TECHNICAL REPORT N-75-5

EFFECT OF CHARGE SHAPE ON CRATER DIMENSIONS

by

John N. Strange

Weapons Effects Laboratory
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

October 1975

Final Report

Approved For Public Release; Distribution Unlimited

Prepared for Office, Chief of Engineers, U. S. Army
Washington, D. C. 20314

Under Project 4A762719AT32, Task 02

DEPARTMENT OF THE ARMY
WATERWAYS EXPERIMENT STATION, CORPS OF ENGINEERS
P. O. BOX 631
VICKSBURG, MISSISSIPPI 39180

IN REPLY REFER TO:

16 January 1976

Errata Sheet

No. 1

EFFECT OF CHARGE SHAPE ON CRATER DIMENSIONS

Technical Report No. N-75-5
October 1975

1. Page 14, second column should read:

   $\left(r_a\right)_n / \left(r_a\right)_1$ [a]

   Dimensionless

2. Page 14, third column should read:

   $\left(d_a\right)_n / \left(d_a\right)_1$ [b]

   Dimensionless

3. Page 14, fourth column should read:

   Volumetric
   Effectiveness Factor, V_e [c]
   $\left(V_a\right)_n / \left(V_a\right)_1$

   Dimensionless

4. Page 15, second column should read:

   $\dfrac{\left(r_a/d_a\right)_n}{\left(r_a/d_a\right)_1}$ [a]

   Dimensionless

5. Page 15, third column should read:

$$\frac{\left(V_a/\pi r_a^2 d_a\right)_n}{\left(V_a/\pi r_a^2 d_a\right)_1}^{b}$$

Dimensionless

6. Page 23, replace with page 23 attached.

7. Page 32, line 16 should read:

V_e Volumetric effectiveness factor $[(V_a)_n/(V_a)_1]$

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Report N-75-5	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) EFFECT OF CHARGE SHAPE ON CRATER DIMENSIONS		5. TYPE OF REPORT & PERIOD COVERED Final report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) John N. Strange		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U. S. Army Engineer Waterways Experiment Station Weapons Effects Laboratory P. O. Box 631, Vicksburg, Miss. 39180		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Project 4A762719AT32, Task 02
11. CONTROLLING OFFICE NAME AND ADDRESS Office, Chief of Engineers, U. S. Army Washington, D. C. 20314		12. REPORT DATE October 1975
		13. NUMBER OF PAGES 39
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Craters
Explosives
Explosion effects

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This study was conducted to determine the effect of charge shape (cylinders with different aspect ratios) on the geometry of explosion-produced craters. For charges having a constant scaled depth of burial (in this case approximately 0.5 $m/kg^{1/3.4}$) and an overall length less than 0.4 $m/kg^{1/3.4}$, the apparent crater volume and the overall shape of the apparent crater remained essentially unchanged for aspect ratios that ranged from 1 to 8.
(Continued)

DD FORM 1473, 1 JAN 73 — EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. ABSTRACT (Continued).

Since charges can be configured with aspect ratios up to 8 without significantly affecting crater shape or volume, it is possible to reduce drilling costs associated with charge emplacement in that drilling costs depend on penetration rate and penetration rates increase as hole diameters decrease. In an excavation program in which many holes are required, cost reductions could be substantial.

PREFACE

The experimental efforts in this study were accomplished as an adjunct to the New Madrid Fuse-Plug Study. Analysis of the data and preparation of this report were accomplished as a part of DA Project 4A762719AT32, Task 02.

Mr. J. N. Strange of the Weapons Effects Laboratory (WEL) prepared the report; Mr. S. B. Price (WEL) executed the field experiments and made appropriate crater measurements; and Mr. Max Ford (WEL) wrote the computer code for calculating crater volumes (see Appendix A). Ms. Virginia Mason typed the manuscript and assisted in the preparation of the Tables and Figures.

During the time this study was being accomplished, COL G. H. Hilt was Director of the Waterways Experiment Station, Mr. F. R. Brown was Technical Director, and Mr. W. J. Flathau was Chief of the WEL.

CONTENTS

EFFECT OF CHARGE SHAPE ON CRATER DIMENSIONS

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Where cylindrical charges are employed to produce craters, it has generally been required by those who routinely conduct crater scaling experiments (experiments that are designed to simulate point source spherical explosions) that the aspect ratio (charge height-to-diameter ratio) be less than three. This requirement on charge shape has been, to some degree, an arbitrary restriction; however, it has been rather widely imposed in an effort to insure that the crater produced by the nonspherical charge would have essentially the same shape and overall size as one that would have been formed by the detonation of a spherical charge having the same yield.

The placement of large charges underground for the purpose of forming large craters can be simplified somewhat if the shape of the charge can be other than spherical, cubical, or cylindrical (assumes the aspect ratio of the latter to be 1). For example, containment of a 1-megagram (Mg) (2200-pound) charge of, say, nitromethane, which has a density of approximately 1.2 g/cm^3, would require a volume equal to 0.83 m^3 (29.3 ft^3). If the charge is configured as a sphere, an access hole 1.2 metres (3.94 feet) in diameter would be required for proper placement. Similarly, a cube would require an access hole 1.4 metres (4.59 feet) in diameter, and a cylindrical charge (aspect ratio of one) would require an access hole slightly larger than 1 metre (3.28 feet) in diameter.

The practicality and economy of hole drilling favor small holes. The question thus arises "How high can the aspect ratio of a given cylindrical charge be and yet not affect significantly the size or shape of the crater formed by an equivalent-yield spherical detonation?" For example, if a cylindrical charge with an aspect ratio of 5 does not significantly affect the size or shape of the resulting crater, then it would be possible to emplace the same 1-Mg (2200-pound) charge through an access hole that is only 60 cm (23.62 inches) in diameter (allows for a 5-cm (1.97-inch) oversize for clearance).

A series of tests was therefore conducted to investigate the effect that charge shape has on crater geometry and size. In these tests the variance in shape was confined to cylindrical charges whose aspect ratios varied from 1 to 8.

1.2 SCOPE

This report describes the geometries of the various craters formed by cylindrical charges having different aspect ratios. The crater profiles along mutually perpendicular diameters (north-south and east-west) are presented, and comparisons are made of crater radius, depth, and volume, as well as certain crater shape parameters.

CHAPTER 2

EXPERIMENTAL PROCEDURES

2.1 TEST SITE

The test series was conducted at the U. S. Army Engineer Waterways Experiment Station's Big Black Test Site, located about 16.09 km (10 miles) east-southeast of Vicksburg, Mississippi. The geology of the site is predominately sandy-silty loam. The test area within the overall test site was at one time under cultivation; therefore, the upper portion of the soil mantle is fertile topsoil.

The moisture content at the time of the tests was determined by sampling to range from 18 percent near the surface to 28 percent at a depth of about 1.5 metres (4.92 feet).

2.2 CHARGE AND SHOT GEOMETRIES

A total of seven cylindrical charges were prepared with the following aspect ratios: 1, 2, 3, 4, 5, 6, and 8. The actual dimensions of the charges are listed in Table 2.1. In every case, the charge weight was 4.54 kg (10 pounds).

All charges were initiated by high-energy blasting caps embedded in the charge at its center of gravity.

The charge center of gravity was used as the point of reference for positioning all charges at their proper depth of burial (DOB). For these tests, the charges were positioned 0.8 metre (2.7 feet) below ground; this DOB corresponds to a scaled DOB of 0.513 $m/kg^{1/3.4}$ (1.37 $ft/lb^{1/3.4}$).

Charge placement was accomplished in the following manner. A 15-cm(6-inch)-diameter hand auger was used to drill the emplacement hole. In every instance, the emplacement hole depth was 0.8 metre (2.7 feet) plus H/2, where H designates the charge height (notations used in this report are listed in Appendix B). The charge initiator was then embedded in the charge (at its center of gravity) and the safe-ready charge was lowered into the emplacement hole. The void space surrounding the charge was filled with native soil and compacted to approximately the same density as that of the in situ material (Figure 2.1).

A polyethylene hole liner was then placed in the emplacement hole (above the charge) and the liner filled with water; all charges were stemmed in this same manner (Figure 2.1). The charge was then fired and appropriate measurements were made to document the crater size and shape.

2.3 CRATER MEASUREMENTS

Prior to each shot, mutually perpendicular axes were established through ground zero (GZ) (epicenter of each explosion). Since the test area was essentially a horizontal plane, it was not necessary to obtain preshot surface profiles along the alignments specified. Postshot surveys were made along the alignments (crater diameters) and differences in elevation were determined at appropriate horizontal ranges. The data thus obtained enabled the plotting of apparent crater profiles along the north-south and east-west axes.

Crater volumes were calculated from the apparent crater profiles. Each radial profile (half-crater profile) was considered an independent data source. From these overlaid profiles, an average profile was developed and thus used to calculate the apparent crater volume. The crater volume computations were done by numerical integration of cylindrical shells formed by rotating vertical increments about the vertical axis through GZ. Details of the computer code that calculated the crater volumes are presented in Appendix A.

TABLE 2.1. CHARGE GEOMETRIES[a]

H-Height of Charge		D-Diameter of Charge		$\frac{H}{D}$ [b]
cm	ft	cm	ft	Dimensionless
15.4[c]	0.504	15.4	0.504	1
24.4	0.801	12.2	0.400	2
32.0	1.05	10.7	0.350	3
38.7	1.27	9.68	0.318	4
44.8	1.48	8.96	0.294	5
50.7	1.66	8.47	0.278	6
61.5	2.02	7.68	0.252	8

[a] All charges were right circular cylinders.
[b] Defined as the Aspect Ratio (AR) of the cylindrical charges.
[c] Numerical values included in the first four columns were recorded to three significant figures.

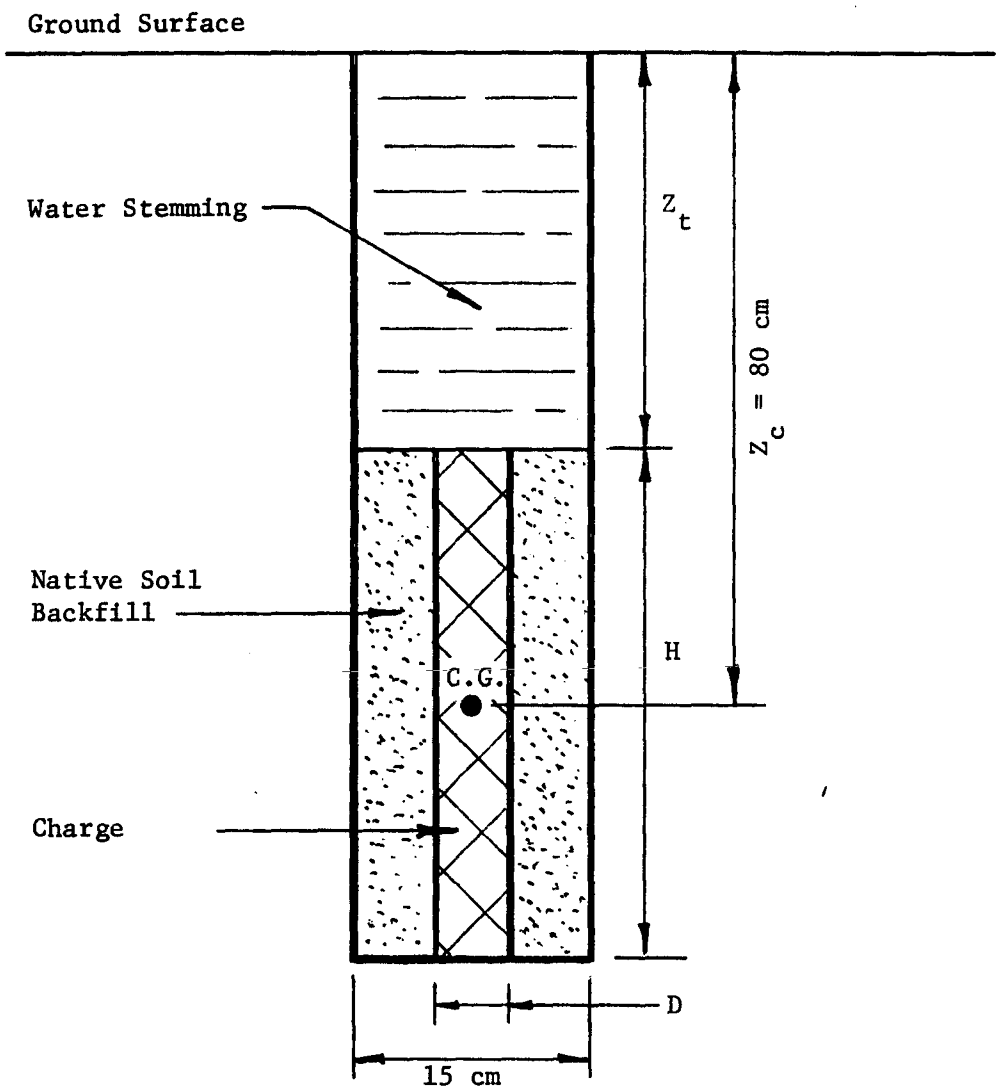


Figure 2.1 Details of the charge emplacement.

CHAPTER 3

EXPERIMENTAL RESULTS

3.1 PRESENTATION

During the course of the experimental program, seven detonations were accomplished. Orthogonal profiles of each of the seven craters formed by the detonations are presented in Figures 3.1 through 3.7. To determine an average profile for any given shot, the two orthogonal profiles were each divided into half-crater profiles, thus forming four such profiles, viz., GZ-north, GZ-south, GZ-east, and GZ-west. These four half-crater profiles were then superimposed and an average profile determined. The dimensions given in Table 3.1 describe quantitatively the average or representative half-crater profile developed for each shot. For volumetric determinations, the average half-crater profile was revolved about a vertical axis through GZ, thus forming the three-dimensional depression that constitutes the average crater.

Table 3.2 presents the linear shape factors and the volumetric shape factors. Table 3.3 provides a quantitative measure of the change in dimensions for each H/D value compared to the dimension when the charge shape was defined by H/D = 1 . Finally, Table 3.4 presents relative parametric changes as a function of H/D by comparing changes in the crater shapes.

3.2 DISCUSSION

3.2.1 General Observations. A comparison of the crater dimensions listed in Table 3.1 shows a variation that is bounded by the mean plus or minus a 20 percent variation from the mean. Since crater dimensions from identical shots are generally characterized by a scatter in the range of ±20 percent, there appears to be no significant difference in the respective crater dimensions as the value of H/D varies from 1 to 8. This observation is borne out by the fact that the crater shape parameters show a variation from the mean in the range of ±15 percent (Table 3.2).

If the relative changes in the crater dimensions are examined as a function of H/D (Table 3.3), then one might conclude that there is a very slight decrease in radius and volume and a very slight increase in crater depth.

Table 3.4, which compares in a relative fashion the crater shape factors listed in Table 3.2, exhibits only a very slight change in crater shape. When H/D varies from 1 to 8, the total change is in the range of -10 percent.

Figure 3.8 shows the variation in the volumetric effectiveness factor as a function of H/D ; the same plot compares the experimental results of this series of tests with results from other sources (References 1 and 2). The scatter observed in the experimental results (plotted points) precludes a definite statement that the experimental results are in agreement with References 1 and 2. The trend of the experimental results seems to agree with the downward trend noted by Reference 2 and agrees roughly with the Reference 1 results for H/D greater than 5.

From the tabular data, particularly Tables 3.2-3.4, and from Figure 3.8, it is obvious that, for a constant DOB, major changes in crater size and volume do not occur when H/D values range from 1 to 8.

3.2.2 Extrapolation of Results. Extrapolation of experimental results beyond the parametric range of the experiments is generally regarded as questionable. In some cases, where scaling laws are not violated regardless of the scale of the experiments, extrapolations prove quite accurate. In instances where scaling laws are violated to a degree that is somewhat dependent on various factors (as is true with the scaling of cratering experiments), the reliability of extrapolations is not predictable per se. In cratering experiments, the gravitational stresses (lithostatic pressures) scale as the length ratio while strength of the test medium and detonation pressures remain constant regardless of scale. Also, the seismic velocity of the test medium and the detonation velocity of the explosive remain constant; this advocates that time scale as the length scale. However, the acceleration due to gravity remains constant in both model and full-scale experiments. This requires that time scale as the square root of the length scale. Thus, in cratering there are present conflicts in scaling that preclude blind extrapolation of results without regard to the discrepancies.

Experience has shown that the several conflicts in scaling are minimized when the length scale (λ) is proportional to the charge weight (W) raised to the 1/3.4 power, or

$$\lambda \propto W^{1/3.4} \tag{3.1}$$

Extrapolations of the experimental results obtained during the course of this study should therefore be in proportion to the rule stated in Equation 3.1 above. In addition, extrapolations should not violate the following constraints if the observed results are to yield valid results when extrapolated:

1. The charge weight should not exceed a few thousand pounds.
2. The aspect ratio should not exceed about 10. Higher aspect ratios may lead to a scaling law different from $W^{1/3.4}$, e.g., line charges follow a $W^{1/2}$ scaling law.
3. The scaled distance from the ground surface to the top of the charge should satisfy the following relation:

$$Z_t \geq 0.3 \ (W)^{1/3.4}$$

where Z_t is the distance from the ground surface to the top of the charge in metres and W is the charge weight in kilograms. By the same token, the scaled depth to the charge center of gravity $(Z_c/W^{1/3.4})$ should not exceed about 0.6 nor be less than 0.4. In order that this overall constraint hold, the charge height should generally be less than $0.4 \ (W)^{1/3.4}$.

TABLE 3.1 APPARENT CRATER DIMENSIONS ASSOCIATED WITH CYLINDRICAL CHARGES HAVING DIFFERENT ASPECT RATIOS[a]

$\frac{H}{D}$ [b] Dimensionless	Apparent Crater Radius, r_a, m (ft)	Apparent Crater Depth, d_a, m (ft)	Apparent Crater Volume, V_a, m^3 (ft^3)
1	1.89 (6.20)	0.914 (3.00)	5.01 (177)
2	1.77 (5.81)	0.792 (2.60)	3.96 (140)
3	2.01 (6.59)	0.975 (3.20)	5.30 (187)
4	1.80 (5.91)	0.914 (3.00)	4.39 (155)
5	1.65 (5.42)	0.975 (3.20)	3.99 (141)
6	1.71 (5.62)	1.04 (3.41)	4.28 (151)
8	1.80 (5.91)	0.975 (3.20)	4.56 (161)

[a] All tabular values are given to three significant figures except for the H/D values, which are discrete.

[b] Charge depth of burial was held constant at 0.8 metre or 2.7 feet.

TABLE 3.2 CRATER SHAPE FACTORS[a]

$\frac{H}{D}$ [b] Dimensionless	(r_a/d_a) [c] Dimensionless	$\left(\frac{V_a}{\pi r_a^2 d_a}\right)$ [d] Dimensionless
1	2.07	0.489
2	2.23	0.509
3	2.06	0.427
4	1.97	0.473
5	1.69	0.478
6	1.64	0.448
8	1.85	0.459

[a] All tabular values are given to three significant figures except for the H/D values, which are discrete.
[b] Charge depth of burial was held constant at 0.8 metre or 2.7 feet.
[c] Linear shape factor.
[d] Volumetric shape factor.

TABLE 3.3 RELATIVE CHANGES IN CRATER DIMENSIONS AS A FUNCTION OF H/D

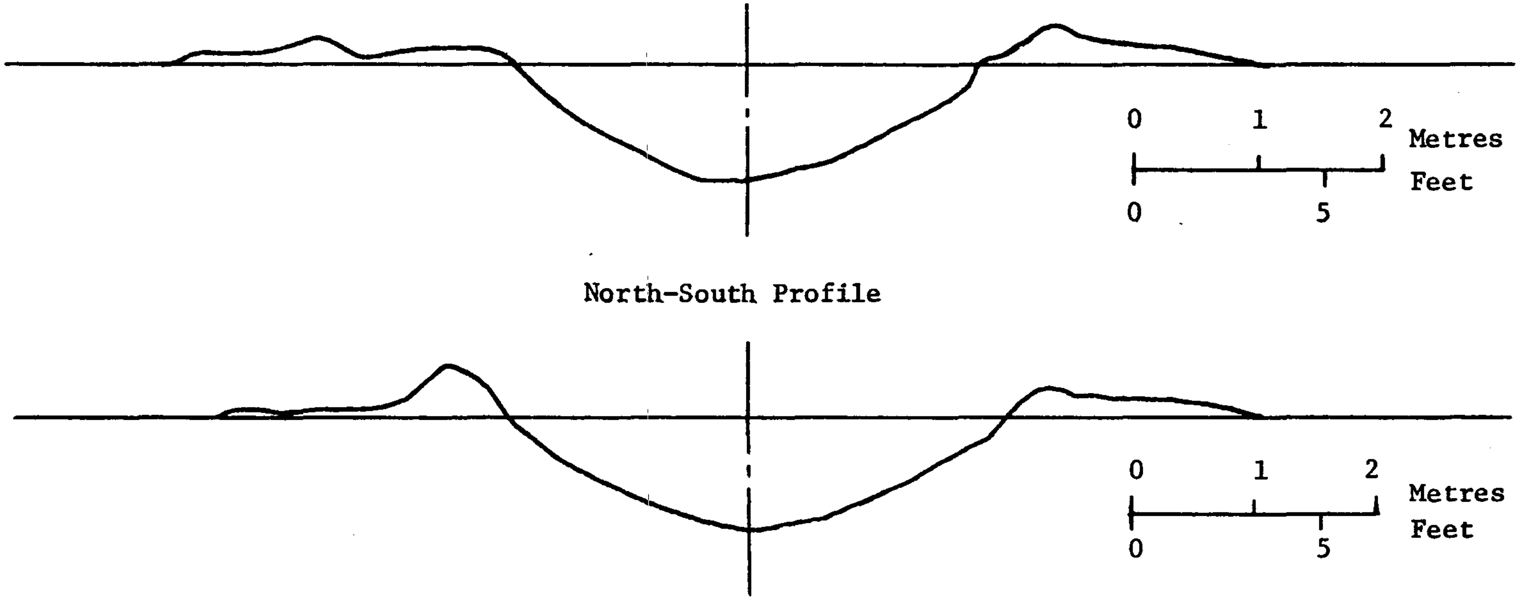
H/D Dimensionless	$(r_a)_1/(r_a)_n$ [a] Dimensionless	$(d_a)_1/(d_a)_n$ [b] Dimensionless	Volumetric Effectiveness Factor, V_e [c] $(V_a)_1/(V_a)_n$ Dimensionless
1	1.00	1.00	1.00
2	0.937	0.867	0.790
3	1.06	1.07	1.06
4	0.952	1.00	0.876
5	0.873	1.07	0.796
6	0.904	1.14	0.854
8	0.952	1.07	0.910

[a] Derived from column 2, Table 3.1.
[b] Derived from column 3, Table 3.1.
[c] Derived from column 4, Table 3.1.

TABLE 3.4 CALCULATION OF RELATIVE PARAMETRIC CHANGES AS A FUNCTION OF H/D

$\frac{H}{D}$ Dimensionless	$\frac{(r_a/d_a)_1}{(r_a/d_a)_n}$ [a] Dimensionless	$\frac{(V_a/\pi r_a^2 d_a)_1}{(V_a/\pi r_a^2 d_a)_n}$ [b] Dimensionless
1	1.00	1.00
2	1.08	1.04
3	0.995	0.873
4	0.952	0.967
5	0.816	0.978
6	0.792	0.916
8	0.894	0.939

[a] Derived from column 2, Table 3.2.
[b] Derived from column 3, Table 3.2.



North-South Profile

East-West Profile

Charge Weight - 4.54 Kg (10 lb)

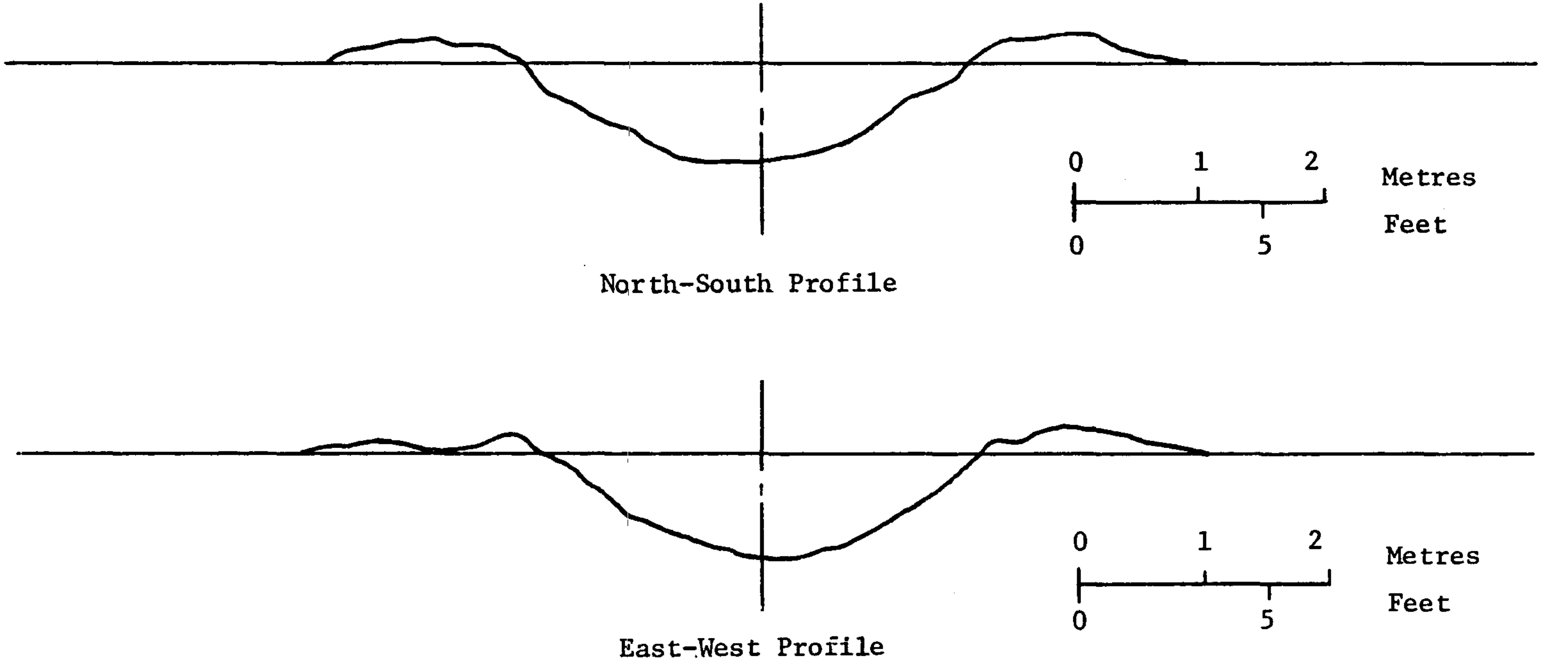
Explosive: C-4

Mean crater depth = 0.914 m (3.00 ft)

Mean crater radius = 1.89 m (6.20 ft)

Mean crater volume = 5.01 m^3 (177 ft^3)

Figure 3.1 Apparent crater profiles: H/D = 1 .



Charge Weight - 4.54 Kg (10 lb)

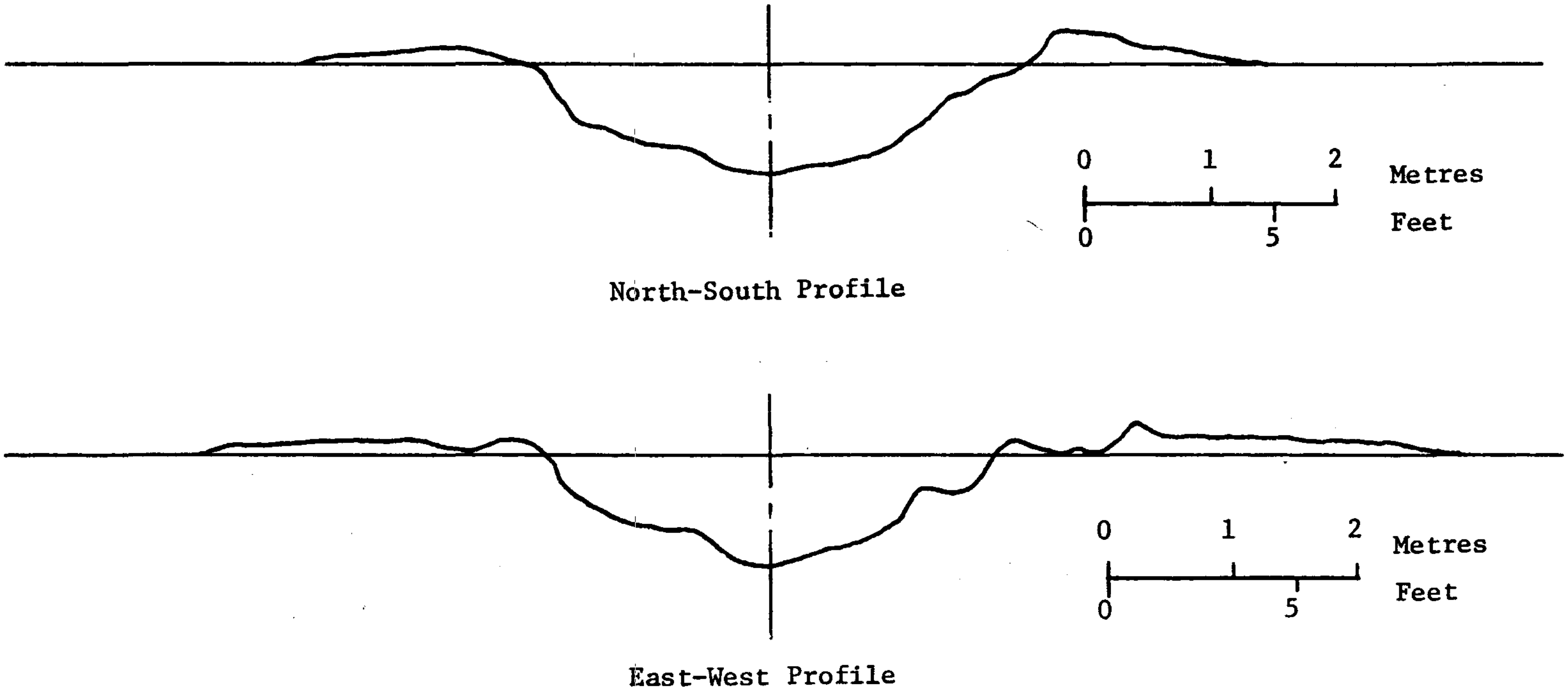
Explosive: C-4

Mean crater depth = 0.792 m (2.60 ft)

Mean crater radius = 1.77 m (5.81 ft)

Mean crater volume = 3.96 m^3 (140 ft^3)

Figure 3.2 Apparent crater profiles: H/D = 2 .



Charge Weight - 4.54 Kg (10 lb)

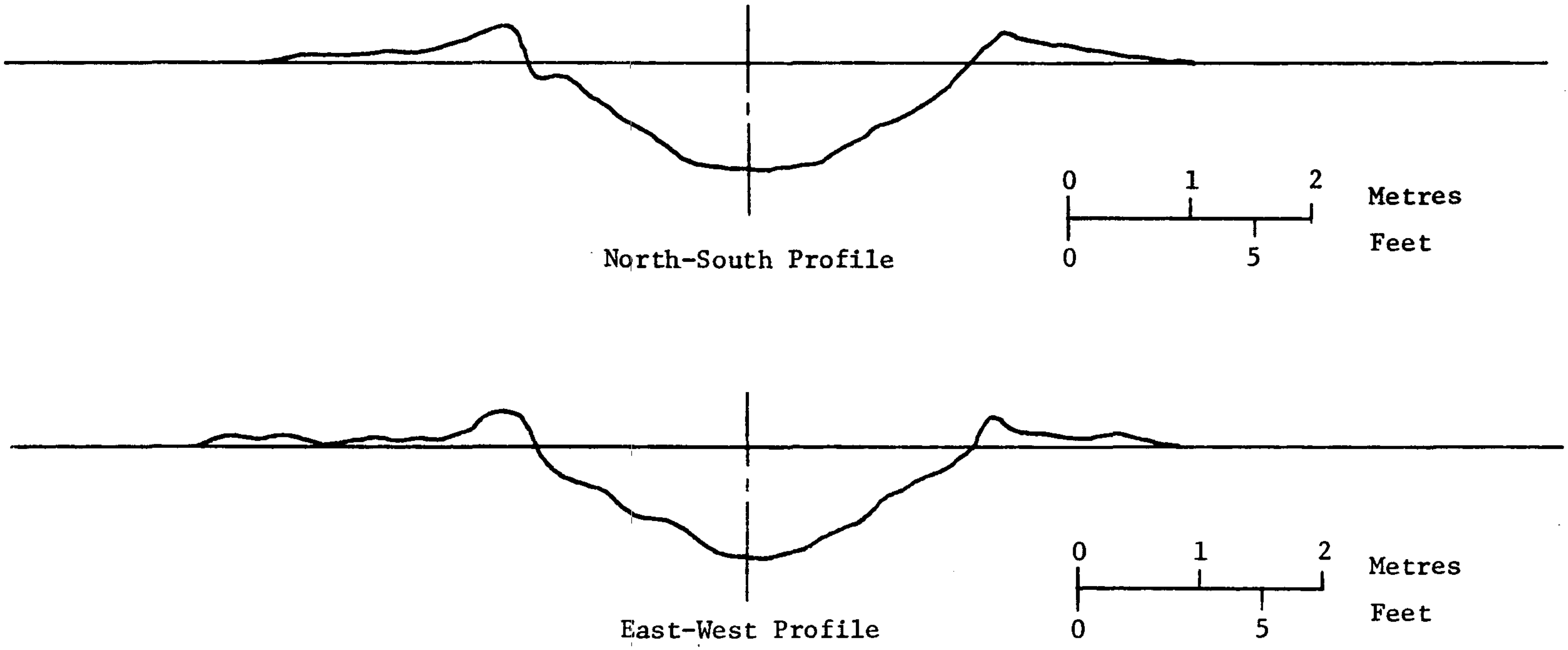
Explosive: C-4

Mean crater depth = 0.975 m (3.20 ft)

Mean crater radius = 2.01 m (6.59 ft)

Mean crater volume = 5.30 m^3 (187 ft^3)

Figure 3.3 Apparent crater profiles: H/D = 3 .



Charge Weight - 4.54 Kg (10 lb)

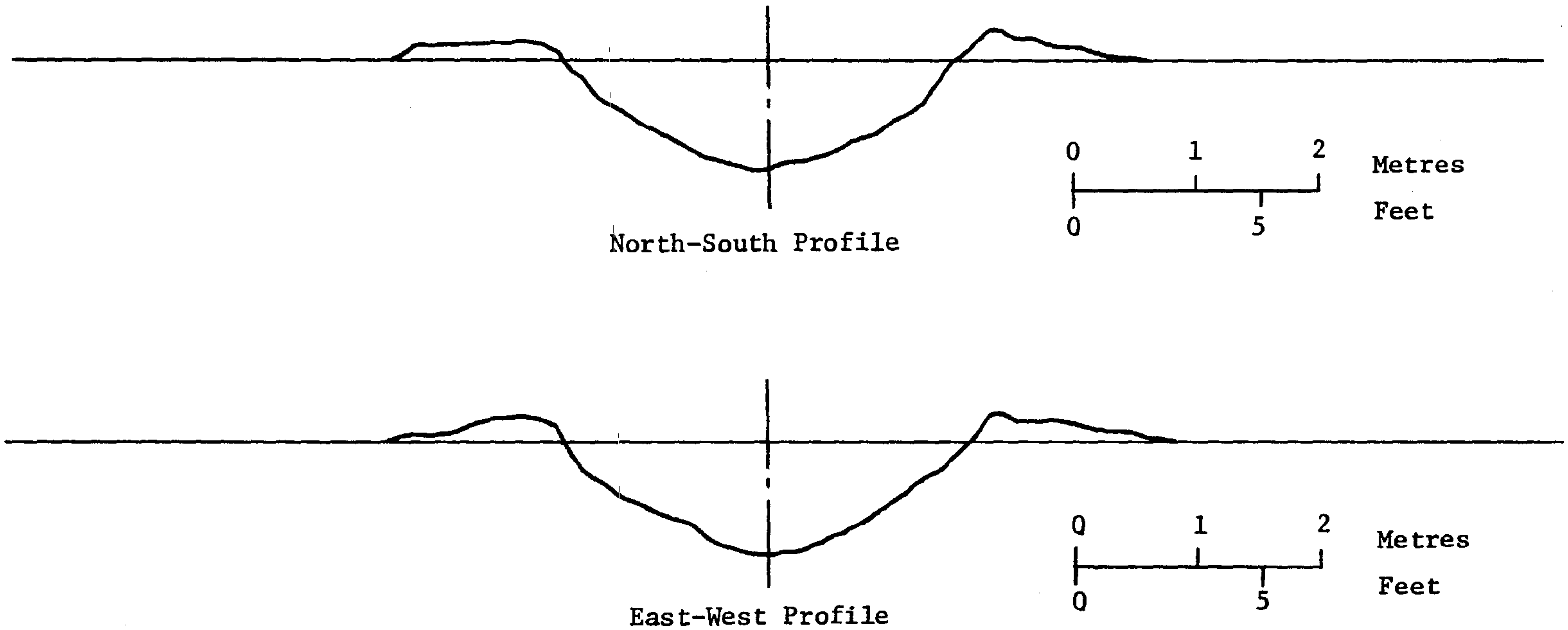
Explosive: C-4

Mean crater depth = 0.914 m (3.00 ft)

Mean crater radius = 1.80 m (5.91 ft)

Mean crater volume = 4.39 m^3 (155 ft^3)

Figure 3.4 Apparent crater profiles: H/D = 4 .



Charge Weight - 4.54 Kg (10 lb)

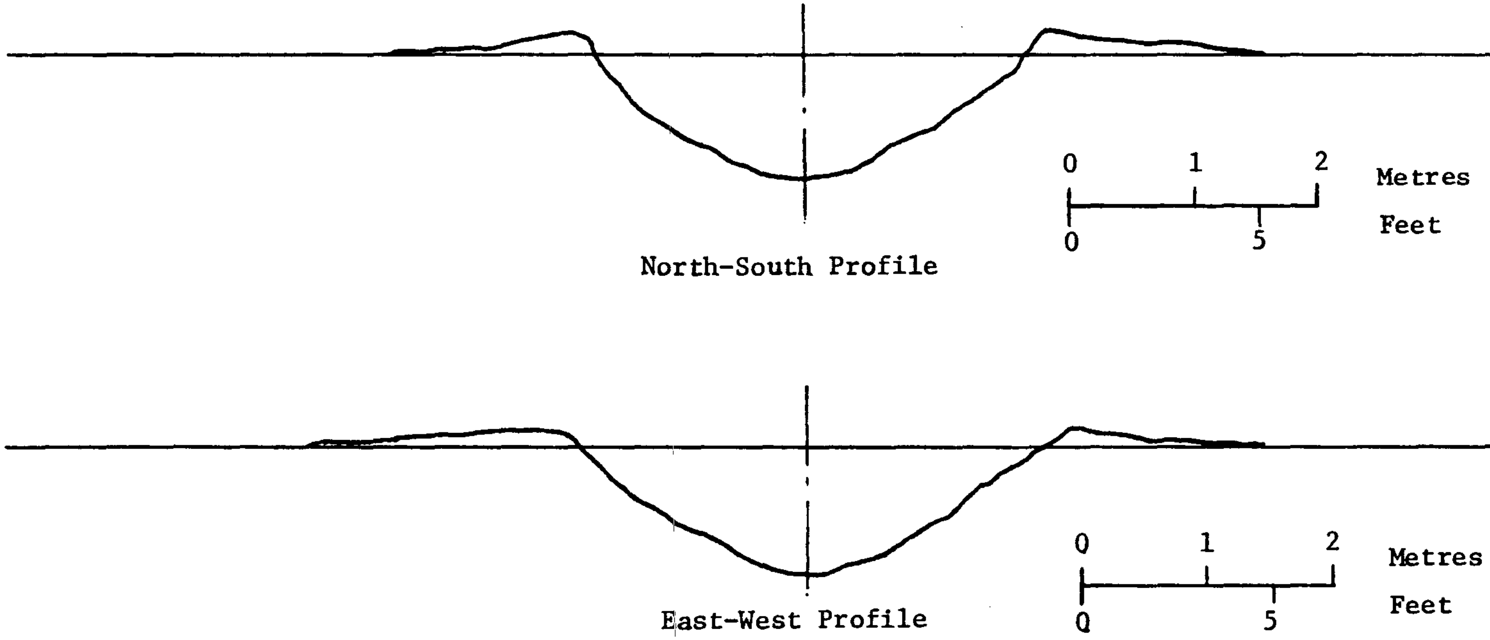
Explosive: C-4

Mean crater depth = 0.975 m (3.20 ft)

Mean crater radius = 1.65 m (5.42 ft)

Mean crater volume = 3.99 m^3 (141 ft^3)

Figure 3.5 Apparent crater profiles: H/D = 5 .



Charge Weight - 4.54 Kg (10 lb)

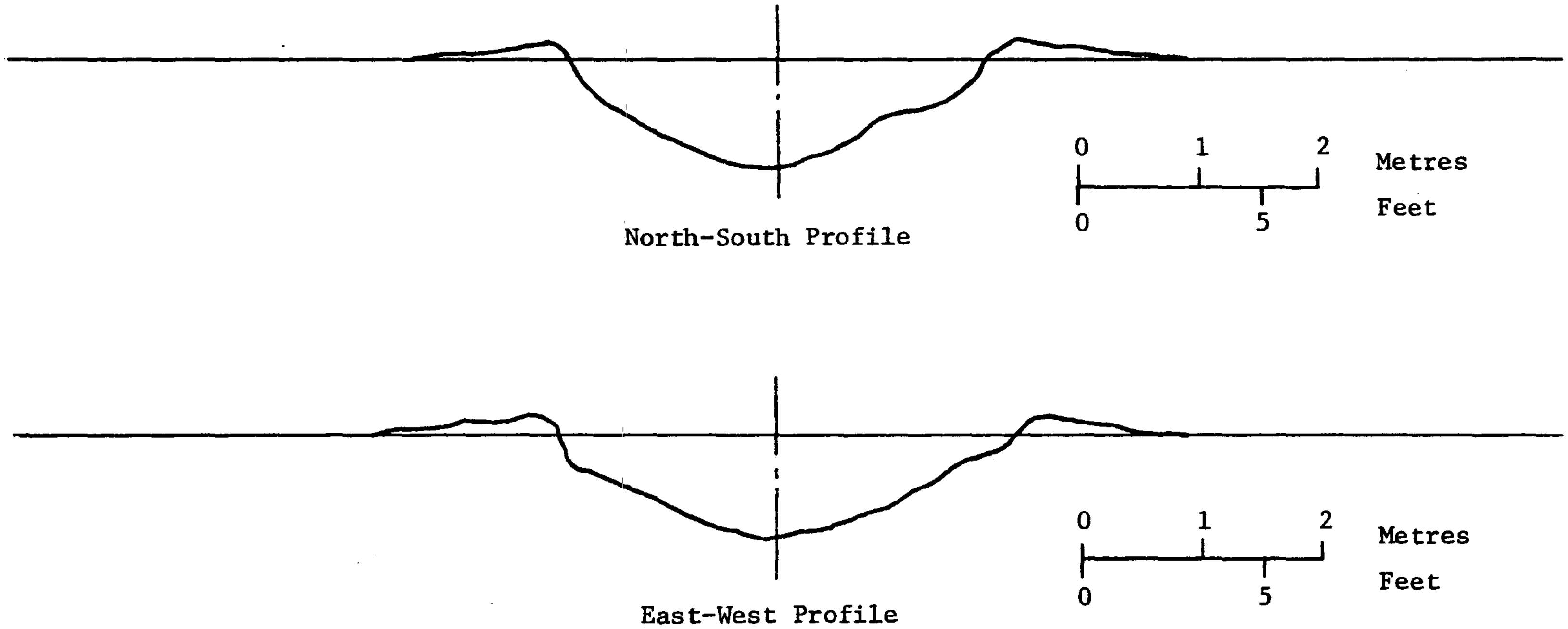
Explosive: C-4

Mean crater depth = 1.04 m (3.41 ft)

Mean crater radius = 1.71 m (5.62 ft)

Mean crater volume = 4.28 m^3 (151 ft^3)

Figure 3.6 Apparent crater profiles: H/D = 6 .



Charge Weight - 4.54 Kg (10 lb)

Explosive: C-4

Mean crater depth = 0.975 m (3.20 ft)

Mean crater radius = 1.80 m (5.91 ft)

Mean crater volume = 4.56 m^3 (161 ft^3)

Figure 3.7 Apparent crater profiles: H/D = 8 .

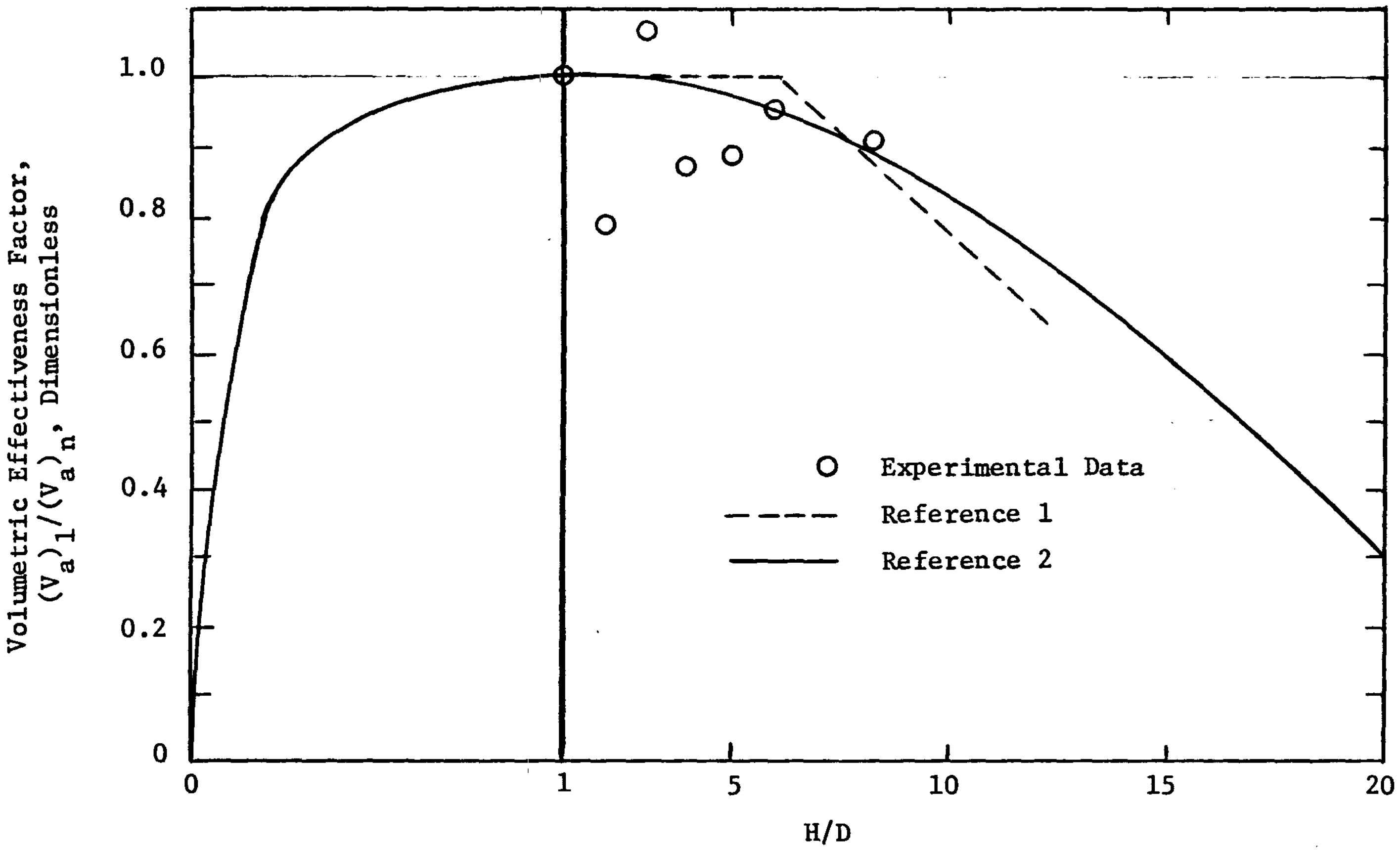


Figure 3.8 Variation of the volumetric effectiveness factor as a function of charge shape (H/D).

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

From the experimental results, it is obvious that changes in the crater size and shape are insignificant as applies to a given charge weight when the aspect ratio (H/D) of cylindrical charges varies from 1 to 8 (assumes a soil medium as opposed to desert alluvium or rock and assumes a constant scaled depth of burial in the range of 0.5 $m/kg^{1/3.4}$ (1.37 $ft/lb^{1/3.4}$)). This observation is supported also by References 1 and 2 which indicate that only minor changes in crater volume occur in the range of H/D greater than 1 and less than 8.

It therefore appears that drilling costs associated with charge emplacement in soil media can be significantly lessened when cylindrical charges with aspect ratios in the range of 5 to 8 are used. For any given size charge, the use of smaller diameter holes will serve to increase the penetration rate, thereby reducing the drill time and thus the drilling cost. However, savings in drilling costs are an interdependent function depending on penetration rate (p_r) as a function of hole diameter for any given medium, depth of hole (d_h), and the fixed unit operating cost (per hour or day) of the rig and crew (C_u). The cost (C) of drilling a given hole can thus be determined from:

$$C = \frac{d_h}{p_r} C_u$$

In minimizing costs for any given excavation project, trade-offs in charge shape versus drilling effort must be carefully studied for cost reductions to be real and significant.

4.2 RECOMMENDATIONS

It is recommended that high-yield tests (charge weights on the order of hundreds of pounds) be performed in order to insure that the low-yield results described in this report are in fact valid for the larger yields. Tests in the range of hundreds of pounds would provide confident scaling of results into the thousand-pound range.

It is further recommended that similar experiments be carried out in desert alluvium and rock to establish whether or not the results presented in this report are applicable to widely differing media.

REFERENCES

1. J. Briggs; "Military Engineering Applications of Commercial Explosives: An Introduction;" Technical Report E-73-2, May 1973; Explosive Excavation Research Laboratory, U. S. Army Engineer Waterways Experiment Station, CE, Livermore, Calif.

2. J. N. Strange; "The Effect of Charge Shape on the Geometry of Craters Formed;" (unpublished notes), June 1970; Weapons Effects Laboratory, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

APPENDIX A

CALCULATION OF APPARENT CRATER VOLUME[1]

Postshot surveys of the cratered area established crater depths at regular intervals along four orthogonal radials extending outward from GZ. For each crater, the four orthogonal radials (half-crater profiles) were considered independent. The four half-crater profiles were then averaged to form the half-crater profile representative of the particular shot. The computed apparent crater volumes were calculated from each of the representative profiles.

The method chosen to calculate the apparent crater volume treats the range (horizontal distance from GZ) as the independent variable. The primary reason for this choice is that range is a nondecreasing function and thus makes for a simpler calculational routine.

Each range and the crater depth at that range (observed from the representative half-crater profile) are input parameters to the computer program. As shown in Figure A.1, each range interval and the depth associated with each end point of the interval form a trapezoid. The area of the trapezoid is given by:

$$\text{Area} = h\left(\frac{a + b}{2}\right)$$

where h is the height and a and b are the bases of the trapezoid. If the depths associated with any two consecutive ranges are considered to be the bases and the interval between the ranges is considered to be the height, then a cross section of the crater can be viewed as a series of rectangles, each with a height of

$$R_n - R_{n-1}$$

and a base of

[1] Prepared by Max B. Ford, Weapons Effects Laboratory, U. S. Army Engineer Waterways Experiment Station.

$$\frac{D_n - D_{n-1}}{2}$$

By revolving each of the trapezoids about the vertical axis through GZ, the crater can now be considered as the summation of a series of concentric hollow cylinders or cylindrical shells, except for the innermost cylinder, which is a solid of revolution. This logic serves as the basis for calculating the apparent crater volumes.

The volume of each cylindrical shell is calculated from the following formula:

$$\text{Volume} = \pi\left(R_n^{\,2} - R_{n-1}^{\,2}\right)\left[\left(D_n + D_{n-1}\right)/2\right]$$

The volumes of the cylindrical shells are then summed to give the total volume of the crater as calculated from the input measurement of that particular representative half-crater profile.

The following computer program was written to calculate crater volumes using the above procedure. It is specifically for use on the Honeywell G 635 time-sharing system.

```
C     PROGRAM TO CALCULATE CRATER VOLUME
C
C    X DISTANCES AND Y DEPTHS MAY BE TYPED IN OR INPUT
C    ON PAPER TAPE,  STARTING AT CENTER OF CRATER OUTWARD
C    OR STARTING AT ONE SIDE OF CRATER AND PROCEEDING ACROSS
C    THE DIAMETER OF THE CRATER
C
C            APRIL 1975,  MBF
C
        DIMENSION X(100), Y(100), ZX(100), ZY(100)
     10 CONTINUE
        KOUNT = 0
        SUMM2 = 0.
     20 CONTINUE
        PRINT, "X DISTANCE AT CENTER OF CRATER?"
        READ 40, DIS
        DO 30 I = 1, 100
     30 ZX(I) =  - 100.
        PRINT, "RANGE?, DEPTH?"
        READ (5,40,END = 50) (ZX(I), ZY(I), I = 1, 100)
     40 FORMAT (V)
     50 CONTINUE
        DO 80 I = 1, 100
        IF (ZX(I).LT. - 90.) GO TO 100
        X(I) = ZX(I)
        Y(I) = ZY(I)
     80 CONTINUE
    100 J = I - 1
        NUM = 1
        IF (DIS) 110, 160, 110
    110 CONTINUE
        SUM = 0
        DO 120 I = 1, J
        IF (X(I).GE.DIS) GO TO 130
    120 CONTINUE
    130 CONTINUE
        NUM = I
        KNUM=2
        KX = NUM
```

```
      DO 140 I = 1, NUM
      X(I) = DIS - ZX(KX)
      Y(I) = ZY(KX)
      KX = KX - 1
  140 CONTINUE
  180 CONTINUE
C
C
C
C   VOLUME CALCULATIONS ARE PERFORMED BELOW
C
C
      DO 150 I=KNUM,NUM
      YY = (Y(I) + Y(I-1)) / 2.
      V = 3.14159 * YY * (X(I)↑2. - X(I-1)↑2.)
      SUM = SUM + V
  150 CONTINUE
C
C
C
C
      KOUNT=KOUNT+1
      SUMM2=SUMM2+SUM
      PRINT, "VOLUME THIS RADIAL IS", SUM
      IF (NUM.GE.J) GO TO 190
  160 CONTINUE
      DO 170 I = NUM, J
      X(I) = ZX(I) - DIS
      Y(I) = ZY(I)
  170 CONTINUE
      KNUM = NUM + 1
      NUM=J
      SUM=0
      GO TO 180
  190 CONTINUE
      PRINT, "AVERAGE VOLUME=1  CONTINUE=0  END=-1"
      READ, M
      IF (M) 210, 20, 200
  200 AVOL = SUMM2 / KOUNT
      PRINT, "AVERAGE VOLUME OF CRATER IS", AVOL
      PRINT, "END=0,  ANOTHER RUN=1"
      READ, MM
      IF (MM.LE.0) GO TO 210
      GO TO 10
  210 CONTINUE
      STOP
      END

READY

*
```

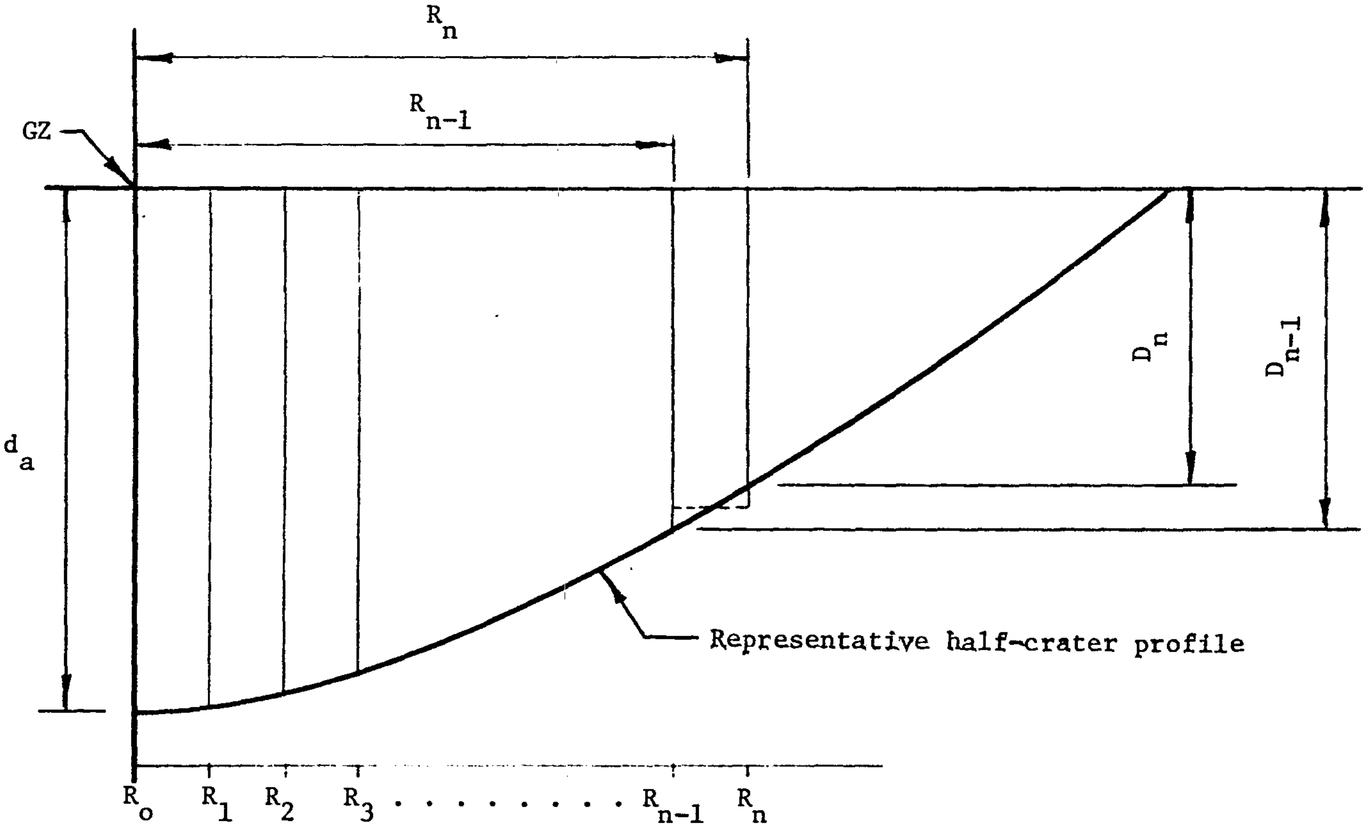


Figure A.1 Methodology for calculating the apparent crater volume.

APPENDIX B: NOTATION

a,b	Bases of trapezoid (Appendix A)
C	Drilling cost
C_u	Unit operating cost of drill rig and crew
d_a	Apparent crater depth
d_h	Emplacement hole depth
D	Diameter of charge
h	Height of trapezoid (Appendix A)
H	Height of charge
H/D	Aspect ratio of cylindrical charge
p_r	Penetration rate
r_a	Apparent crater radius
$\frac{r_a}{d_a}$	Linear shape factor
V_a	Apparent crater volume
$\frac{V_a}{\pi r_a^2 d_a}$	Volumetric shape factor
V_e	Volumetric effectiveness factor $[(V_a)_1/(V_a)_n]$
W	Charge weight
Z_c	Depth below ground to charge center of gravity (depth of burial, DOB)
Z_t	Depth below ground to top of charge
λ	Length scale

DISTRIBUTION LIST

	Address	No. of Copies
	DOD	
	Assistant to the Secretary of Defense, Atomic Energy, Washington, D. C. 20301	
46886	ATTN: Donald R. Cotter	1
	Director, Defense Advanced Research Projects Agency, Architect Building, 1400 Wilson Blvd., Arlington, Virginia 22209	
46047	ATTN: Technical Library	1
	Director, Defense Civil Preparedness Agency, Washington, D. C. 20301	
46879	ATTN: Technical Library	1
	Defense Documentation Center, Cameron Station, Alexandria, Virginia 22314	
12149	ATTN: TC/Myer B. Kahn	12
	Director, Defense Intelligence Agency, Washington, D. C. 20301	
46880	ATTN: DI-7D, Phys. Vul. Div., Edward O'Farrell	1
46792	DT-2, Weapons & Systems Division	1
46881	Technical Library	1
	Director, Defense Nuclear Agency, Washington, D. C. 20305	
46753	ATTN: STSI (Archives)	1
46754	STTL (Technical Library)	2
46755	SPSS	2
46884	DDST	1
46892	SPSS/Tom Kennedy	1
	Director of Defense Research and Engineering, Washington, D. C. 20301	
46885	ATTN: Dep Dir, Tactical Warfare	1
46790	Dep Dir, Strategic Systems	1
	Commander, Field Command, Defense Nuclear Agency, Kirtland Air Force Base, New Mexico 87115	
40721	ATTN: FCTA-C, Publications Office	1
	Commander, Field Command, Defense Nuclear Agency, Lawrence Livermore Laboratory, P. O. Box 808, Livermore, California 94550	
Type	ATTN: FCTA-D	1

	Address	No. of Copies
	Army	
	Office, Chief of Engineers, Department of the Army, Washington, D. C. 20314	
00041	ATTN: DAEN-MCE-D	1
00055	DAEN-RDL	1
	Engineer Studies Group, 6500 Brooks Lane, Washington, D. C. 20315	
17265	ATTN: DAEN-FES/Mr. George H. Orrell	1
	Commander, Harry Diamond Laboratories, Connecticut Avenue and Van Ness St. N. W., Washington, D. C. 20438	
17266	ATTN: AMXDO-NP	1
17286	Technical Library	1
	Office, Chief of Research, Development, and Acquisition, Department of the Army, Washington, D. C. 20310	
17270	ATTN: Technical Library	1
	Commanding Officer, Picatinny Arsenal, Dover, New Jersey 07801	
16276	ATTN: SMUPA-ND-S/E. Zimpo	1
16274	Technical Library	1
16273	P. Angelloti	1
	Director, U. S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland 21005	
15824	ATTN: J. Keefer	1
15823	AMXBR-X/J. J. Meszaros	1
15840	W. J. Taylor	1
15820	Technical Library, Edward Baicy	1
	Commander, U. S. Army Engineer Center, Fort Belvoir, Virginia 22060	
12551	ATTN: ATSEN-SY-L	1
	Division Engineer, U. S. Army Engineer Division, Huntsville, P. O. Box 1600, West Station, Huntsville, Alabama 35807	
00573	ATTN: HNDED-CS/Michael M. Dembo	1
	Division Engineer, U. S. Army Engineer Division, Ohio River, P. O. Box 1159, Cincinnati, Ohio 45201	
07467	ATTN: ORDAS-L/Technical Library	1

	Address	No. of Copies
	Army (Continued)	
	Director, U. S. Army Engineer Waterways Experiment Station, P. O. Box 631, Vicksburg, Mississippi 39180	
12099	ATTN: Library	5
12097	Mr. William J. Flathau	1
12098	Mr. John Strange	1
12090	Mr. L. F. Ingram	1
	Commander, U. S. Army Materiel Command, 5001 Eisenhower Avenue, Alexandria, Virginia 22333	
17020	ATTN: AMCRD-BN	2
17019	Technical Library	1
17030	AMCRD-WN	2
	Commander, U. S. Army Missile Command, Redstone Arsenal, Alabama 35809	
15002	ATTN: Technical Library	1
	Commander, U. S. Army Nuclear Agency, Fort Bliss, Texas 79916	
16810	ATTN: CDINS-E	1
16815	Technical Library	1
	Commander, U. S. Army Armament Command, Rock Island Arsenal, Rock Island, Illinois 61201	
15480	ATTN: Technical Library	1
	Navy	
	Officer in Charge, Civil Engineering Laboratory, Naval Construction Battalion Center, Port Hueneme, California 93041	
17630	ATTN: Technical Library	1
17562	Mr. R. J. Odello	1
	Commander, Naval Facilities Engineering Command, Hoffman Building, 200 Stovall Street, Alexandria, Virginia 22332	
18116	ATTN: Technical Library, Code 0911C	1
Type	Code 03A	1
	Superintendent, U. S. Naval Postgraduate School, Monterey, California 93940	
17513	ATTN: Library, Code 2124	1
	Director, Naval Research Laboratory, Washington, D. C. 20375	
18206	ATTN: Technical Library, Code 2027	1

	Address	No. of Copies
	Navy (Continued)	
	Commander, Naval Surface Weapons Center, Dahlgren Laboratory, Dahlgren, Virginia 22448	
18107	ATTN: Technical Library	1
	Commander, Naval Surface Weapons Center, White Oak, Silver Spring, Maryland 20910	
17826	ATTN: Technical Library, Code 730	1
17827	Code 1224 Navy Nuc Prgms Off	1
	Commander, U. S. Naval Weapons Center, China Lake, California 93555	
17511	ATTN: Technical Library	1
	Air Force	
	Air Force Armament Laboratory (AFSC), Eglin Air Force Base, Florida 32542	
19938	ATTN: Technical Library	1
	Commander, Air Force Cambridge Research Laboratories (AFSC), L. G. Hanscom Field, Bedford, Massachusetts 01730	
20042	ATTN: LWW, Dr. Ker Thompson	1
Type	SUOL AFCRL, Research Library	1
	Air Force Institute of Technology, AFIT Building 640, Area B, Wright-Patterson AFB, Ohio 45433	
20500	ATTN: Technical Library	1
	Commander, Air Force Weapons Laboratory (AFSC), Kirtland Air Force Base, New Mexico 87117	
20260	ATTN: SUL, Technical Library	1
20270	DEV-S/Dr. M. A. Plamondon	1
20290	DEV-F/Mr. J. L. Bratton	1
20140	DEV-G/Mr. R. W. Henny	1
20142	DEV, Mr. R. J. Port	1
	Headquarters, Air Force Systems Command, Andrews Air Force Base, Washington, D. C. 20331	
20705	ATTN: Technical Library	1
	Space and Missile Systems Organization, Norton Air Force Base, California 92409	
Type	ATTN: MMH	1
Type	MNNH	1
Type	MNI	1

	Address	No. of Copies
	U. S. Energy Research and Development Administration	
	Los Alamos Scientific Laboratory, P. O. Box 1663, Los Alamos, New Mexico 87544	
40706	ATTN: Technical Library	1
	Sandia Laboratories, Livermore Laboratory, P. O. Box 969, Livermore, California 94550	
30985	ATTN: Technical Library	1
	Sandia Laboratories, P. O. Box 5800, Albuquerque, New Mexico 87115	
40718	ATTN: Mr. L. J. Vortman	1
40703	Technical Library	1
	U. S. Energy Research and Development Administration, Albuquerque Operations Office, P. O. Box 5400, Albuquerque, New Mexico 87115	
40708	ATTN: Technical Library	1
	U. S. Energy Research and Development Administration, Nevada Operations Office, P. O. Box 14100, Las Vegas, Nevada 89114	
40100	ATTN: Technical Library	1
	Director, Lawrence Livermore Laboratory, P. O. Box 808, Livermore, California 94550	
30922	ATTN: Technical Information Division, Technical Library	1
30984	Larry Woodruff, L-125	1
	DOD Contractors	
	Agbabian Associates, 250 North Nash Street, El Segundo, California 90245	
62504	ATTN: Dr. M. S. Agbabian	1
	Applied Theory Incorporated, 1010 Westwood Boulevard, Los Angeles, California 90024	
62583	ATTN: Dr. John G. Trulio	2
	Braddock, Dunn, & McDonald, Inc., P. O. Box 8885, Station C, Albuquerque, New Mexico 87108	
63060	ATTN: Mr. Richard Hensley	1
	General Electric Company, TEMPO-Center for Advanced Studies, 816 State Street, Santa Barbara, California 93102	
65337	ATTN: DASIAC	1

	Address	No. of Copies
	DOD Contractors (Continued)	
	IIT Research Institute, 10 West 35th Street, Chicago, Illinois 60616	
66230	ATTN: Technical Library	1
	Institute for Defense Analyses, 400 Army-Navy Drive, Arlington, Virginia 22202	
66208	ATTN: Technical Information Office	1
	Martin Marietta Aerospace, Orlando Division, P. O. Box 5837, Orlando, Florida 32805	
67835	ATTN: Al Cowan	1
	Physics International Company, 2700 Merced St., San Leandro, California 94577	
69722	ATTN: Technical Library	1
69704	Mr. Fred M. Sauer	1
69702	Dr. Charles Godfrey	1
	R&D Associates, P. O. Box 9695, Marina Del Ray, California 90291	
70616	ATTN: Technical Library	1
70603	Dr. H. F. Cooper, Jr.	1
70602	Dr. Harold L. Brode	1
70635	Dr. C. P. Knowles	1
70636	Mr. J. G. Lewis	1
	Science Applications, Inc., 1911 North Fort Myer Drive, Suite 808, Arlington, Virginia 22209	
71226	ATTN: Dr. W. M. Layson	1
	Science Applications, Inc., P. O. Box 2351, La Jolla, California 92037	
71269	ATTN: Technical Library	1
	Stanford Research Institute, 333 Ravenswood Ave., Menlo Park, California 94025	
71274	ATTN: Technical Library	1
71275	Dr. G. Abrahamson	1
	Systems, Science and Software, P. O. Box 1620, La Jolla, California 92037	
71216	ATTN: Dr. Robert T. Allen	1
71276	Technical Library	1

	Address	No. of Copies
	DOD Contractors (Continued)	
	Weidlinger Associates, Consulting Engineers, 110 East 59th Street, New York, New York 10022	
72303	ATTN: Dr. Melvin L. Baron	1
	Weidlinger Associates, Consulting Engineers, 2710 Sand Hill Road, Suite 230, Menlo Park, California 99025	
72339	ATTN: Dr. J. Isenberg	1

In accordance with ER 70-2-3, paragraph 6c(1)(b), dated 15 February 1973, a facsimile catalog card in Library of Congress format is reproduced below.

Strange, John Nelson
Effect of charge shape on crater dimensions, by John N. Strange. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1975.
39 p. illus. 27 cm. (U. S. Waterways Experiment Station. Technical report N-75-5)
Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C., under Project 4A762719AT32, Task 02.
References: p. 26.

1. Craters. 2. Explosives. 3. Explosion effects. I. U. S. Army. Corps of Engineers. (Series: U. S. Waterways Experiment Station, Vicksburg, Miss. Technical report N-75-5)
TA7.W34 no.N-75-5