PRINCIPLES OF ROCK FRAGMENTATION

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PREFACE

The mechanics of rock fragmentation involve dynamic applications of energy. This principle applies to the very old processes of fire-setting, picking by hand, as well as mechanical drilling, rock boring, rock splitting, and blasting with conventional and nuclear explosives. While these methods are relatively inefficient, some are much more useful than others. Basic understanding of the energy release mechanisms of high explosives is better developed now than before the discovery and use of the thermohydrodynamic theory of detonation. In the future, significant advances in the efficiency of application of energy transfer in rock fragmentation will probably be made in increments, but these small advances may be critically important. A better understanding of the transfer of explosive energy—particularly to both soil and rock—the resulting wave propagation, and the effects of these waves on rock structures is critical to the solutions of problems of current interest to both civil and military engineers. Because of the nature of experimentation with explosives, the use of the principles of similitude in future rock fracture and fragmentation studies will be predictably greater.

GEORGE B. CLARK

Wheat Ridge, Colorado
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CONTENTS

1

ROCK FRAGMENTATION PROCESSES

1.1 FRAGMENTATION

From the inception of productive applications of modern processes of rock fragmentation, their use has been essential to the progress of civilization in terms of the technical, material, and economic progress of the nations of the earth. Much of the excavation in modern mining and civil engineering could not have been accomplished without the related development of methods of drilling and blasting rock. Recent and current research have laid the background for further technical and operational improvement of these processes and have revealed the critical need for further research. Mechanical methods of tunnel excavation, which have been applied at a usable level only within the past 30 yr, have likewise been developed to a remarkably effective productivity. Although these machines have a specialized application and produce only a limited relative volume of excavated rock materials, they have a critical place in the excavation industry. Meaningful laboratory and field studies have been made of TBM cutters, drills, and other types of rock cutters. While such studies have revealed many of the basic principles of the mechanisms of excavation and machine operation, which has resulted in significant improvements, much further research and evaluation are needed.

One of the purposes of this book is to begin to meet the urgent need for a one-source treatment of the elementary phenomena and the mechanisms of rock fragmentation in relation to commercial mining and related excavation processes, civil and military, in earth materials other than soils, sand, and gravels. As part of the background information for engineering and operation purposes, in addition to mechanisms of rock fracture by various processes, the behavior of fragmented earth material under the force of gravity, a body force rather than an applied force—all of this requires more study, research, and scientific understanding. To date the latter has been studied only in a preliminary, semi-quantitative way. Experimental model studies of the behavior of fragmented, particulate material, with the exception of sand and soil, have not utilized body force loading. This may have markedly different effects from externally applied loading.

1.2 DRILLING

The information in the technical literature of the drilling of rock for excavation purposes is widely scattered in books, journals, symposia proceedings, and other literature. Many of the research results of drilling for petroleum remain locked up in proprietary company files. Most of the drilling for excavation is done by percussive drills, pneumatic or hydraulic. The operation of pneumatic drills may be analyzed on a simplified basis, and the energy transfer from compressed air to piston to drill rod can be evaluated by simple computer programs. The energy transfer in hydraulic drills is similar, but a usable analysis of the same does not appear to be available. Further, the energy transfer at the rock–bit interface requires additional research and analysis and is a function of drill characteristics and rock properties in terms of force–displacement curves, but rock property effects are extremely variable.

Other processes of fragmentation are of equal importance in their place, including methods of mechanical breakage; fracture by heat, crushing, and grinding; water jet cutting; and other novel methods.

There are two basic engineering factors that have led to the development of more effective rock drills, primarily of the pneumatic type. The first, where the greatest progress has been made, is the improvement of the mechanisms of drill operation and metallurgical properties of drill components, drill steel, and drill bits. The second is the increased knowledge of the basic processes of rock fragmentation and energy utilization in achieving effective drilling and blasting.

Rock is drilled for several purposes, and a number of methods have been devised and successfully used for making holes in rock. Such purposes include geologic exploration for mineral deposits, drilling for petroleum, making holes for placement of explosives for blasting, making holes for rock bolts, drilling for research purposes, and other similar objectives. Though many novel methods of cutting holes have been subjected to experimentation, the most successful for practical appli-

TABLE 1.1. Classification of Drilling Methods[a]

Method	Machine
Percussive	Churn drill, cable tool,
Drop tool	pneumatic or hydraulic
Hammer	rock drill
Rotary, drag	
Blade	Auger, high-pressure rotary
Stone	Diamond
Shot	Calyx
Sawing	Wire rope, chain rotary saw
Rotary, roller	Rolling cutter
Rotary-percussion	Drag, roller
Thermal	
Flame	Jet piercer, channeler

[a]See Hartman (1968).

cations are the mechanical and, to a lesser extent, the thermal methods. High-pressure water jets are effective mostly for specialized cutting in softer rocks.

The types of drills that have been used for drilling operations in rock include (1) percussive or impact, (2) abrasion, (3) cutting, (4) crushing, (5) combinations of the above, and (6) thermal spallation (Table 1.1).

The churn drill, which raises and drops a large, heavy bit in the bottom of the hole with cuttings being removed by a bailer, is seldom used at the present time. Pneumatic percussive drills, until the recent development of hydraulically powered impact tools, were restricted to the use of compressed air to energize the drill. A combination of rotation and percussion is employed by a rotary-percussion tool with asymmetrical cutting edges on the bit, the drill being powered pneumatically or hydraulically. Rotary drills may use drag bits, auger bits, diamond bits, or roller cone cutters, the latter using either disc cutters or button inserts to crush the rock. The flame jet drill is usually limited to hard siliceous rocks which spall readily.

1.3 EXPERIMENTAL METHODS

Experimental (novel) methods have been used for melting rock by means of lasers and electron beams, for cutting by sonic vibration, for drilling with shaped (cavity) explosive charges, and for cutting with very high-pressure water jets. None of these appear to have potential applications except water jets at about 15,000 psi. The promising areas for the use of water jets are for cutting softer materials, such as coal; drilling of holes in softer rocks, such as shale and sandstone; or assisting certain types of mechanical cutters, such as those on tunnel-boring machines.

1.4 EXPLOSIVES

It has been over three decades since the discovery and application of the hydrodynamic theory of plane shock waves to solid explosives for the calculation of their detonation and explosion parameters, such as detonation velocity, pressure, and temperature and the explosion state pressure, energy, and temperature. Many computer codes have been developed utilizing different equations of state for gases at high temperatures and pressures and various thermodynamic and thermochemical approaches for the analysis of explosions. As described in this book, Cook's method using a modified Abel equation of state has been found to be useful for engineering calculations for near oxygen-balanced explosives and those containing only small amounts of metallic elements such as aluminum or sodium, as well as for water-based explosives. This modified equation uses experimentally determined values of co-volume as a function of pressure, together with chemical equilibria as a function of temperature with related thermochemical data. The application of Cook's method thus requires a knowledge of advanced chemistry and computer programming. Its presentation is intended primarily for advanced undergraduate engineers, graduate engineers, and field engineers with a similar educational background.

In the development of blasting agents the fortuitous adoption of a manufacturing process for fertilizer grade ammonium nitrate (AN), which produced porous prills, was a major factor in its sensitization and consequent use as a blasting agent ingredient. ANFO, an oxygen-balanced mixture of AN and fuel oil, is a simple do-it-yourself explosive whose advantages outweigh its disadvantages, primarily in material costs and safety. It is relatively inexpensive, strong enough in specific energy content for many blasting processes, and usually not cap-sensitive. This makes it safe to handle, and it has good fume properties when properly designed. It contains a single fuel and oxidizer and illustrates many of the important performance parameters of commercial explosives and blasting agents.

The development of slurries came about as one of the technological events associated with the use of ANFO. A principal thermodynamic question arose as to whether water added to granular explosives or blasting agents in the oxygen-balanced range could increase their density, and consequently their detonation velocity and pressure, and could be heated by the energy of combustion sufficiently to maintain critical hydrodynamic conditions. This was found to be possible, first by computation and then by experimentation, within usable limits and was followed by the addition of gelling agents, other nitrates, metallic elements, sensitizers, and other substances. Slurries have also been called water gels, but the term ''slurries'' appears to be the most appropriate technologically. The water-explosive compositions are easily amenable to computer analysis.

1.5 ROCK BREAKAGE BY EXPLOSIVES

Most rock breakage, except coal, is accomplished by mechanical drilling and rock cutting and by blasting with explosives, with minor amounts accomplished by water jets and such means as rock splitters. The results of experimentation and analysis are available on most of the industrial methods of rock breakage. Most theory involves idealized or simplified assumptions and consequently may be of limited value for application to nonidealized rock. Theoretical models have been devised for drill bit action at the rock–bit interface, as well as for roller cones and for rotary bits and cutters on TBMs. Each has its values and limitations. Some of the basic ideas involved in these theories are given below in appropriate chapters, especially where they support the results of experimentation.

The basic mechanics of rock breakage by explosives have been the subject of a large amount of experimentation. However, much of this is qualitative or semi-quantitative in nature, and, though the results are useful, they do not represent definitive scientific results. Some hypotheses have been put forward as to the details of rock breakage in benches but have not been supported by the results of experimentation or field observation.

Perhaps some of the most definite studies done on rock breakage are the instrumented cratering shots in six types of rock by the U.S. Bureau of Mines personnel. This work has been the subject of considerable analysis and discussion in the literature.

1.6 TUNNEL BORING

Mechanical tunnel boring was first meaningfully initiated in the 1950s and has been used to perform a relatively small but very significant amount of specialized excavation in the United States and abroad. Its particular advantages are the continuity of operation and that the rock excavation, mucking, and support operations can be carried on simultaneously. This method of excavation and rock removal results in more even, stable walls than does drill-and-blast, and the relatively quiet method of rock breakage permits its use much closer to dwellings and similar structures. The large capital investment for TBMs, however, allows them to be used on only relatively large jobs, and the machine wear and consequent costs may be excessively high for excavation in rock masses that are difficult to cut mechanically.

1.7 AUTOMATED DRILL AND BLAST

The operational features of a TBM are so advantageous in construction that research efforts have been designed to adapt some of these principles to automated drill-and-blast systems. Several concepts have been investigated, and some have been patented. These utilize the basic concept of near-simultaneous integral operations, with similar types of equipment for drilling, explosive loading, and mucking. Some provide for remote control, and some for shielded operations. They have shown promising developments, but research has been impeded largely because of lack of funding. A major problem to be solved is automated-explosives handling, but the problems encountered appear to be subject to solution by further well-conceived research.

1.8 ROCK SPLITTING

Various methods of splitting rock have been used since early history. The operational principle of mechanical rock splitters is based on the same concept as manual wedge and feathers, which are employed in quarrying of dimension stone. The most commonly known type of mechanical splitter utilizes a hydraulically driven wedge forced between two feathers placed in a hole in rock, the rear end of the feathers being anchored to the hydraulic cylinder frame. The wedge must be well lubricated, because it exerts side pressures up to 150,000 psi with a cylinder pressure of 2000 psi.

The principle of free faces of rock breakage caused by internal stresses applies to the breaking capabilities of rock splitters in a manner analogous to breakage by explosives. Rock is split most effectively if it is in the form of an isolated boulder, but splitters have been used to break benches and the faces in trenches and small tunnels, where explosives could not be employed because of environmental reasons. Here also the rate of advance was not a critical factor. Of all methods of fragmentation, splitters are the most energy-efficient. Although the splitter method of excavation does not have the disadvantages of drill and blast, it requires too much time for some of the integral operations to be competitive with conventional methods.

An analysis made of the stresses induced by a splitter (Chollette et al., 1976) for two distributions showed that the stress concentration factors varied from 1.0 to 1.65. An extended experimental program with a commercial splitter on operational parameters included effects of lubricants, autolubrication, and longitudinal impact superposed on the thrust of the wedge. Such impact increases the upper limit of stalling of the wedge and may increase its speed if hydraulic flow can be increased (Clark and Maleki, 1978).

1.9 GRAVITY AND MUCK FLOW

The effects of gravity on the behavior of fragmented geologic materials from fine to coarse particulate sizes, including crushed and blasted rock and rock fractured by geologic processes, may be critical design factors in excavation, support of underground openings, and materials handling. Gravity-induced phenomena may be critical in the behavior of fragmented material in bins and chutes, in the flow of materials in caving methods of mining, in excavated areas in fault zones in tunnels, in open-pit mines, and in zones cratered by nuclear explosives. With lateral confinement, fragmented materials are subject to arching. Experimentation on this phenomenon to the present time appears to have been limited to tests on sand.

Some effective experimentation on gravity effects on spoil piles in surface mining has been done in centrifuges, and this relatively novel method appears to be the most viable for meaningful research on gravitational effects on flow and related behavior of particulate material. These effects are critical in true cratering by large explosive charges in both solid rock and soil. Centrifugal testing has also been found to be necessary to simulate stress fields caused by gravity around underground openings.

1.10 PRACTICE AND RESEARCH

There have been many books and technical articles published on the practices of drilling, blasting, and mucking, so its treatment here would be duplication of information available in existing sources. This consists of information from detailed minutae of blasting arithmetic to the valuable results of technical analysis of research and practice, as well as effective engineering and scientific research.

In the whole field of rock excavation there is a need for both applied and basic research. One of the purposes of compiling the technological information on rock excavation in this book is to stimulate more creative thinking into current and future needs of research. There are many gaps that remain to be filled in the national and international technological libraries and in the data banks for sources of background material for industrial development.

2

WAVE EQUATIONS FOR ROCK FRAGMENTATION

In percussive drilling, energy is transferred to the rock by the mechanics of elastic waves (pulses) traveling in steel rods of relatively small diameter, or rod waves. For most practical purposes, the waves in rock are also considered to be elastic, their geometry being either plane, cylindrical, or spherical, and simple waves or pulses are assumed to be mostly longitudinal in character. In these types of waves, the particle velocity is in the same direction as the direction of wave propagation. In shear waves, which are of relatively minor importance in blasting, the direction of the particle velocity is perpendicular to the direction of propagation. Strong waves in explosives, where the pressures are high enough to cause the material to behave hydrodynamically, are properly designated as shock waves, and hydrodynamic equations apply. Pressures generated by explosives are strong enough to crush rock and to cause it to behave plastically in the immediate vicinity of boreholes, but true shocks are not induced by chemical explosives in rock.

The equations for plane, cylindrical, and spherical waves are easily derived and can be readily evaluated for rod waves without resorting to the solution of a differential wave equation. However, for dilatation waves for transient conditions, the differential equations can only be solved by use of transform calculus or other specialized methods. The wave equations for plane shock waves are derived in the chapter on explosives.

2.1 STRESS WAVES IN ROCK

There are several types of waves that may be generated in rock, such as large-scale disturbances resulting from earthquakes, nuclear explosions, or more local waves generated by explosives for seismic prospecting. The waves that are generated by confined explosives immediately around blast holes are very intense. Geometrically, they are approximately plane, cylindrical, or spherical in shape. Usually, only the symmetrical forms are considered in theoretical analyses for the sake of simplicity. These types serve to illustrate the basic mechanics of wave propagation and consequent fracturing of the rock near an explosive because of its confinement and nearness to free faces. Also, the propagation of waves in the rock and air at some distance from the blast may cause damage to structures or cause environmental disturbances that must be controlled.

Most studies of waves in rock assume that they are elastic in character and that the corresponding relationships between stress, strain, Poisson's ratio, dilatation, and so on, can be applied with reasonable accuracy to both transients and waves of long duration. Usually transient models are assumed to have the form of rectangular or triangular pulses, and important parameters are pulse length, rise time, fall time, and peak values of stress, strain, particle velocity, or acceleration. The rise and fall times for a rectangular or square pulse are approximately zero.

2.1.1 Transient Waves

Transient parameters (except shock waves in explosives) are governed by the same basic wave equations that govern other types of waves, all of which travel with a characteristic velocity, the value of which depends upon the density and elastic contents of the medium. For a longitudinal wave, the stress σ is the tensile or compressive stress in the direction of velocity and propagation of a longitudinal wave. The strain is likewise the unit deformation at a point in the wave in the direction of propagation. In a shear wave, the stress τ and other parameters are normal to the direction of propagation. The particle velocity v is the velocity of movement of a particle as the wave moves it in the direction of the wave propagation for a longitudinal wave and normal to the direction of propagation in a shear wave.

The direction of particle acceleration is the same as that for velocity but is never in phase with the velocity. This latter condition is obvious from the mathematical relationship $a = (dv)/(dt)$. Thus, if the velocity is represented by a sin ωt curve, the acceleration is ω cos ωt.

For a longitudinal rectangular plane wave for velocity, the relations between the

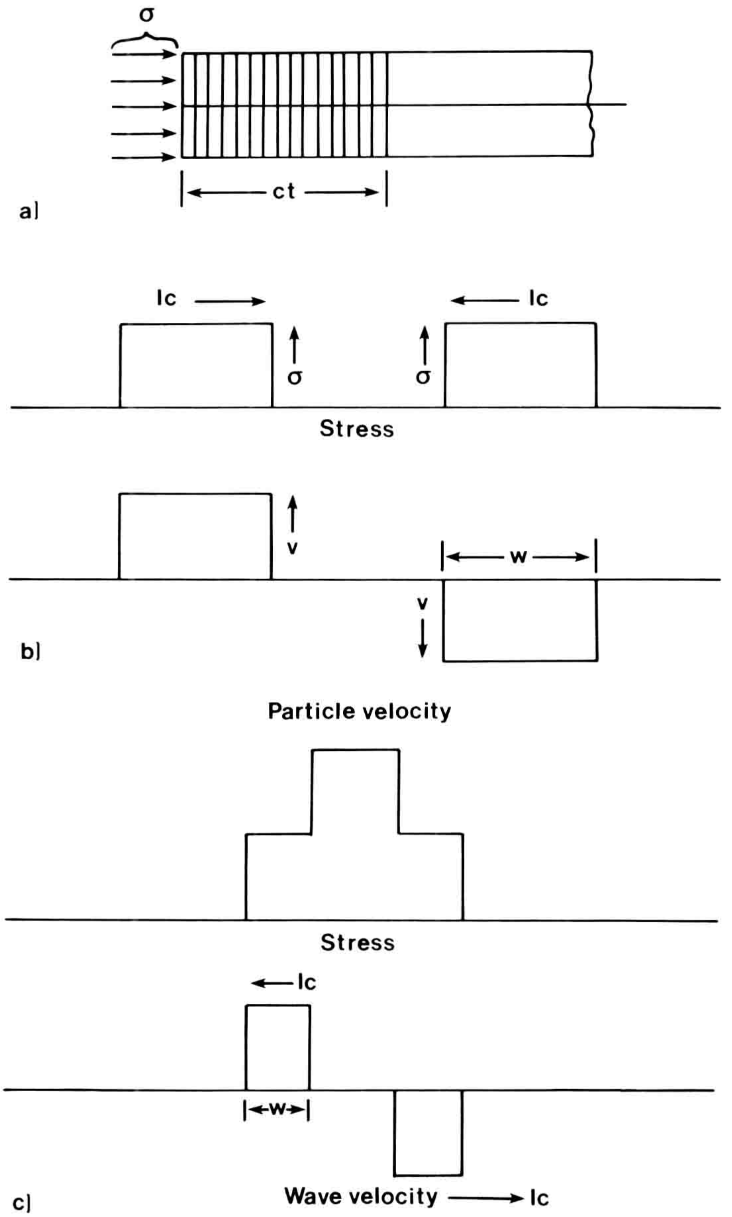

Figure 2.1 (*a*) Square wave induced by impact; (*b*) colliding compressive waves; (*c*) tensile and compressive waves colliding.

basic wave parameters are shown in Figure 2.1. Thus, the curves for particle velocity, stress, and strain are the same shape.

2.1.2 Transients in Rock

All of the waves generated in rock by explosives are transient in character; that is, they are of relatively short duration and have different shapes depending on such items as the properties of the explosive, the (elastic) properties of the rock, the stemming, the rock structure near the detonating explosive, the loading density of the explosive, and similar factors. Most analyses of transient waves also assume elastic behavior.

Such waves are also studied assuming that the blast geometry creates (1) plane, (2) cylindrical, or (3) spherical waves, but most investigations assume that a wave is plane after it has traveled a short distance from the explosion cavity.

2.2 PLANE WAVES

The wave equation for a plane wave may be developed by considering an element of the elastic material (rock) through which the wave is passing. Two types of plane waves must be considered. The first is that in a rod or bar of small diameter in which the lateral effects of a longitudinal wave may be neglected; that is, the Poisson's ratio effects due to lateral extension caused by longitudinal stress are negligible.

2.2.1 Rod Wave

A small longitudinal section of a solid rod subject to a stress wave moves in accordance with Newton's law of motion $F = ma$ (Figure 2.2). The mass of a unit cross section is equal to the volume times the density:

$$m = \rho dx \tag{2.1}$$

The summation of the forces in the x direction is

$$F = \left(\sigma + \frac{\partial \sigma}{\partial x} dx\right) - \sigma = \frac{\partial \sigma}{\partial x} dx \tag{2.2}$$

Application of Newton's law gives

$$\frac{\partial \sigma}{\partial x} dx = \rho dx \frac{\partial^2 u}{\partial t^2} \tag{2.3}$$

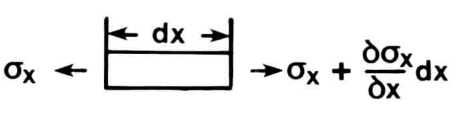

Figure 2.2 Stresses on an infinitesimal section, rod wave.