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CRATERING IN GREENLAND ICECAP SNOW

by

J. A. Conway, J. W. Meyer

July 1970

Sponsored by Defense Atomic Support Agency

Conducted by U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi

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ABSTRACT

Predicting cratering effects from explosions in various media and with various charge geometries is a primary purpose of nuclear weapons research. This report deals with crater formation resulting from high-explosive surface bursts in a snow medium.

The test program for which crater data were obtained consisted of nine 256-pound TNT charges, one 500-pound C-4 charge, one 1,860-pound C-4 charge, and two 4,180-pound C-4 charges. All were surface bursts fired on the Greenland icecap. Results show that craters produced in snow are larger than those produced in other media, presumably due to greater vaporization and compaction of material. These craters have a characteristic wide, shallow appearance; it is believed that pseudoelastic rebound is the mechanism that diminishes crater depth. Analysis of the crater data shows that scaling exponents for craters in snow are lower than cube-root or other scaling exponents generally used for craters in soil or rock media.
PREFACE

The work reported herein was performed by personnel of the U. S. Army Engineer Waterways Experiment Station (WES) under the sponsorship of the Defense Atomic Support Agency.

The work was accomplished during the summer of 1962 under the general supervision of Mr. E. P. Fortson, Jr., Chief of the Hydraulics Division, Mr. G. L. Arbuthnot, Jr., then Chief of the Engineering Research Branch, Nuclear Weapons Effects Division (NWED), and Mr. L. F. Ingram, Chief of the Blast and Shock Section, NWED. Members of the field party were Messrs. L. F. Ingram, R. A. Sager, K. Daymond, A. G. Reno, C. M. Wright, and SP4 D. Gee of WES and Mr. N. Smith of the U. S. Army Cold Regions Research and Engineering Laboratory.

This report, which documents the apparent crater measurements, was prepared by Mr. J. A. Conway and Mr. J. W. Meyer under the general supervision of Mr. G. L. Arbuthnot, Jr., now Chief of NWED, and Mr. J. N. Strange, Chief of the Engineering Research Branch, NWED, and under the direct supervision of Mr. A. D. Rooke, Jr., Chief of the Earth Kinetics Section, NWED.

Directors of the WES during the conduct of the field work and the preparation of this report were COL Alex G. Sutton, Jr., CE, COL John R. Oswalt, Jr., CE, COL Levi A. Brown, CE, and COL Ernest D. Peixotto, CE. Technical Directors were Mr. J. B. Tiffany and Mr. F. R. Brown.
3.6 Apparent crater profiles for Shots 10 and 12 ................................................. 24
3.7 Apparent crater profiles for Shots 11 and 13 ................................................. 25
4.1 Apparent crater dimensions as functions of charge weight ................................. 29
4.2 Apparent crater volume as a function of charge weight ....................................... 30
4.3 Comparison of apparent crater radius versus charge weight for surface-burst craters
in snow, clay, sand, basalt, and shale ................................................................. 31
4.4 Comparison of apparent crater depth versus charge weight for surface-burst craters
in snow, clay, sand, basalt, and shale ................................................................. 32
NOTATION, ABBREVIATIONS, AND DEFINITIONS

NOTATION

\(d\)  Density
\(d_a\)  Depth of apparent crater at ground zero
\(d_d\)  Depth of permanent deformation at ground zero
\(d_r\)  Depth of apparent rupture at ground zero
\(d_t\)  Depth of true crater at ground zero
\(h\)  Height of apparent crater lip crest; also depth of snow
\(r_a\)  Radius of apparent crater
\(r_d\)  Radius of area of permanent deformation
\(r_e\)  Radius of ejecta deposition, excluding that essentially windborne ( fallout)
\(r_h\)  Radius to apparent lip crest
\(r_r\)  Radius to apparent limit of rupture
\(r_t\)  Radius of true crater
\(r_u\)  Radius to true lip crest
\(u\)  Height of true lip crest (up thrust)
\(V_a\)  Volume of apparent crater
\(W\)  Width of apparent crater lip
\(W_{Q}\)  Charge weight

ABBREVIATIONS

CRREL  U. S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire
C-4  Composition 4, a plastic high explosive
DOB  Depth of burst
GZ  Ground zero, the hypocenter or epicenter of the charge, or the actual center of gravity of the charge for a surface burst
HE  High explosive (chemical)
NE  Nuclear explosive
**TNT**  Trinitrotoluene, a standard chemical explosive

**WES**  U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi

**DEFINITIONS**

**Apparent crater**  The visible crater, bounded at the top by the plane of the original ground surface

**Crater lip**  The distinctly raised portion of the earth mass immediately surrounding the apparent crater

**Surface burst**  A spherical charge (or nuclear shot) fired with center of gravity at ground surface

**True crater**  The crater prior to fallback of dissociated material, bounded at the top by the plane of original ground surface. It represents the surface of undissociated material

**Upthrust**  Permanent upward movement of original ground surface surrounding the true crater
CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows.

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<tr>
<td>knots</td>
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<td>kilometers per hour</td>
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\(^a\) To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula:

\[ C = \frac{5}{9} (F - 32) \]

To obtain Kelvin (K) readings, use:

\[ K = \frac{5}{9} (F - 32) + 273.15 \]
CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The ability to predict crater size and cratering effects from an explosion, whether nuclear (NE) or high-explosive (HE), has assumed increasing importance in recent years. Craters can present serious obstacles to a military force and, when used for excavation purposes, can make possible the construction of roadways, canals, etc., at substantial savings in time and money. Cratering and its associated effects also represent damage mechanisms that are important in military targeting and structural design.

Figure 1.1 is a schematic illustration of a crater formed by a surface burst, showing descriptive nomenclature and notations. Since crater size varies primarily with charge yield, depth of burst (DOB), and the cratered medium, it is desirable that tests be conducted with as many different charge geometries and in as many different media as possible in order that a comprehensive set of curves can be established for the various crater parameters. This also involves the development of suitable scaling exponents by which results of small-scale tests can be extrapolated to indicate results that might be obtained with much larger yields. Thus far, attempts to correlate theory with empirically developed exponents, or scaling laws, have met with only limited success. This is probably attributable to certain environmental effects, such as gravity, and some characteristics of the medium that do not readily lend themselves to scaling, as well as to the fact that the mechanics of the cratering process are not completely understood.

1.2 PURPOSE

The main purpose of the Greenland high-explosive test series of 1962 was to assess the blast and shock waves partitioned into the air (above the snow surface) and into the upper mantle of the deep snow deposits for surface-burst explosions. Cratering information was gathered from certain of these shots as bonus information, and the data were included in the U. S. Army Engineer Waterways Experiment Station's compendium of cratering data. Several requests for information on cratering in an arctic environment led to the decision to publish
these data even though considerable time has elapsed between the time of acquisition of the data and the date of publication.

1.3 SCOPE

The test program discussed herein consisted of 13 HE charge detonations ranging in size from 256 to 5,000 pounds\(^1\) of trinitrotoluene (TNT) or its equivalent, all fired as surface shots on the Greenland icecap. In addition, to pressure and acceleration measurements (Reference 1), the field party obtained, as a secondary effort, profiles of the apparent craters resulting from detonation of these charges. This report presents the results of those crater measurements.

\(^1\) A table of factors for converting British units of measurement to metric units is presented on page 9.
Figure 1.1 Typical half-crater profile and nomenclature for surface burst. Profiles and dimensions are symmetrical about the centerline.
CHAPTER 2

PROCEDURE

2.1 ENVIRONMENTAL CONDITIONS

The tests reported herein were conducted approximately 2 miles north-northeast of Camp Century, Greenland (Figure 2.1). The test site is approximately 6,000 feet above mean sea level.

2.1.1 Site Description. The area at the test site is composed of layers of snow and thin ice lenses to a depth of approximately 100 feet. Below 100 feet, the medium becomes solid ice. The density of the snow is assumed to vary with depth according to the approximate relation

\[ d = 0.40 + 0.16h \]

where

- \( d \) = density, \text{gm/cm}^3
- \( h \) = depth of snow, meters (Reference 1)

This relation was believed valid below a depth of about 10 feet. The density in the top one or two feet was approximately 0.30 \text{gm/cm}^3.

2.1.2 Weather Conditions. During the entire test program, which lasted about three weeks, the temperature varied from 15 to 30 F and the wind speeds from 10 to 22 knots.

2.2 CHARGE AND SHOT GEOMETRIES

All the charges were emplaced so that their centers of gravity were at the ground surface. The 256-pound charges were cast TNT spheres with a 1.7-foot diameter, and the remaining charges were made of Composition 4 (C-4) blocks stacked in a box that was parallelepiped in shape and measured 44 by 44 by 39 inches (Figure 2.2). Each of the C-4 blocks measured 2 by 2 by 11 inches and weighed 2.5 pounds. All the charges were centrally detonated by an automatic timing device.

2.3 SHOT PROGRAM

The charges were fired during the period 9 July to 3 August 1962. There were nine
256-pound charges, one 500-pound C-4 charge (considered the equivalent of 600 pounds of TNT), one 1,860-pound C-4 charge (the equivalent of 2,230 pounds of TNT), and two 4,180-pound C-4 charges (each equivalent to 5,000 pounds of TNT). Several 36-pound TNT charges were also fired, but no crater measurements were made.
Figure 2.1 Vicinity map.
Figure 2.2 Wooden box containing 4,180 pounds of C-4 blocks after emplacement. (U. S. Army photograph.)
Prior to each shot, a line extending through ground zero (GZ) was surveyed using differential leveling techniques. After each detonation, the same line (along a crater diameter) was resurveyed in order that the dimensions of the apparent crater could be obtained. Table 3.1 presents the charge yield, shape, type of explosive, and apparent crater dimensions for each shot in the test program. The volume of each crater was calculated by planimetering the areas of its half-crater profiles, averaging them, and then revolving this averaged area 360 degrees about a vertical axis through the crater GZ. This procedure is fully described in Reference 2. Figure 3.1 is a photograph of the detonation of Shot 11, and Figure 3.2 is a photograph of the resulting apparent crater. Figures 3.3 through 3.7 show the apparent crater profiles for each shot in the program.
### TABLE 3.1 SHOT DATA AND APPARENT CRATER DIMENSIONS

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<tr>
<td>13</td>
<td>4,180</td>
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</table>

$^a$ To three significant figures.
Figure 3.1 Detonation of Shot 11. (U. S. Army photograph.)
Figure 3.2 Apparent crater resulting from Shot 11. (U. S. Army photograph.)
Figure 3.3 Apparent crater profiles for Shots 1 through 3.
Figure 3.4  Apparent crater profiles for Shots 4 through 6.
Figure 3.5 Apparent crater profiles for Shots 7 through 9.
SHOT 10, 500-LB C-4 CHARGE, 3 AUG 62

SHOT 12, 1,860-LB C-4 CHARGE, 27 JULY 62

Figure 3.6 Apparent crater profiles for Shots 10 and 12.
Figure 3.7 Apparent crater profiles for Shots 11 and 13.
CHAPTER 4
DISCUSSION

4.1 CRATERING MECHANISMS IN SNOW

Due to the unique physical properties of snow, craters formed by explosions in this medium will be somewhat different in appearance and size from craters formed in other media. Snow is a composite material that consists of a relatively incompressible crystalline solid (ice) and a compressible gas (air). The air is found in interconnecting voids in the ice matrix and comprises up to 70 percent of the volume of snow near the surface of an icecap. Other snow properties of considerable importance in cratering are the relatively low melting and vaporization points.

The sequence of events in crater formation for a surface burst in snow, as given in Reference 3, is discussed in the following paragraphs.

4.1.1 Cavity Formation and Ejection of Material. Immediately after detonation, as the hot gas bubble begins to form a cavity by vaporization, the surrounding snow is compacted radially, and the air in the voids is compressed. Cavity walls are fractured and an ice skin is formed by fusion. During this loading of the snow, a substantial proportion of the explosive energy is expended in compacting and deforming the material without destroying cohesion. An undetermined amount of snow is dissociated and thrown from the crater as ejecta.

4.1.2 Pseudoelastic Rebound. Much of the energy used to compress the air in the voids during loading is recovered during unloading (after the pressure wave has passed) and then re-expended in fracturing and deforming the snow. The primary cavity then exhibits a reversal in the direction of displacement as the snow attempts to regain its original shape. Since this action is primarily due to an increase in volume of the interstitial air as pressure is reduced, it is referred to as pseudoelastic rebound. Simultaneously, the compacted snow zone and the ice skin formed at the conclusion of cavity growth are disrupted.

4.2 CORRELATION WITH PREVIOUS SHOTS

In general, the same mechanisms of crater formation have been observed in other media. These have been identified as vaporization, compaction, plastic flowage (forming the upthrusted region in the crater lip—Figure 1.1), and ejection (References 4 and 5). In soil and rock,
however, vaporization is negligible, even in a nuclear detonation. On the other hand, the plastic flowage mechanism in such craters is significant; there is no way to determine whether such a mechanism even existed in the Greenland tests, but the crater profiles show that if it did exist, it could not have been an important contributor to crater volume.

Figure 4.1 shows the variation of apparent crater depth and apparent crater radius with charge weight. Figure 4.2 shows apparent crater volume as a function of charge weight. Other cratering data for surface shots in snow are virtually nonexistent. Data from four small surface shots (ranging in size from 0.5 to 2.0 pounds) in snow (Reference 6) are also plotted in Figures 4.1 and 4.2 along with the Greenland data. Data from a single 32-pound TNT surface shot from the 1960 Greenland test series (Reference 7) are also included in Figure 4.1.

Figure 4.3 shows the variation of apparent crater radius with charge weight for surface bursts in snow as compared with that of surface TNT shots in clay, sand, basalt, and shale. Similarly, Figure 4.4 presents a comparison of apparent crater depths versus charge weights. Data for the shots in the clay, sand, basalt, and shale were selected from Reference 6 to cover the same range of charge yields as the data for the explosions in snow. Figures 4.3 and 4.4 show that craters in snow tend to be larger than craters in other media for the same charge yield. This increased size appears to be due to the greater amount of material vaporized and compacted during the explosion. Although no ejecta measurements were made, examination of the crater lip profiles indicates that the contribution (to volume) of the ejection mechanism in snow craters is correspondingly less than in craters in other media. Craters in snow have a characteristic wide, shallow appearance. The magnitude of the pseudoplastic rebound in snow is greater directly under the charge than in the material pushed laterally outward because of the greater lateral confinement of the material at this point.

4.3 SCALING CONSIDERATIONS

Equations for scaling crater dimensions in snow within a range of yields of 0.5 to 5,000 pounds, as determined by use of the method of least squares, are presented in Figures 4.1 and 4.2. These equations show a significant departure from customarily used cube-root scaling, which has been adopted on the basis of dimensional analyses presented in Reference 8. For the apparent crater radius, a slightly smaller scaling exponent of 0.26 is indicated. The scaling exponent for apparent crater depth, 0.15, is considerably smaller than that normally
applied to craters in soil. These scaling exponents are probably best explained by the magnitude of the pseudelastic rebound in snow. A correspondingly low scaling exponent of 0.75 is derived for the apparent crater volume. It should be noted that these empirical scaling exponents are based on a limited amount of data and should be considered as approximations until more data are available. The use of these exponents to scale nuclear explosions from HE charges would be questionable because of the magnitudes of the NE yields and the difference in thermal energy release, which appears to influence crater formation in snow significantly.
Figure 4.1 Apparent crater dimensions as functions of charge weight.
Figure 4.2 Apparent crater volume as a function of charge weight.
Figure 4.3 Comparison of apparent crater radius versus charge weight for surface-burst craters in snow, clay, sand, basalt, and shale. Curve is fitted to snow data and is taken from Figure 4.1b.
Figure 4.4 Comparison of apparent crater depth versus charge weight for surface-burst craters in snow, clay, sand, basalt, and shale. Curve is fitted to snow data and is taken from Figure 4.1a.
CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Results of the test program reported herein show that, for a given charge weight, explosions in snow produce larger craters than those in soil or rock. Also, the scaling exponents used to scale the results for snow craters are smaller than those customarily used to scale results for craters in other types of media. These differences are attributed to greater vaporization and compaction that occur during the explosion and to the greater magnitude of the pseudoelastic rebound in snow, which in turn result from the unique physical properties of the medium.

5.2 RECOMMENDATIONS

Due to the scarcity of crater data for explosions in snow, it is recommended that advantage be taken of further explosion tests similar to those discussed herein, but with various charge sizes and geometries, to obtain more complete data. Provision should be made for collecting data concerning ejecta, ground shock, and pressure waves in snow, as well as data on crater parameters. However, the need for conducting such tests should be weighed against the need for collecting information about other media in which engineering and military works are more commonly carried out. Thus, tests in rock, soil, or even frozen ground may of necessity take priority over further tests in snow.
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Predicting cratering effects from explosions in various media and with various charge geometries is a primary purpose of nuclear weapons research. This report deals with crater formation resulting from high-explosive surface bursts in a snow medium. The test program for which crater data were obtained consisted of nine 256-pound TNT charges, one 500-pound C-4 charge, one 1,860-pound C-4 charge, and two 4,180-pound C-4 charges. All were surface bursts fired on the Greenland icecap. Results show that craters produced in snow are larger than those produced in other media, presumably due to greater vaporization and compaction of material. These craters have a characteristic wide, shallow appearance; it is believed that pseudoelastic rebound is the mechanism that diminishes crater depth. Analysis of the crater data shows that scaling exponents for craters in snow are lower than cube-root or other scaling exponents generally used for craters in soil or rock media.
Cratering
Explosion effects
Greenland icecap
Snow