A CONCEPT OF ROW CRATER ENHANCEMENT

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INTRODUCTION

Linear craters formed by the simultaneous detonation of a row of buried explosives will probably have a wider application than single charges in the explosive excavation of engineering structures. Most cratering experience to date has been with single charges, and an analytical procedure for the design of a row of charges to excavate a crater with a specified configuration has been lacking. There are no digital computer codes having direct application to a row of charges as there are for single charges. This paper derives a simple relationship which can be used to design row charges with some assurance of achieving the desired result and with considerable flexibility in the choice of explosive yield of the individual charges.

BACKGROUND

A characteristic of row craters is that their width [W_a] and depth [D_{ar}] are generally larger than the diameter [$2R_a$] and depth [D_a] of a single crater excavated by a charge equal in yield to one of the charges in the row. This characteristic is called enhancement, and the size of a row crater can be expressed in terms of enhanced single crater dimensions. Because enhancement increases as the charge spacing is decreased, the size of a row crater can be altered by changing the layout of the charges rather than their yield. This concept found particular application in the design of detonation programs for the Interoceanic Canal Studies [IOCS] where, in response to potentially severe ground shock hazards, the total yield of a number of critical detonations was reduced by employing relatively closely spaced charges.

It became apparent in developing the nuclear excavation technology for the IOCS that the results of existing row crater experience were too inconsistent for direct quantitative application to the design of detonation programs. Fig. 1 shows the dimensions of several of these experimental row craters as a function of charge spacing and relative to single crater dimensions. It was primarily in response to the need of the IOCS program that an attempt was made to arrive at a quantitative rule relating enhancement and spacing.

The successful development of a relationship between enhancement and spacing would mean that a row charge design could be based on single crater dimensions, and these dimensions can be acquired either from calibration shots or from the computational techniques currently in use at institutions such as the Lawrence Radiation Laboratory.

This paper also presents the preliminary results of an experimental program of row cratering designed to test the dependence of enhancement on charge spacing.

CONCEPT

The following assumptions were made in deriving a plausible connection between row crater size and charge spacing:

[1] A decrease in the spacing of the explosives in a row is equivalent to increasing the apparent yield of each explosive.

[2] The cross sectional geometry of a row crater is a hyperbola, is not dependent on charge spacing over the range of interest (spacing = 0.5 R_a to $1.2R_a$), and is the same as the optimum (largest) single crater in the same medium.

[3] The volume of apparent crater excavated by each charge in a row is independent of charge spacing and is greater, by some factor 'k', than the volume of the largest crater excavated by a single charge of the same yield.

The second assumption implies that the width and depth of a row crater will be enhanced equally at any given spacing, and that the depth of burst [DOB] of the charges should be the optimum single charge depth increased by the amount of enhancement. The assumption of an hyperbolic cross section is, in fact, an experimental observation.

The third assumption can be stated:

$$A_r \, e^2 \, S = k \, V_s$$

where A_r = cross section area of optimum single crater or unenhanced row crater

e = enhancement

S = charge spacing

k = volume excavated by a charge in a row relative to a single charge

V_s = volume of optimum single charge crater so that:

$$e = \left[\frac{k \, V_s}{A_r \, S}\right]^{1/2}$$

i.e. the enhancement of row crater dimensions is inversely proportional to the square root of the charge spacing.

Fig. 2 is a schematic cross section of a crater illustrating the elements of hyperbolic geometry. The area A_r and the volume V_s are easily evaluated for any crater.

The equation above can also be written:

$$e = \left[\frac{k \, V_s}{A_r \, R_a \, [S/R_a]}\right]^{1/2}$$

and it is interesting to note that the quantity:

$$\frac{V_s}{A_r \, R_a}$$

varies only over the range of 1.05 to 1.15 for an extremely wide range of crater

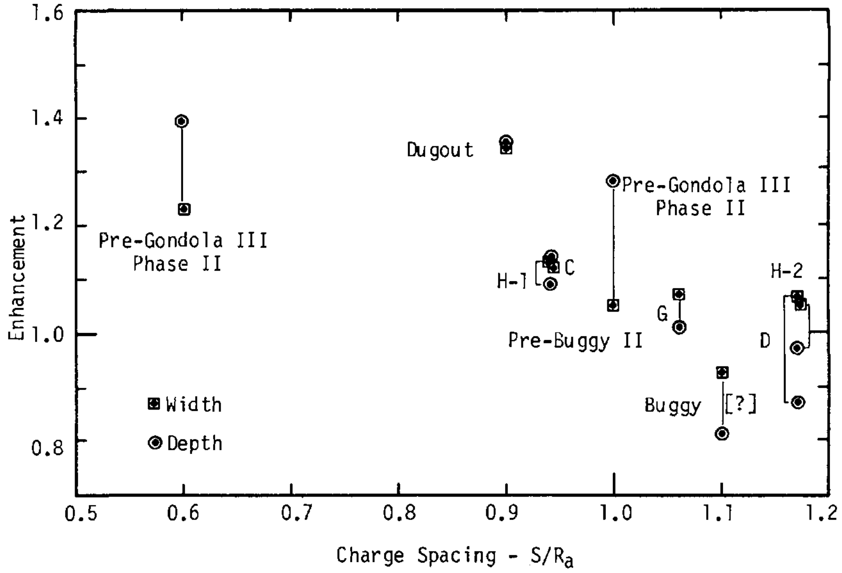
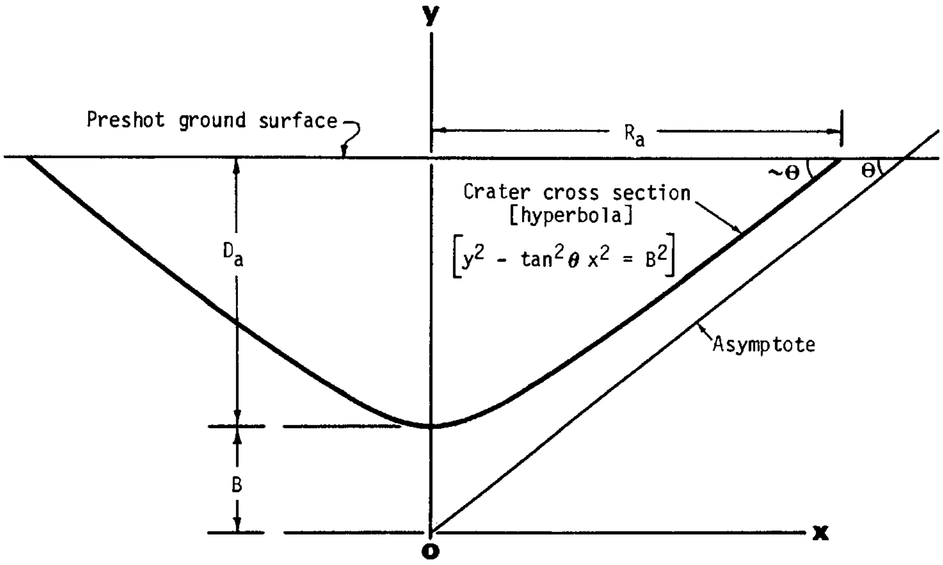


Fig. 1 Enhancement of row crater dimensions as a function of charge spacing.



Volume of crater: $V_s = \frac{\pi}{3\tan^2\theta}[1 + 3b]\, D_a{}^3$

Cross sectional area: $A_r = \frac{1}{\tan\theta}\left[(1 + b)\sqrt{1 + 2b} + b^2 \ln\left(\frac{b}{1 + b + \sqrt{1 + 2b}}\right)\right] D_a{}^2$

$b = \frac{r^2\tan^2\theta - 1}{2}$ $\qquad B = b\, D_a$

$r = \frac{R_a}{D_a}$

Fig. 2 Schematic cross section of a crater illustrating hyperbolic geometry.

geometries, and has a value of approximately 1.1 for most craters. As a consequence, the enhancement equation can be simplified to:

$$e = \left[\frac{1.1\ k}{[S/R_a]}\right]^{1/2}$$

It is evident that the volume factor k is now the most important unknown.

The volume factor k has been determined in a number of experiments and some of these values are listed in Table I.

TABLE I

Volume Efficiency of Row Charges

Experiment	Medium	$k = \left[\frac{\text{Volume per row charge}}{\text{Single crater volume}}\right]$	
Pre-GONDOLA II	Shale	0.82	(entire crater)
Pre-GONDOLA III Phase II [$S=0.6\ R_a$]	Shale	0.78	linear section of crater
Pre-GONDOLA III Phase II [$S=1.0\ R_a$]	Shale	1.05	
Pre-BUGGY II [C]	Alluvium	1.12	
Pre-BUGGY II [D]	Alluvium	1.18	
DUGOUT	Basalt	1.70**	

It is believed that the large variations in the value if k have been caused by the lack of a consistent design procedure and less than optimum placement of charges in some experiments. The next section discusses further work on the experimental determination of k.

EXPERIMENT

The enhancement concept was the basis for a series of row cratering experiments using 1-ton charges of nitromethane. The objectives were to verify the inverse square root relation between enhancement and charge spacing and to determine the relative efficiency of row charges. The experiment was conducted as part of Phase III of Project Pre-GONDOLA III in October 1969 by the U. S. Army Engineer Nuclear Cratering Group in a shale medium adjacent to the Fort Peck Reservoir in Montana.

The single crater dimensions shown in Fig. 3 had been obtained previously by detonating 1-ton charges in an adjacent area. The following parameters are applicable to the optimum 1-ton single crater:

$$R_a = 27 \text{ ft}$$

$$D_a = 13 \text{ ft}$$

$$\theta = 33°$$

The value of k was judged to be approximately 1.1 on the basis of information

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** The value of k = 1.70 for DUGOUT is suspect because more than 40 tons of the explosive nitromethane leaked from the cavities during filling operations.

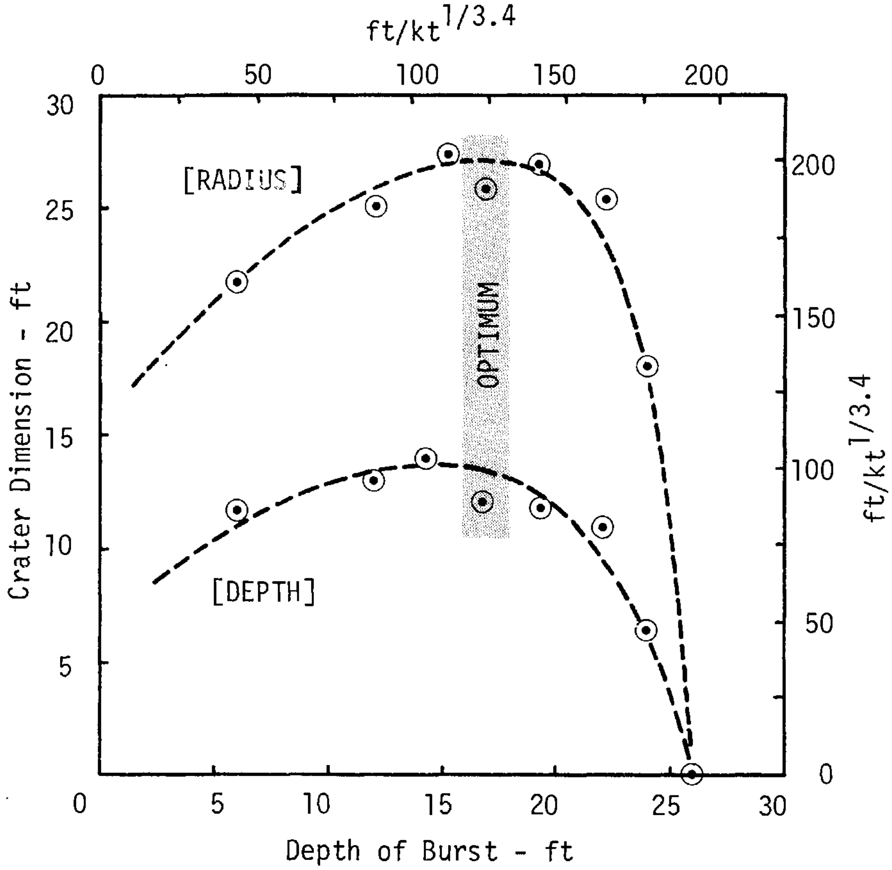

Fig. 3 Crater dimensions vs depth of burst for 1-ton charges in shale.

available from previous experiments [Table I]. The value of $[V_s/(A_r\ R_a)]$ is 1.1 so that the equation for enhancement was assumed to be:

$$e = \left[\frac{1.21}{S/R_a}\right]^{1/2}$$

A total of six row charges with five combinations of DOB and spacing and one duplication were detonated. Table II summarizes the shot layouts. An additional objective of this series was to test several schemes for smoothly connecting one row crater to another, however, this aspect of the experiment will not be discussed here. Also, in some rows the placement of the end charges differed from the remainder of the row.

Longitudinal profiles and typical cross sections of the craters are shown in Fig. 4 and aerial views are shown in Fig. 5. It should be noted that the center rows [A1 and B1] were detonated and surveyed before the end rows. When the end rows were fired they deposited some material in the center craters as shown on the longitudinal profiles and in the photographs.

The preliminary dimensions were averaged over the linear section** of each crater and are shown in Fig. 6 together with the 1-ton single crater dimensions. Despite the scatter, it is evident that the row crater dimensions plot along lines which pass through zero and the peaks of the single charge curves. This indicates that the cross sections of the rows are very similar to that of the optimum single charge crater.

The preliminary dimensions are shown in Fig. 7 in the format of enhancement vs. charge spacing. A curve which varies as the inverse square root of the charge spacing has been drawn through the data points in Fig. 7. The widths show less scatter about this curve than the depths, and the two rows with a spacing of 0.85 R_a demonstrate the scatter inherent in the data. The predicted enhancement is also shown in Fig. 7 and it is evident that the craters were larger than anticipated. There are two primary factors which may account for this. First, there is no single charge 1-ton crater immediately adjacent to the rows; previous experience in this region has demonstrated that the surface geology and its effect on crater dimensions are variable. Consequently, the size of the single crater to which the enhancements are referenced may be incorrect. An increase of 10% in the reference crater dimensions would shift the observed values of enhancement onto the predicted curve. Second, it is very probable that the factor k, assumed to be 1.1, is actually higher. If the reference crater were correct, then the observed row crater dimensions indicate that k is approximately 1.3.

Crater volume excavated per ton of explosive is plotted against charge spacing in Fig. 8 together with a volume computed for the reference crater on the basis of its geometry. The row craters averaged approximately 16,000 cu. ft. per ton of explosive compared with about 12,000 cu. ft. for the optimum one-ton single crater.

The row charge detonations were photographed with high speed motion picture cameras and mound surface velocities were obtained from analysis of the films. The peak mound surface velocities are plotted as a function of scaled depth of burst in Fig. 9 together with maximum single charge mound surface velocities observed in previous Pre-GONDOLA experiments. Although the row

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** The linear section of a row crater is generally the portion bounded by points midway between the two charges at each end. In some of the rows the position of the end charges was varied for other reasons. Dimensions were measured only over the portion of the rows where the charge layout was uniform.

TABLE II

Pre-Gondola III Phase III Row Charges

	Charge Spacing		Depth of Burst				Predicted Dimensions	
Row	S/R_a	Absolute	Scaled	Absolute	Number of Charges	Predicted Enhancement	$W_a/2$	D_{ar}
A1	1.0	27 ft	143	19.3 ft	6	1.10	29.7 ft	14.3 ft
A2	0.85	23	155	21.0	7	1.20	32.4	15.6
A3	1.15	31	133	17.9	5	1.03	27.8	13.4
B1	0.7	19	170	23.0	7	1.32	35.6	17.2
B2	0.85	23	155	21.0	6	1.20	32.4	15.6
B3	0.55	15	192	26.0	9	1.49	40.4	19.4

[= ft/kt$^{1/3.4}$]

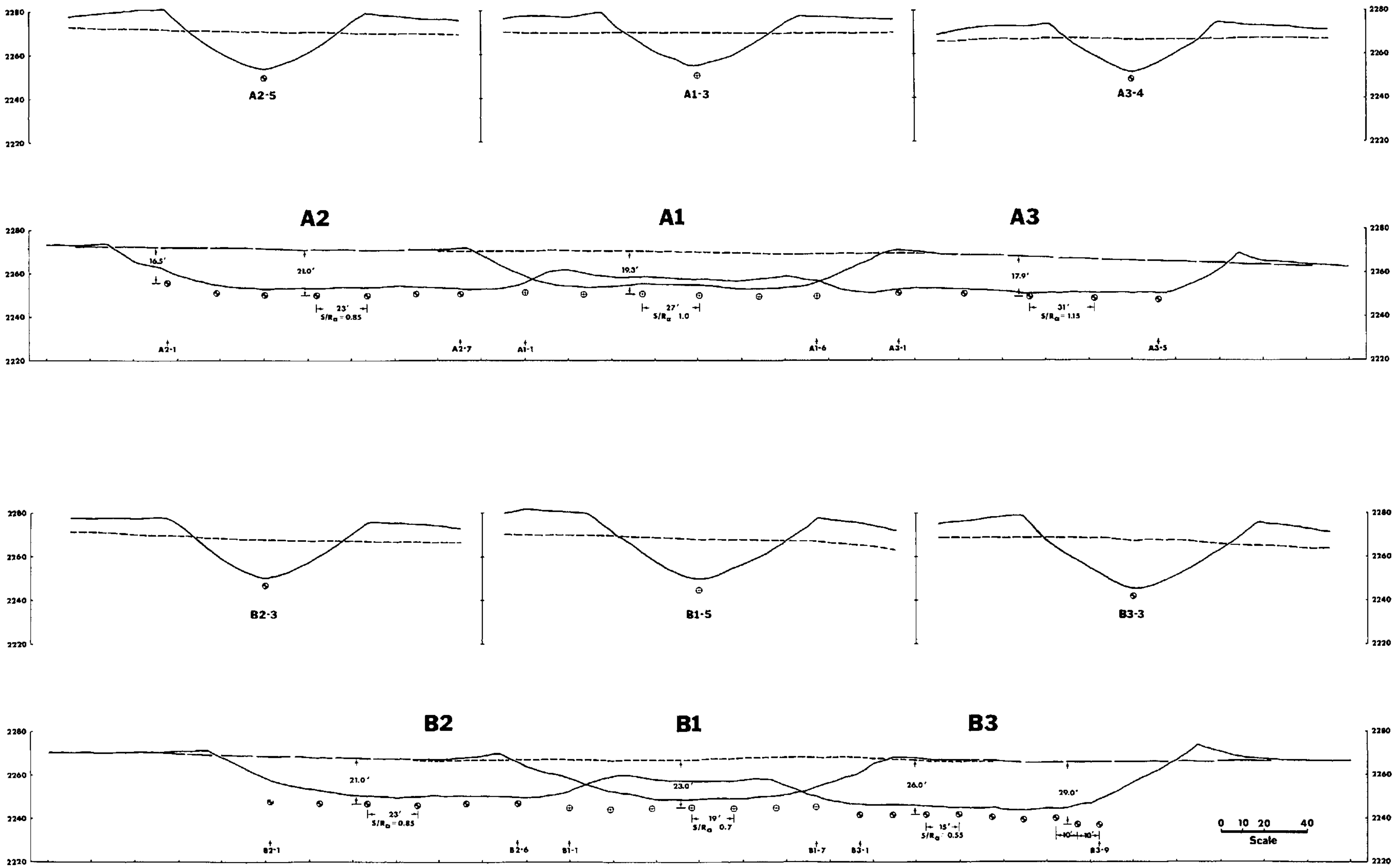
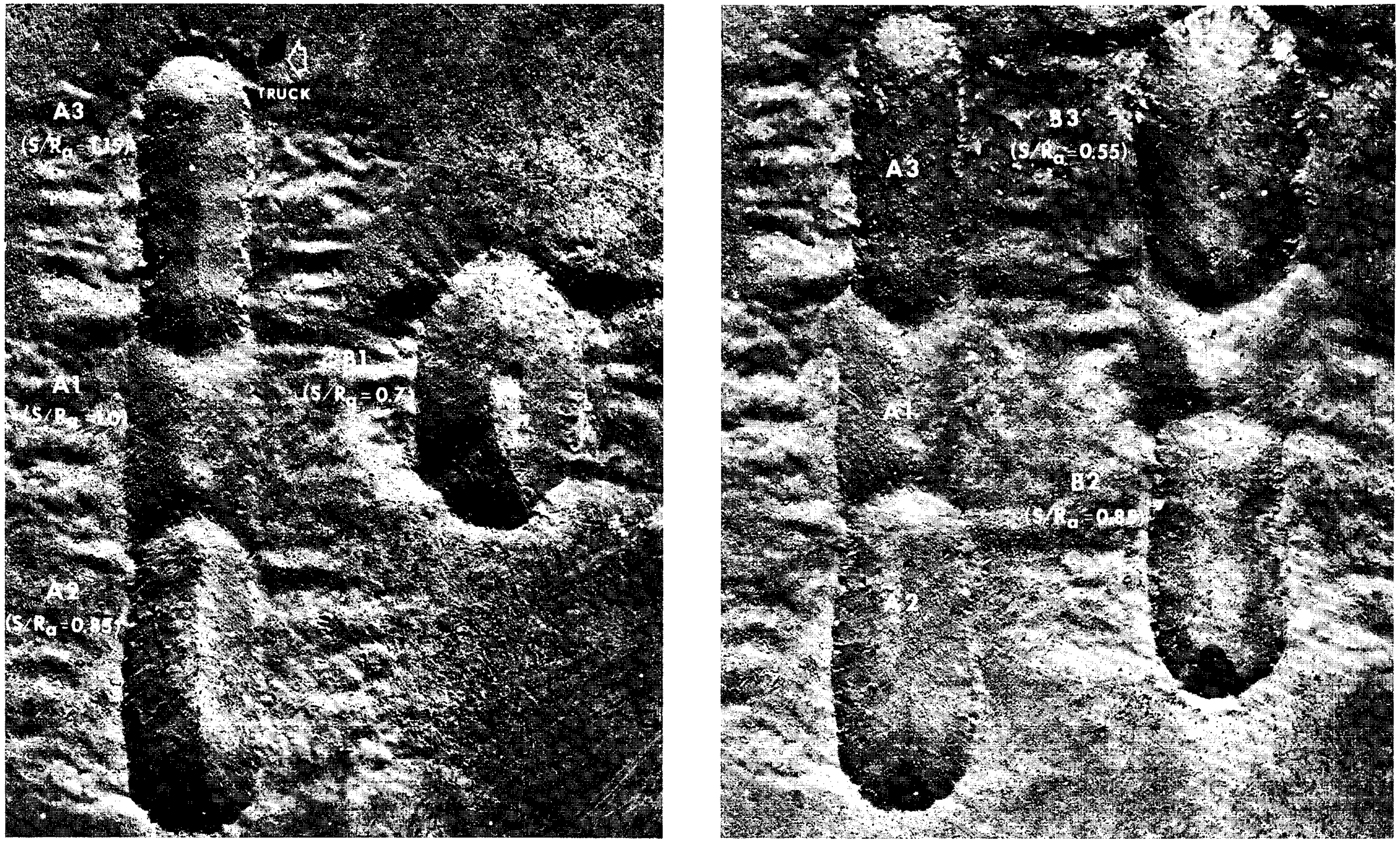


Fig. 4 Longitudinal profiles and typical cross sections for Pre-GONDOLA III Phase III row craters.



(a) (b)

Fig. 5 Pre-GONDOLA III Phase III row crater experiment in shale at Fort Peck, Montana. [a] Aerial view of craters A1, A2, A3, and B1. [b] Aerial view of row craters after detonation of rows B2 and B3.

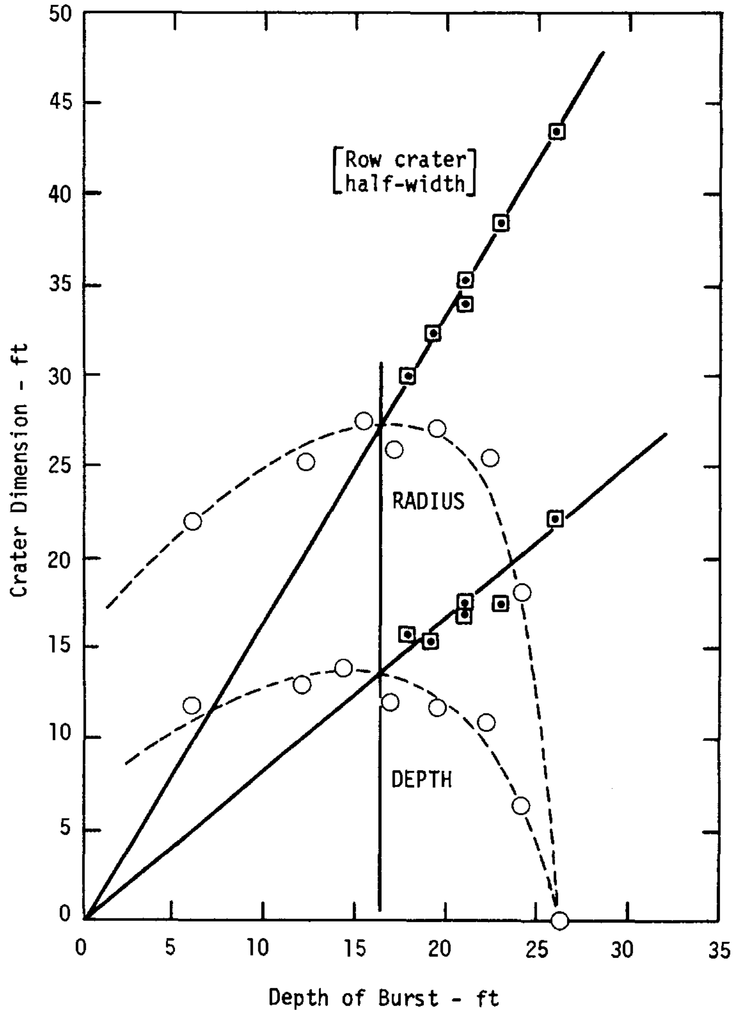


Fig. 6 Dimensions of single and row craters vs depth of burst.

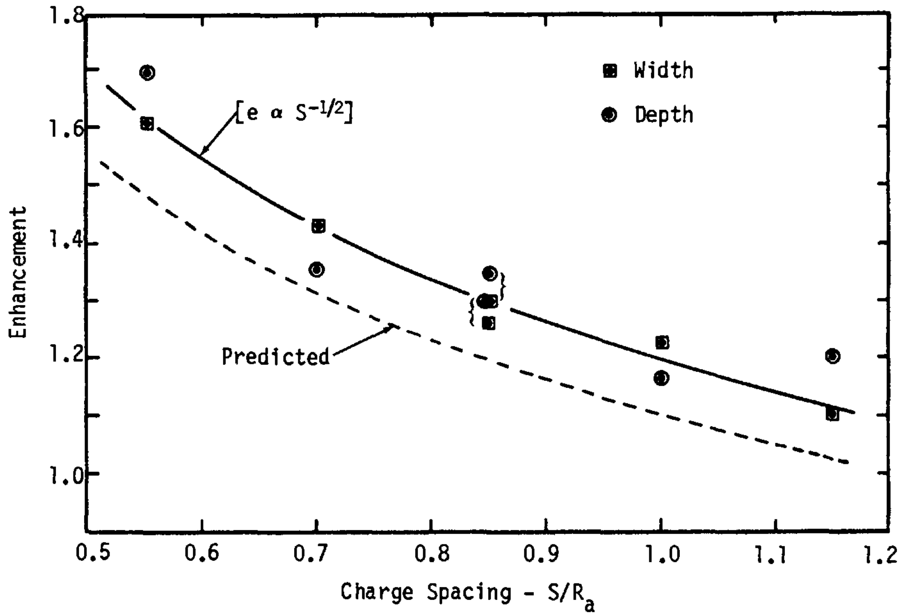


Fig. 7 Enhancement of Pre-GONDOLA III Phase III row crater dimensions as a function of charge spacing.

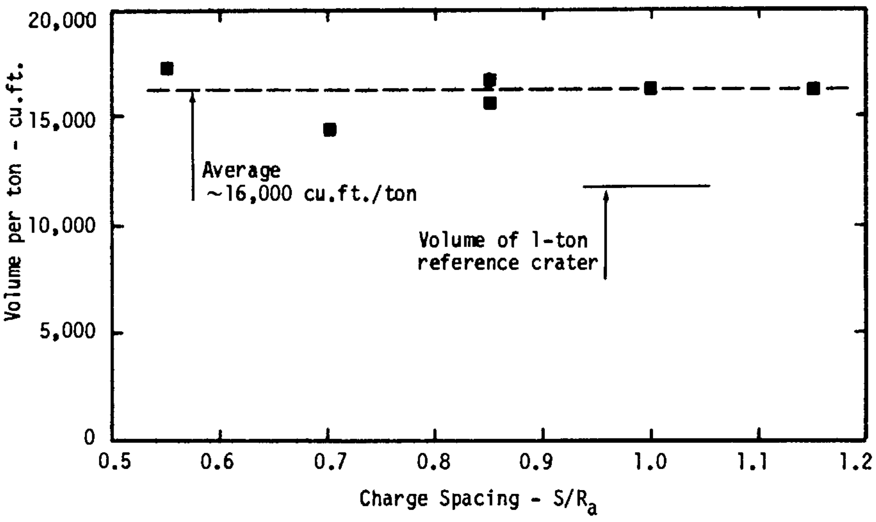


Fig. 8 Volume of apparent crater per ton of explosive as a function of charge spacing.

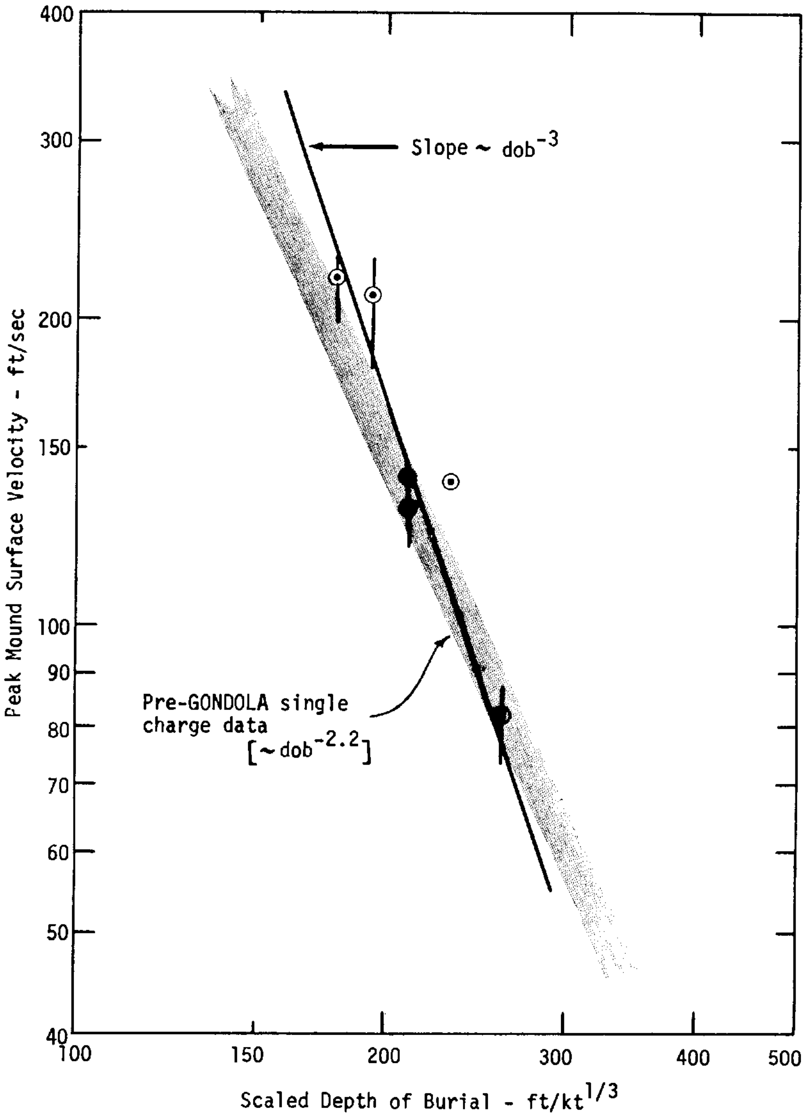


Fig. 9 Variation of maximum surface velocity with depth of burst

charge velocities appear to be more dependent on depth of burst than the single charge mound surface velocities, they are approximately the same as the single charge velocities. It is interesting to note that row crater dimensions increased as the peak mound surface velocity decreased, and that the largest of the six row craters had depth of burst and a peak mound surface velocity which would be characteristic of a retarc in the case of a single charge in the same material. Previously, craters have not been produced in either shale or dry hard rock when peak mound surface velocities were observed to be less than about 100 ft/sec.

It will be noted that more charges were used in the rows with the closer charge spacings. This was done to insure that the craters would have a reasonable ratio of length to width and not be elliptical in plan.

APPLICATION

In order to illustrate application of the concept, assume that we wish to excavate a 15 ft. deep channel in rock and that 1-ton charges are desirable from a construction standpoint. What is the appropriate charge spacing and DOB assuming that the optimum single crater has the following properties:

$$r_a = 150 \text{ ft/kt}^{1/3.4}$$

$$d_a = 90 \text{ ft/kt}^{1/3.4}$$

$$\text{optimum dob} = 140 \text{ ft/kt}^{1/3.4}$$

$$\theta = 37^\circ$$

and assuming, for the present, that k = 1.2.

The required scaled crater depth is

$$\frac{15}{.001^{1/3.4}} = 114 \text{ ft/kt}^{1/3.4}$$

so that the necessary enhancement of single crater depth is

$$e = \frac{114}{90} = 1.27$$

the appropriate charge spacing will be given by

$$\frac{S}{R_a} = \frac{1.1\ k}{e^2}$$

$$= 0.82, \text{ say } 0.8,$$

therefore,

$$S = 0.8\ R_a$$

$$= 0.8 \times 150 \times .001^{1/3.4}$$

$$= 15.7 \text{ ft.}$$

and the DOB will be

$$= 140 \times 1.27 \times .001^{1/3.4}$$

$$= 23.3 \text{ ft.}$$

It is interesting to note that if enhancement were not used, then each charge would require a yield of

$$\left[\frac{15\text{ ft.}}{90\text{ ft/kt}^{1/3.4}}\right]^{3.4} = 2.3\text{ tons}$$

in order to excavate the same channel.

CONCLUSIONS

It appears that the concept relating enhancement and charge spacing is essentially correct. The experiment based on this concept indicates that enhancement does vary inversely as the square root of the charge spacing provided that the depth of burst is increased correspondingly. The efficiency of a row charge in excavating shale appears to be about 30 percent greater than a series of single charges. The relative efficiencies of row charges and single charges in other media should be determined empirically.

The observation that mound surface velocity decreased with increasing crater size and the association of the largest row crater with a velocity characteristic of a single charge retarc would suggest that peak mound surface velocity should be used cautiously as a row charge design tool.

A departure from a row charge design consisting of charges spaced one radius apart and buried at optimum DOB for a single charge has been, in the past, an uncertain procedure. It is believed that there is now a flexible and reliable basis for row charge design.

This concept has already found application to the feasibility studies of an interoceanic canal, however, it is anticipated that it will find the widest application to excavation projects with chemical explosives where emplacement costs can be reduced by employing smaller charges.