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UCRL-52253

SITE CHARACTERIZATION REQUIREMENTS FOR NUCLEAR-CRATERING DESIGN

R. W. Terhune and R. C. Carlson

March 24, 1977

Prepared for U.S. Energy Research & Development Administration under contract No. W-7405-Eng-48

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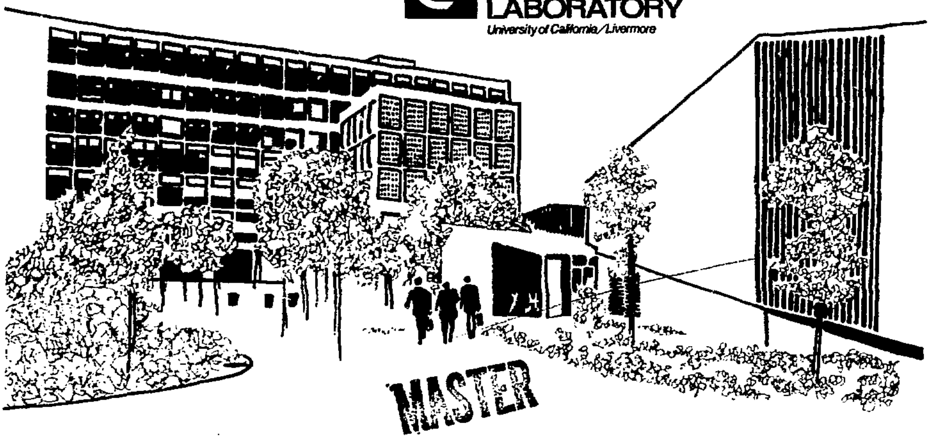

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Available from
National Technical Information Service
U.S. Department of Commerce
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Springfield, VA 22161
Price: Printed Copy $; Microfiche $3.00

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Contents

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Abstract

This paper presents a material properties measurement program for the design of large engineering, nuclear-excavation projects by computer calculation. Material properties of the site and their relative effect on crater size are analyzed and ordered in relation to their importance in determining the overall cratering efficiency. The measurement program includes both *in situ* logging and laboratory measurement of core samples, together with the reason for each measurement and its use in the calculations.

Introduction

Large engineering excavation projects that require the use of nuclear explosives for economic feasibility (e.g., canals, reservoirs, dams, and harbors) must be designed to ensure success before any nuclear detonation takes place. The cratering efficiency of the geologic environment must be determined to define the project in terms of yield and number of explosives, spacing between explosives, and depth of burial. Cratering efficiency is volume excavated per kiloton of yield at a constant scaled depth and is highly dependent on the material properties of the rock medium.

The material properties for deep and/or long excavations may vary considerably with depth such that determining the cratering efficiency empirically with chemical explosives may not produce relevant results. Cratering efficiency can be determined by two-dimensional numerical computer calculations that simulate a nuclear detonation and the effect of the resultant shock wave on the surrounding rock.[1-3] Cratering phenomenology is such that relatively simple material-behavior models[4-6] can produce excellent results if basic material properties are provided.

It is the purpose of this paper to delineate the mechanics of nuclear-explosive cratering, the material properties that are the most critical in the cratering process,[1] and a measurement program explaining the use of various measurements in a calculational analysis.

Mechanics of Cratering

Boundary conditions determine the nature of the solution in all wave-propagation problems. The principal boundaries in cratering are the ground surface and the cavity formed by the explosion. Both boundaries are free. Stress-wave interaction on these boundaries divides the process of crater formation into four observable and sequential phases: shock (compressive wave from cavity to ground surface), spall (rarefaction wave from ground surface to cavity), gas acceleration (recompaction wave toward ground surface), and ballistic trajectory (free fall).

SHOCK

A shock wave is a large stress discontinuity created when the restrained internal energy of a nuclear device is released. As the shock wave propagates in the medium, it compresses the rock, distributing internal and kinetic energy as it moves outward. The wave's energy decays with distance from the source; changes in the state of the rock depend on the energy deposited. The rock is vaporized immediately around the source, and is molten for some intermediate distance. Crushed and fractured rock extends a considerable distance beyond the region of melt. The shock wave develops the conditions for forming a large cavity around the source and imparts a momentum to the rock through which it travels.

SPALL

A rarefaction wave is reflected when the shock wave reaches the free (ground) surface, relieving pressure in the rock as it travels back toward the cavity. Tension is developed in the rock, causing horizontal fractures to develop within the resulting slabs of material traveling at a velocity characteristic of the momentum trapped in the rock. This trapped momentum establishes the conditions necessary for development of the gas-acceleration phase. It also establishes the limits of the true crater above the shot point.

GAS ACCELERATION

Because rarefaction has relieved the pressures in the rock above the cavity (which still contains several hundred atmospheres of pressure), the resulting pressure differential accelerates the growth of the upper part of the cavity. Growth of the cavity may ultimately recompact the rarefied rock above it and additionally increase its momentum. The cavity expands rapidly toward the initial ground surface, forming large observable mounds. Unrestrained spherical divergence of a mound leads to its distintegration, the horizontal component of velocity tending to drive the sides of the mound away from the crater area.

BALLISTIC TRAJECTORY (FREE FALL)

The final cavity pressure (1 or 2 atm) is vented during mound disintegration. The forces of gravitation and friction alone now affect each particle on its own ballistic trajectory. The depth of the crater depends on the amount of fallback material and its bulking characteristics.

Figure 1 shows the effect of each mechanism on the particle velocity for material above the detonation point as a general function of time. The relative effect of each mechanism on the total mound-velocity field depends on the material properties and the cratering characteristics of a medium. The mound-velocity field at the end of the gas-acceleration phase determines the crater geometry.

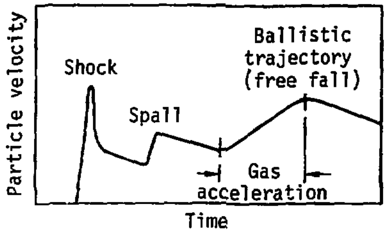

Fig. 1. Cratering mechanisms.

Material Characteristics Important in Cratering

The equation of state (EOS) defines the cratering efficiency of a medium; that is, the equation of state specifies how much of the explosive's internal energy will be converted into kinetic energy in the mound above the explosive by shock, spall, and gas acceleration.

We have found the following four equation-of-state parameters important in determining cratering efficiency:

- Compressibility
- Gas-filled porosity (ultimate compactibility)
- Water content
- Strength

The first three relate to the hydrostatic loading and unloading characteristics of the medium. The fourth limits the permissible deviatoric stress in the rock.

Figure 2 compares the hydrostatic compressibility of the various types of rock listed in Table 1. The difference between hydrostatic loading and unloading (dashed line) in these types of rock is a measure of their nonrecoverable porosity. Table 1 gives the density, bulk modulus, and sound speed for the various rock types in their respective groupings.

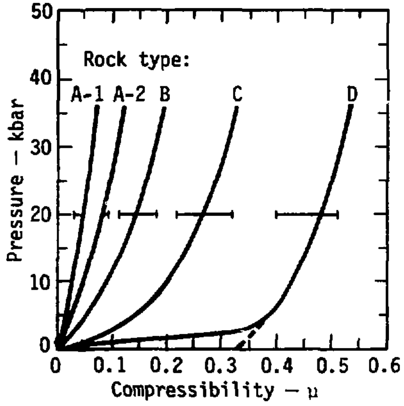

Fig. 2. Pressure-volume relationship for various rock types. [$\mu = (V_0/V) - 1$]

Figure 3 shows the wide range of shear strengths vs pressure found among various rock samples in three general states: solid, fractured, and wet. Strength does not correlate as well with the rock type (A-1, A-2, etc.) as it does with the state of the rock. The curves in this figure indicate a general trend in strength behavior; however, there are many exceptions to this idealized picture.[7]

The effect of material properties on the cratering mechanism can be

Table 1. Significant parameters of various rock types.

Rock type	Rock and experiment	Density, Mg/m^3	Sound speed, m/sec	Bulk modulus, kbar	Ref.
A-1	Canal basalt	2.65	6264	388	10
	Cabriolet (deep layer)	2.53	3966	394	8
	Hardhat	2.65	6264	552-333	8
	Buggy basalt (type 1)	2.60	2743	480	9
	Buckboard basalt (type 1)	2.6	2194	2[illegible]6	8
	Pre-Schooner VIT (type 2)	2.3	2438	256	8
A-2	Palanquin type 1	2.5	2426	149	8
	Palanquin type 2	2.4	1524	116	8
	Cabriolet type 2	2.3	1524	97	8
	Faultless tuff	2.283	3505	160	9
B	Bear Paw (Fort Peck) shale	2.2	1828	50.5	9
	Buggy basalt (type 3)	2.38	1524	77	9
	Greeley tuff	2.0	3093	47.5	9
	Gas Buggy sandstone	2.48	4145	100	9
C	Cabriolet (type 3)	1.98	1097	13.5	8
	Palanquin (type 3)	2.0	906	19.4	8
D	Buggy basalt (type 5)	1.94	1097	18	9
	Alluvium	1.5	914	18	8
	Scroll	1.4	1280	19-28	9

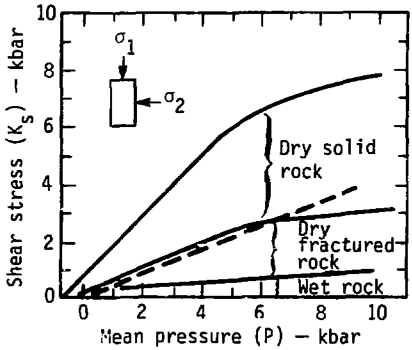

Fig. 3. Shear strength trends as a function of mean stress. [$K_s = (\sigma_1 - \sigma_2)/2$; $P = (\sigma_1 + 2\sigma_2)/3$]

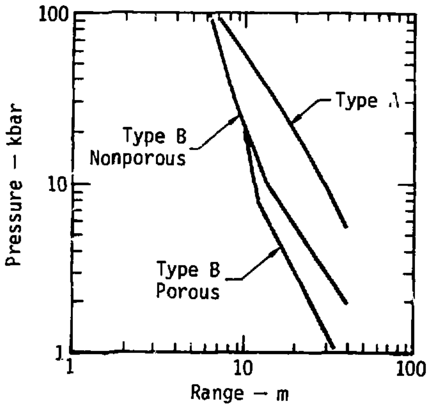

Fig. 4. Shock attenuation as a function of compressibility and gas-filled porosity.

readily illustrated by a parameter study on SOC (1-D) or TENSOR (2-D).[5,11,12]

COMPRESSIBILITY AND GAS-FILLED POROSITY

Figure 4 is a plot of the peak shock stress vs distance as calculated by SOC and illustrates the effects of compressibility and gas-filled porosity on shock-wave attenuation. Peak pressures are attenuated more rapidly for the more compressible rock. If the rock is compactible (porous), peak pressures are further attenuated. Figure 5 shows the particle velocity vs range (corresponding with Fig. 4) at a specific time. (For the corresponding equation of state, see Fig. 2.) The peak-particle velocity of the shock front is proportional to the shock stress and thus is controlled

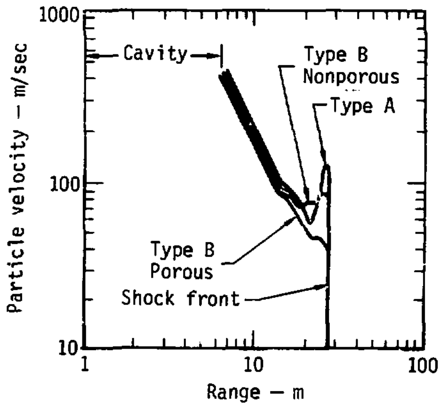

Fig. 5. Particle velocity as a function of compressibility and gas-filled porosity.

by stress attenuation. It is interesting to note that the velocity field in the mound behind the shock varies only slightly with compressibility and gas-filled porosity.

WATER CONTENT

Static tests have demonstrated that the presence of free water within a rock significantly reduces both its nonrecoverable porosity and its ultimate shear strength (Fig. 3). Reducing either of these parameters leads to an increase in the cratering efficiency of the medium. Also, vaporization of free water in the rock by the shock wave (outside the initial radius of rock vaporization) creates a larger source region, a significant fraction of which is noncondensable water vapor.[13,14]

This larger effective source region maintains higher pressures than dry rock and increases spall velocity about 10%. Most significantly, this provides a strong, long-lasting, gas-acceleration phase.[1]

STRENGTH

The behavior of the shock wave due to shear-stress variations is not a simple function of the shear strength but depends on the entire equation of state. Naturally, the higher the shear stresses that are allowed to develop, the more severe is the attenuation.

An interesting parameter study is the effect of the fractured strength of the failed rock on the particle velocity of the entire mound. Figure 6 shows the decay of particle velocity behind the shock wave as the fractured strength is increased from 0-0.5 to 5.0 kbar. The failed rock strength is one of the primary equation-of-state parameters that determine the cratering efficiency of the rock.

CRATERING EFFICIENCY

We have defined the cratering efficiency of the medium in terms of the kinetic energy developed in the mound by the explosive. The kinetic energy is determined in turn by the equation of state of the rock. To illustrate these relationships, mound-velocity profiles were calculated on SOC for three media in which there is cratering experience. The first medium was Bear Paw shale from the Fort Peck reservoir — saturated, nonporous, and extremely weak; the second was Sedan alluvium — very porous, moderately weak, and moist (10% water by weight at the depth of the calculation); and the third was Nevada Test Site (NTS) Buckboard basalt — dry, porous, and moderately strong.

Figure 7 shows the velocity profiles between the cavity and the free surface for the three media. These calculations were for a 1-kt nuclear yield at a depth of 40 m. The plots were taken at the moment the rarefaction wave arrived at the cavity, which varied because of differences in the compressional-wave velocity

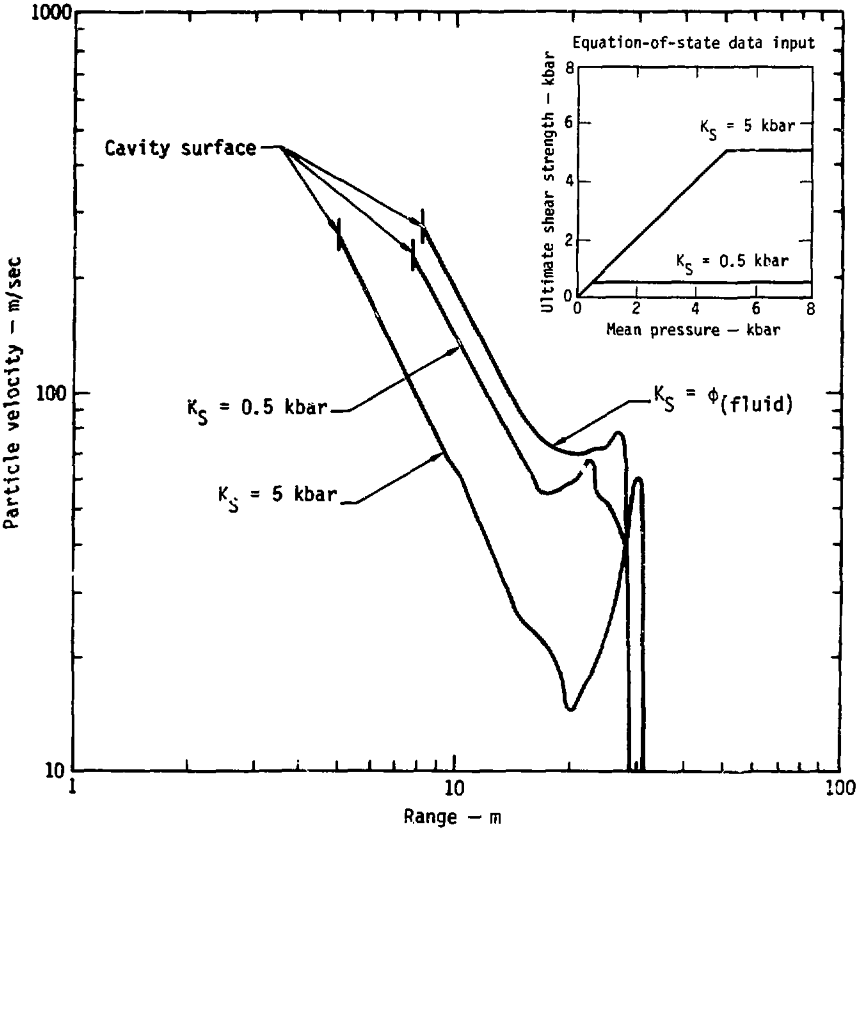

Fig. 6. Particle velocity as a function of shear strength. $[K_s = (\sigma_1 - \sigma_2)/2;$ $P = (\sigma_1 + 2\sigma_2)/3]$. (a) Shear strength as a function of mean stress. $[K_s = (\sigma_1 - \sigma_2)/2;$ $P = (\sigma_1 + 2\sigma_2)/3]$.

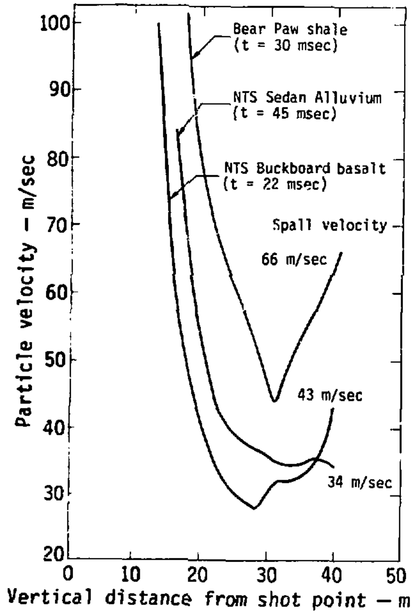

Fig. 7. Mound velocity field for three cratering media where t = time of arrival of rarefaction wave at cavity surface.

for the medium. Figure 8 shows empirical, scaled cratering curves for the apparent crater radius in the three media. Comparison of the velocity curves with the cratering curves at optimum depth shows a definite correlation between the velocity field behind the spalled region and the crater radius.

In summary, the compressibility and gas-filled porosity of the rock are the dominant factors in determining the energy delivered to a point in that medium. However, the velocity field behind the shock or spalled region is determined primarily by the shear stress and the length of time that the stress operates. The final velocity field through the mound then depends on the effectiveness of the gas-acceleration phase.

If the material properties were listed in order of importance for determining the cratering efficiency of the medium, the list should be:

1. Water content
2. Shear strength
3. Gas-filled porosity
4. Compressibility

The water content is of primary importance because it decreases the rock compressibility and gas-filled porosity and drastically reduces its shear strength. Water content also provides an additional energy source in the expansion of noncondensable water vapor. All the above factors increase the velocity field of the mound and therefore the cratering efficiency of the medium.

Measurement Program

To characterize a site, it is necessary to drill a sufficient number of exploratory holes to fully define the geologic structure and lithology in the region of the proposed detonation depths and between

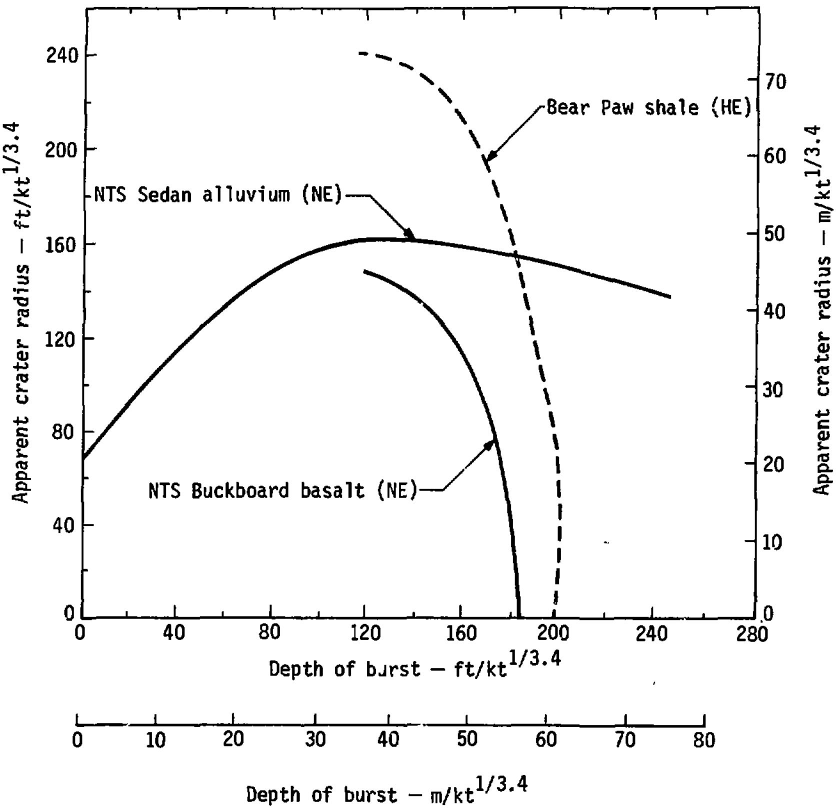

Fig. 8. Scaled crater radius curves.

those depths and the surface. The major rock types in the region must be identified and core samples must be obtained. Chips from the drilling between core runs should be sampled at regular intervals and preserved with the depths noted. Analysis of the chips helps to determine how well the small core samples represent the site and aids in resolving inconsistencies in the other data.

THE LOGS

An important part of site characterization is the logging program. Logs give a continuous record of the measured variable with depth and provide the calculational physicist with the data necessary to simulate the important features of the site.

The calculational model of the site is represented by a series of homogeneous layers, each with its specified properties. The logs are the primary means of determining the average properties of these layers over any depth interval.

Those variables that can and should be measured are the caliper of the hole, the bulk density, and the sound velocity. Additional measurements that are helpful are fracture frequency and any regions of full water saturation.

A wide range of geophysical-logging methods exist, each with its own major parameter of interest and susceptibility to perturbing influences. The particular methods used on a given project should be carefully chosen to suit the needs and constraints of that project. Sometimes standard instrumentation can be used; other times one-of-a-kind equipment is required.[15,16] The following describes specific methods that have proved useful on past projects.

The Caliper Log

The caliper log is a necessary adjunct to log interpretation since the response of most borehole logging instruments is affected by the size and roughness of the hole. In addition, caved regions of the hole indicate regions where the rock is weak, fractured, or susceptible to water damage. This information and other data aid in the decision-making process of modeling the site computationally.

The Bulk-Density Log

The cratering efficiency of a site is almost independent of the density of the rock. However, because of the high correlation of the density with other important parameters, the bulk-density log is one of the most necessary logs for site characterization. The density log and the sound-velocity log together pinpoint regions of elastic-impedance contrast. The existence of a high-impedance contrast subsurface affects not only the magnitude of the stress transmitted across the boundary but also the direction of the momentum vector. A low-impedance material overlaying a high-impedance rock will enhance the vertical component of the momentum vector but will severely reduce the horizontal component. This can lead to less material being ejected from the crater area with a reduction in crater depth and must be accounted for in the design of the explosive placement.

The bulk-density log when combined with the measurement of grain density and water content of core samples allows a calculation of gas-filled porosity that is more representative over large intervals than that obtained from density measurements on individual core samples. Gas-filled porosity has been identified as one of the key parameters in cratering efficiency.

There are two principal methods of measuring bulk density *in situ*:

1. The gamma-gamma density method infers bulk density from the degree of scattering and attenuation of gamma rays in the formation. The reliability of the measurement depends on borehole roughness and somewhat on one's knowledge of the atomic species present in the formation. Sample size is approximately 0.5 m by 0.1 m.

2. The borehole-gravity method measures the mass of the rock by its gravitational effect.[17] Local geologic structure and surface terrain can affect the measurement; conversely the method can be used in combination with other density knowledge to infer structure.[18]

The Sound-Velocity Log

The importance of sound velocity when combined with the bulk-density log was explained above. In addition, the velocity of wave propagation controls the timing of the various dynamic phases of cratering and is important in determining the overall cratering efficiency of the medium. The homogeneous layering required by calculational methods must have wave-propagation velocities that are consistent with the site. Sound velocity is a key parameter in defining these calculational layers.

A number of methods for obtaining this data are listed in order of preference below:

1. An uphole-velocity survey uses geophones placed in a pattern on the surface. A small chemical explosive is lowered to the bottom of the hole, is detonated, and the resultant time of arrival of the shock wave is recorded by the geophones. This is repeated as the explosive is detonated higher and higher in the hole at regular intervals. This method provides information on the rock unaffected by the hole as well as producing the average or integrated velocity data required by the model. This should be the last measurement made because of severe hole damage.

2. A downhole-velocity survey is simply the reverse of the above procedure. The geophones are emplaced downhole and the small explosive charge is placed near the surface at a small distance from the exploratory hole.

3. A dry-hole acoustic log (DHAL) uses a tool which measures the acoustic travel time along the wall of the hole over the 1- to 2-m length of the tool. As the name implies, it

operates in a dry hole and can thus be used above the water table.

4. A continuous-velocity log (full-wave recording) works well below the water table and provides sound- or compressional-velocity data, and shear-velocity data. In some cases, fractures have been detected with this tool. Like the DHAL, the log measures interval velocity over the 1- to 2-m length of the tool.

5. A vibrator-seismic survey is similar to the downhole survey, except that a vibrator is used on the surface instead of explosives. This often produces a weak, broad-signal waveform that results in less resolution but has the advantage of not requiring explosives.

NATURAL FRACTURE FREQUENCY

Fracture frequency is not a critical parameter but is useful if it can be obtained. Decisions on whether the measured shear strength from small samples is representative of the geologic structure are often based on the preexisting fracture frequency. A high-frequency, acoustic-scanning device can provide this information or an examination of the core sample may be sufficient.

REGIONS OF FULL SATURATION

Knowledge of any regions between the detonation point and the free surface where the rock is fully saturated can be important in calculating the crater efficiency of the site. The interface between a saturated rock and a partially saturated rock forms an impedance contrast to the high-intensity stress wave with results similar to an elastic impedance (as explained in the discussion for the bulk-density log). Analysis of neutron logs and electric logs can locate regions of full saturation and can be helpful in intervals where coring is lacking.

THE CORE TESTS

In order for the laboratory tests on the core to be valid, the core samples must receive special handling (wrapped and protected) so that the *in situ* properties are preserved as well as possible. In rocks of high permeability particular care must be taken in regard to contamination or loss of water in the core sample.

Basic Classification Parameters

Three basic parameters should be measured on as many core samples as possible. These are:

1. Water content
2. Grain density
3. Bulk density

Measurement of these three parameters provides two of the four EOS parameters important in cratering. These are water content and gas-filled porosity. In addition, empirical models[18] have been developed so that the entire EOS required for the calculations can be estimated from these three measurements and the density and sound-velocity logs. Confidence in the application of the empirical models is enhanced considerably when mineralogy analyses and mechanical tests are performed on selected representative samples. Representative samples are chosen based on the logging program and measurements of bulk and grain density and water content.

Compressibility

Three recommended core-sample tests provide information on compressibility and gas-filled porosity as a function of the stress state; these are:

1. Hydrostatic compressibility
2. Uniaxial strain
3. Hugoniot

The minimum data from the hydrostatic compressibility test should provide pressure as a function of specific volume, both on loading and unloading from 0 to 30 or 40 kbar of pressure. Additional unloading data from 0.5, 1.0, 2.0, 5.0 and 10 kbar of pressure on porous, unsaturated rocks allow a better modeling of the compactability of the medium as a function of stress.

The uniaxial strain test is the best quasi-static approximation to the actual shock-loading path. The pressure range, however, is limited to a maximum stress of 0.2 or 2 kbar, depending on the rock type. Data from this test provide compressibility as a function of both mean stress (pressure) and shear stress. The most important datum from this test is the loading path in mean-stress/shear-stress space. The slope of this curve provides Poisson's ratio as a function of the stress state and provides a more relevant measurement than that obtained from compressional- and shear-velocity data.

The Hugoniot data provide compressibility at high-stress states (100 kbar to 1 Mbar range). As such, it is useful only for those rocks near the detonation point. Considerable Hugoniot data exist for many major rock types, allowing an interpolation based on density that is sufficient for most cratering calculations. Hugoniot data is required only for rocks not presently in the current data base. Decisions on whether Hugoniot measurements are needed can be made after the classification parameters are analyzed.

Strength

Along with the classification parameters, a measurement of the strength of the rock (consolidated and fractured) is the most important and necessary measurement of all the mechanical properties. This is because the cratering efficiency is sensitive to the strength of the rock to a degree that exceeds any correlation between the classification parameters and the strength. On the other hand, compressibility correlates well with the classification parameters and is less sensitive in determining cratering efficiency than is strength.

Those tests which provide the required data on the strength of the rock are:

1) Triaxial shear
   a) Consolidated
   b) Prefractured
2) Brazil

The triaxial shear test should result in a series of data points where failure of core samples of the same rock occurs at various confining stresses. A curve passing through these points denotes the failure envelope of that rock type. Two curves — one representing consolidated and the other prefractured core samples — should be given. The type of failure mode (i.e., brittle or ductile) should be noted for each test and a few samples should be tested at the same confining pressure to check the reproducibility of the data.

The strength of a rock is known to be sensitive to the degree of saturation. If there is serious doubt as to the degree of saturation of *in situ* type rock, or if a wide variety of degrees of saturation exist for a particular rock type, then a series of strength tests should be made at various percentages of saturation.

The Brazil test measures the tensile strength of the rock. This may be important in a consolidated rock with a low-fracture frequency and a high-shear strength.

Conclusions

The size of a crater for a given explosive yield and depth of burial depends on the material properties of the medium. Crater geometry can be calculated if the material properties are known. Thus large excavation projects can be designed with the use of computers when scaling laws and cratering curves, developed empirically with small chemical explosives, may not produce relevant results.

A measurement program is required to determine these important material properties (water content, shear strength, gas-filled porosity, and compressibility). The program includes both *in situ* logging measurements and laboratory measurements on small core samples. A complete measurement program has been given in the paper, with an explanation of how each measurement is used in the calculations. Some measurements are more important than others. Those measurements deemed critical to the calculational approach are:

1. The caliper log
2. The bulk-density log
3. The sound-velocity log
4. Classification parameters from core
   a. Water content
   b. Grain density
   c. Bulk density
5. Triaxial shear-strength tests on core samples
   a. Consolidated
   b. Prefractured

The above measurements together with empirical models of the behavior of earth-type media under stress are, in most cases, sufficient to determine the four parameters that dominate the cratering process. If, however, the classification parameters reveal a rock type outside the current empirical data base, then additional measurements given in the paper may be required.

Acknowledgments

We are indebted to Jon Bryan and Don Burton for reviewing this paper and for their help during its preparation. We also wish to express our special thanks to Bert Abey for many helpful discussions on laboratory-measurement techniques.

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