF BLASTING WITH CYLINDRICAL CHARGE (CONTINUED)

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§ 10. Previous researches on blasting with cylindrical charges.

10-1. Fraenkel's formula

K. H. Fraenkel[15] has described the following formula for a bench blasting.

$$S=\frac{50V_{\max}}{H^{0.3}h^{0.3}d^{0.8}} \qquad (112)$$

where

S=figure for resistance to blasting,

$V_{\max}$=burden in m determined by trial blasts, H=drill hole depth in m

h=length of the charge in m (Ladungshöhe)

d=bottom diameter of the drill hole in mm.

According to him experience shows that $S=1\sim6$ where 1 corresponds to rock that is very difficult to break (small burden) and 6 to rock that is broken very easily (large burden) and the figures occurring most frequently lie between 1.8 and 2.4.

The above experimental formula may be interpreted in terms of the shock wave theory of blasting as follows:

The volume of a charge is expressed by the following equation.

$$\frac{4}{3}\pi a_s^3=\pi l_c a^2 \text{ or } a_s=\left(\frac{3}{4}\right)^{\frac{1}{3}} l_c^{\frac{1}{3}} a^{\frac{2}{3}} \qquad (113)$$

where

a_s=radius of a corresponding spherical charge cm

l_c=length of a cylindrical charge $=100h$ cm

a=radius of a cylndrical charge $=\frac{d}{2\times10}$cm

For a bench blasting with a concentrated charge with a radius a_s the following relation exists with respect to burden d_f, detonation pressure p_D, tensile strength of rock S_t.

$$S_t=p_D\left(\frac{a_s}{2d_f}\right)^n \qquad (82)$$

$$\text{or } \frac{d_f}{a_s}=\frac{1}{2}\left(\frac{p_D}{S_t}\right)^{\frac{1}{n}} \qquad (82)'$$

The height of a bench $H_f=2d_f$ ……(81)

$$\text{or } d_f=\frac{1}{2}H_f \qquad (81)'$$

while $\quad d_f=100V_{\max}$ cm

$\quad H_f\doteqdot100\ H$ cm

Now the effective tensile strength of rock may be expressed by the following relation.[12]

$$S_t=S_{t_0}V^{-\frac{1}{m}}=S_{t_0}d_f^{-\frac{3}{m}} \qquad (114)$$

where m=5.14

Combining the equations (82)', (113), (114) with (81)' we find:

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15) K. H. Fraenkel: Factors influencing Blasting results: Manual on Rock Blasting: (Aktiebolaget Atlas Diesel, Stockholm, Sweden) 1953, 6: 02~1,6: 02-15.

12) pp. 5, 6.

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$$\frac{d_f}{a_s}=\frac{d_f}{\left(\frac{3}{4}\right)^{\frac{1}{3}}l_e^{\frac{1}{3}}a^{\frac{2}{3}}}$$

$$=\frac{1}{2}\left[\frac{p_D}{S_{t_0}\left(\frac{1}{2}H_f\right)^{-\frac{3}{m}}}\right]^{\frac{1}{n}}\cdots\cdots(115)$$

or

$$\frac{d_f}{H_f^{\frac{3}{mn}}l_e^{\frac{1}{3}}a^{\frac{2}{3}}}=\frac{1}{2}\left(\frac{3}{4}\right)^{\frac{1}{3}}\left(\frac{1}{2}\right)^{\frac{3}{mn}}\cdot$$

$$\left(\frac{p_D}{S_{t_0}}\right)^{\frac{1}{n}}\cdots\cdots\cdots\cdots(116)$$

Introducing the numerical values $mn=10.28$ we have the following relation.

$$\frac{d_f}{H^{0.29}l_e^{0.33}a^{0.66}}=0.371\left(\frac{p_D}{S_{t_0}}\right)^{\frac{1}{2}}\cdots\cdots\cdots\cdots(117)$$

If we use the system of units of Fraenkel in (117) we have.

$$\frac{100V_{\max}}{(100H)^{0.29}(100h)^{0.33}\left(\frac{d}{20}\right)^{0.66}}$$

$$=0.371\left(\frac{p_D}{S_t^0}\right)^{\frac{1}{2}}\cdots\cdots\cdots\cdots(118)$$

or

$$\frac{50V_{\max}}{H^{0.29}h^{0.33}d^{0.66}}=\frac{0.371\times100^{0.29+0.33}}{2\times20^{0.66}}\cdot$$

$$\left(\frac{p_D}{S_{t_0}}\right)^{\frac{1}{2}}=C\cdots\cdots\cdots\cdots(119)$$

or

$$\frac{50V_{\max}}{H^{0.29}h^{0.33}d^{0.66}}=0.445\left(\frac{p_D}{S_{t_0}}\right)^{\frac{1}{2}}=C$$

$$\cdots\cdots\cdots\cdots(120)$$

The result shows the empirical formula of Fraenkel may be explained from the standpoint of the shock wave theory of blasting. As is obvious from (120) C decreases for a stronger rock whose tensile strengsh S_{t_0} is higher.

10-2. Brook and Stenhouse[16)]

16) Manual on Rock Blasting: 8: 40~1.

According to D. H. Brook and D. Stenhouse the weight of charge in each shot hole in a benching is usually calculated from a formula of type:

$$Q=0.074V\cdot E\cdot H\cdot q\cdots\cdots\cdots\cdots(121)$$

where Q=charge weight in lbs.
V=toe burden of hole in feet
E=spacing between holes in feet
H=depth of hole in feet.
$1/q$=expected yield in tons of rock per pound of explosive.

$1/q$ is estimated from experience and depends on the hardness of rock to be blasted, the joints and bedding planes present, whether the blast has an "open end" or not, and the degree of fragmentation and the steepness of muck pile required. It normally varies from $4\frac{1}{2}$ to 6 tons of rock per pound of explosive. Having calculated the weight of charge to be inserted in each shothole it is necessary to select a diameter of explosive cartridge that will fill a suitable portion of the shothole and leave sufficient room for stemming.

It is considered, according to them, that a shot hole is well balanced if the explosive charge occupies two-thirds and the stemming one-third.

From the description described above it is clear that the formula (121) has no theoretical basis and it may be taken to be an empirical formula based on the principle of "loading factor q" defined by (73) (74)(84) and (91).

It deals with both concentrated charges and cylindrical charges without any discrimination between them, however, the deeper becomes the depth of a bore hole then inevitably it deals with a cylindrical charge. The authors give, in graphical form, typical charges, depths, spacings and burdens.

From these curves data have been reproduced in Table 3. For normal work they recommend an ammonium nitrate gelatine.

From the standpoint of the shock wave theory of blasting the ratio of height to burden should be for a concentrated charge $H/d \fallingdotseq 2$ while for a cylindrical charge H is independent of d and H/d can be increased to any value as a height or a length of a cylindrical charge is increased. The values of H/d in Table 3 for smaller depths are 1.6-2.2 while for deeper holes the ratio H/d increases steadily. The values of $d/W^{\frac{1}{3}}$ in Table 3 are almost constant 2.46-2.90-2.63 which indicate

Table 3. Data on benching (D. H. Brook and D. Stenhouse)

H Depth of hole	d Burden	S_e Spacing	$2a$ Chartridge diameter	W Charge	Calculated				
					H/d	S_e/d	$d/W^{\frac{1}{3}}$	$d/W^{\frac{1}{2}}$	d/a
ft	ft	ft	inch	lbs					
5	3.1	4.4	$^7/_8$	2	1.61	1.42	2.46	2.19	85
10	5.7	6.9	$1\ ^1/_4$	6	1.75	1.21	3.13	2.33	109
15	6.8	8.7	$1^7/_{16}-1^3/_4$	14	2.21	1.28	2.82	1.82	113
20	7.9	9.4	$1\ ^3/_4-2$	23	2.53	1.19	2.78	1.65	94
25	9.4	10.0	$2\ ^1/_2$	34	2.66	1.06	2.90	1.61	90
30	10.0	10.2	$2\ ^1/_2$	45	3.00	1.02	2.81	1.49	96
35	10.6	10.6	$2\ ^1/_2$	57	3.30	1.00	2.75	1.40	102
40	11.25	10.70	$2\ ^1/_2$	73	3.55	0.95	2.69	1.32	108
45	11.85	11.00	$2\ ^1/_2$	88	3.80	0.93	2.66	1.26	114
50	12.50	11.45	$2\ ^1/_2$	107	4.00	0.96	2.63	1.21	120

that it deals with rather concentrated charges. However, practically in concentrated charges burden d is proportional to $W^{\frac{1}{2}}$ and not to $W^{\frac{1}{3}}$ due to the decrease of tensile strength of rock for bigger burdens. The value of $d/W^{\frac{1}{2}}$ in Table 3 decreases steadily as burden d increases while "reduced burden d/a for cylindrical charges" remain actually constant. (85-113-120), and this indicates that here we are dealing with rather cylindrical charges.

The numerical value of loading factor q given by them (4.5 to 6 tons of rock per pound of explosive = 101 to 76 gram explosive per ton of rock) corresponds to the numerical value 122 gram calculated by the formula(74) on the basis of the shock wave theory of blasting with a cylindrical charge.

10-3. Langefors[17]

Ulf Langefors suggested the following empirical formula for weight of charge Q_t,$(=W)$ height of bench K,$(=H)$ burden V $(=d)$ and resistance to blasting S.

$$Q_t = 0.4\left(\frac{K}{V} + 1.5\right)(0.07V^2+SV^3) \quad \cdots\cdots(122)$$

or

$$Q_t=0.4\{(0.07+SV)KV+1.5(0.07+SV)V^2\}$$
$$=Q_1+Q_2 \quad (123) \quad \text{where } S \fallingdotseq 0.4$$

The first term Q_1 represents column charge while the second term Q_2 bottom charge.

From the standpoint of the shock wave theory of blasting with concentrated

17) Manual on Rock blasting. 6 : 05~1.

charge the height of bench H should be:

$$H=2d \quad \text{or} \quad K=2V \cdots\cdots\cdots\cdots(124)$$

and the weight of charge:

$$W=\left(\frac{4}{3}\pi\Delta_e\right)a_s^3 \quad \text{while} \quad \frac{d}{a_s}=\frac{1}{2}\left(\frac{p_D}{S_t}\right)^{\frac{1}{2}}$$

then

$$W=\frac{32}{3}\pi\Delta_e\left(\frac{S_t}{p_D}\right)^{\frac{3}{2}} d^3 \ (125) \ \text{or} \ Q\infty V^3$$

From (123) and (124) we have:

$$Q_t=0.4\{(0.07+SV)2V^2+1.5(0.07+SV)V^2\}$$
$$=0.4\times3.5(0.07+SV)V^2=1.4(0.07+SV)V^2$$

or $Q_t=0.098V^2+1.4SV^3 \cdots\cdots\cdots\cdots(126)$

If we take into consideration the decrease of effective tensile strength of rock due to increase of burden then we have:

$$S_t=S_{t_0}\,d^{-\frac{3}{m}}=S_{t_0}\,d^{-\frac{3}{5.14}}$$

or $W=\frac{32}{3}\pi\Delta_e\left(\frac{S_{t_0}}{p_D}\right)^{\frac{3}{2}} d^{2.125}$ (127) or

$$Q\infty V^{2.125}$$

The relations (125) and (127) correspond to the equation (126).

For a cylindrical charge or a columnar charge which is long enough K may become so great as to make the second term in (123) negligible against the first term, then we have for a long cylindrical charge the following relation.

$$Q_t=0.4(0.07+SV)KV$$

or $Q_t=0.028KV+0.4SKV^2 \cdots\cdots\cdots\cdots(128)$

From the standpoint of shock wave theory of blasting with a cylindrical charge we have the following relation.

$$W=\pi\Delta_e l_e a^2$$

where l_e=length of charge $\fallingdotseq K$ for long charge

or $W=\left\{4\pi\Delta_e\left(\frac{S_t}{p_D}\right)^{\frac{2}{1.5}}\right\}l_e d^2$ (129) or

$$Q\infty KV^2$$

If we take into consideration the decrease of tensile strength of rock due to increase of burden then we have:

$$W=\left\{4\pi\Delta_e\left(\frac{S_{t_0}}{p_D}\right)^{\frac{2}{1.5}}\right\}l_e d^{1.222} \cdots(130)$$

or $Q\infty KV^{1.222}$

The relations (129) and (130) correspond to the equation (128).

As to the sub-drilling l_s Langefors gives the following relation.

$$l_s=0.3d \cdots\cdots\cdots\cdots(131)$$

where d=burden. The shock wave theory gives the corresponding relation.

$$l_s=0.35d \cdots\cdots\cdots\cdots(63)$$

As to the spacing S_e between two bore holes he gives the following relation.

$$S_e=1.3d \cdots\cdots\cdots\cdots(132)$$

while the shock wave theory gives the following relation.

$$S_e=1.4d \cdots\cdots\cdots\cdots(51)$$

For length of stemming he gives:

$$l_n=(0.5\sim1)d$$

10-4. B. F. Belidor

The Belidor equation[18]:

$$W=A\,d^2+Bd^3 \cdots\cdots\cdots\cdots(133)$$

may be explained from the standpoint of the shock wave theory as follows:

18) The same form has been used by Boris J. Kochanowsky in the calculation of Coyote blasting although in his case only a concentrated charge has been considered: B. J. Kochanowsky: Anlage und Berechnung von Kammerminensprengung als Beitrag zur Ermittlung des Sprengstoffbedarfes in der Hartsteingewinnung. 1955.

Constant tensile strength

If we assume a constant value of tensile strength of rock the weight of charge W of a concentrated charge is as follows:

$$W=\frac{32}{3}\pi\Delta_e\left(\frac{S_t}{p_D}\right)^{\frac{3}{2}} d^3 \cdots\cdots\cdots\cdots(125)$$

For a long cylindrical charge:

$$W=4\pi\Delta_e\left(\frac{S_t}{p_D}\right)^{\frac{2}{1.5}} l_e d^2 \cdots\cdots\cdots(129)$$

Therefore if we assume a case where we deal with an intermediate condition between two extreme cases, that is, a con centrated charge and a long cylindrical charge, then we may have the following relation:

$$W=\left\{A'\pi\Delta_e\left(\frac{S_t}{p_D}\right)^{\frac{2}{1.5}} l_e\right\}d^2 + \left\{B'\pi\Delta_e\left(\frac{S_t}{p_D}\right)^{\frac{3}{2}}\right\}d^3 = Ad^2+Bd^3 \cdots\cdots\cdots(134)$$

where A' and B' are numerical constants. The above equation corresponds to the Belidor equation (133).

Effective tensile strength variable

In general effective tensile strength of rock may be assumed to decrease as the size of rock increases because the points of weakness which determine effective tensile strength of rock may increase as size of rock increases. Therefore the following relation may be assumed:

$$S_t=S_{t_0}d^{-\frac{3}{m}}$$

where d=burden, S_{t_0}=tensile strength of unit rock.

Empirically m has been found to be about 5.14.

Then for a concentrated charge:

$$W=\frac{32}{3}\pi\Delta_e\left(\frac{S_{t_0}}{p_D}\right)^{\frac{3}{2}} d^{2.125} \cdots\cdots\cdots(127)$$

For a cylindrical charge:

$$W=4\pi\Delta_e\left(\frac{S_{t_0}}{p_D}\right)^{\frac{2}{1.5}} l_e d^{1.222} \cdots\cdots(130)$$

Then in an intermedi atecase where no sharp discrimation is realized between a concentrated charge and a long cylindrical charge we may have the following relation.

$$W=\left\{A'\pi\Delta_e\left(\frac{S_{t_0}}{p_D}\right)^{\frac{2}{1.5}} l_e\right\}d^{1.222} + B'\pi\Delta_e\left(\frac{S_{t_0}}{p_D}\right)^{\frac{3}{2}}\Big\}d^{2.125} \fallingdotseq Ad^{1.2}+Bd^{2.1} \cdots\cdots\cdots(135)$$

The above equation combined with equation (134) may give the following general form:

$$W=A_1 d^{1.222}+B_1d^2+B_2d^{2.125}+C_1d^3 \cdots\cdots\cdots(136)$$

or approximately:

$$W\fallingdotseq A_3d+B_3d^2+C_3d^3 \cdots\cdots\cdots(137)$$

The above equation corresponds to the general expression described by Ulf Langefors[17] as follows

$$W=k_0+k_1d+k_2d^2+k_3d^3+ \cdots\cdots\cdots(138)$$

The constant k_0 should be zero because no charge is required for zero burden.

10-5. Peele's Handbook[19]

In Peele's Handbook the following formula is described:

$$Y=\frac{d}{2}\;\frac{\text{Tensile resistance}}{\text{Tensile resistance}+(\text{Shearing resistance}+\text{frictional resistance})} \cdots\cdots\cdots(139)$$

19) Robert Peele: Mining Engineers' Handbook. 1950. Vol. I. 5~12.

where Y=half of a cylindrical cartridge length

d=depth of hole, b=burden

The formula assumes that the mass of rock to be blasted behaves as a rigid mass which actually is not a case, moreover, it does not take into account a decisive roll played by a diameter of a bore hole in bench blasting with a long cylindrical charge. We cannot calculate required weight of charge by this formula. The various important variables have been summarized in Table 4.

In Table 4 the reduced burden d/a which

Table 4. Variables in deep holes in Quarry with vertical face (average between limestone and granite)

Depth of hole l_h	Height of face H	Burden d	Spacing S_e	Height of bottom charge l_c	Diameter of hole $2a$	Depth of top tamping d_n	d/a	S_e/d	Subdrilling l_s	l_s/d	l_n/d
ft	ft	ft	ft	ft	in	ft			ft		
20	18	13.0	10.5	3.5	4.00	9	78	0.81	2	0.154	0.692
30	28	14.5	12.0	6.5	4.25	10	82	0.83	2	0.138	0.690
40	37	16.0	13.0	10.0	4.50	12	85	0.81	3	0.188	0.750
50	47	17.5	14.0	13.0	4.75	13	89	0.80	3	0.171	0.748
60	56	19.0	15.5	16.0	5.00	14	91	0.82	4	0.210	0.737
70	66	20.5	16.5	20.0	5.25	15	94	0.81	4	0.195	0.732
80	75	22.0	18.0	23.0	5.50	16	96	0.82	5	0.227	0.889
90	85	23.5	19.0	27.0	5.75	17	98	0.81	5	0.213	0.895
100	94	25.0	20.0	30.0	6.00	18	100	0.80	6	0.255	0.720
160	152	35.0	20.0	52.0	8.00	25	105	0.57	8	0.228	0.714

should be a constant from the standpoint of the shock wave thory for a long cylindrical charge varies little (78~105) over a wide range of burden (13ft.~35ft) and height(18ft~152ft).

The value of S_e/d which should be about 1.4 from the standpoint of the shock wave theory indicates that the spacing is too narrowly taken or the reduced burden d/a for an individual charge is taken too big.

The reduced sub-drilling l_s/d ranges from 0.15 to 0.23 while the shock wave theory indicates its upper limit to be 0.35. The reduced length of top tamping l_n/d ranges from 0.7 to 0.9 while the upper limit due to the shock wave theory is 1.65. It may be considered that the data described in Table 4 support the principle of the shock wave theory of blasting with a long cylindrical charge.

10-6. A. W. Daw and Z. W. Daw[20]

According to their theory if rupture takes place by shearing and S denotes the periphery of the chamber, W the line of resistance, and K_1 the modulus of shearing, the force P required to produce rupture is described as follows:

$$P=SWK_1 \quad \cdots\cdots\cdots\cdots(140)$$

Let l and l_1 be the lengths, and d and d_1 the diameters of two cylindrical chambers or bore holes in rock, which are placed at right angles to the line of resistance or parallel to the free face; then, if A and A_1 are the areas of projection of the chambers parallel to their axes,

$$A=ld \quad \text{and} \quad A_1=l_1d_1$$

20) Albert W. Daw and Zacharias W. Daw: The Principles of Rock Blasting and their General application. 1909. London; E. & F. N. Spon, Limited.

Therefore ; $\frac{A_1}{A}=\frac{l_1 d_1}{l d}$

But $\frac{A_1}{A}=\frac{P_1}{P}$, P and P_1 being the forces developed by the charges filling the chambers before rupture takes place ; and since

$$\frac{P_1}{P}=\frac{S_1 W_1}{SW} \text{ we have } \frac{A_1}{A}=\frac{S_1 W_1}{SW}$$

Substituting for $\frac{A_1}{A}$ the value given above, we get

$$\frac{l_1 d_1}{l d}=\frac{S_1 W_1}{SW}$$

When, however, the lengths of the chambers are given by multiple of the diameters,

$$\frac{l_1}{l}=\frac{S_1}{S} \text{ and consequently}$$

$$\frac{d_1}{d}=\frac{W_1}{W} \quad \text{.........................(141)}$$

Therefore, in blasting the same kind of rock when the cohesive risistance is not affected by joints and fissures, the diameters of the boreholes should be directly proportional to the lines of resistance.

In the case of spherical chambers, whose projections are A and A_1, and diameters d and d_1, we have

$$\frac{A_1}{A}=\frac{\frac{\pi}{4}d_1^2}{\frac{\pi}{4}d^2}=\left(\frac{d_1}{d}\right)^2$$

and $\left(\frac{d_1}{d}\right)^2=\frac{S_1 W_1}{SW}$. But $\frac{S_1}{S}=\frac{d_1}{d}$

and substituting $\frac{d_1}{d}$ for $\frac{S_1}{S}$ in the above equation, we get

$$\frac{d_1}{d}=\frac{W_1}{W} \quad \text{..................(142)}$$

Consequently the same relations of the diameters to the lines of resistance subsistfor spherical as for cylindrical chambers, viz. the diameters should be proportional to the lines of resistance.

By experiments in rock with a number of boreholes, varying in diameter from $^3/_4$ to $2\frac{1}{4}$ inches, they have obtained results quite in accordance with the above formula, thus proving its correctness and establishing the principles on which it is based. With gelatine dynamite in a very homogeneous and strong granite their experiments gave the following results:

Table 5. Diameter of borehole and line of resistance.
(A. W. Daw and Z. W. Daw)

No.	Diameter of borehole $2a$	Depth of borehole l_h	Length of charge l_c	Weight of charge W	Line of resistance d	Reduced burden d/a
	inches	ft-in	inches	lbs	ft-in	
1	$^3/_4$	3 - 2	9	0.22	2 - $4^1/_2$	76
2	1	4 - 2	12	0.50	3 - 2	76
3	1 $^1/_4$	5 - 3	15	1.00	4 - 0	78
4	1 $^1/_2$	6 - 3	18	1.75	4 - 9	76
5	1 $^3/_4$	7 - 3	21	2.80	5 - 6	76
6	2	8 - 4	24	4.20	6 - 4	76
7	2 $^1/_4$	9 - 5	27	6.00	7 - 2	76

Their equations (141) and (142) correspond to the equation of reduced burden $=\frac{\text{burden } d}{\text{radius of a charge } a}$ described by the shock wave theory, that is,

for a cylindrical charge

$$\frac{d}{a}=\frac{1}{2}\left(\frac{p_D}{S_t}\right)^{\frac{1}{1.5}}$$

and for a concentrated charge

$$\frac{d}{a}=\frac{1}{2}\left(\frac{p_D}{S_t}\right)^{\frac{1}{3}}$$

Their fundamental formula (140) is based on statical principle and statical experiments on ice, therefore, their principle cannot explain dynamical phenomena, such as mechanism of simultaneous blasting, milli- second delay blasting and fragmentation. Their principle demands that there should exist only two extreme cases, that is, no crater or a full crater, while actually we have the intermediate cases and their principle cannot explain the geometry of general craters.

The fact that in general craters are produced near free surfaces leaving the part of rock near charges intact cannot be explained on the basis of their principle.

Because of these fundamental defects of their theory their book has developed a considerable misleading ideas and formulas, although it has played an important role for a long time in the development of the theory and practice of blasting.

10-7. Du Pont Blasters Handbook[21]

Du Pont Blasters' Handbook recommends for large hole drilling in limestone the following patterns:

Table 6. Patterns of large hole drilling (Du Pont)

diameter of hole $2a$	burden d ft	spacing S_c ft	height of face H ft	sub drilling l_s ft	d/a	S_c/d	l_s/d
$5^5/_8$ inch	14	20	30 - 50	3 - 6	60	1.43	0.21-0.42
$6^1/_2$ inch	19	24	30 - 75	3 - 6	59	1.50	0.21-0.42

The numerical values of d/a, S_c/d, l_s/d are nearly the same with those described in the shock wave theory of blasting with a long cylindrical charge.

10-8. Manuel Bickford[22]

He gives the following data.

Table 7. Data on hard limestone with Martinite.
(detonation velocity $D=3{,}060$m/s. density $\Delta=1.35$) (Davey Bickford Smith)

diameter of hole $2a$	burden at crest d_1	burden at toe d_2	spacing S_c	height of face H	length of charge l_c	length of stemming l_n	length of hole l_h	d_1/a	d_2/a	S_c/d	l_n/d_1
30mm	2.5m	3.0m	2.0m	8.0m	5.0m	3.0m	8.0m	167	200	0.67	1.2

loading factor $F=\frac{\text{112kg explosive}}{\text{1500 ton rock}}$

$=\frac{\text{75gram explosive}}{\text{Ton of rock}}$

21) Du Pont Blasters'Handbook 1954. p. 333.

22) Manuel Bickford, Davey Bickford Smith & Cie. 6 Rue Stanislas Girardin, Rouen. 1949. p. 148.

It seems that reduced burden d/a (167~200) is too big for an individual charge to produce a full crater while reduced spacing S_e/d is taken very small to compensate for too big an individual burden. From the standpoint of the shock wave theory the reduced spacing S_e/d should be 1.4 and reduced burden $d/a \fallingdotseq 100$ then the number of boreholes required and loading factor remain the same with those in Table 7.

10-9. Yamamoto[23]

Sukenori Yamamoto describes the following numerical values based on experiences.

10-10. Nohara[24]

Table 8. Data on long hole blasting (S. Yamamoto)

Hight of face H	Burden d	Length of hole l_h	Spacing S_e	Diameter of hole $2a$	d/a	S_e/d	Sub. drilling l_s	l_s/d
m	m	m	m	cm			m	
5.5	4.0	6	3.0	120	67	0.75	0.5	0.125
8.5	4.5	9	3.5	130	69	0.78	0.5	0.111
11.5	5.0	12	4.0	135	75	0.80	0.5	0.100
14.5	5.5	15	4.3	145	76	0.78	0.5	0.091
17.0	6.0	18	4.7	150	80	0.78	1.0	0.167
20.0	6.5	21	5.0	160	81	0.77	1.0	0.154
22.5	7.0	24	5.5	170	82	0.79	1.5	0.214
25.5	7.5	27	5.8	175	85	0.77	1.5	0.200
28.0	7.5	30	6.0	180	83	0.80	2.0	0.267

Nohara recommends for a long bore hole the following relations. Weight of charge W=const. $d^2\ l_e$ (143)

For spacing $S_e/d>1$.

For reduced burden d/a=const.

For length of stemming $l_n \leq d$

He derived the equation (143) from the equation W=const.d^3. He quotes the following data on limestone with carlit explosive:

$l_h=4$m, $d=2.2$m, $2a=30$mm.

$l_e=2$m $l_n=2$m. $S_e=1.9$m. Then we have:

$d/a=147$ $l_n/d=0.91$ $S_e/d=0.86$

10-11. Pearse's formula[25]

G. E. Pearse has derived the following formula for a long cylindrical charge whose detonation velocity is assumed to be infinite.

$$R=KD\sqrt{\frac{p_s}{S}} \quad\text{......................}(144)$$

where R=critical radius normal to the drill hole length beyond which fracture will not occur.

D=cartridge diameter

p_s=pressure exerted after detonation

S=tensile strength of rock

K=0.8 (0.7~1.0)

He derived the equation (144) from the strain energy per unit volume.

If we use the notation of the shock wave theory $R=d$, $D=2a$, $p_s=p_D$, $S=S_t$ then (144) is expressed as follows:

23) Sukenori Yamamoto: Outline of Industrial Blasting (In Japanese) (Sangyo Bakuha Gairon) 1947. p.155-

24) Nohara: Blasting (In Japanese) Happa 1956.

25) G. E. Pearse: Mine & Quarry Engineering, Jan. 1955. Vol. 21. No. 1. pp. 25~30.

$$\frac{d}{a}=K\sqrt{\frac{p_D}{S_t}} \quad \cdots\cdots\cdots\cdots\cdots\cdots(144)'$$

This equation corresponds to the equation derived from the shock wave theory of blasting with a long cylindrical charge;

$$\frac{d}{a}=\frac{1}{2}\left(\frac{p_D}{S_t}\right)^{\frac{1}{1.5}}$$

According to his results the ratio $\frac{\text{Spacing}}{\text{radius}}$ found experimentally and calculated by (144) is as follows:

Table 9. Data on anhydrite (S_t=1,220~800psi) (G. E. Pearse)

Explosive	Detonation pressure p_D	Cartridge diameter $2a$	Spacing/a	
			Experiment	Calculated
Ammon Gelignite	16×10^5psi	$1^1/_4$ inch	68	78 ~ 72
Permitted Gelatinous	11×10^5	$1^1/_4$	58	50 ~ 46
Permitted Powder	4.5×10^5	$1^1/_4$	48	34 ~ 40

In Table 9. the calculated spacing is the same with the calculated critical radius while he describes that it is generally accepted that a spacing is 1.5 times the burden "d" (or critical radius), that is,

Spacing$S_e=1.5d$.

The calculated burden=critical radius for example, for Ammon Gelignite, should be then $\frac{1}{1.5}$ (78~72) = 51~48 which

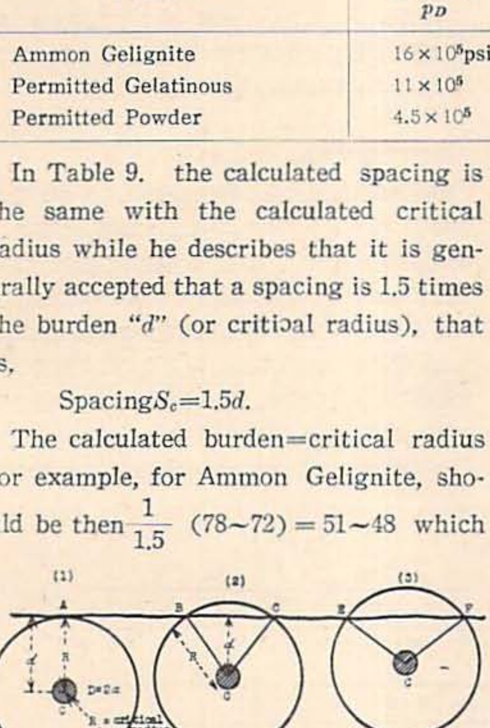

Fig. 8. Critical radius

seems too small from experience.

Whereas the shock wave theory gives:

$$\frac{d}{a}=\frac{1}{2}\left(\frac{16\times10^5}{1220\sim800}\right)^{\frac{1}{1.5}}=56\sim79$$

for $S_e/a=1.4d$ =78~111

In his theory the critical radius R seems to represent the case (1) Fig. 8, while to produce a crater of some depth the case (2) or case (3) seems to be more reasonable, then, the burden d_1 to be blasted becomes much smaller than critical radius R leading to much smaller value of d/a than that found by experience. It seems difficult to explain the geometry of craters and process of fragmentation on the basis of this theory.

長 装 薬 発 破 の 理 論

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先に報告した集中装薬発破の理論とその応用に関する諸研究におけると同じくショック波発破理論に基づく長装薬発破の理論を述べその実用問題に対する応用を計算例を示して説明した。また集中装薬発破と長装薬発破の特質を比較説明した。従来報告された諸研究者の発破基礎式を比較考察し集中装薬と長装薬が理論的に区別されていないため多くの混乱錯誤が生じていることを述べまた多くの従来式がショック波発破理論から誘導されることを論じた。