Information Circular 8550

Designing Blast Patterns Using Empirical Formulas

A Comparison of Calculated Patterns With Plans Used in Quarrying Limestone and Dolomite, With Geologic Considerations

By Joseph M. Pugliese
Twin Cities Mining Research Center, Minneapolis, Minn.

US Department of Interior
Office of Surface Mining
Reclamation and Enforcement

Kenneth K. Eltschlager
Mining/Explosives Engineer
3 Parkway Center
Pittsburgh, PA 15220

Phone 412.937.2169
Fax 412.937.3012
Keltschl@osmre.gov

UNITED STATES DEPARTMENT OF THE INTERIOR
Rogers C. B. Morton, Secretary

BUREAU OF MINES
Elburt F. Osborn, Director

This publication has been cataloged as follows:

Pugliese, Joseph M
Designing blast patterns using empirical formulas: a comparison of calculated patterns with plans used in quarrying limestone and dolomite, with geologic considerations. [Washington] U.S. Dept. of the Interior, Bureau of Mines [1972]

33 p. illus., tables. (U.S. Bureau of Mines. Information circular 8550)

Includes bibliography.

1. Blasting—Mathematical models. I. U.S. Bureau of Mines. II. Title. (Series)

TN23.U71 no. 8550 622.06173

U.S. Dept. of the Int. Library

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price 45 cents
Stock Number 2404-1145
Catalog No. 128.27:8550

CONTENTS

ILLUSTRATIONS

TABLES

TABLES--Continued

DESIGNING BLAST PATTERNS USING EMPIRICAL FORMULAS

A Comparison of Calculated Patterns With Plans Used in Quarrying Limestone and Dolomite, With Geologic Considerations

by

Joseph M. Pugliese[1]

ABSTRACT

This work was done by the Bureau of Mines to provide quarry operators with an uncomplicated, first-approximation method for designing blast patterns, considering geologic structure, and to show the valid use of the technique by comparing drill and blast pattern dimensions used in the quarry with those determined by the presented method. The author visited 12 limestone and dolomite quarries in Ohio (Adams, Crawford, and Highland Counties), Wisconsin (Milwaukee, Racine, and Waukesha Counties), and Minnesota (Fillmore, Olmsted, and Wabasha Counties); observed the blasting practices; studied the major geologic features; and after discussion with the quarry managers, foremen, and blasters, compared the quarry blasting patterns with those as calculated by the empirical formulas (after R. L. Ash), with geologic structural considerations. When geologic structure such as bedding, jointing, folding, and caves, as well as explosive properties and field performance characteristics are accounted for in a manner suggested by the research, the presented empirical formulas may be used as a good first approximation. The included steps in planning a blast design and generalized blast patterns should be of help to the quarry operator. Design changes are recommended for those quarries where problems are occurring.

INTRODUCTION

The Bureau of Mines has been conducting field studies of explosive blasting in rock for a number of years. Concerning the topic of this paper, a few of the studies are reported here. Atchison and Pugliese (5),[2] in their comparative studies of explosives in limestone with tight joints, found that repeated blasting in an area opened the tight separations in the rock. Their results reflected the effect of this joint opening. Nicholls and Duvall (13) studied the effect a charge diameter has on explosive performance. A recent study (14) showed horizontal bedding without or with conspicuous jointing, folds, faults, caves, and filled joints influence blasting and mining in limestone and dolomite quarries. The quarry operators attempt to minimize

---

[1] Geophysicist.

[2] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

detrimental geologic effects and maximize beneficial geologic effects. Outside of the Bureau, other investigations are noteworthy. Belland (6) concluded that geologic structural controls on rock fragmentation upon explosive blasting do exist and that explosive blast patterns should be designed to make optimum use of geologic controls. Ash (3) has developed five basic empiric ratios for designing blasts. Ash and others (4) investigated further to determine conditions for optimizing spacing of simultaneously initiated multiple explosive columns. Ash's recent study (2) demonstrates the validity of his earlier work on determining blasting relationships useful for estimating blast pattern dimensions. Grimshaw and Watt (11) commented on innovations in the quarry blasting field being introduced to assist the quarry operator in producing stone with improved economy, safety, and efficiency. They note some possible benefits to be associated with shallow face working which emphasize the interdependence of the drilling, blasting, and materials-handling operations.

While the author was conducting his study (14), he noted many quarry operators were not cognizant of the work mentioned above. There was a lack of awareness of uncomplicated, first-approximation blast pattern design criteria, including geologic considerations. In many instances, blast patterns providing satisfactory results had been developed on a trial and error basis, which is costly in time and money. The author felt the need for a report containing: Simplified formulas (after Ash)[3] that may be used in making first approximations of drilling and blasting patterns, with geologic considerations; suggested sequence of steps in planning the blast design; generalized blasting pattern views that may be used; and direct comparisons with patterns used in the quarry.

In collecting information for this report, the author visited 12 quarries in Ohio (Adams, Crawford, and Highland Counties), Wisconsin (Milwaukee, Racine, and Waukesha Counties), and Minnesota (Fillmore, Olmsted, and Wabasha Counties); observed the blasting practices; studied the major geologic features; and after discussion with the quarry managers, foremen, and blasters, compared the blast patterns calculated by empirical formulas to quarry blasting patterns producing satisfactory results, with geology considered in the blast designs. Design changes were recommenced for those quarries where problems were occurring and where the calculations suggested a change.

In this report, explosive ingredients, properties, and field performance characteristics are included only when necessary. The reader is referred to Dick (8) and Yancik (15) if more extensive information is desired.

ACKNOWLEDGMENTS

The author wishes to thank David E. Fogelson, supervisory geophysicist at the Bureau of Mines, Twin Cities Mining Research Center, for his suggestions and guidance in the early phase of this study. The author also thanks

---

[3] Use of these formulas is by the author's choice and does not imply endorsement by the Bureau of Mines. Other formulas are available in publications (10, 12).

Richard A. Dick, mining engineer at this Center, and Richard L. Ash of the University of Missouri at Rolla for their helpful suggestions in interpreting the data.

The author wishes to acknowledge the generous cooperation of those quarry operators who participated in this study by permitting access to their property and providing much of the data that made this report possible.

COMPOSITION AND ORIGIN OF LIMESTONE AND DOLOMITE

According to Bowles (7), limestone is composed mainly of calcium carbonate ($CaCO_3$). The rock is known as a high-calcium limestone if the magnesium carbonate content is small. The rock is called a magnesium or dolomitic limestone if 10 percent or more of magnesium carbonate is present. When the magnesium carbonate content approaches 45 percent, the rock is known as dolomite, the double carbonate of calcium and magnesium $CaMg(CO_3)_2$.

Limestone consists chiefly of calcium carbonate shells and skeletons of organisms that inhabited oceans and lakes. Uncounted generations of these organisms lived and died to leave their shell and skeletal remains accumulated on sea and lake floors. Such shell supplies are supplemented by chemically precipitated calcium carbonate and, according to some geologists, chemically precipitated magnesium carbonate. During later geologic ages, beds of other material were deposited over the carbonates and thus caused pressures that gradually consolidated the carbonates into limestone. Limestones can contain large amounts of impurities such as clay and silica.

Opinions differ on the formation of dolomite. Some geologists believe that dolomite was formed directly from precipitation of calcium and magnesium carbonate while others hold that dolomite was formed from limestone through the replacement of some of the calcium by magnesium.

The individual limestone and dolomite layers range from a fraction of an inch to many feet in thickness. Massive strata of uniform texture indicate relatively long periods of uniform conditions of sedimentation. A bedding plane is introduced when these conditions are temporarily changed. In general, each bedding plane marks the termination of one deposit and the beginning of another.

DEFINITION OF MAJOR GEOLOGIC FEATURES IN THESE ROCK TYPES OBSERVED TO INFLUENCE EXPLOSIVE BLASTING

The following major geologic features were observed to affect explosive blasting in limestone and dolomite quarries. The terminology used here is that of the Dictionary of Geological Terms prepared by the American Geological Institute (1).

Bedding is a collective term signifying existence of beds. A bed is the smallest division of a stratified series and is marked by a reasonably well-defined divisional plane separating its neighbors above and below.

Jointed bedding is composed of fractures (joints) in the rock, generally vertical or transverse to bedding, along which no appreciable movement of rock has occurred. A joint set is a group of approximately parallel joints. If clay and/or mud accumulate in an open joint, it will be considered as a filled joint. The filled joint may have a few discontinuous open channels.

Folded bedding is marked by a bend in the strata. In this report, bedding is considered folded when this feature is present to a major extent within the confines of and in relation to the blast or quarry area. Faulted bedding is characterized by a fracture in the rock with a displacement of the sides relative to one another parallel to the fracture.

An unconformity is a surface of erosion or nondeposition, usually the former, that separates the younger strata from older rocks. A bed is unconformable when it does not succeed the underlying strata in immediate order of age.

A cave is a natural cavity, chamber, or series of chambers beneath the surface of the earth. Such underground openings are usually produced by solution of limestone and dolomite.

PRODUCTION BLAST TERMINOLOGY

The following list of blasting-pattern dimension symbols will be used in this report. The symbols are the same as those used by Ash (2-3). The bench cross section view (fig. 1) and the plan view of generalized blasting patterns (fig. 2) should facilitate understanding of the symbols. The blasting patterns shown in figure 2 can be used as a first approximation. In multirow blasting (fig. 2, plans A-E), a row is considered as an array of two or more holes such that a line drawn through the hole centers is perpendicular to the final rock displacement direction, indicated by the arrow on each plan. In plans F and G (fig. 2), the one array of holes will be considered as a row.

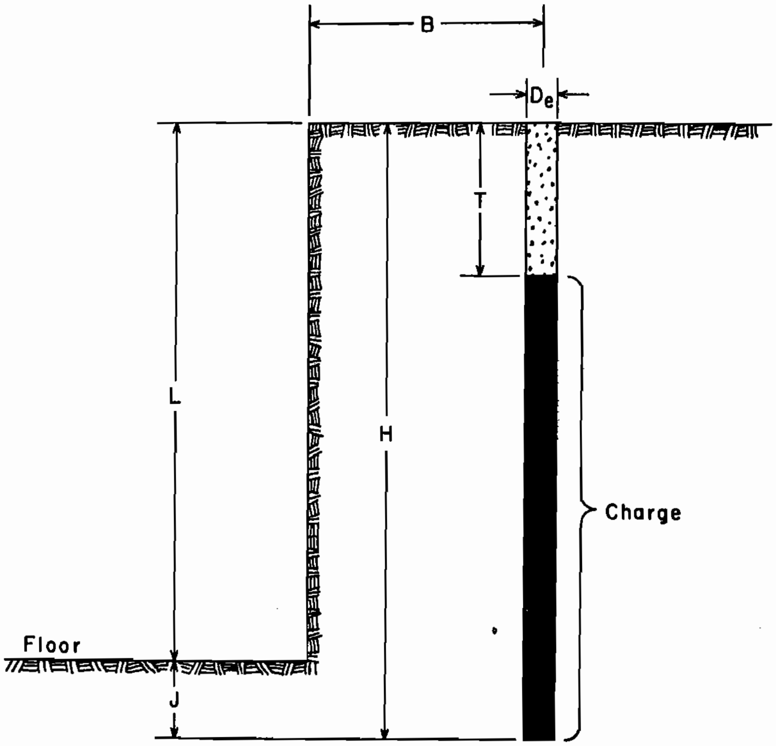
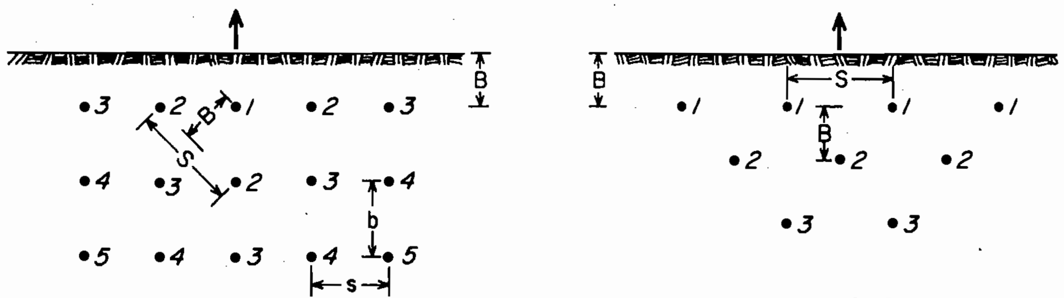
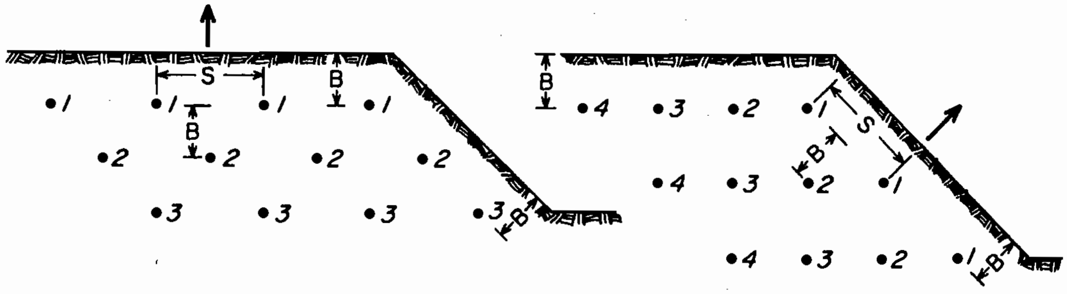


FIGURE 1. - Bench Cross Section View Showing D_e, B, H, J, T, and L (2-3).



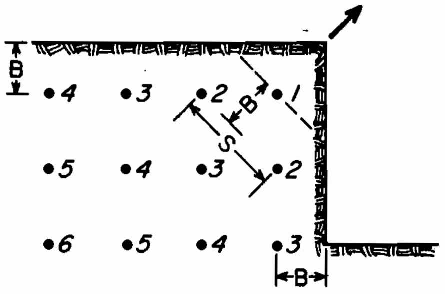
BOX CUT, EXPANDING V
PLAN A

BOX CUT,
EXPANDING FLAT BOTTOMED V
PLAN B

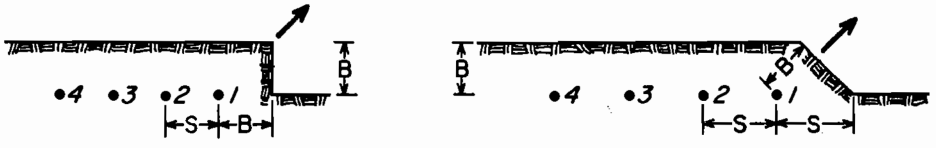


CORNER CUT, ECHELON
PLAN C

CORNER CUT, ECHELON
PLAN D



CORNER CUT, ECHELON
PLAN E



CORNER CUT, ECHELON
SINGLE ROW, PLAN F, S=B

CORNER CUT, ECHELON
SINGLE ROW, PLAN G, S=1.4B

FIGURE 2. - Generalized Blasting Patterns Showing B, S, b, and s (2).
(Numbers indicate firing sequence.)

D_e = Diameter of the explosive in the borehole (in).

B = Burden, distance from a charge measured perpendicularly to the nearest free face and in the direction that displacement will most likely occur at the time of charge firing (ft).

S = Spacing, distance between two holes such that the spacing is always measured perpendicular to its corresponding burden (ft).

H = Hole length (ft).

J = Subdrilling length, depth hole is drilled below the established quarry floor (ft).

T = Collar distance, the portion of the borehole not containing explosive (ft).

L = Bench height (ft).

b = Distance perpendicular to the original free face, measured between two rows of holes (ft). See figure 2, plan A.

s = Separation between adjacent holes in a row (ft). See figure 2, plan A.

The terms b and s are used by quarry operators for convenience in describing such patterns as plan A, a square grid. These terms should not be confused with burden and spacing. The word "explosives" is used as a collective term for "blasting agents" and "explosives."

EMPIRICAL FORMULAS THAT MAY BE APPLIED TO DRILLING AND BLASTING PATTERN DESIGN

Ash (3) has suggested five basic ratios for blasting design. The standard blasting ratios are for vertical boreholes for all types of bench-blasting in 20 different rock types with hole depths from 5 to 260 ft, hole diameters from 1-5/8 to 10-5/8 in, and for all grades of explosives. Although the ratios can be used as first approximations in blasting design, modifications to the ratios will be pointed out where major geologic features influence blasting results.

Ash's ratios will be shown as equations solving the unknown dimensions:

where $B = K_B D_e/12$; K_B = Burden ratio, (1)

$S = K_S\ B$; K_S = Spacing ratio, (2)

$H = K_H\ B$; K_H = Hole length ratio, (3)

$J = K_J\ B$; K_J = Subdrilling ratio, (4) and $T = K_T B$; K_T = Collar distance ratio. (5)

D_e is expressed in inches, and all other dimensions are in feet.

Calculation of Burden, B, From Equation 1

To use a certain explosive type with diameter, D_e, the burden, B, can be calculated from equation 1. The following values for K_B are for rock with a solid density of around 2.7 gm/cc, a common value for limestone and dolomite. For calculating B, use:

K_B = 30 (average conditions--first approximation),

K_B = 25 (for low-density explosives, such as AN-FO),

and K_B = 35 (for dense explosives, such as slurries and gelatin).

If the rock has a density much different from 2.7 gm/cc, further adjustments of K_B can be made. A lower K_B value could be used for rocks of density much greater than 2.7, for example 3, and a higher K_B value could be used for rocks of density much less than 2.7, for example 2.4.

Calculation of Spacing, S, From Equation 2

K_S = 1.8 - 2 for simultaneous initiation of holes in the same row. Staggered drill hole patterns should be preferred between rows within which all charges are initiated simultaneously. Rock movement will generally be perpendicular to the original free face.

According to Ash and others (4), larger K_S values, for example K_S = 3 - 5, could be used under favorable conditions for charges initiated together as opposed to the commonly accepted limit of 2. The charges would need to be fired however at exactly the same time, otherwise spacing would have to be reduced because of the lack of enhanced stress effects. In addition, the length of the charges must be sufficiently long.

In regard to a minimum H/B condition, a recent study (2) showed:

$$S \approx (B\ H)^{1/2} \text{ for } 2B \leqq H < 4B \tag{6}$$

and

$$S \approx 2B \text{ for } 4B \leqq H. \tag{7}$$

K_S = 1.8 - 2 is satisfactory however although K_S could possibly be reduced further if H/B is much less than 3.

According to (4), individual blasting conditions will limit the value of the optimum spacing that might be used in any given situation.

The above information should be kept in mind when calculating S by equation 2 for simultaneous initiation of holes in the same row.

K_S = 1 - 1.2 for sequence delays in the same row. The square drill pattern should be used for sequence timing in the same row and simultaneous initiation laterally between holes in adjacent rows. Rock movement will generally be in a direction 45 degrees to the original open face, for example, the box cut, expanding V rock progression. The spacing ratio K_S = 1 - 1.2 applies to the ratio of s, the separation between adjacent holes in a row, to b, the perpendicular distance measured between two rows of holes. In terms of burden, b = 1.4 B. Equation 2 thus becomes:

$$s = K_S \ b = K_S \ (1.4 \ B),$$

where K_S = 1 - 1.2.

K_S will need to be adjusted further between 1 and 2 to meet local use and conditions, for example, period of delay between charges. When K_S is much larger than 2, the spacing is so much larger than the burden that cratering on the vertical face and large rock humps on the floor may result. When K_S is smaller than 1, too close a separation of holes can cause premature breaking between holes; this breaking results in finely broken rock in the immediate vicinity of the holes, and boulders, slabs, and toe problems in the burden area. Premature breaking between holes can promote loss of explosive detonation confinement with subsequent pressure drop in the borehole regions. Often under this condition, the spacing should be slightly extended rather than reducing the burden.

All these equations assume ideal energy balancing between charges (3) and serve only as an approximation. The equations do not relieve the quarry operator from further experimenting to cope with the problems associated with his particular quarry conditions. For instance, there will be slight adjustments to individual S's and B's between holes and rows so that boreholes do not intersect near vertical joint planes or mud seams.

Calculation of Hole Length, H, From Equation 3

In practice K_H ranges from 1.5 to 4 with a value of 2.6 being most frequently used. Generally a blasthole should never be drilled to a depth less than the burden; that is, K_H less than 1. When K_H is less than 1, overbreak and cratering can develop. A K_H greater than 4 can cause bootlegging and resultant toe problems when a single primer is used. For multiple priming of a charge in a hole, the hole depth can be larger than that predicted by the average value of K_H = 2.6 and may even exceed K_H = 4. Ash cautions that there is no definite value of K_H which can be applied easily without considering the materials cratering properties, explosive characteristics, and primer location (personal communication).

Calculation of Subdrilling Length, J, From Equation 4

K_J should not be less than 0.2 with a value of 0.3 being preferred to insure a full face and even quarry floor. In quarries having a pronounced parting as a quarry floor, however, no subdrilling may be necessary, that is, K_J = 0. In some cases, a $-K_J$ is beneficial to prevent loss of explosion gas when the bedding at the toe is open. In extremely dense rock with no fractures, a K_J value of 0.4 to 0.45 can be used to eliminate humps and toes. A K_J greater than 0.5 is generally considered wasted drill footage.

Calculation of Collar Distance, T, From Equation 5

T is the length of borehole at the collar which is not loaded with explosive. This zone is normally filled with stemming material. This stemming material helps confine the gases produced upon explosive detonation and thus helps reduce airblast. The gases contained are then available to do further work in moving the rock. $K_T = 0.7$ is a reasonable approximation for the control of airblast and fly rock and serious overbreak in the collar region. In very solid rock, a value of K_T less than 1 can cause some cratering with backbreak and possible violence, particularly with collar priming.

These calculations are summarized in table 1. Multiple priming may allow K_H to exceed 4.

TABLE 1. - Calculation sheet-drill pattern dimensions for average and alternative blasting conditions

Quarry location ____________________ Date ____________

D_e = __________ in; Cut __________; Desired rock progression __________

$B = K_B D_e/12 =$ __________ ft for $K_B \approx 30$ (average)
$B = K_B D_e/12 =$ __________ ft for $K_B \approx$ ___ (alternative)

For staggered pattern, simultaneous timing

$S = K_S B =$ __________ ft for $K_S \approx 2$ (average)
$S = K_S B =$ __________ ft for $K_S \approx 1.8$ (alternative)

For square pattern, sequence timing

$s = K_S\ b = K_S\ (1.4\ B) =$ __________ ft for $K_S \approx 1$ (average)
$s = K_S\ b = K_S\ (1.4\ B) =$ __________ ft for $K_S \approx 1.2$ (alternative)

$H = K_H B =$ __________ ft for $K_H \approx 2.6$ (average)
$H = K_H B =$ __________ ft for $K_H \approx$ ___ (alternative)
$H_{Min} = K_H B =$ __________ ft for $K_H \approx 1.5$ (minimum)
$H_{Max} = K_H B =$ __________ ft for $K_H \approx 4$ (maximum)

$J = K_J B =$ __________ ft for $K_J \approx 0.3$ (average)
$J = K_J B =$ __________ ft for $K_J \approx$ ___ (alternative)

$T = K_T B =$ __________ ft for $K_T \approx 0.7$ (average)
$T = K_T B =$ __________ ft for $K_T \approx$ ___ (alternative)

$L \approx H - J =$ __________ ft (average or alternative)
$L_{Min} \approx H_{Min} - J =$ __________ ft (minimum)
$L_{Max} \approx H_{Max} - J =$ __________ ft (maximum)

The author suggests the following sequence of steps in planning the blast design:

1. A plan view showing the original face(s) and desired direction of total rock movement should be made. Major geologic features such as horizontal bedding without or with conspicuous jointing, folds, faults, unconformities, caves, and filled joints should be taken into account (14). The cut, corner or box, can also be determined.

2. Given a certain explosive type with diameter, D_e, and a given rock type (density), the burden, B, can be calculated from equation 1.

3. The drill hole pattern that will obtain the desired rock progression, for example, echelon, or proper direction of rock movement should be selected. The charge weight or number of holes per delay will need to be considered because of vibration problems (9).

4. Determine the spacing, S, from equation 2.

5. Indicate drill holes with the initiation sequence on the plan view. At this point, the operator can obtain a good idea of how the blast will proceed and generally can determine the number of rows and number of holes per row that are needed.

6. Check the hole length, H, from equation 3, to see if priming restrictions are in order and if the shot is in good proportion.

7. Calculate subdrilling length, J, from equation 4, and collar distance, T, from equation 5.

DIRECT COMPARISONS OF BLAST PLANS CALCULATED BY THE EMPIRICAL FORMULAS WITH ACTUAL EXAMPLES OF BLASTING PATTERNS USED BY THE QUARRIES VISITED

In tables 2 to 13, the millisecond delay notation is approximate because of the considerable scatter among firing times of delay electric blasting caps. The blast pattern sketches are not exactly to scale. See tabular values for dimensions.

$D_e \approx$ hole diameter for free flowing and packaged explosives. $D_e <$ hole diameter when cartridged explosives are used. If the hole contains a mix of cartridged and free flowing/packaged explosives, D_e is determined by what explosive form predominates.

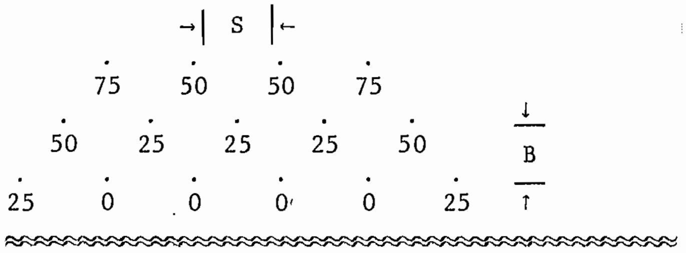
TABLE 2. - Blasting pattern dimensions for Ohio, Adams County, Quarry No. 1

Cut Box Desired rock progression Expanding flat-bottomed V

	Dimensions used in quarry	Calculated drill pattern dimensions	K-values used
Hole diameter, inches..	2.5-2.75		
D_e, inches............	1.25-1.5; 2.5-2.75	2.5	
B, feet................	6	6	$K_B = 30$
Pattern................	Staggered	Staggered (plan B)	
Timing.................	Modified simultaneous	Simultaneous	
S, feet................	9	11-12	$K_S = 1.8\text{-}2$
H, feet................	30-50	[1]9-16-24	$K_H = 1.5\text{-}2.6\text{-}4$
J, feet................	0 or 3	0 or 2	$K_J = 0, 0.3$
T, feet................	5	4	$K_T = 0.7$
L, feet................	30-50	[1]9-16-24 [1]7-14-22	

Plan view:[2]

Example - 3 rows



Except for H and thus L, the calculated dimensions compare favorably with those used by the quarry. Since the AN-FO is not pneumatically loaded, D_e should be increased for example to 4 in to obtain a higher detonation velocity. This increased D_e would provide a calculated L value which would compare to the actual ledge height range in the quarry. If the quarry used a larger D_e, B and S would need to be increased. Multiple priming would allow a higher bench to be used.

---

[1] Minimum value-average condition value-maximum value.

[2] Numbers indicate millisecond delay.

Quarry No. 1 Explosive Blasting Details

Required is a box cut with a desired rock throw progression as an expanding flat-bottom V. Full column charges are loaded into the holes and bottom-primed. When the holes are wet, they are bottom-loaded with 1-1/4- by 8-in and 1-1/2- by 8-in sticks of 40-percent weight strength water-resistant gelatin. The electric blasting cap is placed in a cartridge of 60-percent weight strength gelatin. The gelatin has excellent water resistance and the smaller diameter charges will displace less water than the 2-in-diameter cartridges. Unless the rock is very easy to break at the toe, enough explosive might not be present to break the rock to the desired quarry floor. The water does aid in letting more energy into the rock than does air which helps the blasting foreman in this instance. As soon as the dry part of the hole is reached, premixed, free running AN-FO is poured into the hole. The holes are stemmed about 5 ft and always less than the burden as a rule of thumb. Since the drill holes are of small diameter, drill cuttings or <1/4-in fines are used with excellent results. In the last line, the holes have less stemming than the others so that the confining pressure of detonation is lessened possibly to eliminate back shattering and breaking.

Holes are subdrilled 3 ft unless the desired quarry floor is a predominant parting where no subdrilling is done. If this predominant parting causes severe lack of loading and detonation confinement, a negative J could be used.

The blasting foreman is experimenting with different blasting techniques. At present, the quarry is using the same explosives and blast design to break up the Peebles Dolomite, the Greenfield Dolomite, and the dolomite of the Tymochtee Formation with fair results. Benches are separated by major bedding planes or unconformities. For example, the Peebles Dolomite and overlying Greenfield Dolomite are being blasted as separate benches. The top of the Peebles is an unconformity. When the quarry operator blasts in the Greenfield Dolomite, he does not subdrill and load explosives below the unconformity since the rock breaks to the unconformity anyway.

Packaged AN-FO instead of free running AN-FO could be used to provide a margin against water desensitizing the blasting agent.

TABLE 3. - Blasting pattern dimensions for Ohio, Highland County, Quarry No. 2

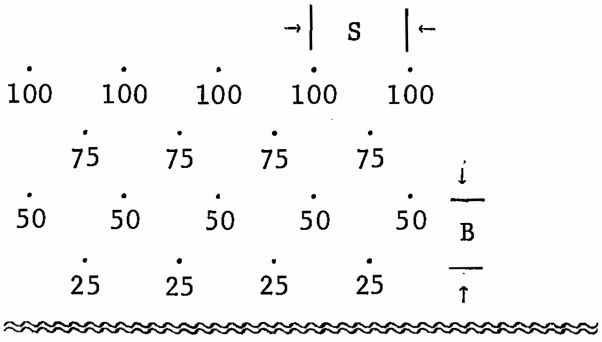
Cut Box

Desired rock progression Expanding flat-bottomed V

	Dimensions used in quarry	Calculated drill pattern dimensions	K-values used
Hole diameter, inches.	3		
D_e, inches..........	2; 3	2.5	
B, feet..............	6	6	K_B = 30
Pattern..............	Staggered	Staggered (plan B)	
Timing...............	Simultaneous	Simultaneous	
S, feet..............	9	11-12	K_S = 1.8-2
H, feet..............	23-25	9-16-24	K_H = 1.5-2.6-4
J, feet..............	1	2	K_J = 0.3
T, feet..............	5.5-7	4	K_T = 0.7
L, feet..............	22-24	7-14-22	

Plan view:[1]

Example - 4 rows



The quarry uses 7 ft of stemming in holes that are waterfilled and need to be fully charged with gelatin. To calculate T for these holes, K_B could be assumed at 40 which would give a value of 6 ft of stemming. If the gelatin-loaded holes are few, K_B should be $\approx$30 for calculating B of the overall production round. This quarry pattern produces a somewhat ragged box cut because the side holes do not line up.

[1] Numbers indicate millisecond delay.

Quarry No. 2 Explosive Blasting Details

In this quarry, "dry" holes have around 5 ft of water in the bottom and "wet" holes have water to their collars. All of the 3-in boreholes are bottom-loaded with six 2- by 12-in sticks of water resistant 60-percent weight strength gelatin, the sixth stick loaded having an electric blasting cap inserted in its bottom. In dry holes, packaged AN-FO prills are loaded into the hole which is then stemmed with 5.5 to 7 ft of drill cuttings. Wet holes are loaded to within 7 ft of the collar with the water-resistant gelatin, and the remaining 7 ft of hole is stemmed. No toe is present after the blast because of the many bedding planes in the Brassfield Limestone and the bottom loading of holes with gelatin. Subdrilling is at a minimum because any one of a large number of bedding planes can be used as a quarry floor and no difficult toe problems will be encountered. The bottom priming of the charge aids greatly in alleviating toe problems.

Fly rock produced from gelatin loading of holes is greater than that produced by AN-FO loading because of the greater stress-producing capabilities of gelatin and because of the presence of much water in the gelatin-loaded holes. The water acts as a greater stress coupler than air. In one production blast, the hole was bottom-loaded only with gelatin because a large shale zone in the vicinity of the borehole had been blown out by the previous blast. Full loading of the hole would have produced premature lack of explosive detonation confinement with consequent possibility of fly rock violence and airblast. Shale layers will sometimes blow out of the face when the bench is composed of limestone and shale layers and when the holes are loaded to break limestone.

If the packaged AN-FO cartridge breaks open, water can desensitize it. If the water level in the "dry" hole is still above the bottom load of gelatin, the subsequently loaded AN-FO may float in the water and bridge the hole as additional AN-FO cartridges are loaded. This bridging will cause a gap in the total explosive column. Since the rock is highly bedded, the bedding planes serve as excellent channels for water migration. The quarry operator blasts in such a direction that water will be flowing away from the active face.

TABLE 4. - Blasting pattern dimensions for Ohio, Crawford County, Quarry No. 3

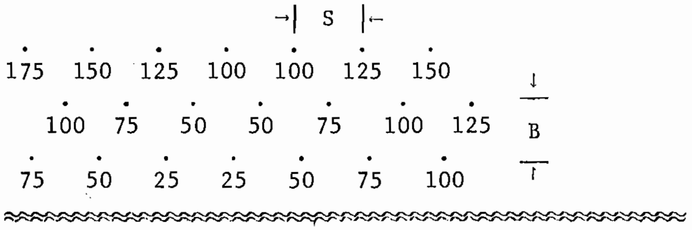
Cut Box

Desired rock progression Expanding flat-bottomed V

	Dimensions used in quarry	Calculated drill pattern dimensions	K-values used
Hole diameter, inches....	7.25		
D_e, inches..............	7.25	7.25	
B, feet..................	12	15	K_B = 25
Pattern..................	Staggered	Staggered (plan B)	
Timing...................	Sequence-simultaneous	Simultaneous	
S, feet..................	21	27-30	K_S = 1.8-2
H, feet..................	47	23-39-60	K_H = 1.5-2.6-4
J, feet..................	5	0 or 5	K_J = 0, 0.3
T, feet..................	12	11	K_T = 0.7
L, feet..................	42	23-39-60 18-34-55	

Plan view:[1]

Example - 3 rows



Let K_B = 25 since AN-FO is used for a very large portion of the borehole. The quarry operator subdrills even though the quarry floor is a major bedding plane because water and mud flow into the hole and raise the borehole bottom level. The water table is high in the area. The operator could expand his pattern and still obtain satisfactory results.

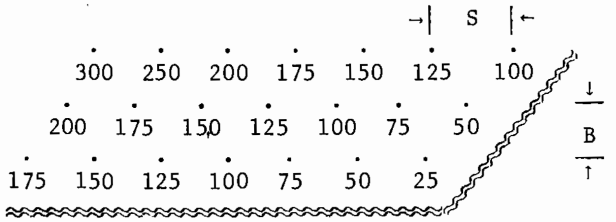
Cut Corner

Desired rock progression Echelon

	Dimensions used in quarry	Calculated drill pattern dimensions	K values used
Hole diameter, inches....	7.25	7.25	
D_e, inches..............	7.25	7.25	
B, feet..................	12	15	K_B = 25
Pattern..................	Staggered	Staggered (plan C)	
Timing...................	Sequence	Simultaneous	
S, feet..................	21	27-30	K_S = 1.8-2
H, feet..................	47	23-39-60	K_H = 1.5-2.6-4
J, feet..................	5	0 or 5	K_J = 0, 0.3
T, feet..................	12	11	K_T = 0.7
L, feet..................	42	23-39-60 18-34-55	

Plan view:[1]

Example - 3 rows



Let K_B = 25 since AN-FO is used for a very large portion of the borehole. The quarry operator subdrills even though the quarry floor is a major bedding plane because water and mud flow into the hole and raise the borehole bottom level. The water table is high in the area. The operator could expand his pattern and still obtain satisfactory results.

[1] Numbers indicate millisecond delay.

Quarry No. 3 Explosive Blasting Details

The rock being quarried is from the Delaware Limestone and Columbus Limestone. The two rock types are similar in composition and are quarried together.

The larger diameter air-flushed, rotary-drilled holes are used. With the larger diameter holes, the burden and spacing can be increased with a decrease in number of drill-rig setups and drill footage. A major bedding plane is the quarry floor. Even though the holes are subdrilled below this bedding plane, the rock below the bedding plane is not thrown out upon blasting. Bedding, jointing, and a high water table create severe water problems. The bedding and joint planes serve as excellent channels for water migration into the boreholes. Compounding the problem is surface mud that flows into the holes after a rain. Even though the major portion of overburden can be stripped off, pockets of mud will exist in the vicinity of many borehole collars. Plugging the hole at the surface helps keep the surface mud out if there is a minimum of overburden.

If the holes stand unused for a long time, they will fill with mud and water. Subdrilling allows some of the mud to settle below the predetermined quarry floor depth. Before the holes are loaded with AN-FO, the hole depths are remeasured, and if mud has built up into the holes, the holes are redrilled or pumped out. The holes are of a diameter too large for the use of air pressure to force the mud and water out.

After the holes have been cleaned, they are loaded as follows:

First and third rows.--Three and one-half lb of gelatin containing an electric blasting cap and the bottom end of the downline of detonating fuse are placed into the borehole. The fuse is cut off at the collar and secured. Next, 50 lb of bulk AN-FO is poured into the hole, and then a 1/2-lb primer is slid down the fuse line. Next, 100 lb of bulk AN-FO is poured into the hole followed by another primer. The hole is loaded in this manner until the explosive is 12 ft from the surface. The remainder of the hole is stemmed. No trunkline is used.

Second row.--The loading is the same as above except that 50 lb of gelatin is placed at the hole bottom rather than 3.5 lb to displace the muck produced from the first and second rows of charges.

The quarry operators fight the water problems and use the inexpensive AN-FO rather than using a slurry or gelatin in hole loading. The quarry operators wish to use the inexpensive AN-FO which produces a large volume of gas and consequently causes a heaving action of the highly bedded rock and a good muck pile displacement. When AN-FO is used under wet conditions, there must be sufficient water protection. Protection can be obtained through the use of a factory-produced cartridged product or a polyethylene borehole liner.

TABLE 5. - Blasting pattern dimensions for Wisconsin, Waukesha County, Quarry No. 4

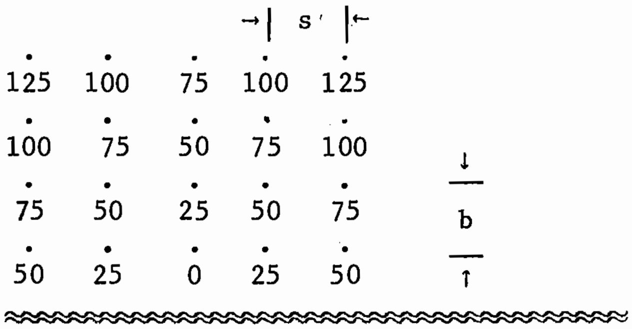
Cut Box

Desired rock progression Expanding V

	Dimensions used in quarry	Calculated drill pattern dimensions	K-values used
Hole diameter, inches.	3		
D_e, inches..........	3	3	
B, feet..............		7.5	
b,[1] feet............	8	10.5	$K_B = 30$
Pattern.............	Square	Square (plan A)	
Timing..............	Sequence	Sequence	
s,[2] feet............	10	10.5-12.5	$K_S = 1\text{-}1.2$
H, feet.............	24-28	11-19-30	$K_H = 1.5\text{-}2.6\text{-}4$
J, feet.............	0	0	$K_J = 0$
T, feet.............	6	5	$K_T = 0.7$
L, feet.............	24-28	11-19-30	

Plan view:[3]

Example - 4 rows



125	100	75	100	125
100	75	50	75	100
75	50	25	50	75
50	25	0	25	50

---

[1] $b = 1.4B = 1.4\ K_B D_e/12$.

[2] $s = K_S b = K_S (1.4\ B)$.

[3] Numbers indicate millisecond delay.

Quarry No. 4 Explosive Blasting Details

The water prevalent throughout the quarry greatly influences the explosive loading technique in quarry No. 4. The holes are bottom-loaded with a 75-percent weight strength water-resistant gelatin. Next, a special powder (40 percent weight strength gelatin) is alternated with packaged AN-FO until 6 ft from the hole collar. The hole is stemmed the remaining 6 ft. The charge column is bottom and two- or three-point primed depending on the wetness of the hole and the amount of AN-FO used.

In this quarry, the Niagara Dolomite faces are vertical joint planes intersecting at nearly right angles. No subdrilling is necessary because a major horizontal bedding plane is used as a quarry floor. Blast patterns are planned such that these geologic features are the final in situ rock surfaces after a production round because of the normal tendency of the rock to break to these surfaces.

Because neighboring property owners complained about air and ground vibrations, the quarry operator uses 3-in holes instead of the previously used 6-in holes, keeping the number of holes/delay the same. The charge weight/delay is reduced and so are the air and ground vibrations. Since going to the 3-in holes, he has had no complaints from neighbors. He has also reduced the burden and spacing and thus created a closer blasting pattern grid. Since the holes are closer together, there is a better chance of drilling more holes in isolated rock blocks that are defined by intersecting joints and bedding planes than was possible with the 6-in holes and larger blasting pattern grid. With the closer grid, the quarry operator obtained better rock fragmentation. He also feels the odd powder loading of the holes, that is, gelatin alternated with AN-FO, gave better rock block fragmentation than AN-FO alone. The gelatin provided a greater shattering action than if the holes were loaded only with AN-FO. The author feels the overriding factor in rock-block fragmentation is the importance of drilling a hole or holes into each rock block so that explosive is available to act within the boundaries of the block. The author has seen rock that was jointed and thick-bedded where rock blocks that were missed in drilling were merely heaved out onto the quarry floor upon blasting. These blocks remained visibly intact unless an ill-defined parting caused the rock block to separate at the parting upon impact on the quarry floor.

TABLE 6. - Blasting pattern dimensions for Wisconsin, Waukesha County, Quarry No. 5

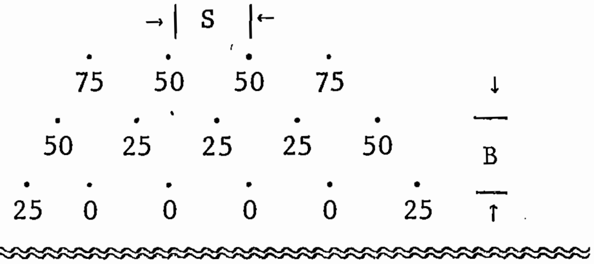
Cut Box

Desired rock progression Expanding flat-bottomed V

	Dimensions used in quarry	Calculated drill pattern dimensions	K-values used
Hole diameter, inches.	3		
D_e, inches..........	2; 3	2.5	
B, feet.............	6	6	K_B = 30
Pattern.............	Staggered	Staggered (plan B)	
Timing..............	Modified simultaneous	Simultaneous	
S, feet.............	9	11-12	K_S = 1.8-2
H, feet.............	12-30	9-16-24	K_H = 1.5-2.6-4
J, feet.............	0	0	K_J = 0
T, feet.............	4-5	4	K_T = 0.7
L, feet.............	12-30	9-16-24	

Plan view:[1]

Example - 3 rows



---

[1] Numbers indicate millisecond delay.

Quarry No. 5 Explosive Blasting Details

Eight to 10, 2- by 16-in. sticks of 50 percent weight strength, good water-resistant, extra dynamite are loaded into the wet portion of the hole. Free running dry blasting agent (AN-FO) is used for the remainder of the hole, and the top 4 or 5 ft of hole is stemmed with drill cuttings. Since the bench is low, the quarry operator only bottom primes. The quarry has been mined in three small benches in Niagara Dolomite, their heights being 12 to 17 ft, 15 to 30 ft, and 30 ft. Two reasons for using small benches are: (1) the low and stable muck pile produced upon blasting can be dug by a front-end loader rather than the cumbersome shovel and (2) fewer drill rods and bits are lost by becoming jammed in joints. The quarry operator would double prime the charge when the bench is 30 ft and higher to assure complete charge-column detonation. Since a bedding plane defines the quarry floor, no subdrilling is necessary.

If the quarry face appears fragmented from a previous blast, the quarry operator will drill the first line of holes 8 to 10 ft from the face instead of 6 ft. By this increase of burden for the first line of holes, the expanding gas produced upon charge detonation moves out the already defined blocks with a minimum of throw.

Water dictates the use of extra dynamite over AN-FO. Water resistant slurries without high strength additives are available however. These slurries are nearly the same as AN-FO in strength and are less expensive than the extra dynamite.

TABLE 7. - Blasting pattern dimensions for Wisconsin, Waukesha County, Quarry No. 6

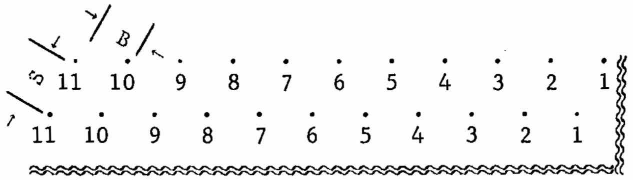
Cut Corner

Desired rock progression Echelon

	Dimensions used in quarry	Calculated drill pattern dimensions	K-values used
Hole diameter, inches.....	5		
D_e, inches................	4.5	4.5	
B, feet....................	13	9.5	$K_B = 25$
Pattern....................	Staggered	Staggered (plan E)	
Timing.....................	Simultaneous	Simultaneous	
S, feet....................	17-18	17-19	$K_S = 1.8\text{-}2$
H, feet....................	40	14-25-38	$K_H = 1.5\text{-}2.6\text{-}4$
J, feet....................	0	0	$K_J = 0$
T, feet....................	10	7	$K_T = 0.7$
L, feet....................	40	14-25-38	

Plan view:[1]

Example - 11 rows

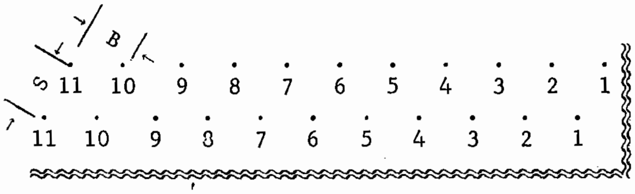


The quarry was using AN-FO supplied in sturdy, wax-sealed, spiral-wound cartridges. The cartridge gives the AN-FO external water protection. Because of the exclusive use of AN-FO, $K_B = 25$ and B would be calculated at 9.5 ft. The quarry used a burden of 13 ft and experienced the difficulty described in the explosive blasting details section.

	Dimensions used in quarry	Calculated drill pattern dimensions	K-values used
Hole diameter, inches.....	5		
D_e, inches................	4.5	4.5	
B, feet....................	13	13	$K_B = 35$
Pattern....................	Staggered	Staggered (plan E)	
Timing.....................	Simultaneous	Simultaneous	
S, feet....................	17-18	23-26	$K_S = 1.8\text{-}2$
H, feet....................	40	19-34-52	$K_H = 1.5\text{-}2.6\text{-}4$
J, feet....................	0	0	$K_J = 0$
T, feet....................	10	9	$K_T = 0.7$
L, feet....................	40	19-34-52	

Plan view:[1]

Example - 11 rows



The problem mentioned before did not occur when the quarry switched from AN-FO to the more dense explosive and kept the blasting pattern the same. Note how closely the calculated burden compares with that used in the quarry when $K_B = 35$ for the dense slurry and special purpose powder.

---

[1] Numbers indicate sequence of charge detonation.

Quarry No. 6 Explosive Blasting Details

The Niagara Dolomite quarry had been using a dry blasting agent supplied in sturdy, wax-sealed, spiral-wound cartridges. Because the first line of holes was too far back from the face, the burden dimension was too large for the use of AN-FO, and the rock did not fragment properly and move out from the backface upon explosive detonation. The quarry has therefore abandoned the exclusive use of cartridged AN-FO. A special purpose, water-resistant, cartridged explosive with a 70-percent cartridge strength and high detonation velocity is used for bottom loading. This explosive is initiated by a primer and has the bottom end of a detonating fuse downline attached. Sock-loaded explosive slurry is used in the wet portion of the borehole and cartridged AN-FO is used in the dry portion of the hole. A primer is slid down the fuse line after several socks of slurry or cartridges of AN-FO are loaded. This slurry is more generally used than AN-FO because of the predominance of water in the holes. Ten feet of stemming are used. Because a major bedding plane serves as the quarry floor, no subdrilling is required.

In view of the higher cost of the slurry and the special purpose cartridged explosive, a larger diameter of AN-FO or a smaller pattern (with AN-FO) could be tried.

TABLE 8. - Blasting pattern dimensions for Wisconsin, Milwaukee County, Quarry No. 7

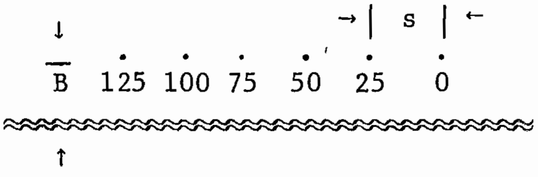
Cut Box

Desired rock progression Expanding V (one-sided)

	Dimensions used in quarry	Calculated drill pattern dimensions	K-values used
Hole diameter, inches.	4		
D_e, inches...........	4	4	
B, feet..............	13	11.5	$K_B = 35$
Pattern..............	Single row	Single row (plan A)	
Timing...............	Sequence	Sequence	
s, feet..............	18	16-19	$K_S = 1-1.2$
H, feet..............	28-33	17-30-46	$K_H = 1.5-2.6-4$
J, feet..............	3	3	$K_J = 0.3$
T, feet..............	10	8	$K_T = 0.7$
L, feet..............	25-30	14-27-43	

Plan view:[1]

Example - 1 row



Some large blocks were seen in the muck pile, possibly because of the larger burden used by the quarry. Blocks defined by joints and bedding planes can remain unbroken if they do not contain explosive.

---

[1] Numbers indicate millisecond delays.

Quarry No. 7 Explosive Blasting Details

Since little or no water was encountered in the earlier quarry operations, dry blasting agents were used almost exclusively. As the Niagara Dolomite quarry was deepened, the large amount of water encountered made a new explosive loading technique desirable. The drill pattern dimensions shown in table 8 apply to the new technique. The hole is bottom-loaded with explosive slurry in socks with the socks being slit. The bottom charge is primed and has the detonating fuse downline attached. Two more slit socks of explosive slurry are lowered followed by a booster slid down the fuse line. Another two slit socks of explosive slurry are loaded followed by another booster. This loading technique is continued in the wet portion of the hole. Depth measurements are made after each sock is loaded. When the dry portion of the holes has been reached, cartridged AN-FO is loaded into the holes until 10 ft from the collar, and this remaining length of borehole is filled with stemming. At the present pit level, explosive slurry is used almost exclusively.

TABLE 9. - Blasting pattern dimensions for Wisconsin, Milwaukee County, Quarry No. 8

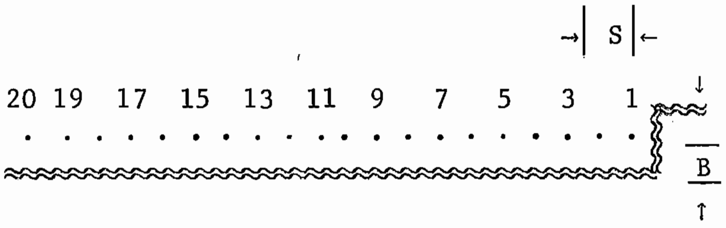
Cut Corner

Desired rock progression Echelon

	Dimensions used in quarry	Calculated drill pattern dimensions	K-values used
Hole diameter, inches.	5.5, 6		
D_e, inches..........	5.5, 6	5.75	
B, feet.............	12	14.5	$K_B = 30$
Pattern.............	Single row	Single row (plan F)	
Timing..............	Sequence	Sequence	
S, feet.............	15	14.5-17.5	$K_S = 1\text{-}1.2$
H, feet.............	25-35	22-38-58	$K_H = 1.5\text{-}2.6\text{-}4$
J, feet.............	0-10	4	$K_J = 0.3$
T, feet.............	10	10	$K_T = 0.7$
L, feet.............	25	18-34-54	

Plan view:[1]

Example - one row



Folding causes an uneven quarry floor. Even though a K_J greater than 0.5 is considered to produce wasted drill footage, the quarry operator is experimenting with large subdrilled depths to provide leeway in building back to a smooth floor. One-row blasting cannot be used for higher benches because the charge weight/delay would be too great which would cause air and ground vibration disturbances to the nearby community. Using several millisecond delays within a single hole could reduce vibrations from large hole blasting such as this.

See footnotes at end of table.

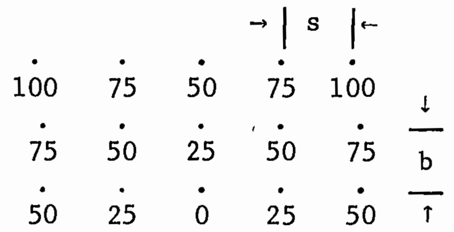
TABLE 9. - Blasting pattern dimensions for Wisconsin, Milwaukee County, Quarry No. 8--Continued

Cut Box Desired rock progression Expanding V

	Dimensions used in quarry	Calculated drill pattern dimensions	K-values used
Hole diameter, inches.	3		
D_e, inches..........	3	3	
B, feet.............		7.5	
b, feet.............	8	10.5	$K_B = 30$
Pattern.............	Square	Square (plan A)	
Timing..............	Sequence	Sequence	
s, feet.............	10	10.5-12.5	$K_S = 1\text{-}1.2$
H, feet.............	25-35	11-19-30	$K_H = 1.5\text{-}2.6\text{-}4$
J, feet.............	0-10	2	$K_J = 0.3$
T, feet.............	5	5	$K_T = 0.7$
L, feet.............	25	9-17-28	

Plan view:[2]

Example - 3 rows



100	75	50	75	100
75	50	25	50	75
50	25	0	25	50

---

[1] Numbers indicate sequence of charge detonation.
[2] Numbers indicate millisecond delay.

Quarry No. 8 Explosive Blasting Details

This quarry operation in Niagara Dolomite produces crushed limestone for concrete and road stone use. A special-purpose, cartridged, water-resistant explosive with 70 percent cartridge strength and high detonation velocity is used for bottom loading and is primed. The detonating fuse downline is attached to this bottom charge. Sock-loaded explosive slurry and cartridged or free-running, premixed AN-FO are loaded alternately. Two or more primers are used with the dry blasting agent always being primed. There has been no trouble with detonation cutoff because of the priming practice. The operator allows time for the dry blasting agent to settle. The holes are always stemmed, and the fuse is cut off at the collar of the hole. By using no trunkline, the quarry operators reduce air vibration which could affect some nearby houses. If the bottom cap malfunctions, a cap can be attached to the downline at the collar of the hole and the charge can be initiated from the top. Rock fragmentation is better when the quarry uses the 3-in charges in the box cut rather than the 5-1/2- or 6-in charges in the corner cut with the larger burden and spacing. The geometry of the cuts, however, makes the charge diameter or burden and spacing comparison difficult.

TABLE 10. - Blasting pattern dimensions for Wisconsin, Racine County, Quarry No. 9

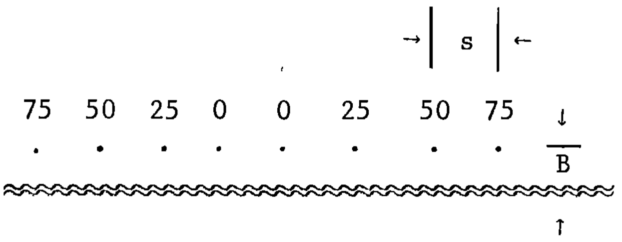
Cut Box

Desired rock progression Expanding V

	Dimensions used in quarry	Calculated drill pattern dimensions	K-values used
Hole diameter, inches.	≈5.5		
D_e, inches...........	5.5	5.5	
B, feet..............	12	11.5	$K_B = 25$
Pattern..............	Single row	Single row (plan A)	
Timing...............	Sequence	Sequence	
s, feet..............	15	16-19	$K_S = 1\text{-}1.2$
H, feet..............	20-50	17-30-46	$K_H = 1.5\text{-}2.6\text{-}4$
J, feet..............	0-10	3	$K_J = 0.3$
T, feet..............	11-12	8	$K_T = 0.7$
L, feet..............	20-40	14-27-43	

Plan view:[1]

Example - 1 row



The quarry operator feels it necessary to subdrill holes up to 10 ft with heavy bottom loading of explosive slurry to prevent toe buildup. Others contend that subdrilling this deeply is wasted drilling.

See footnote at end of table.

TABLE 10. - Blasting pattern dimensions for Wisconsin, Racine County, Quarry No. 9--Continued

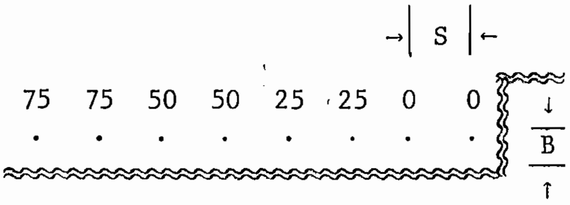
Cut Corner

Desired rock progression Echelon

	Dimensions used in quarry	Calculated drill pattern dimensions	K-values used
Hole diameter, inches.	≈5.5		
D_e, inches..........	5.5	5.5	
B, feet.............	12	11.5	K_B = 25
Pattern.............	Single row	Single row (plan F)	
Timing..............	Sequence	Sequence	
S, feet.............	15	11.5-14	K_S = 1-1.2
H, feet.............	20-50	17-30-46	K_H = 1.5-2.6-4
J, feet.............	0-10	3	K_J = 0.3
T, feet.............	11-12	8	K_T = 0.7
L, feet.............	20-40	14-27-43	

Plan view:[1]

Example - 1 row



[1] Numbers indicate millisecond delay.

Quarry No. 9 Explosive Blasting Details

This quarry operation in Niagara Dolomite produces crushed rock for use as aggregate. The holes are normally bottom-loaded with explosive slurry after the detonating fuse downline containing the primer has been lowered into the hole. The downline is cut off at the collar of the hole. No trunkline of detonating fuse is used because of the fear of air vibration from blasting affecting the nearby populated area. Free-running dry blasting agent is poured into dry holes, and cartridged AN-FO is used in wet holes. When a marked bedding plane is encountered at the bottom of a borehole, however, no heavy bottom priming with the explosive slurry is needed to pull the toe; AN-FO is used exclusively with a primer at the bottom. The holes are stemmed for 11 to 12 ft. The quarry is experimenting with different subdrilling depths so that the rolling (folded) quarry floor formed upon blasting can be filled to produce a level floor at the desired depth.

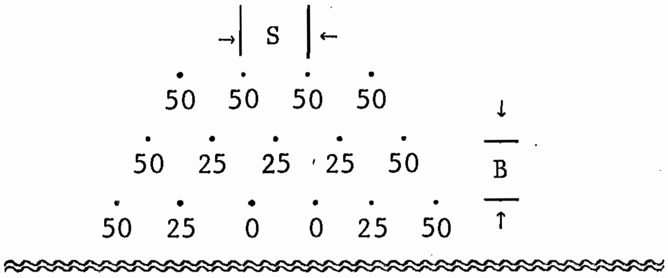
TABLE 11. - Blasting pattern dimensions for Minnesota, Olmsted County, Quarry No. 10

Cut Box   Desired rock progression Expanding flat-bottomed V

	Dimensions used in quarry	Calculated drill pattern dimensions	K-values used
Hole diameter, inches.	3		
D_e, inches...........	2.5, 3	2.75	
B, feet..............	6-7	7	K_B = 30
Pattern..............	Staggered	Staggered (plan B)	
Timing...............	Simultaneous-sequence	Simultaneous	
S, feet..............	6-7	12.5-14	K_S = 1.8-2
H, feet..............	30	11-18-28	K_H = 1.5-2.6-4
J, feet..............	0	0	K_J = 0
T, feet..............	4-5	5	K_T = 0.7
L, feet..............	30	11-18-28	

Plan view:[1]

Example - 3 rows



Upon blasting, the close spacing of holes of the same delay interval caused premature breakage between these holes which produced boulders and slabs in the burden area. The spacing between the same delay periods should be expanded.

---

[1] Numbers indicate millisecond delay.

Quarry No. 10 Explosive Blasting Details

Rock being quarried is in the Oneota Dolomite member for concrete use. Water-resistant gelatin (2-1/2- by 16-in) is loaded into the wet portion of the borehole with an electric blasting cap for bottom initiation. AN-FO is poured into the dry portion of the hole. If moderate water problems are encountered along the full length of borehole or if the rock is extremely hard and unbroken, the gelatin charges are alternated with the AN-FO in the uppermost 12 ft. An electric blasting cap is used near the top of the powder column to assure complete detonation of the column. Severe water problems would dictate the elimination of AN-FO. The holes are stemmed for 4 to 5 ft with drill cuttings. No subdrilling is necessary because a bedding plane is used for the quarry floor. Good breakage in the toe area results from the presence of the bedding plane and the bottom load of gelatin. On one occasion, the free flowing AN-FO appeared at the bottom of the face while being poured into a borehole. In this case, a large fracture produced by a previous blast extended from the vertical free face to the borehole and provided a migration channel for the AN-FO. Loading the AN-FO into a plastic liner or using cartridged AN-FO for loading would eliminate this loss of blasting agent, but the problem of lack of confinement would still be present.

TABLE 12. - Blasting pattern dimensions for Minnesota, Fillmore County, Quarry No. 11

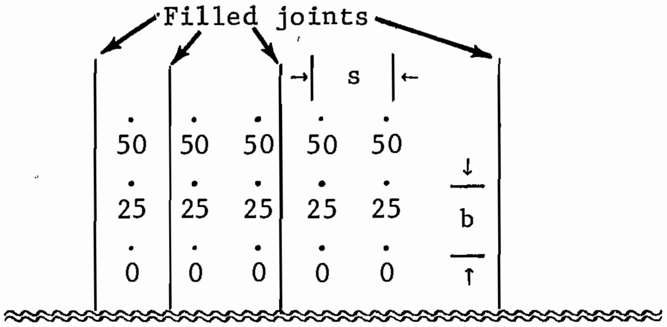
Cut Box

Desired rock progression Expanding V

	Dimensions used in quarry	Calculated drill pattern dimensions	K-values used
Hole diameter, inches.	4.75		
D_e, inches...........	4.75	4.75	
B, feet..............	9	10	$K_B = 25$
b, feet..............	9	14	
Pattern..............	Square	Square (plan A)	
Timing...............	Simultaneous	Sequence[1]	
s, feet..............	7	14-17	$K_S = 1\text{-}1.2$
H, feet..............	75	15-26-40	$K_H = 1.5\text{-}2.6\text{-}4$
J, feet..............	0	0	$K_J = 0$
T, feet..............	10-12	7	$K_T = 0.7$
L, feet..............	75	15-26-40	

Plan view:[2]

Example - 3 rows



A spacing less than the burden and simultaneous initiation of holes in each row explain why large unbroken boulders were produced upon blasting. The small spacing and simultaneous initiation of holes in each row caused premature breaking between holes in rows which reduced borehole pressure and expanding gas action in the rock; thus, boulders and slabs resulted away from the vicinity of the boreholes. The excessive collar distance also assured the operator of a blocky shot. The quarry operator has recently gone to a wider spacing which is near that predicted by the empirical formulas.

---

[1] Sequence timing is used with plan A.

[2] Numbers indicate millisecond delay. In this view, b = B and s = S.

Quarry No. 11 Explosive Blasting Details

The rock being quarried is in the Galena Limestone formation. The lower three-fourths of the 75-ft bench is a massive limestone, and the top one-fourth is composed of thin-bedded limestone and shale. Caves are also present in the upper part of the rock. Since no water is present, premixed AN-FO is poured into the boreholes after a stick of dynamite and electric blasting cap are placed in the hole bottom. (A stick of dynamite is generally considered an inadequate primer for AN-FO.) Ten to 12 ft of stemming are placed at the collar of the holes since the top portion of the rock is rubbly, and top explosive loading would produce excessive fly rock. Because a bedding plane is used as the quarry floor, no subdrilling is done.

The following problems were encountered:

1. When the quarry operator blasted in the thin limestone and shale layers and caves were close to the borehole(s), the rock broke into the cave before complete charge-detonation. Further rock breakage was reduced.

2. Large amounts of explosives were lost into caves when the explosive was loaded into a borehole that intersected a cave.

3. A pinnacle of rock is separated from the main rock body by a cave and filled joint. If the pinnacle contains no explosive and the main rock body is blasted, this pinnacle can shift forward intact upon the basal bedding plane.

4. When a borehole intersects a joint, the filled joint poses more threat to loss of explosives or to reduced explosive detonation confinement than does the tight joint.

The quarry operator and author propose the following possible reasons for the above problems and suggestions for improvement:

1. When holes are drilled near caves and loaded with explosives, stress action and expanding gases from explosive detonation break the rock at its weakest point into the caves. The reduced borehole pressure and lessened expanding gas action from explosive detonation limits further rock breakage. When possible, drilling holes for charge loading at a distance from known caves has helped lessen this problem.

2. When a hole intersects a cave, explosives loaded into the hole can be lost into the cave. Drilling into caves can be avoided when a consistent cave-pattern is present and has been determined from previous drill holes. The following procedure has provided satisfactory blasting results when a hole is drilled through a cave and continued into the rock below: The downline, or length of detonating cord slightly longer than the borehole depth, is lowered into the hole with the primer attached to the downline bottom. The bottom of the hole is loaded with explosives until the top of the charge column is near the bottom of the cave. The hole is filled with sand or drill cuttings, or stemmed, until the cave bottom is reached. The hole is plugged

at the cave top, loaded with explosives, and then stemmed. The downline should have primers spaced up the hole to assure complete detonation of the charge.

3. If the large pinnacle contains no explosive, the pinnacle will not be fragmented and may be displaced intact by the movement of fragmented rock and expansion of gases upon blasting in the main rock body. If the basal bedding plane is not well defined, no displacement of the rock pinnacle is possible. Holes should be drilled into the pinnacle of rock and also into the solid rock behind the pinnacle. The pinnacle would be blasted first, with the solid rock behind the pinnacle blasted in delayed sequence. This delayed sequence in blasting would allow the broken rock from the pinnacle to be displaced enough to provide room for displacement of broken rock from the main rock body.

4. The filled joints in this quarry cause more loss of explosive and explosive detonation confinement than do the tight joints. Drill rods and bits jam easily in the filled joints. Because the filled joints contain large amounts of soft clay and a few small open channels, explosives can be lost into the channels, and the clay provides less explosive detonation confinement than does the solid rock bounding the tight joint. Filled joints are surveyed and drill holes are spaced so as to avoid as much as possible having holes in a production round intersect the filled joints.

TABLE 13. - Blasting pattern dimensions for Minnesota, Wabasha County, Quarry No. 12

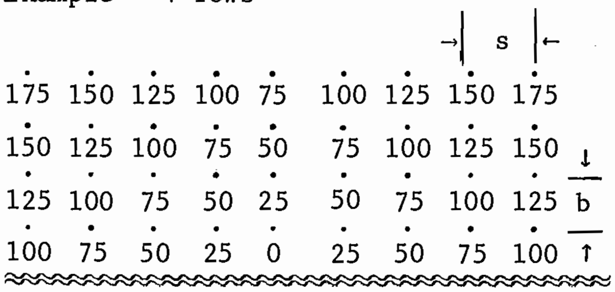
Cut Box

Desired rock progression Expanding V

	Dimensions used in quarry	Calculated drill pattern dimensions	K-values used
Hole diameter, inches.	3		
D_e, inches..........	3	3	
B, feet.............		6	
b, feet.............	6-7	8.5	$K_B = 25$
Pattern.............	Square	Square (plan A)	
Timing..............	Sequence	Sequence	
s, feet.............	6-7	8.5-10	$K_S = 1\text{-}1.2$
H, feet.............	45-50	9-16-24	$K_H = 1.5\text{-}2.6\text{-}4$
J, feet.............	0	0	$K_J = 0$
T, feet.............	8	4	$K_T = 0.7$
L, feet.............	45-50	9-16-24	

Plan view:[1]

Example - 4 rows



175	150	125	100	75	100	125	150	175
150	125	100	75	50	75	100	125	150
125	100	75	50	25	50	75	100	125
100	75	50	25	0	25	50	75	100

---

[1] Numbers indicate millisecond delay.

Quarry No. 12 Explosive Blasting Details

The rock is quarried from a 45 to 50 bench in the Prairie du Chien Dolomite formation. The bench is composed of massive dolomite except for the top 10 to 15 ft where the rock is thin-bedded. Quartz blocks and joints filled with clay are present in the formation. In drilling the rock, the filled joints are avoided whenever possible for reasons presented in the discussion of Quarry No. 11. Because of marked bedding near the top, slabs sliding into the top portion of the hole while the bottom portion of the hole is being drilled cause the rods and bit to jam. The drill rods and bit also bind in fractures present from previous blasts, especially near the face. To recover the rods and bit, the drill bit has a cutting edge on top so that the bit can be drilled back out of the hole.

Since no water is present, the 3-in holes are bottom primed with a stick of dynamite and then loaded with free-running AN-FO. Eight feet of stemming are used because of the thin-bedded rock near the top surface. Any less stemming produced too much fly rock which endangered the nearby crusher and shop. The slabs near the top surface remain unbroken upon blasting and are shattered by a 2-ton headache ball.

Several problems were encountered in blasting. The quartz blocks were thrown out onto the quarry floor unbroken. Use of 3-in holes in a high bench with AN-FO charges produced a toe upon blasting. A lift shot was made to break the toe that was partially buried under muck. A 2-ton headache ball and shovel were used to further break and remove the rock that had formed the toe. Even though a bedding plane is used as the quarry floor, the operator may do well to experiment with subdrilling as a replacement for lift blasting because of the high cost of this type of blasting. A high detonation pressure primer for AN-FO should be used instead of a stick of dynamite. Explosive column cutoff was experienced near the top of the holes because of the small diameter boreholes, the high bench, the explosive being only bottom primed, and the top slabby section of rock. Since the column was only bottom primed, the rock slabs near the top of the hole shifted across the small diameter borehole before the whole column of explosive was completely detonated. The author suggests that the explosive column be multiple-primed.

SUMMARY

The presented empirical formulas may be applied to drilling and blasting pattern design as a good first approximation. When geologic structure, such as bedding, jointing, folding, and caves, as well as explosive properties and field performance characteristics are accounted for in a manner suggested by the research, the drill pattern dimensions as calculated by these formulas compare favorably with actual examples of blasting patterns used in the quarries visited. Based on the good correlation between actual blasting practices and the calculated blasting design, design changes are suggested for those quarries where problems are occurring.

There were a number of poor blasting practices observed which should be avoided or corrected. Some examples of these are as follows:

1. The burden dimension should never exceed the spacing dimension except when presplitting.

2. A number of quarries use a disproportionately high bench. Remedies for this disparity are multiple priming, a larger charge diameter, or a lower bench.

3. External protection must always be given to dry blasting agents when using them in wet conditions. This protection was not provided in many instances.

4. Building out of a wet borehole with undersized cartridges may enable the operator to use the less expensive AN-FO for a major portion of the boreholes, but toe problems may develop because of the lighter bottom loading.

5. In some instances, AN-FO was inadequately primed. A high detonation pressure primer should be used with AN-FO.

REFERENCES

1. American Geological Institute. Dictionary of Geological Terms. Doubleday and Company, Inc., Garden City, N.Y., 1962, 545 pp.

2. Ash, R. L. Cratering and Its Application in Blasting. Unpublished report for Dept. of Min. and Civil Engr., Univ. of Minn., July 1970.

3. _____. The Mechanics of Rock Breakage, Parts I through IV. Pit and Quarry, v. 56, Nos. 2, 3, 4, and 5, 1963, pp. 98-100, 112; 118-123; 126-131; 109-111, 114-118.

4. Ash, R. L., C. J. Konya, and R. R. Rollins. Enhancement Effects From Simultaneously Fired Explosive Charges. Soc. of Min. Eng. (AIME), Trans., v. 244, December 1969, pp. 427-435.

5. Atchison, Thomas C., and Joseph M. Pugliese. Comparative Studies of Explosives in Limestone. BuMines Rept. of Inv. 6395, 1964, 25 pp.

6. Belland, J. M. Structure as a Control in Rock Fragmentation, Carol Lake Iron Ore Deposits. Canadian Min. and Met. Bull., v. 59, No. 647, March 1966, pp. 323-328.

7. Bowles, Oliver. Limestone and Dolomite. BuMines Inf. Circ. 7738, 1956, 29 pp.

8. Dick, Richard A. Factors in Selecting and Applying Commercial Explosives and Blasting Agents. BuMines Inf. Circ. 8405, 1968, 30 pp.

9. Duvall, Wilbur I., Charles F. Johnson, Alfred V. C. Meyer, and James F. Devine. Vibrations From Instantaneous and Millisecond Delayed Quarry Blasts. BuMines Rept. of Inv. 6151, 1963, 34 pp.

10. Gregory, C. E. Explosives for Engineers. University of Queensland Press, St. Lucia, Queensland, Australia, 1966, 145 pp.

11. Grimshaw, G. B., and R. Watt. The Current Scene in Quarry Blasting. The Quarry Managers' Journal, v. 55, No. 4, April 1971, pp. 119-129.

12. Langefors, U., and B. Kihlstrom. The Modern Technique of Rock Blasting. John Wiley & Sons, Inc., New York, 1963, 405 pp.

13. Nicholls, Harry R., and Wilbur I. Duvall. Effect of Charge Diameter on Explosive Performance. BuMines Rept. of Inv. 6806, 1966, 22 pp.

14. Pugliese, Joseph M. The Effects of Geology on Explosive Blasting in Limestone and Dolomite Quarries (abstract). The Geological Soc. of America, Circ. 2, v. 2, No. 7, October 1970, p. 659.

15. Yancik, J. J. Monsanto Blasting Products AN/FO Manual: Its Explosive Properties and Field Performance Characteristics. Monsanto Company, St. Louis, Mo., 1969, 37 pp.

U.S. GOVERNMENT PRINTING OFFICE:1972 O—472-190

E/MJ

Reprinted from ENGINEERING AND MINING JOURNAL

Model rock blasting measures effect of delays and hole patterns on rock fragmentation

O. R. Bergmann, F. C. Wu, and **J. W. Edl,**
Experimental Station Laboratory, Polymer Intermediate Dept.
E. I. Du Pont de Nemours & Co., Wilmington, Del.

Model rock blasting measures effect of delays and hole patterns on rock fragmentation

O. R. Bergmann, F. C. Wu, and **J. W. Edl,**
Experimental Station Laboratory, Polymer Intermediate Dept.
E. I. Du Pont de Nemours & Co., Wilmington, Del.

IN INSTRUMENTED MODEL ROCK BLASTING EXPERIMENTS in granite blocks, best fragmentation results were obtained when delays between holes were 1 to 2 milliseconds per ft of burden and when a rectangular shothole pattern was used with spacings larger than the burden. Effective fragmentation in multiple hole blasts seemed to depend primarily on the full development of the crack network around each hole before the charge in the next hole was detonated. The test results showed that simultaneous or almost simultaneous initiation of shotholes in bench blasting resulted in poor fragmentation.

Over the past 20 years, practice in all types of rock blasting operations has firmly established the technique of delayed blasting using millisecond delay intervals between holes and rows of holes. The main advantages of millisecond delay blasting are improved rock fragmentation and reduced ground vibrations.

Numerous reports on this subject have appeared in the literature over the years, and a selection of references in this field is included at the end of this article. However, most of the reports have been qualitative with regard to fragmentation. In particular, there is a lack of information about the effects of very short and precisely controlled delay times on fragmentation in rock blasting and about the effects of different hole patterns.

Recently, Langefors reported results of blasting experiments on a very small scale in "Lucite" acrylic resin,[19] and his work indicated that rectangular borehole patterns having larger spacings than burdens produced considerably better fragmentation than square patterns in which spacings and burdens were equal. However, the properties of Lucite acrylic resin are considerably different from those of typical rocks, and it was highly uncertain whether the results obtained in a plastic such as Lucite could be applied to blasting in natural rock formations.

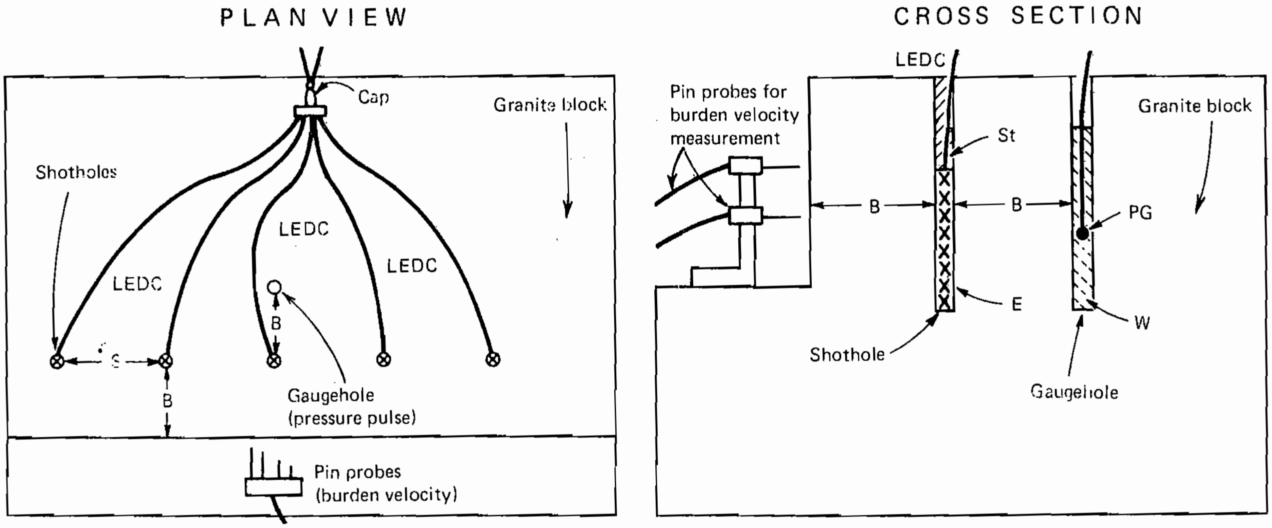
The work described here attempted to determine quantitatively the effect of very short delay times and of different shothole patterns on fragmentation in rock blasting. The information was obtained from relatively large scale model blasting experiments in homogeneous blocks of granite. This approach was taken in preference to field tests in quarries in order to obtain quantitative determination of fragment size distributions resulting from the blasts, which would have been very difficult in field tests.

Using crack-free homogeneous blocks of granite also provided a better basis for comparing results from separate experiments made under different shooting conditions, because the unpredictable effects of preexisting cracks in normal rock formations were eliminated. Granite was chosen because it is a typical representative of hard rocks encountered in many operations in the field, and it was reasonable to expect that results obtained in granite could realistically be applied to many actual blasting situations.

Tests shot in Vermont granite

The model blasting experiments were carried out as single-row bench blasting shots on homogeneous granite blocks obtained from the E. L. Smith Quarry in Barre, Vt. The granite used had a compressive strength of about 30,000 psi, a tensile strength of about 1,200 psi, a density of 2.66 g per cc, and a sonic velocity of 5,200 m per sec. Some of the experimental techniques used in the work were similar to those developed

FIG. 1—SCHEMATIC OF BOREHOLE ARRANGEMENT AND CHARGE INITIATION



B = Burden distance
S = Spacing between shotholes
ST = Stemming
E = Explosive
W = Water
PG = Pressure gauge
LEDC = Low energy detonating cord

in a previous model rock blasting study by the authors.[20]

A critical consideration in the design of the experiments was to make the significant geometric ratios comparable to those used in field blasting operations. Therefore, all experiments used columnar explosive charges in boreholes that had a reasonably high length-to-diameter ratio (about 40) and burden-to-borehole-radius ratios between 50 and 70, corresponding to typical field blasting conditions.

The shots were made in rock blocks of sufficient size to simulate reasonably well the presence of a semi-infinite rock mass in back of the shotholes and to the sides. To meet all of these requirements, it was necessary to work with relatively large blocks of rock, measuring in most cases about 80 in. x 80 in. x 50 in. and weighing about 15 tons each. Each block was used only once to make certain that results from a second test were not influenced by the presence of cracks produced in preceding shots.

On all shots, measurements were made of 1) the fragment size distribution of the broken rock resulting from the blast, 2) burden velocity at the free face opposite the shothole, and 3) "gauge-hole pressure" produced in water-filled boreholes at one burden distance behind the shothole.

The blasting technique simply consisted of using a single cap to simultaneously initiate lines of "low energy" detonating cord ("LEDC" from Ensign Bickford Co., detonation velocity 7,100 m per sec) leading to each shothole (Fig. 1). By adjusting the length of cord to each hole, timing of the detonations in the holes could be controlled very accurately.

The explosive used in the shotholes was in all cases EL-506C, a plastic PETN-base explosive having a density of 1.48 g per cc and a detonation velocity of about 6,900 m per sec.

Two sets of pin probes, separated by a small distance from two grounded metal plates that were cemented to the rock on the vertical bench face opposite the center shothole face, were used in conjunction with an oscilloscope circuit to determine burden velocity from distance-time records.

At one burden distance behind one of the shotholes, the rock contained a water-filled "gaugehole," and a piezoelectric Tourmaline pressure gauge (from Crystal Research Corp.) was placed halfway down the hole and connected to an amplifier-oscilloscope system to measure the pressure pulse produced in the water-filled gaugehole by the blast.

The blocks of rock were placed partially inside a "rock catcher"—a simple structure made of plywood and lined with heavy canvas curtains. The purpose of the rock catcher was to collect all the rock fragments resulting from a blast for subsequent determination of the fragment size distribution of the broken rock by screening and weighing.

The shotholes were arranged in either a square pattern of 13.0-in. burden and 13.0-in. spacing (S/B = 1.0), a rectangular pattern (I) of 11.0-in. burden and 15½-in. spacing (S/B = 1.41), or a rectangular pattern (II) of 9.2-in. burden and 18.4-in. spacing (S/B = 2.0); see accompanying table. The third of these arrangements is of particular interest because many commercial blasts are shot using an effective S/B ratio of 2, drilling a square pattern but shooting in "echelon" or "double echelon."

Bench height for all shots was the same and all shots used the same powder factor. Delays ranged from precisely simultaneous initiation of all holes to about twice the delay ratio recommended by Langefors[15] for commercial blasts.

In one experiment, delay times were chosen to permit the stress wave to travel from one hole to the next before detonation in the neighboring hole was initiated. In other experiments, the delay between holes was based on the time required for cracks to propagate between holes.

(Crack propagation velocities had been determined previously in separate experiments[20] and had been found to have typical values of about 1,400 m per sec in granite at several inches from the shothole.)

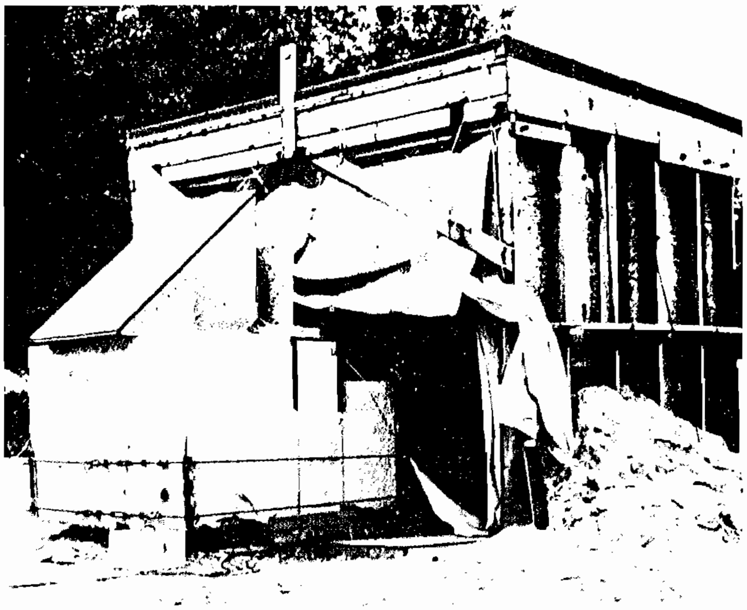


Fig. 2—Model blasting facility is designed to capture rock fragments for determination of fragment size distribution.

FIG. 3—EFFECT OF DELAY TIME BETWEEN SHOTHOLES ON AVERAGE FRAGMENT SIZE

(Same powder factor – burden x spacing – for all shots)

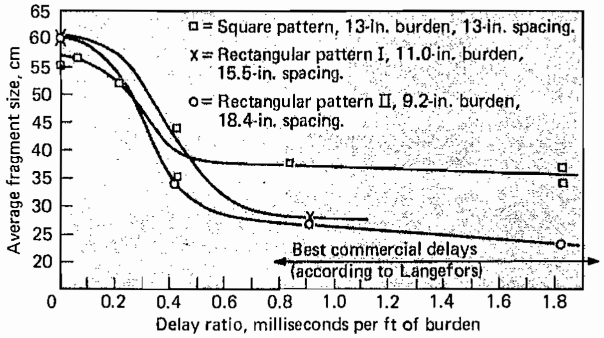


Fig. 4—Bench face of a granite block after typical blast.

The experimental results are listed in the accompanying table and graphed in Fig. 3, which plots the influence of delay time (expressed as "delay ratio" in milliseconds per ft of burden) on the average rock fragment size for the square pattern and the two rectangular patterns.

As is indicated, simultaneous or almost simultaneous shooting produces poor fragmentation (large fragment size) for both square and rectangular shothole patterns. This is particularly well illustrated in Fig. 5 and Fig. 6, which show that large parts of the bench encompassing the burden of several shotholes were removed as single pieces. Such pieces indicate that the interaction of the initial shock waves between holes, such as is obtained by simultaneous or almost simultaneous initiation of several shotholes, does not aid in obtaining good overall fragmentation.

On the contrary, simultaneous initiation of holes seemed to produce a more uniform stress distribution in the rock, resulting in a smaller number of well defined fractures and therefore poorer fragmentation.

In simultaneously initiated shots, it might have been expected that fractures would form midway between shotholes at right angles to the bench face. Examination of large fragments such as the one in Fig. 5 showed no indication of preferential crack formation in these areas and practically all observed cracks were related to the radial crack system emanating from each shothole.

There was some indication, however, that the new bench face that resulted from a blast was smoother and more regular when the holes were initiated simultaneously or almost simultaneously. This is in agreement with generally recommended practice in "smooth-blasting" and "presplitting."

The data in Table 1 and Fig. 3 show clearly that fragmentation improves greatly when the crack network around one shothole is allowed to develop fully, and cracks are permitted to open up somewhat, before the explosive in the next hole is detonated. There is a large decrease in fragment size (better fragmentation) when the delay is increased to about twice the crack propagation time across the burden. Further increases in delay time give only small additional improvements in fragmentation.

The contrast in fragmentation between simultaneous or almost simultaneous initiation and sufficiently delayed initiation of holes is clearly illustrated by comparing the Figs. 5 and 6 photographs with Figs. 7 and 8.

As indicated by the curves in Fig. 3, the trend is quite similar for square and rectangular shothole patterns. The curves also show that rectangular shothole patterns (spacing larger than burden) will produce considerably smaller fragments than square patterns when the proper delays are used. These results are in agreement with results from blasting experiments that were made on a very small scale in Lucite acrylic resin.[19]

The data in Table 1 do not indicate a strong influence of delay time on burden velocity for a given shothole pattern, but there is a suggestion that simultaneous shooting results in higher velocities. Delay time does not appear to significantly influence the measured gaugehole pressure.

In conclusion, the results of the work described above showed that interaction between primary stress waves from adjacent holes did not noticeably contribute to rock fragmentation in blasting. Effective fragmentation in bench blasting with a row of holes seemed to depend primarily on the full development of the crack network around each hole before the charge in the next hole was detonated. The use of extremely short delay times between holes therefore resulted in poor fragmentation.

Best fragmentation results were obtained when delays between holes were 1 to 2 milliseconds per ft of burden, and these delay times are in agreement with earlier recommendations of Langefors,[15] which were based mainly on qualitative observations from field blasts. The present work also showed that rectangular patterns with spacings larger than burdens gave considerably better fragmentation than square patterns when the proper delays were used. ☐

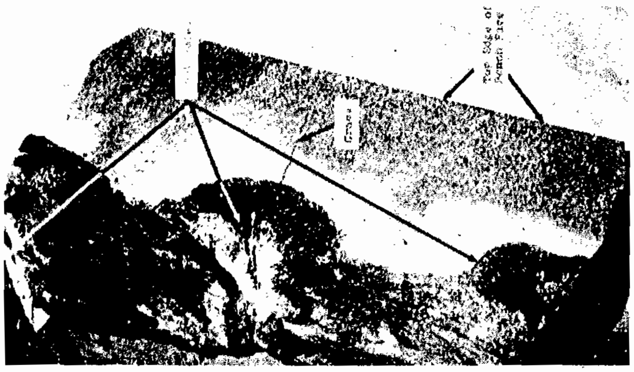


Fig. 5—Poor rock fragmentation resulting from simultaneous initiation of holes for square pattern RB21.

Fig. 6—Poor rock fragmentation resulting from almost simultaneous initiation of blasts in holes for square pattern RB26.

Fig. 7—Good fragmentation resulting from delayed initiation of holes (about 1 millisecond per ft of burden), square, RB28.

Fig. 8—Excellent fragmentation with delayed initiation using rectangular pattern, 2 milliseconds per ft of burden, RB82.

Table 1—Effect of delay time and shothole pattern on fragmentation

(Granite, five shotholes in one row, all shots 12-in. bench height, ⅜-in.-dia x 15-in.-deep shotholes, 36.05 g EL-506C explosive per hole)

Shot No.	Burden B (in.)	Spacing S (in.)	$\frac{S}{B}$	Delay between holes (μsec)	Delay ratio (ms/ft of burden)	Basis for selection of delay	Av. fragment size (cm)	Burden velocity (m/sec)	Measure peak gaugehole pressure for No. 3 hole (psi)
Square pattern									
RB-21	13.0	13.0	1.0	0	0	Simultaneous shot	55.0	5.7 top 6.5 bottom	1,800
RB-26	13.0	13.0	1.0	62.3	0.058	Time for stress wave to get from one hole to next (stress wave velocity 5,200 m/sec)	56.5	3.9 top 4.4 bottom	–
RB-34	13.0	13.0	1.0	228	0.211	Time for cracks to propagate from one hole to next (crack velocity about 1,400 m/sec)	52.0	5.7 top 3.6 bottom	1,550
RB-40 RB-45	13.0	13.0	1.0	456	0.422	2 x time for cracks to propagate from one hole to next	44.4 35.0	– –	– –
RB-28	13.0	13.0	1.0	906	0.840	Commercial delay ratio (Langefors)	37.5	— top 5.0 bottom	
RB-41 RB-50	13.0	13.0	1.0	1,960	1.82	2 x commercial delay ratio (Langefors)	36.4 34.0	– 7.8 top	1,115,632 (cracks?)
Rectangular pattern I									
RB-49	11.0	15.5	1.41	0	0	Simultaneous shot	60.0	–	1,560
RB-51	11.0	15.5	1.41	835	0.915	Commercial delay ratio (Langefors)	28.0	7.8 top	1,420
Rectangular pattern II									
RB-52	9.2	18.4	2.0	0	0	Simultaneous shot	60.0	9.8 top 6.1 bottom	2,370
RB-81	9.2	18.4	2.0	322	0.420	2 x time for cracks to propagate from hole to free face (crack velocity about 1,400 m/sec)	34.2	8.7 top 6.4 bottom	2,790
RB-53	9.2	18.4	2.0	700	0.912	Commercial delay ratio (Langefors)	27.0	7.3 top 4.6 bottom	2,640
RB-82	9.2	18.4	2.0	1,400	1.82	2 x commercial delay ratio (Langefors)	22.6	6.4 top —bottom	2,320

References

1) Hancock, J. and Taylor, W., "Short Delay Detonators—Their Use in Blasting Practice," MINE AND QUARRY ENG., June 1948.
2) Fish, B.G. and Hancock, J., "Short Delay Blasting," MINE AND QUARRY ENG., Nov. 1949.
3) Johansson, C.H. and Langefors, U., "Short Delay Blasting in Sweden," MINE AND QUARRY ENG., pp 287-293, Sept. 1951.
4) Agnew, W.G., "Blasting Raise Rounds with Millisecond Delays," MINING CONGRESS JOURNAL, pp 70-71, April 1949.
5) Agnew, W.G., "More About Blasting Raise Rounds," MINING CONGRESS JOURNAL, pp 30-32, Oct. 1949.
6) Wright, F.D., "Millisecond-Delay Blasting of Bench Rounds," MINING CONGRESS JOURNAL, p 51, June 1953.
7) McCormick, R.F. and Hancock, J., "Millisecond Delay Blasting in Rippings and Drifts," paper presented at meeting of Mining Institute of Scotland at the Royal Tech. Inst., Glasgow, Sept. 1953.
8) Larby, W.G., "Short Delay Blasting," INDIAN MINING JOURNAL, pp 9-16, May-June 1954.
9) Habbel, F., "Theory of Blasting with Millisecond Ignitors," GEOL. EN MIJNBOUW, pp 118-119, April 1954.
10) Baule, H., NOBELHEFTE, pp 132-150, Sept. 1955.
11) Habbel, H.G., NOBELHEFTE, pp 40-44, Jan. 1956.
12) Ito, I., "A Study on the Mechanism of Millisecond Delay Blasting," MEM. FAC. ENG., Kyoto Univ., 149-161, 1956.
13) Hahn, L. and Christmann, W., NOBELHEFTE, pp 1-35, Jan. 1958.
14) Mecir, R. and Valek, D., "The Question of Optimum Timing in Millisecond Delay Blasting of Ores," International Symposium on Mining Research, Vol. II, University of Missouri School of Mines & Metallurgy, US Dept. of Interior, Bureau of Mines, Rolla, Mo., Feb. 22-25, 1961.
15) Langefors, U. and Kihlstrom, B., *The Modern Technique of Rock Blasting*, John Wiley & Sons, Inc., New York, 1963.
16) Obert, L., "Bureau of Mines Investigation of Vibration Produced by Quarry Blasting," paper presented at 46th Annual Convention of the National Crushed Stone Assn., Miami Beach, Fla., Jan 29-Feb. 1, 1963.
17) Duvall, W.I., Johnson, C.F., Meyer, A.V.C., and Devine, J.F., "Vibrations from Instantaneous and Millisecond-Delayed Quarry Blasts," Bureau of Mines Report of Investigation RI-6151, 1963.
18) *Neuzeitliche Sprengtechnik*, edited by G. Biermann, Bauverlag GmbH-Wiesbaden, Berlin, 1966.
19) Langefors, U., "Fragmentation in Rock Blasting," paper presented at the VII Symposium on Rock Mechanics, The Pennsylvania State University, University Park, Pa., June 14-16, 1965.
20) Bergmann, O.R., Edl, J.W., and Wu, F.C., "Model Rock Blasting—Effect of Explosive Properties and Other Variables on Blasting Results," paper to be published in the INTERNATIONAL JOURNAL OF ROCK MECHANICS AND MINING SCIENCES.

Acknowledgments—The authors would like to thank D. L. Coursen, C. G. Rudershausen, C. O. Davis, and H. F. Ring for their continued encouragement during this project. Thanks are also due to Al Ashenfelter, Bob Burns, and Jerry Rusk for their assistance in carrying out the experimental work.

E/MJ

ENGINEERING AND MINING JOURNAL

Printed in U.S.A.