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**PROJECT LOST CREEK: FIELD TESTS OF MOUNDING AND
CONTROLLED BLASTING**

Colin C. McAneny

January 1975

950-0147

U.S. Army Engineer Waterways Experiment Station
Explosive Excavation Research Laboratory
Livermore, California

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20. continued,

with mounding charges to diminish shock and to improve excavation slope control.

It was shown that mounding rows can be designed on the basis of the equation

$$DOB = K \sqrt{\frac{Y}{S}},$$

where DOB is the depth of burial of the center of the charge, Y is the charge weight, S is the spacing between charges, and K is a constant dependent on the explosive and the rock. For ANFO in the rock at the Lost Creek test site, K had an optimum value of $5.1 \text{ ft}^{3/2} \text{ lb}^{-1/2}$. A complete multi-lift excavation using mounding charges can be designed by a step-by-step procedure, an example of which is given.

The Lost Creek experiments were performed in a basaltic andesite rock, which showed columnar jointing a network of closely spaced irregular fractures. Mounding blasts in this rock produced good fragmentation, such that the material was quite acceptable for rock fill. The natural fracture pattern exerted the main control on fragment sizes.

Of three bulk explosives tested as mounding charges, ANFO proved to be the most effective, on the basis of total volume of rock broken. Two slurry explosives showed markedly differing effectiveness, although the less effective slurry produced slightly higher measured values of ground motion.

Zones in which small-diameter blastholes, located between presplit surfaces and mounding charges, are loaded and fired in advance of the firing of the mounding charges are termed "buffer zones". Limited data from the project suggest that buffer zones of various designs exert little attenuative effect on shock from the main mounding charges, over and above the effect of presplit planes alone. Further testing of buffer zones may be warranted, however.

A two-lift prototype spillway cut was excavated following blasting with mounding charges. Presplitting and buffer zones were used to control the side slopes. This achievement demonstrated that mounding offers a feasible method of blast design for structural excavations.

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EXPLOSIVE EXCAVATION RESEARCH LABORATORY
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Preface

The Explosive Excavation Research Laboratory (EERL), located at Livermore, California, is a laboratory of the U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi. The Laboratory is the successor to the USAE Nuclear Cratering Group (NCG), which was founded in Livermore, in 1962. The NCG was reorganized to become EERL and was assigned to WES in 1971.

Project Lost Creek involved the efforts of many people. Virtually every person and agency mentioned in Fig. A1 of this report deserve credit, as well as several who are not formally mentioned. The author wishes to acknowledge, in particular, the assistance of the following: B. B. Redpath, who wrote Appendix D and much of the material on ground shock and mounding row design, and offered valuable comments and encouragement; H. A. Washburn and C. M. Snell, who wrote Appendix F and most of the material on airblast; T. M. Tami, who wrote most of the material on seismic motions; M. Zahn, who devoted much effort to measurement of mound and excavation dimensions; R. S. Holmes and W. C. Day, whose critical reviews materially improved the report; H. Kay and G. Newman, of the Photogrammetry Section of Portland District, Corps of Engineers, and J. D. Day, of the Weapons Effects Laboratory, Waterways Experiment Station, who rendered repeated assistance on technical matters during the period of report preparation; and C. A. Lanfear, whose cooperation and good humor, as superintendent for Oregon Crane Service, made carrying out of the field work a genuine pleasure.

The Director of WES during the preparation of this report was COL G. H. Hilt; the Director during the planning and execution of Project Lost Creek was COL E. D. Peixotto. The Director of EERL during report preparation was LTC R. R. Mills, Jr.; the Director of EERL during the planning and execution of the Project was LTC R. L. LaFrenz.

Abstract

A concept of blasting termed "mounding" involves using relatively compact explosive charges and breaking to the horizontal ground surface. Project Lost Creek comprised a group of single-charge and row-charge blasting experiments designed to investigate the concept of mounding. Mounding-row design criteria, fragmentation produced by mounding charges, and performance of mounding explosives with differing properties were studied, as were suitability of mounding for producing rock fill and use of controlled blasting in conjunction with mounding charges to diminish shock and to improve excavation slope control.

It was shown that mounding rows can be designed on the basis of the equation

$$DOB = K \sqrt{\frac{Y}{S}},$$

where DOB is the depth of burial of the center of the charge, Y is the charge weight, S is the spacing between charges, and K is a constant dependent on the explosive and the rock. For ANFO in the rock at the Lost Creek test site, K had an optimum value of $5.1 \text{ ft}^{3/2} \text{ lb}^{-1/2}$. A complete multi-lift excavation using mounding charges can be designed by a step-by-step procedure, an example of which is given.

The Lost Creek experiments were performed in a basaltic andesite rock, which showed columnar jointing a network of closely spaced irregular fractures. Mounding blasts in this rock produced good fragmentation, such that the material was quite acceptable for rock fill. The natural fracture pattern exerted the main control on fragment sizes.

Of three bulk explosives tested as mounding charges, ANFO proved to be the most effective, on the basis of total volume of rock broken. Two slurry explosives showed markedly differing effectiveness, although the less effective slurry produced slightly higher measured values of ground motion.

Zones in which small-diameter blastholes, located between presplit surfaces and mounding charges, are loaded and fired in advance of the firing of the mounding charges are termed "buffer zones." Limited data from the project suggest that buffer zones of various designs exert little attenuative effect on shock from the main mounding charges, over and above the effect of presplit planes alone. Further testing of buffer zones may be warranted, however.

A two-lift prototype spillway cut was excavated following blasting with mounding charges. Presplitting and buffer zones were used to control the side slopes. This achievement demonstrated that mounding offers a feasible method of blast design for structural excavations.

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Conversion Factors

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

Multiply	By	To obtain
inches	2.54	centimeters
feet	0.3048	meters
cubic feet	0.02832	cubic meters
cubic yards	0.764555	cubic meters
pounds	0.4535924	kilograms
pounds per square inch	0.00689476	meganewtons per square meter
pounds per cubic foot	16.02	kilograms per cubic meter
Fahrenheit degrees	^a	Celsius or Kelvin degrees
foot-pounds	0.138255	meter-kilograms

^aTo obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9) (F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9) (F - 32) + 273.15$.

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PROJECT LOST CREEK: FIELD TESTS OF MOUNDING AND CONTROLLED BLASTING

Introduction

PURPOSE AND SCOPE

This report is an account of Project Lost Creek, an experimental blasting program carried out by EERL in April-July 1972. The project was conducted in Jackson County, Oregon, at the quarry site for the Lost Creek Dam, a project now under construction by the U. S. Army Engineer District, Portland (NPP). The site location is shown in Fig. 1.

Project Lost Creek was carried out to investigate mounding and controlled blasting. Mounding is a blasting procedure in which breakage is induced toward the horizontal ground surface, using relatively compact explosive charges. Controlled blasting refers to several systems of small-scale drilling and blasting used to preserve neat finish excavation surfaces.

The following were the technical objectives of Project Lost Creek:

Fig. 1. Location of test site.

(1) To develop design criteria for mounding detonations in hard rock.

(2) To compare fragment sizes created by mounding detonations in a strong, moderately fractured rock with those obtained in conventional quarrying operations.

(3) To compare three blasting agents in terms of crater dimensions and the degree of rock fragmentation.

(4) To test the effectiveness of controlled-blasting techniques (presplitting and "buffer zones") in preventing overbreak, improving side slope control, and reducing damaging blast-induced stress waves beyond the excavation limits.

(5) To evaluate the use of relatively large but compact explosive charges for the production of rock fill.

A contractor hired through NPP performed the necessary clearing, drilling, and excavating, and furnished the explo-

sives. Personnel from EERL designed the tests, loaded and fired the explosive charges, and with the assistance of several agencies of the U.S. Army Corps of Engineers carried out technical programs to gather data. The project organization and a listing of participating personnel are given in Appendix A.

SUMMARY OF TESTS

The project was composed of four main experimental series summarized in Table 1. Within each of these four major test series there was more than one detonation; these were designated sequentially by number. Several supplemental blasting experiments were also carried out. Basic information on all of the explosive tests carried out during Project Lost Creek is given in Table 2, and the locations of the specific tests within the quarry site are shown in Fig. 2. Detailed

Table 1. Lost Creek experimental series.

Series	Principal points of interest	Description	Remarks
VS (Variable Spacing)	(1) In-row spacings (2) Different explosives	Three mounding rows, with varying charge spacing a. ANFO b. Slurry A c. Slurry B	Initial mounding series; results form design basis for CS and ML series
CS (Constant Spacing)	(1) Timing of mounding row blast	a. Instantaneous detonation b. Delayed detonation	To verify optimum spacing selected from VS series
ML (Multiple Lift)	(1) Controlled blasting with mounding (2) Double lift procedure	a. Double mounding row, with presplitting and buffer zones b. Single mounding row, with presplitting and buffer zones, emplaced after excavation of double mounding row	Demonstration project; prototype structural excavation
ILIR (In-house Laboratory Independent Research)	(1) Stress-wave attenuation by buffer zones	Single mounding charges with and without buffer zones; test panels	Subsurface instruments to measure close-in particle velocity

Table 2. Explosive events, Project Lost Creek.

Date fired (1972)	Event	Description	Explosives ^a	Initiation ^b	Technical programs ^c	Figure ^d	Excavated ^e
1 May	VS-1	Mounding row, 7 charges, varying spacings	(1)	(1)	1,2,3,4,5,6	7,8	Yes
13 May	VS-2	do.	(2)	(1)	1,2,3,4,5,6	7,8	Yes
12 May	VS-3	do.	(3)	(1)	1,2,3,4,5,6	7,8	Yes
2 Jun	CS-1	Mounding row, 6 charges, equal spacings	(2)	(2)	1,2,3,4,5,6	22	Yes
1 Jun	CS-2	do.	(2)	(3)	1,2,3,4,5,6	22	Yes
30 May	ML-1	Twin mounding rows, each 7 charges; buffer zones; presplit panels.	(4)	(4)	1,2,3,4,5,6, 7,8	31,32	Yes
10 Jun	ML "Daylight"	Conventional pattern, 87 small-diameter blast holes	(5)	(4)	—	—	Yes
22 Jun	ML-2	Mounding row; buffer zones; presplit panels (second lift after excavation of ML-1)	(4)	(4)	1,3,4,5,6	36,32	Yes
5 Jul	ML Remedial	Reloading at "bootleg" ML-2 presplit and buffer holes to blast out hump	(6)	(1)	—	—	Yes
20 Apr	IL-1A	Presplit test panel	(6)	(1)	—	43	Yes
20 Apr	IL-1B	do.	(6)	(1)	—	43	Yes
20 Apr	IL-1C	do.	(6)	(1)	—	43	Yes
20 Apr	IL-2A	Buffer-zone test panel	(6)	(1)	—	44	Yes
20 Apr	IL-2B	do.	(6)	(1)	—	44	Yes
9 Jun	IL-2C	do.	(8)	(1)	—	—	No
25 Apr	IL-3A	Presplit and buffer-zone test panel	(6)	(5)	—	45	Yes
3 May	IL-3B	do.	(6)	(4)	—	46	Yes
3 May	IL-3C	do.	(6)	(4)	—	47	Yes
1 May	IL-3D	do.	(8)	(4)	—	48	Yes
1 May	IL-3E	do.	(8)	(4)	—	49	Yes
25 May	IL-4 Main	Single mounding charge	(2)	(6)	1,2,3,4,7,8	— ^f	Attempted
22 May	IL-4A	Presplit and buffer-zone panels	(6)	(4)	1,2,3,7,8	— ^f	do.
22 May	IL-4B	Presplit panel	(6)	(1)	1,2,3,7,8	— ^f	do.
22 May	IL-4C	Presplit and buffer-zone panels	(6)	(4)	1,2,3,7,8	— ^f	do.
22 May	IL-4D	do.	(6)	(4)	1,2,3,7,8	— ^f	do.
17 May	IL-5 Main	Single mounding charge	(2)	(6)	1,2,3,4,7,8	— ^f	No
16 May	IL-5 Panel	Presplit and buffer-zone panels	(6)	(4)	1,2,3,7,8	— ^f	No
4 May	IL-6	Buffer-zone panel	(6)	(1)	1,2	—	No
26 May	IL-7	Single mounding charge using Army cratering charges	(7)	(1)	1,2(e),3,4	G1	Attempted
25 Apr	IL-8A	Small conventional quarry blast	(6)	(4)	1	G3	Yes
18 May	IL-8B	Trimming shot at small quarry	(6)	(1)	1	G3	Yes
2 Jun	IL-8C	do.	(6)	(1)	1,3	G3	Yes
9 Jun	IL-8D	do.	(6)	(1)	1	G3	Yes
20 Jun	IL-9A	Single mounding charge	(2)	(6)	1,3,5	G6	No
20 Jun	IL-9B	do.	(3)	(6)	1,3,5	G6	No
21 Jun	IL-9C	do.	(1)	(6)	1,3,5	G6	No
21 Jun	IL-9D	Double mounding charge	(2)	(6)	1,3,5	G6	No
7 Jun	VS-1TA	Trimming test	(8)	(1)	—	G12	Attempted
9 Jun	VS-1TB	Trimming test	(8)	(1)	—	G12	do.
23 Jun	—	Detonating-cord test	(9)	(7)	3	—	No
23 Jun	—	Detonating-cord test	(9)	(7)	3	—	No

^aExplosives

1. ANFO, boosters
2. Slurry A, boosters
3. Slurry B, boosters
4. Main charges: ANFO, boosters. Presplit, buffer-zone: Trimtex, dynamite
5. ANFO, primed by Trimtex
6. Trimtex, dynamite
7. Army MO39 cratering charges
8. Trimtex
9. Detonating cord

^bInitiation (all blasting caps were electric)

1. Instantaneous blasting cap(s); detonating-cord trunk line(s) and down lines
2. Instantaneous down-hole blasting caps
3. Instantaneous and delay down-hole blasting caps
4. Instantaneous and delay blasting caps; detonating-cord trunk lines and down lines
5. Instantaneous blasting caps; "Prima-det" delay fuze; detonating-cord trunk lines and down lines
6. Instantaneous blasting cap(s); detonating-cord down line(s)
7. Instantaneous blasting cap

^cTechnical programs

1. High-speed photography
2. Subsurface close-in ground shock measurements
3. Seismic vibrations
4. Air blast
5. Topographic mapping
6. Fracture logging, block size measurements
7. Borehole photography
8. Permeability testing

^dFor details of experiment, see figures as indicated, also text associated with cited figures.^eWhere indicated, program was attempted but gages malfunctioned; no data.^fRefer to Ref. 1.

rock produced. The In-House Laboratory Independent Research (ILIR) test series sought to measure the ability of controlled blasting panels to attenuate stress wave amplitudes.¹ In the MS series, a model structural excavation was excavated in two lifts using mounding charges, with controlled blasting panels along the side slopes.

Outlining the test program briefly: the VS series tested the mounding effectiveness of three different explosives and examined the effect of varying in-row spacings between individual charges. The CS series tested the effect of millisecond-delay detonations on the volume of broken

Fig. 2. Site map of Lost Creek test area.

Technical Background

EERL has a continuing program of research into the more effective use of explosives to accomplish excavation tasks in civil and military construction. A principal goal is to establish methods to achieve cost reductions for Civil Works projects. It is believed that significant cost savings may result from the use of fewer, more concentrated charges to break rock. This is in contrast with the current practice of using relatively small, distributed charges in conventional drilling and blasting patterns.

Concentrated charges can be used in cratering, mounding, or bench blasting. Cratering and mounding both involve breaking to the horizontal ground surface, as distinguished from breaking to a vertical surface in conventional bench blasting. The difference between cratering and mounding lies in the depth at which the explosive charges are buried. The concepts of cratering and mounding are expanded upon in the following sections.

CRATERING

A cratering detonation breaks rock and ejects a large part of the broken rock in one operation. The resulting visible excavation is called the apparent crater, and consists of a true crater partially filled with rubble. The lip around the crater is formed by ejecta and upthrust rock. The optimum depth for a cratering charge is defined as that which produces the apparent crater with the greatest volume. Several charges detonated simultaneously in a row will form a linear, smooth-walled crater. EERL, and its

predecessor organization, the Nuclear Cratering Group (NCG), have conducted and monitored research in cratering for several years.²⁻⁴

Cratering is generally limited to construction in areas removed from population centers or engineering structures. The limitations on the applicability of cratering stem from the dispersal of the ejecta and relatively large airblast and seismic signals.

The depth of burial (DOB) of any concentrated charge, whether for cratering or mounding, can be expressed in terms of depth "scaled" to the weight of the charge. The concept of a scaled depth implies that the charge is relatively compact; i.e., we think of it as being a "point-source" of energy. A scaled depth of burial will not apply to a long, thin cylindrical charge, as normally used in drilling and blasting, because the energy of the charge is released over a wide range of depths. This concept is quantitatively expressed as follows:

$$\text{dob} = \frac{\text{DOB}}{Y^n},$$

where:

dob = scaled depth of burial

DOB = absolute depth of burial in feet

Y = charge weight in pounds

n = scaling exponent

Dimensional analysis requires that the exponent "n" have the value of 1/3 if gravity is not considered. Because gravity does affect the cratering process due

to its influence on the material ejected from a crater, the actual value of n is slightly less than $1/3$. For cratering, the exponent " n " has been empirically determined to be approximately 0.3; i.e., apparent crater dimensions will vary as the charge weight raised to the 0.3 power. The optimum depth of burial for a cratering charge in rock lies in the range of 1.2 to 1.6 ft/lb^{0.3}.

MOUNDING

In mounding, the charges are buried at a scaled depth greater than the optimum depth for cratering. The effect of mounding is to break a larger amount of rock but to impart less vertical velocity than in cratering, so that the material is bulked and falls back into the crater leaving a mound of rubble. Because gravity is not a factor that influences the amount of rock broken by a mounding charge, and because there is almost no throwout of the broken rock, the scaling exponent for mounding charges is $1/3$ rather than the 0.3 used for throwout cratering. The progression from cratering to mounding is illustrated in Fig. 3.

Mounding has not been used in the construction industry. A system of blast design similar to mounding, in that it involves breaking to a horizontal free face, rather than to a vertical face as in conventional bench blasting, has been used in open-pit mining.⁵ (The term "cratering" as used in Ref. 5 is synonymous with the word "mounding" used in this report.)

Mounding is of interest to EERL because of its advantages over cratering and its potential advantages over conven-

tional blasting practices. Conventional blasting involves many small, distributed charges, each of which makes up only a small part of a total blast. Drilling and blasting costs in conventional blasting may be high because of the large number of blastholes to be drilled and loaded.

The primary advantage of mounding with large charges may lie in the potential for reducing overall drilling and blasting costs because fewer holes need to be drilled and loaded. Large-diameter blastholes will be required necessitating

(a) Shallow burial for cratering, $0.5 \text{ ft/lb}^{0.3}$

(b) Optimum burial for cratering, $1.5 \text{ ft/lb}^{0.3}$

(c) Optimum burial for mounding, $3.0 \text{ ft/lb}^{1/3}$

Fig. 3. Relationship between cratering and mounding (boundary between rubble and undistorted rock is highly gradational).

large drilling equipment and probably incurring high per-hole drilling cost. In a large project, however, in which the capital cost of such equipment could be absorbed, economy of scale would lead to lower total drilling cost. It is conceivable that mounding may present certain technical drawbacks that would tend to offset any economical advantages of the technique. The distribution of explosives, rather than the total amount, is one of the predominant factors in producing uniform fragmentation.⁶ The concentration of explosives inherent in the mounding system, therefore, might invite poor fragmentation in massive rocks with widely spaced natural fractures. Prior work by EERL, however, suggested that the concept was worth investigating further in a more systematic series of experiments.^{7,8}

CONTROLLED BLASTING

Controlled blasting is a general term for several systems of drilling and blasting, all of which are designed to minimize overbreak and thus to preserve a neat finish excavation surface, given suitable geological site conditions.⁹ Controlled blasting systems are characterized by closely spaced patterns of small drill holes, with or without light explosive charges.

Existing controlled blasting practices fall into three categories, according to how and when explosives are used. One category, called line-drilling, uses closely spaced drilling only, and no blasting. A second category, called trimming or smooth blasting, is characterized by blasting after the main explosive round

has been fired (and the broken material excavated) to create a finished surface. The third type, which is called presplitting, involves blasting and creating the finish surface before the main rounds are fired. Presplitting is in common use to produce clean excavation side slopes, which need little scaling or maintenance. In recent years it has been adopted in open-pit mining as a method of wall control.

Because of the relatively larger charge weights demanded by the technique of breaking rock with mounding charges, it was considered desirable to investigate the concept of introducing an attenuating screen of broken rock between the main charges and the presplit plane. A planar zone of rock broken by explosives has been termed a "buffer zone," and its purpose is to prevent overbreak occurring beyond the presplit plane. In many respects, such a buffer zone can be considered as one or two heavily loaded presplit arrays placed inside the main presplit plane. The concept is illustrated in Fig. 4.

An open question is whether a presplit fracture by itself forms a barrier to the transmission of stress from blasting. Presplitting has been reported to decrease the severity of blasting vibrations on contiguous works or structures (Ref. 10, p.2); and a dry presplit plane has been reported to reflect explosive shock waves and to improve rock breakage inside it.¹¹ However, a study of the effect of presplit surfaces on the transmission of blasting vibrations by the U. S. Bureau of Mines¹² concluded that the introduction of a vertical presplit plane did not cause a significant reduction in blasting vibrations behind the plane.

It was decided that some of the buffer-zone tests at Lost Creek would be instrumented with particle-velocity gages in order to resolve quantita-

tively the effectiveness of such a zone in attenuating stress waves. This aspect of the program is reported in Ref. 1.

Fig. 4. Schematic of buffer-zone concept.

Site Description

LOCATION

Project Lost Creek was carried out at the site of the quarry for the Lost Creek rock-fill dam, a flood control project designed by the Portland District, Corps of Engineers (NPP). As shown in Fig. 1, Lost Creek Dam is situated on the main stem of the Rogue River, about 10 miles upstream from Shady Cove, Jackson County, Oregon. The quarry site is located in Section 25, T33S, R1E, on a ridge overlooking the left abutment of the dam. Access to the site during Project Lost Creek was via a gravel road through private forest lands of the Medford Cor-

poration. At the time of Project Lost Creek, construction on the dam and quarry had not been started. Project Lost Creek was conducted from April till early July, 1972. Construction on Lost Creek Dam commenced in August 1972.

GEOLOGY

Regional Geology

The site is located in the Western Cascades province of southern Oregon. Rocks in the area are volcanic, chiefly basaltic andesites of Oligocene and Miocene age, to which no geologic formation name has been applied.¹³ The

regional structural attitude of rock unit is nearly flat lying, with a gentle easterly dip under the Cascade Range.

Site Geology

Rock Type

All of the blasting experiments were performed in a fine-grained, dense, porphyritic igneous rock, dark gray when freshly exposed and brown on weathered surfaces. It had the appearance of a basalt; however, it was classified as basaltic andesite on the basis of petrographic examination, and is so referred to in this report.

Structural Geology

Three notable structural features were shown by the basaltic andesite. One was a system of jointing, which can be described as "columnar," though it varied from fairly regular and nearly vertical to contorted and inclined, and was not everywhere present. The diameter of the columnar pillars varied from 3 to 6 in. up to about a foot. Secondly, the rock showed an extensive network of fracturing, with no apparent preferred orientation. This fracture system, together with the columnar jointing, caused NX drill core to be usually recovered in pieces less than 1 foot long. Exploratory borings during the NPP quarry site investigation detected the same types of fractures at depths greater than 200 ft; they are therefore not a surface-related phenomenon. Thirdly, there were subhorizontal undulating discontinuities, which could be seen in pit walls, separating one set of columnar jointing from another set above or below. These discontinuities probably

represented lava flow bottoms. Figure 5 is a view of the basaltic andesite, which shows the structural features mentioned.

The rock showed no bedding or other systematic anisotropy, no folding, no slickensides, nor any other evidence of shearing. The jointing in a few localized places was roughly parallel causing the rock to break into slabby pieces.

Overburden, Weathering

All soil at the site was residual, and variable overburden conditions prevailed. In places the bedrock outcropped at the surface or was only a few inches below it. In other places there was 1 to 4 ft of clayey soil, which graded downward into rock that was dissected by weathered fractures but firm between the fractures, and spheroidal weathering was pronounced through a depth interval of 2 to 3 ft. Going downward one encountered progressively more intact bedrock.

Most of the fracture surfaces, at least to the depths of the EERL excavations, were stained a light brownish color with

Fig. 5. Basaltic andesite rock exposed in wall of a Medford Corporation quarry pit (wall is 10 ft high).

an iron oxide weathering product (limonite). Near the ground surface, the rock was stained for an inch or more on either side of some fracture surfaces. Many stained fracture surfaces were extensively spotted with a black surface mineralization, possibly pyrolusite (manganese oxide). Stained fractures were observed not only at the depth of the EERL work, about 35 ft below ground, but also as deep as 350 ft in the NPP quarry site test borings.

Petrography

Petrographic studies were made on core drilled for the NPP quarry site investigations.¹⁴ Consideration of the rock's mineral composition, especially the feldspars, its color index, its silica content, and its specific gravity led to classification of the rock as a porphyritic olivine basaltic andesite. However, it could also be called an andesitic basalt.

Groundwater Conditions

When the project was started in early spring, the ground was still moist from recent snowmelt, and there were several small springs or seeps in the experimental area. As the project progressed into late spring and early summer, the ground and the seeps dried up. Water was encountered in numerous drill holes in the early spring, but in none in late spring. The site location near the top of a hill, gradual warming temperatures and lengthening days, and a general diminution in precipitation as summer approached all contributed to the dewatering of the site.

When water was being encountered in early spring, it was common for standing water levels to vary in elevation by sev-

eral feet between nearby drill holes, with no apparent correlation with surface topography. Such channels for subsurface flow as existed, therefore, were discrete; there was not a widespread permeable aquifer system in the subsurface.

SITE INVESTIGATIONS

Geologic site investigations included surface mapping, NX-diameter core borings, shallow refraction profiles with a portable seismograph, and laboratory tests of rock core specimens. Surface mapping was performed and a set of core borings were drilled by NPP in 1964-1965 to explore and prove the quarry site. Additional borings were made in the EERL test area during this project.

Drilling Behavior, RQD

The basaltic andesite cored well with NX-size tools, and recoveries in the EERL borings were near 100% except in the upper few feet of weathered rock. Core was recovered in pieces generally less than 1 ft long, however, because of the extensive system of fractures. The core from a typical drill hole is shown in Fig. 6.

Rock quality designator, or RQD, is a criterion for the engineering soundness of rock.¹⁵ It is computed from the core recovery in sound pieces 4 in. in length or longer, as a percentage of total interval cored. No systematic computation of RQD for the site rock was attempted; but a brief examination of photographs of boxed NX cores from two EERL borings gave an estimated RQD of 70%.

Fig. 6. NX drill core from Hole ML-1C (Q-41).

Seismic Velocity

The acoustic velocities of the rock and the overburden depths were measured with a refraction seismograph. Seven traverses ranging from 150 to 210 ft in length were surveyed. Except for two profiles that traversed areas of deep soil (probably overlying a different pyroclastic type of rock), the P-wave velocities were 12,000 to 13,000 ft/sec. The average sonic velocity obtained from measurements on intact rock specimens in the laboratory was 17,550 ft/sec. The difference between the field and laboratory velocities is attributable to the fractured nature of the rock in the ground.

Mechanical Properties of the Rock

Tests were performed in the Corps of Engineers North Pacific Division (NPD) laboratory on specimens of basaltic andesite from eight NX core holes. Tests were performed on fresh, intact rock, and also on rock specimens showing brown staining. The tests performed and the test results are listed in Tables C1 and C2 in Appendix C. The average unconfined compressive strength of the intact rock was 32,420 lb/in.² In the weathered, stained rock, compressive strength averaged 17,080 lb/in.² Apparent specific gravity of both the intact and weathered rock averaged 2.70 (unit weight 164 lb/ft³).

TOPOGRAPHY

The topography of the test areas is shown on the site map (Fig. 2). The site was located at the top of a ridge, and although there was considerable level ground at the ridge summit most of it was underlain by deep soil. Areas where firm basaltic andesite rock was close to the surface were mostly located along the southeast sloping side of the ridge. For experimental purposes it was desirable that experiments be sited on the most level ground possible. Selection of individual experiment sites therefore involved a compromise between topography and rock quality, and virtually all tests were conducted in ground that had some slope to it.

Technical Programs

A number of technical studies were made during the course of the blasting experiments. There were two principal goals of the technical programs: to provide diagnostic information that would assist in assessing the results of the Lost Creek blasting, and to extend the EERL library of knowledge about explosion effects in general. The following sections summarize the scope and the nature of these programs.

HIGH-SPEED PHOTOGRAPHY

The purpose of this program was to record the dynamic progress of mound formation. Motion picture color photography at speeds of 250 to 500 frames/sec was carried out at principal experiments. In the case of row-charge experiments, a camera was located normal to the axis of the row and another was located off the end. Color motion pictures were also taken for documentary purposes.

CLOSE-IN SUBSURFACE PARTICLE VELOCITY MEASUREMENTS

This program was an attempt to measure the influence that controlled-blasting panels might exert in protecting the rock beyond them from damaging blast-induced stress waves.¹

Subsurface particle-velocity gages were grouted into the rock at depths of 20 ft and at ranges up to 50 ft from mounding charges. Particle velocities in a radial direction from the blast or blast center were recorded on magnetic tape and on oscillographic recorders. The

magnetic tape records were later digitized and numerically integrated to give displacement records.

SEISMIC VIBRATIONS

A ground-surface seismic-vibration measurement program was carried out to document ground motion levels for legal purposes and to define a ground motion attenuation curve for the rock in the Lost Creek area. Also, in the ILIR program it was desired to investigate whether the presence or absence of presplit surfaces and buffer zones might produce detectable differences in intermediate-range ground vibrations from mounding blasts. The radial, transverse, and vertical components of ground vibration were measured at four locations.

AIRBLAST

The principal objectives of the airblast experiments were to test a newly assembled system for measuring low-amplitude overpressure pulses, to observe the peak overpressures and impulses from the major detonations, and to improve airblast prediction capability for deeply buried mounding blasts in rock. Airblast overpressures were measured at distances from 150 to 1000 ft from the various mounding blast locations. Monitoring for legal purposes was not required because there were no vulnerable structures close to the site. Each of the ten major experiments was instrumented with five airblast gages at selected ranges and at various angles to the row axis for the row-charge events.

MAPPING

At experiments in which the size of the rubble mound or of the subsequent excavation was of interest, dimensions were obtained by topographic mapping. The initial mapping was done by plane-table surveying; thereafter, more favorable weather permitted the topographic information to be acquired by photogrammetry. In cases in which extremely steep slopes caused shadows, conventional survey profiles were taken to supplement the air-photo information.

FRAGMENTATION

The fragmentation studies program comprised two activities: fracture logging and block size measurements. Fracture logging was carried out to document the natural fracture pattern in the rock so that any observed differences in fragment sizes could be properly attributed to blasting or to natural conditions. The walls of selected 10-in.-diameter drill holes were examined with a mirror-and-light system lowered into the hole. Descriptive oral logs of the fracture patterns were prepared with a hand-held tape recorder; these were reduced to written logs and then plotted.

To document the gradation of the broken rock, a "point-counting" system of selecting and measuring rubble blocks or particles was used.¹⁶ Point-counting

was performed at rubble mounds prior to excavation, and at one rubble stockpile. It can be shown that a size distribution measured by point-counting corresponds to one obtained by sieving and weighing, provided the blocks exposed on the surface are representative of the deposit as a whole (see Appendix H).

BOREHOLE PHOTOGRAPHY

In an effort to detect the presence of new fractures, the walls of certain NX diamond-drill holes were photographed before and after blasting, using the Walla Walla Engineer District's borehole camera. In cases where there were two episodes of blasting (firing of presplit and buffer-zone charges followed by the firing of mounding charges), the holes were photographed after the presplit and buffer zone blasting as well as after the mounding blast.

PERMEABILITY TESTING

The NX boreholes that were photographed were also subjected to water pressure tests to monitor increases in permeability attributable to fresh fracturing or opening of existing fractures. The tests were run according to standard Corps of Engineers procedures, using a single packer at the top of the zone to be tested, and using low pressures because the holes were shallow.

Explosives and Equipment

This chapter describes the explosives and equipment used to carry out the ex-

perimental detonations and the subsequent excavation of the broken rock.

EXPLOSIVES

Three bulk explosives and several cartridged explosives were used at Project Lost Creek. The bulk explosives were used in the main charges. The cartridged explosives included boosters for the latter, and dynamite and Trimtex for the controlled blasting tests. Boosters were placed axially the full length of the bulk explosive charge in all Project Lost Creek mounding charges. The explosives and some of their properties are summarized in Table 3. For experimental and comparison purposes it was desired to test three bulk explosives of widely varying properties, two of which were to be slurry-type blasting agents. ANFO was also selected because of its low cost and its widespread use in mining and quarrying.

It was specified that the two slurry (water gel) explosives should have the following general characteristics: Slurry A was to have a high detonation velocity but only a moderate total energy, and Slurry B was to have a high total energy but only a moderate detonation velocity. It was expected that Slurry B would be a high-energy aluminized-slurry blasting agent. Such properties were specified in the contract between the Portland District Corps of Engineers (NPP) and Oregon Crane Service, Medford, Oregon, the site contractor, who furnished the explosives and carried out the drilling and rock excavation. Procurement problems led the contractor to furnish the two slurries described in Table 3. Tests of these slurries were subsequently carried out at EERL's request by the Lawrence Livermore Laboratory. The detonation veloc-

ity test, carried out above ground using 4-in. Lucite cylinders and rate sticks, proved that neither slurry met the velocity specifications. Energy was not tested.

EERL was forced to use the furnished explosives because of time limitations; the project had to be completed and the site vacated by early July so as not to interfere with quarrying operations for Lost Creek Dam.

DRILLING AND EXCAVATING EQUIPMENT

Two types of drills were used at Project Lost Creek. The mounding-charge emplacement holes were drilled by an Ingersoll-Rand "Drillmaster," a truck-mounted down-the-hole hammer drill with a self-contained air compressor, using button-type bits.¹⁷ Both the 10-in. holes used for mounding charges and the 6-in. holes used to emplace subsurface particle-velocity gages were drilled by this machine.

Small-diameter blastholes were drilled by Ingersoll-Rand "Air-track" crawler-type drills.¹⁷ The bit diameter was a nominal 2-7/8 in.; however, the holes were effectively 3 in. in diameter. These drills were used for all presplit and buffer-zone blastholes; one was also used to probe through overburden and to determine bedrock depths in the process of finding a suitable location for one of the experimental series.

Excavating equipment included a Gradall, a truck-mounted mechanical hoe with a rotatable bucket, capable of digging at an angle as well as straight down (Warner & Swasey); a D-8 bulldozer with hydraulic-operated blade and double-tooth ripper (Caterpillar); a D-9 bulldozer with

Table 3. Explosives.^a

Project Lost Creek Designation	Manufacturer trade name	Density, g/cm ³	Detonation velocity, m/sec		Computed detonation pressure, ^b kbar	Total energy, cal/g		Ingredients	Remarks
			Specified ^c	Actual		Specified ^c	Actual		
ANFO	Du Pont (pack- aged by Timber Supply Explosives, Inc., Philomath, Ore.); ANFO	0.93	—	4560 ^d	92	—	890 ^{d,e}	Ammonium ni- trate (94%), fuel oil (6%)	Premixed bagged prills, supplied in 50-lb bags
Slurry A	Trojan-U. S. Powder Co.; "TROJEL"	1.38	5800 or greater	4925 ^f	82	800 ± 80	—	Ammonium ni- trate, nitro- starch, sodium nitrate, water	Gray; supplied in 30-lb plastic "sausages"
Slurry B	Oriard Powder Co.; "ZERITE"	1.22	4000-4700	3660 ^f	44	1400 ± 140	1025 ^{e,g}	Ammonium ni- trate, sodium nitrate, sulphur, water	Yellow-orange; supplied in 25-lb plastic "sausages"

^aExplosives other than those listed included:

- (1) Boosters — Du Pont HDP-1, 1-lb cylinders
- (2) Dynamite — 40% gelatin dynamite, Hercules and Du Pont, in 2- and 1-1/4-in. diameter sticks
- (3) "Trimtex" — Du Pont dynamite-based explosive especially formulated for controlled blasting, 7/8- and 1-in. diameter cylinders
- (4) Detonating cord — 50-grain and 25-grain Primacord, manufactured by Ensign-Bickford Co.
- (5) Blasting caps — electric, instantaneous, and various millisecond delays
- (6) Millisecond delay connectors — Du Pont

^b

$$P_{\text{kbar}} = (485\rho - 175\rho^2) \left(\frac{V_{\text{DET}}}{10,000} \right)^2, \text{ where } \rho = \text{g/cm}^3, V_{\text{DET}} = \text{m/sec.}$$

^cIn construction contract between NPP and Oregon Crane Service, Medford, Oregon (site contractor).^dFrom Ref. 2.^eHeat of detonation.^fAverage result of tests at Lawrence Livermore Laboratory.^gManufacturer's data; from underwater test.

single-tooth ripper (Caterpillar); a Michigan tire-mounted front-end loader (Clark Equipment Co.); and a 7-G "Traxcavator," a track-mounted front-end loader with a

toothed bucket (Allis-Chalmers). The Traxcavator supplanted the Michigan loader midway through the project when the latter proved unsuited to working in the mounding cuts.

Experiment Results

INTRODUCTION

This section presents the designs and the results of the various mounding experiments. Each of the mounding experiments will be initially discussed in sequence, followed by a discussion of some of the common features and results, such as the fragmentation of the rock. The section concludes with a summary of the results of several of the key technical programs. It is appropriate to introduce this section with a brief account of the elements of mounding design.

The design of a row of mounding charges involved primarily the following parameters:

- (1) Type of explosive or blasting agent
- (2) Weight and shape (L/D ratio) of charge
- (3) Depth of burial (DOB) of charge
- (4) Spacing between charges in a row
- (5) Separation between rows for multiple rows.

At Lost Creek, hole diameters of 10 in. and 6 in. were available. All mounding charges were emplaced in 10-in. holes.* The explosives were selected in advance as discussed in the preceding section.

For the VS series, the first mounding rows to be detonated, charge weights and

*With one exception: Event IL-9D (see below).

burial depths were selected to be 200 lb and 18 ft, respectively, on the basis of successful use of these quantities at Project Mini Mound.⁷ This is a scaled depth of $3.08 \text{ ft/lb}^{1/3}$. A primary objective of the VS experiments was to determine the optimum spacing for the charge weights and depths being used; therefore, the spacing between the charges was progressively increased from one end of a VS row to the other.

It had been planned that the optimum spacing determined in the VS rows would be used in the follow-on ML experiment. However, under the pressure of time, drilling on the ML experiment had to proceed without full evaluation of the results of the VS series. This required the selection of an in-row spacing, with charge weight and charge depth being decided afterward on the basis of the phenomenon of enhancement (the interaction of charges in a charge row) noted in cratering research.² The following expression was derived to relate these three quantities (the derivation is given in Appendix D):

$$\text{DOB} = K \left(\frac{Y}{S} \right)^{1/2},$$

where:

DOB = depth of burial

Y = charge weight of explosive
yield

S = in-row charge spacing
K = empirically determined
constant

The constant K, which is a function of the explosive used and the rock being blasted, represents a scaled depth of burial for row mounding charges. The optimum form of a mound and true crater would be the one in which the greatest volume of broken and excavable rock was produced by a given weight of explosive, and this would correspond to an optimum value for K. Smaller values of K would correspond to a shallower true crater and with the formation of a throw-out crater; larger values of K would relate to a deeper true crater with poor rock breakage at the surface. It should be possible to determine experimentally the optimum mound and true crater form, and thus the corresponding optimum value of K. This was effectively what was done at Project Lost Creek.

Applying the equation above to the results of the VS series, the known quantities DOB and Y were substituted, and the optimum value of S was selected on the basis of the best appearing portion of the mound. The optimum value of K was then computed. The mounding rows subsequent to the VS series (i.e., the CS and ML series) were designed using this relationship and the optimum value of K determined from VS-1. The limits of applicability of the equation were not ascertained. It is obvious, however, that with excessive spacing a discontinuous rather than a smooth mound would be produced.

Mounding row design is discussed later and in Appendix D. As shown in the latter, the constant K can be expressed

as a function of the optimum scaled depth of burial of a single mounding charge, the corresponding true crater radius, and an enhancement factor. This fact should make it possible to determine an optimum value of K by a series of single-charge calibration mounding shots at a new blasting site.

MOUNDING

Variable Spacing Rows

The Variable Spacing series comprised three rows of mounding charges in which the charges were all approximately the same weight and were buried at the same depth. The spacing between charges in each row varied so that each interval was about 15% greater than the previous one. Thus at one end charges were 12 ft from one another, and at the other end they were 24 ft apart. The layout of the charges is illustrated in Fig. 7. The objectives of varying the spacing were to determine the optimum spacing, to see how far apart the charges could be spaced and still get satisfactory interaction, and to determine how mound and crater dimensions varied with charge spacing.

The emplacement holes were 10 in. in diameter and the L/D ratios ranged between 5 and 8. Appendix B contains detailed information about each charge. The centers of all charges were 18.0 ± 0.5 ft below ground surface. Preshot cross sections through the three variable spacing rows are shown in Fig. 8. A quantity of 200 lb of ANFO was used in each VS-1 charge, 210 lb of Slurry A in each VS-2 charge, and 200 lb of Slurry B in each VS-3 charge. It was hoped that

Fig. 7. Plan view of VS-1, VS-2, and VS-3 series.

differences in fragmentation and in the amount of rock broken could be recognized and correlated with the properties of the different explosives, such as their detonation velocity and total energy. All three rows were laid out end-to-end on a bench along the side of the hill on which the test site was located (see Fig. 2). Two particle-velocity gages were installed at each experiment, 20 and 50 ft from the row on the uphill side. These were grouted in place in the rock at depths of 20 ft, approximately the same depth as the mounding charges.

All of the charges in each individual row were fired simultaneously. Charges were initiated by detonating-cord down-lines, initiated in turn by a detonating-cord trunk line loop, which was initiated by blasting caps (Fig. 7).

The VS-1 blast created an asymmetric mound, high and wide at the close-spaced end and tapering downward and narrowing toward the wide-spaced end. Figure 9 shows the mound in the process of formation, and Fig. 10 shows the final rubble mound. The VS-1 blast developed a series of rifts in the ground, parallel to the axis of the row, along the northwest side of the mound. The rifting extended 10 to 15 ft out beyond the edge of the rubble mound.

The VS-2 mound was similar in form to the VS-1 but smaller in dimensions. A view of it is shown in Fig. 11.

The VS-3 detonation scarcely produced a mound at all. Some rifting, upward thrusting of the ground, and some breakage were produced at the close-spaced end. Figure 12 shows the VS-3 mound viewed from the north end of the VS-2 experiment. Several of the charge emplacement drill holes were intact, or nearly so, for their upper few feet. Bulking of the material in the VS-3 mound was distinctly less than in either the VS-1 or VS-2.

Topographic maps of the mounds, with a 2-ft contour interval, were prepared by plane-table surveying or from aerial photographs. Figures 13, 14, and 15 show the maps of the VS-1, -2, and -3 mounds as well as the original ground at each experiment site.

The mounds of broken rock were removed and the rock below ground level was excavated by a D-8 bulldozer working, first, with a tire-mounted front-end loader, and later with a track-mounted toothed-bucket front-end loader (Traxcavator). Getting all of the broken rock out of the pits was impractical because of

Fig. 8. Preshot cross sections through VS-1, VS-2, and VS-3 series.

Fig. 9. VS-1 mound in process of formation shortly after detonation.

Fig. 10. VS-1 mound.

the necessity to maintain ramps for the equipment.

The VS-1 pit was the largest excavation in the VS series. A view of it is given in Fig. 16 and three cross sections are shown in Fig. 17. At shallow depths, in the layer of rock that was character-

Fig. 11. VS-2 mound.

Fig. 12. VS-3 mound (end-on view from southwest).

ized by weathered fractures, it was possible for the bulldozer to dislodge and remove rock almost at will in a lateral direction. Rock in this layer had been keyed tightly enough together before blasting so that the dozer was not able to dislodge it with its blade. Once a trench was started into the blasted rock, however, and the rock was free to move horizontally, it was readily moved. In the immediate vicinity of the explosive charges, fine fragmentation was noted, and the Traxcavator could dig the rock down to the bottom of the charge.

(a) Ground (preshot), showing charge locations

(b) Mound (postshot)

Fig. 13. Topography, VS-1 ground and mound (contour interval, 2 ft).

Elsewhere, solid rock was encountered in the lower part of the pit.

The VS-2 pit was smaller than the VS-1 pit; the pit was not dug out to the sides at shallow depths as the VS-1 had been, so that the VS-2 excavation was narrower and deeper. Figure 18 is a view of the VS-2 excavation; cross sections are shown in Fig. 19.

When starting to excavate the VS-3 experiment, the bulldozer had difficulty breaking through the slightly broken rock at the surface. It was eventually able to do so by ripping. The pit then developed narrow and deep like the VS-2.

(a) Ground (preshot)

(b) Mound (postshot)

Fig. 14. Topography, VS-2 ground and mound (contour interval, 2 ft).

Figure 20 shows the VS-3 excavation, and Fig. 21 shows cross sections. Charge F of VS-3 apparently detonated low order because the rock in the vicinity was unbroken and impossible to excavate. The VS-3 excavation was thus considerably shorter than it should have been.

Although Charge G detonated properly, the surrounding rock could not be excavated because of the restricted working room available. Table 4 gives the dimensions and cross-sectional areas of the three VS excavations.

The principal goal of the VS series was to determine the optimum charge spacing was to determine the optimum charge

(a) Ground (preshot)

(b) Mound (postshot)

Fig. 15. Topography, VS-3 ground and mound (contour interval, 2 ft).

Fig. 16. VS-1 excavation.

spacing for the charge size and burial depth used; i.e., that spacing which produced the largest volume of broken rock per unit weight of explosive. Table 4 lists the average charge spacings at each cross section and the product of charge spacing and cross-sectional area. These latter numbers represent the volume of

Fig. 17. Cross sections, VS-1 excavation.

Fig. 18. VS-2 excavation.

broken rock per charge and are therefore considered to be figures of merit for the corresponding spacing. The optimum performance at VS-1 occurred at a spacing of about 17 ft; at VS-2 at about 20 ft; and at VS-3 at about 17 ft.

Fig. 19. Cross sections, VS-2 excavation.

Fig. 20. VS-3 excavation.

End effects probably occurred through a certain portion of each experiment, but the middle portions of VS-1 and VS-2 were probably free from them. In VS-1 the efficiency of the charges was approximately the same over the region from 0 + 22 (spacing about 14.5 ft) to 0 + 62 (spacing about 20 ft). In VS-2, a fairly wide spacing was most efficient. Notably, considerably greater efficiency is found at section 0 + 62 (spacing about 20 ft) than at section 0 + 32 (spacing about 16 ft). It is difficult to be certain about the best spacing for VS-3 because of the abbreviated length of the pit.

Referring back to the equation

$$DOB = K (Y/S)^{1/2},$$

the optimum performance at VS-1 represents a value of K of 4.6 to 5.4 $\text{ft}^{3/2} \text{lb}^{-1/2}$.

Constant Spacing Series

The Constant Spacing series was designed to compare the effects of

Fig. 21. Cross sections, VS-3 excavation.

Table 4. Depths, widths, and cross-sectional areas of VS excavations.

Station ^a	Depth, ^b ft	Width, ^c ft	Area, ft ²	Average charge spacing, ft	Spacing times area, ft ³
<u>VS-1</u>					
0 - 08	5	56	135	—	—
0 + 02	14.5	57.4	363	11.4	4,140
0 + 12	17.8	59.4	559.5	13.0	7,270
0 + 22	17.2	62.1	567	14.4	8,160
0 + 32	15	57.8	586.5	15.7	9,210
0 + 42	13.8	53.4	552	17.0	9,380
0 + 52	13.4	57.4	516	18.2	9,390
0 + 62	13	57	456	19.8	9,030
0 + 72	12.2	62.6	432	21.2	9,160
0 + 82	11.4	51.4	348	22.5	7,830
0 + 92	9.8	40.4	271.5	23.8	6,460
1 + 02	7.2	43.2	181.5	25.1	4,560
1 + 12	4.	35.4	70.5	—	—
<u>VS-2</u>					
0 - 08	7.4	46.4	163	—	—
0 + 02	9.1	45.2	229	11.4	2,610
0 + 12	12.4	43.4	329	13.0	4,280
0 + 22	16.2	48.4	360	14.4	5,180
0 + 32	16.2	43.	396	15.7	6,220
0 + 42	16.6	47.2	450	17.0	7,650
0 + 52	16.6	52.5	496	18.2	9,030
0 + 62	16.7	53.6	516	19.8	10,220
0 + 72	14.5	54.4	459	21.2	9,730
0 + 82	14.6	49.	439	22.5	9,880
0 + 92	10.5	48.8	312	23.8	7,430
1 + 02	5.2	39.6	141	25.1	3,540
1 + 12	3.2	40.4	80	—	—
<u>VS-3^d</u>					
0 - 08	1.7	28.2	43	—	—
0 + 02	11.6	31.2	165	11.4	1,880
0 + 12	15.7	26.8	223	13.0	2,900
0 + 22	15.2	28.4	214	14.4	3,080
0 + 32	13.2	38.6	254	15.7	3,990
0 + 42	10.2	40.4	248	17.0	4,220
0 + 52	8.8	38.5	170	18.2	3,090
0 + 62	6.4	24.2	97	19.8	1,920
0 + 72	—	—	—	21.2	—
0 + 82	—	—	—	22.5	—
0 + 92	—	—	—	23.8	—
0 + 02	—	—	—	25.1	—
1 + 12	—	—	—	—	—

^aStationing: Charge A: 0 + 00

B: 0 + 12

C: 0 + 26

D: 0 + 42

E: 0 + 60

F: 0 + 81

G: 1 + 05

^bDepth is maximum below original ground surface.^cWidth is width at original ground surface.^dVS-3 was not excavated northeast of Sta. 0 + 67 because of faulty detonation of Charge F.

detonating rows of mounding charges both simultaneously and in a delay sequence. The layout of the two rows was identical as shown in Fig. 22. Six identical charges of 158 lb total weight each (150 lb of Slurry A plus 8 lb of boosters) were spaced 16 ft apart and were buried at a depth of 15.5 ± 0.2 ft in both rows.

It had originally been intended to use 200-lb charges and the optimum spacing determined from VS-2 to design the CS rows, but there was an insufficient area of suitable rock available at the CS site to make use of the 200-lb charges feasible. The experiment was therefore scaled down to six 158-lb charges (total), spaced 16 ft apart by means of the equation:

$$DOB = K (Y/S)^{1/2},$$

that is:

$$DOB = 5.0 \left(\frac{158}{16} \right)^{1/2} \approx 15.5 \text{ ft},$$

where the value of 5.0 for K was judged to be appropriate on the basis of the VS detonations.

In the CS-1 experiment all charges were detonated simultaneously by six instantaneous blasting caps. In the CS-2 experiment, delay blasting caps were used so as to cause a sequence of detonations at 25-msec intervals, starting at the north end and proceeding down the row. The questions of interest in comparing the results of CS-1 and CS-2 were the differences in close-in subsurface particle velocity, seismic effects, fragmentation, and the amount of broken rock produced. Particle-velocity gages were

emplaced at a 20-ft depth, 20 and 50 ft off the sides of the rows, as shown in Fig. 22.

Both CS experiments appeared to detonate satisfactorily. Both produced little airblast because they were fired with downhole blasting caps rather than with detonating cord. That CS-1 had suffered a partial low-order detonation, however, became evident during excavation, and was confirmed by study of the high-speed motion pictures and the particle-velocity records. Both mounds were approximately the same size with CS-2 being slightly longer. Photographs of the two mounds are shown in Figs. 23 and 24 and topographic maps are shown in Figs. 25 and 26. Notable ground rifting, shown in Fig. 27, was produced along the east side of the CS-2 mound, and these rifts determined the eventual extent of the CS-2 excavation.

In attempting to excavate CS-1, conditions were found that suggested that low-order detonation had taken place in the charges in the center of the row. Digging was easy at the north and the south ends, but a mass of firm rock was encountered east of the center line, as shown in Fig. 28. The movies of the detonation showed a normal mound rise at the ends of the row, but little in the center. The incomplete detonation of CS-1 complicates the comparison of results between CS-1 and CS-2. Cross sections of the CS-1 excavation are shown in Fig. 29.

The CS-2 experiment was excavated with relative ease. Cross sections are shown in Fig. 30. It is noteworthy that the mound of CS-2 was located asymmetrically with respect to the charges and to the excavation.

(a) Plan view of CS experiments.

Note:
CS-1 and -2 designs are identical

(b) Sectional view AA' of CS experiments.

Fig. 22. Plan and sectional views of constant spacing (CS) experiments.

Multiple Lift Experiment

The Multiple Lift experiment was carried out to test the feasibility of constructing a structural excavation using mounding charges in conjunction with controlled blasting to shape and to protect the side walls. If mounding is to be used to excavate deep cuts, then it will be necessary to excavate in successive lifts, as is the case with conventional drilling and blasting. Therefore, an integral part of this experiment was a test of a two-lift excavation. The first lift was a double-row mounding experiment designated ML-1,

Fig. 23. CS-1 mound.

Fig. 24. CS-2 mound (view from south).

and the second lift was a single-row experiment designated ML-2.

The design of each phase of the ML experiment required some judgment because it was simply not possible to acquire and to analyze the necessary

(a) Ground (preshot)

(b) Mound (postshot)

Fig. 25. Topography, CS-1 ground and mound (contour interval, 2 ft).

information from the preceding experiments. The charge spacing in each row of ML-2 was selected to be 18 ft in the planning stage of the Lost Creek program. It was recognized beforehand that the time schedule for the field program would preclude the complete analysis of prior experiments that is normally desirable.

Fig. 26. Topography, CS-2 ground and mound (contour interval, 2 ft).

Fig. 27. Ground rift, center to lower right, formed along east side of CS-2 mound.

Fig. 28. CS-1 excavation (centerline of charges lay only 4 ft to left of small rock cairn at top of face—right center; incomplete detonation occurred in center of row).

Because charge weight, spacing, and depth of burial are interrelated, adjustments to the charge weights and depths could be made when it came time to load the holes. The adjustments were to be made according to the preliminary observations of the VS-1 detonation.

A constraint upon the overall design of the ML-1 phase was that the total width could not exceed the approximately 80 ft of good, suitable rock available for the experiment.

The optimum portion of the VS-1 excavation suggested a geometric relation (between the width of the true crater and the charge depth of burial) of:

$$W_t = 2.8 \text{ DOB},$$

where W_t is the true-crater width measured at the original ground surface. This equation implies that the DOB is dependent upon the width constraint, and therefore, the only remaining design variable is the charge weight, which can be adjusted to suit the DOB and the spacing.

A1. appropriate separation between the two rows in ML-1 was judged to be 0.85 times the true-crater width on the basis of cross sections of the VS-1 excavation. Too great a spacing would leave an excessive ridge of unbroken rock between the rows. Too small a spacing would require

Fig. 29. Cross sections, CS-1 excavation.

Fig. 30. Cross sections, CS-2 excavation.

second-lift charge emplacement holes to be drilled through broken rock, and would also produce too deep and steep a final excavation, without room for benches between lifts. The total width of the ML-1 double-row mounding excavation was therefore determined to be:

$$L = 0.5 W_t + 0.85 W_t + 0.5 W_t = 1.85 W_t$$

$$\approx 5.2 \text{ DOB (because } W_t = 2.8 \text{ DOB),}$$

plus the widths of the controlled blasting regions on both sides of the excavation. The total width of the controlled blasting panels was 11 ft in ML-1. Thus:

$$5.2 \text{ DOB} \approx 80-11;$$

therefore:

$$\text{DOB} \approx 13.5 \text{ ft,}$$

which was the depth of burial used.

The charge weights were then determined by:

$$\text{DOB} = K \left(\frac{Y}{S} \right)^{1/2},$$

where:

$K \approx 5.0$ on the basis of the
VS experiments;

i.e.,

$$Y = S \left(\frac{\text{DOB}}{K} \right)^2$$

$$= 18 \left(\frac{1.35}{5} \right)^2$$

$$\approx 131 \text{ lb.}$$

It was decided that each charge would consist of 125 lb of ANFO with a 10-lb booster, for a total of 135 lb. The scaled depth of the ML-1 charges was $2.63 \text{ ft/lb}^{1/3}$.

The final design of the ML-1 detonation is shown in Figs. 31 and 32. The presplit holes were loaded below a depth of 4 ft with 0.25 lb/ft of explosive in the form of Trimtex, with an extra bottom load of two sticks of $1\frac{1}{4}$ -X 8-in. "hi-drive" dynamite. The presplit holes were sand-stemmed above a depth of 4 ft and air-stemmed below 4 ft by use of newspaper plugs. The buffer-zone holes were loaded below 4 ft with 1/2 lb of Trimtex per foot and two or three sticks of dynamite bottom load, and were sand-stemmed throughout. Initiation of all charges was by detonating-cord down-lines tied to ring trunk lines fired by twin electric blasting caps. The ML-1 experiment was fired as a single event, with firing of the buffer-zone charges delayed 50 msec, and that of the main charges delayed 150 msec, with respect to the presplit charges. The presplit and buffer-zone holes were inclined at 4 V on 1 H, as shown in Fig. 32.

Two particle-velocity gages were installed at depths of 20 ft in drill holes to the east of the eastern presplit line, to record the shock generated by the combined three-pulse ML-1 detonation. It was originally attempted to locate the gages on the west side of the experiment, but in drilling the emplacement hole for the outer gage, no hard rock was encountered to a depth of 40 ft. A single NX-size diamond-drill hole 4 ft west of the west presplit line was photographed with the borehole camera and was

water-pressure-tested before and after the ML-1 blast.

Detonation of ML-1 produced a highly irregular mound; the topography is shown

in Fig. 33. The mound was better defined, with a more linear outline, along the west side.

The ML-1 rubble was excavated by pushing southeastward with a D-8 dozer

Fig. 31. Plan view, ML-1 design.

aided by a 7-G Traxcavator. It soon became evident that a larger machine than the D-8 was required, and a D-9 with a single-tooth ripper was put to work. This powerful machine was able to dislodge broken rock even though it was fairly tightly keyed together. When the ML-1 pit had been excavated to refusal, a well-formed presplit wall lay along the west side, and a fairly regular trough had been dug along the west row of main charges. Along the east side, where some overburden had been present, the excavation was more irregular and a poorly formed presplit wall (or none at all) was found. The floor of the pit was

irregular, with a large hump of unbroken rock in the northeast corner in the vicinity of Charges M and N. Between the two sides was a ridge of unbroken rock, which was 2 to 3 ft higher than the troughs on either side. The west presplit wall, the west trough, and the central ridge are shown in Fig. 34.

During the initial ML-1 excavation some large blocks were noted with incipient fractures, along which the rock later broke into smaller fragments when moved by the bulldozer. Such a block is shown in Fig. 35.

After the rubble from the ML-1 detonation had been excavated to refusal, it

Fig. 32. Cross-sectional view, ML experiment.

Fig. 33. Topography, ML-1 ground and mound (contour interval, 2 ft).

was desirable to remove a hump of rock (or "daylight") at the south end of the pit in order to facilitate the removal later of rock broken by the follow-on ML-2 detonation. A conventional pattern of 3-in. holes drilled by a track-mounted crawler drill was used to remove this material. This detonation was designated the ML daylighting shot.

The daylighting shot consisted of eighty-seven 3-in.-diameter blastholes, 20 ft deep except for a few shallower ones

Fig. 34. ML-1 excavation (west side).

Fig. 35. Slab with incipient cracks, west row, ML-1.

around the edges. The pattern of drill holes was basically 8- X 6-ft rectangular, adjusted to wider spacings in places. Explosives used consisted of Trimtex and ANFO - 20 lb of ANFO per hole. Just before loading, the holes were blown out with compressed air to remove the water from the previous night's rain, and a newspaper plug was used near the bottom to keep the ANFO up out of residual water. The charges were initiated by detonating-cord downlines tied to ring trunk lines. The pattern was fired in four delays, the outside ring first, the center last, with 25 msec per delay. A total of 1700 lb of ANFO and 535 lb of Trimtex was used. The powder factor was about 1.5 lb/yd³.

The ML daylighting shot produced an elongated crater, with its axis perpendicular to the ML-1 and ML-2 rows. Immediately after the daylighting shot, the bulldozer commenced pushing the rubble out to the southeast. There was no opportunity for a quantitative block size determination. The observation was recorded at the time, however, that the rubble blocks appeared smaller and more uniform than had generally been observed at the mounding shots.

There was no specific design objective for the second lift of the Multiple Lift experiment, at least in terms of achieving a specified set of dimensions. The experiment as a whole was intended primarily to be a prototype of an excavation concept. It was decided that a single row of 200-lb charges spaced at 18 ft would provide the necessary information for evaluation of the concept. The charges were buried at 18 ft and the row was, in nearly all

respects, a duplication of the best-appearing portion of VS-1.

The emplacement holes for ML-2 were drilled as shown in Fig. 36. The single line of main charge holes was drilled down through a rock ridge that stood between the two main charge rows of ML-1. At the south end of the main row, it was necessary to use a double row of main charges because shallower holes were required. This was in the daylighted area, and the 10-in.-diameter percussion drill had considerable difficulty because of broken rock. A presplit hole spacing of 3 ft was used, because this interval had proved satisfactory in a short segment of the ML-1 west presplit wall. It was decided to use a single-line buffer zone on both sides, because the single-line zone had done well on ML-1. A single line of presplit holes was drilled around the north (closed) end of the row, to give a cleaner final excavation and also to test the capability of a presplit plane to survive without a buffer zone.

The ML-2 event was fired with the same sequence of delays as ML-1. The rubble was excavated by means of a D-8 dozer and a Traxcavator. The result of the ML-2 mounding blast was a linear trough of rubble, neatly centered on the ML-2 charge row and nearly filling the ML-1 excavation as shown in Fig. 37. This material was excavated without difficulty by the D-8 dozer and the Traxcavator, but at lower depths problems (such as a rough bottom with unbroken masses of rock) were encountered. Small-scale secondary blasting was necessary to clean up the toes of presplit faces. One particularly large hump of unbroken rock along the west face of ML-2 was successfully

(a) Section AA' Longitudinal view

- 10-in.-diameter main charge emplacement holes
- 3-in.-diameter presplit and buffer-zone drill holes

Note: Buffer-zone and lateral presplit holes angled at 4V on 1H toward centerline. End presplit holes angled at 10V on 1H toward center of excavation.

(b) Plan

Fig. 36. Longitudinal section and plan, ML-2 experiment.

blasted by loading the surviving presplit and buffer-zone holes with dynamite.

The final ML excavation is shown in Figs. 38 and 39. It was possible to excavate to a grade of 2511 and still maintain a level pit floor. The elevations of the bottoms of the mounding charges averaged 2507.

The ML-1 presplit wall was examined for fresh cracking after the daylighting shot and after the ML-2 detonation. A few cracks were noted along natural fractures, but the wall was quite intact. One flow-bottom crack was opened at one

Fig. 37. ML-2 rubble nearly filling ML-1 excavation.

Fig. 38. Completed ML excavation (view southeastward).

point to a width sufficient to insert the fingers. The presplit face at the north end was comparable in quality to that along the sides. Considerable unbroken rock was present in front of the toe, however. The control that geologic structure exerts over presplitting was seen where columnar jointing overruled presplitting in the east wall of ML-2, an example of which is shown in Fig. 40.

The volumes of broken rock excavated from each of the mounding rows just discussed are given in Table 5, together with explosive quantities and computed powder factors. It should be noted that these quantities are lumped values for each excavation and do not necessarily represent optimum values that could be achieved in a production operation. As a comparative value, the portion of VS-1 that was judged to have the most appropriate spacing (i.e., 18 ft) represents a powder factor of about 0.6 lb/yd^3 .

The same degree of fragmentation was observed at virtually all mounding blasts; blocks were generally equidimensional, irregular in shape, and with no platiness suggestive of bedding or foliation. Elongate-irregular blocks were not uncommon and such blocks were probably columnar-joint column remnants. Typical rubble is shown in Fig. 41.

Block size distribution curves for VS-1 are representative of all experiments and are shown in Fig. 42; block size distribution curves for the remainder of the mounding blasts are contained in Appendix E. The dimension plotted is the intermediate dimension of the block. In general, the median (50%) sizes were between 12 and 7 in., and the curves steep, indicating a well-sorted or poorly

Fig. 39. Completed ML excavation (view northwestward).

graded material. Points logged as "soil" (i.e., where original ground surface material had been heaved up but only partially disrupted by the blasting action) were rejected in computing block size distributions. Material from about 17 ft below

Fig. 40. South part of east ML-2 pre-split wall, showing predominance of natural columnar jointing over presplit fracturing.

ground near shot point "D," VS-1, had a median size of about 3-1/2 in., thus demonstrating that finer fragmentation does occur in the immediate vicinity of a charge. As indicated by the curves in Appendix E, fragmentation in the CS experiments was comparable to that at the VS rows, although a layer of unusually massive rock present at the CS-1 site did cause the maximum block size and the percentage of large blocks to be higher than those of other experiments. Fragmentation at ML-1 and ML-2 was excellent.

A number of NX holes located close to blasts* were photographed both before and after detonations to determine whether existing fractures had been widened or new fractures introduced. In

*For the most part, these NX holes were associated with the ILIR program of tests rather than with the mounding blasts.

Table 5. Excavation volumes and powder factors.

Experiment	Excavation volume, yd ³	Weight of explosives, lb			Total	Powder factor, lb/yd ³	Remarks
		Blasting agent (type)	Boosters	Pre-splitting and buffer zone			
VS-1	1830	1400 (ANFO)	105	—	1505	0.82	Measurements before trimming experiments
VS-2	1570	1470 (Slurry A)	77	—	1547	0.98	
VS-3	530	1400 (Slurry B)	77	—	1477	2.78	Volume low due to partial detonation
CS-1	490	900 (Slurry A)	48	—	948	1.93	do.
CS-2	1170	900 (Slurry A)	48	—	948	0.81	
ML-1	5400	1750 (ANFO)	140	836	2726	0.51 ^a 0.35 ^b	Volume slightly high due to daylighting detonation
ML-2	2860	1550 (ANFO)	109	1258	2917	1.02 ^a 0.58 ^b	

^aIncluding presplitting and buffer-zone charges.

^bExcluding presplitting and buffer-zone charges.

many cases the collar of the NX hole was damaged and displaced by the adjacent blasts, but careful study of the photographic records revealed only very minor changes at depth due to blasting. In a very few cases new fractures were induced. The general observation was that, except for their upper portions, the holes had sustained remarkably little damage.

Fig. 41. Rubble at VS-2 mound.

The same NX holes that were photographed were also subjected to water testing in an attempt to determine whether permeability changes occurred after a nearby blast. Because of the nature of the data acquired in this program, a graphic presentation of the results is not feasible. In all cases, however, there was a higher permeability after blasting, and the increased permeability was localized in the upper parts of the holes. This observation is in accord with the description of the rock at the surface around the hole collar that occurred at each blast.

As mentioned in the introduction of this report, a program of ILIR-funded tests was carried out in conjunction with the Lost Creek experiments. Although these tests to measure quantitatively the effectiveness of buffer zones are the subject of a separate report,¹ the initial

portion of the ILIR program, in which the presplit panels and buffer zones were developed, is pertinent to the mounding experiments in Project Lost Creek and is discussed in the following paragraphs.

Prior to attempting to measure whether a buffer zone was effective in attenuating shock waves from an adjacent subsurface detonation, it was necessary to arrive at a reasonable design for arrays of buffer-zone charges. The first three stages of the ILIR program, designated IL-1, IL-2, and IL-3, were trials of presplit panels, buffer zones, and combined presplit panels and buffer zones, respectively. Those designs that were judged to be the best were then used

in the remainder of the ILIR series and in the Multiple Lift experiment.

The layout of the IL-1 presplit panels is shown in Fig. 43, the IL-2 buffer zones are shown in Fig. 44, and the combined panels are shown in Figs. 45 through 49.

Following detonation, the IL-1, IL-2, and IL-3 test panels were excavated with the Gradall. The IL-1 and IL-2 panels were disappointing because the upper 3 to 4 ft of rock was weathered along joints to the extent that a presplit face would not stand in this interval. Below the level at which rock became firm it was difficult to remove the broken rock; only for the 2½-ft spacing (IL-1B) was it possible to expose some presplit face, a portion of

Fig. 42. Rubble size distribution, VS-1 mound.

which is shown in Fig. 50. A splitting action was observed in the sides of the holes with 3-ft spacing (IL-1C) suggesting that 3-ft spacing might be successful. Because $2\frac{1}{2}$ ft had been shown without doubt to be successful, it was used as a presplit-hole interval in succeeding experiments.

All of the IL-2 detonations produced small rubble-filled craters. The IL-2A and IL-2B detonations were excavated

Vertical view, each hole
Presplit charges IL - 1A, 1B, 1C
(b) Section through charge

Fig. 43. IL-1 test panels.

with the Gradall to the point of refusal; IL-2C was located in a different part of the site and was not excavated.

The IL-3 tests were conducted in firm, columnar-jointed rock in the eastern part of the site (see Fig. 2) where the 3- to 4-ft layer of weathering along joints was lacking. At IL-3A, in which the drill holes were vertical, the rubble from the detonation was dug to about 7 ft below ground surface; however, no presplit face was preserved. At the remaining IL-3 tests the drill holes were inclined and several well-formed presplit faces were exposed. Figure 51 shows the presplit face at IL-3D.

It was not possible to judge visually which of the buffer-zone designs in the IL-2 and IL-3 tests was the most promising. In all cases the rock appeared to have been broken to approximately the same extent. Experimentation with buffer zones was continued in the later ILIR tests, but even the subsurface particle-velocity measurements made in these later tests were not a definitive diagnostic tool.¹ The presplit face in the IL-3A test was the only one not to survive the buffer-zone detonation, but this fact was largely due to the close proximity of the buffer zone rather than the design of the buffer zone itself. The buffer zones used in the Multiple Lift experiment were believed to represent reasonable designs based on the experiments performed at Lost Creek.

CLOSE-IN PARTICLE VELOCITY

In addition to the particle velocity measurements made in the ILIR program to evaluate buffer zones, subsurface

velocities were also recorded during the detonation of all the mounding rows except ML-2. The purpose of the measurements was to provide additional information about the effects of subsurface explosions in general, and to provide comparative data for the Lost Creek mounding experiments. The locations of the velocity gages for each experiment are shown in the respective charge-layout figures; a description of the gages and electronics is contained in Ref. 1.

Representative recordings are shown in Fig. 52 for the VS-1, CS-2, and ML-1 detonations. Note that the integrated velocity (i.e., the displacement) is also given in Fig. 52. A tabulation of peak velocities and displacements for all of the mounding experiments is given in Table 6.

There does not appear to be any correlation between the properties of the explosives used in the VS rows and the respective particle-velocity amplitudes.

Fig. 44. IL-2 buffer-zone test panels.

Fig. 45. IL-3A test panel.

Fig. 46. IL-3B test panel.

Fig. 47. IL-3C test panel.

Fig. 48. IL-3D test panel.

Fig. 49. IL-3E test panel.

The lowest amplitudes were generated by the fastest and most dense explosive (Slurry A); i.e., the explosive that should have had the highest detonation pressure. It is also surprising that Slurry B, which appeared to be markedly less powerful

than ANFO on the basis of mound development, generated particle velocities close to those generated by ANFO. The six individually detonated mounding charges at CS-2 produced six distinct velocity

Fig. 50. Presplit face, IL-1B test panel, 2-1/2-ft spacing.

Fig. 51. Presplit face at IL-3D test panel.

peaks. The first peak, 23 and 4.5 in./sec at 20 and 50 ft from the row, respectively, represents Charge F, and the last peak, 18 and 2.4 in./sec, represents Charge A. The velocity recorded at the 20-ft gage from Charge C of CS-2, 96 in./sec, was greater than the peak velocity of 75 in./

sec from the six simultaneously detonated CS-1 charges.

SEISMIC MEASUREMENTS

There was sufficient instrumentation available to record seismic vibrations at four locations during each detonation. All of the stations used triaxial arrays of velocity-sensitive geophones with natural frequencies of 1 Hz. Signals were recorded on an oscillograph and on pen recorders.

Locations of seismograph stations are shown in Fig. 53. Motions were recorded at the four stations identified as GM-3, GM-4, GM-5, and GM-6 for all of the main mounding detonations. The two stations labeled GM-1 and GM-2 were used only for the ILIR experiments. With the exception of GM-4, which was located on bedrock, all the stations were located in areas where the underlying material was soil.

Table 7 lists the observed peak particle velocities by component and the shot-to-station distance for each event. These tabulated values are considered to be accurate within 20%. From an inspection of Table 7, it is apparent that the peak particle velocity at a particular location occurred most often in the radial direction. The peak scaled velocities for 56 detonations, which include the ILIR series, are plotted in Fig. 54. A regression analysis of the data points results in the following equation:

$$V = 5.848 \times 10^3 R^{-2.11} Y^{0.70},$$

where:

Fig. 52. Peak particle velocity records and their integrals (displacement) for VS-1, CS-2, and ML-1.

V = peak particle velocity, in/sec
R = horizontal distance, blast center to seismograph, ft
Y = charge weight per delay, lb

This equation for peak particle velocity can be used to predict velocities for future detonations at the Lost Creek site.

The peak velocities from VS-1, VS-2, and VS-3 at any given range are consistent, indicating that the three different explosives used in these blasts were about equal in production of seismic vibrations.

The CS-1 and CS-2 blasts were identical except that CS-1 was detonated instan-

taneously while CS-2 was detonated with delays between the charges. An inspection of the values in Table 7 will show that the amplitudes generated by the delayed detonation were substantially lower than those from the simultaneous CS-1 detonation. It is apparent that the type of explosive is far less important than the manner in which charges are detonated in determining the level of seismic vibrations.

AIRBLAST MEASUREMENTS

Because of the large volume of collected data, only a brief summary of the airblast results from Project Lost Creek is presented in this section. Appendix F gives complete tabular and graphical compilations of the airblast results.

Figure 55 shows observed overpressure-time histories for some typical events. The airblast pulse in Fig. 55(a) was recorded at a range of 144 ft from ILIR-5, a single 200-lb mounding charge, and reveals a single well-defined ground-shock-induced peak, followed by a negative overpressure excursion and a positive return pulse of lower amplitude. Figure 55(b) shows the airblast pulse from ILIR-7, a 200-lb cratering shot, which produced an initial ground-shock-induced peak, followed by a gas-vent peak caused by a strong vent of the explosion gases. Airblast pulses observed 583 ft perpendicular to and 475 ft off the end of row VS-1 are shown in Figs. 55(c) and 55(d). These peaks are ground-shock-induced. Note the relatively long pulse duration perpendicular to the row, and the very long duration and smooth shape of the pulse off the end of the row.

Table 6. Close-in subsurface velocity data for mounding detonations.

Event	Gage location	Peak velocity, in/sec	Peak displacement, in.
VS-1	20 ft from row	144	0.42
	50 ft from row	38	0.22
VS-2	20 ft from row	96	0.32
	50 ft from row	15	0.17
VS-3	20 ft from row	132	0.24
	50 ft from row	23	0.23
CS-1	20 ft W of row	75	0.25
	50 ft W of row	19	0.16
CS-2	20 ft W of row	23 ^a	0.024
		28	0.028
		54	0.041
		96	0.11
		36	0.047
		18	0.04
	50 ft W of row	4.5 ^a	0.009
		3.6	0.009
		3.9	0.011
		4.3	0.011
		3.6	0.013
		2.4	0.007
	33 ft E of main row	7.0 ^b	0.006
			(0.029) ^c
		11	0.026
		23	0.086
		16 ^b	0.041
			(0.102) ^c
ML-1	46 ft E of main row	20 ^d	0.072
		23	0.014

^aSix peaks from six main charges (CS-2).

^bPresplit blast peak.

^cDouble peak on velocity record.

^dBuffer-zone blast peak.

Fig. 53. Location map of seismic vibration measurement stations.

Figure 56(a) shows the measured peak overpressures as a function of range from the blast for some of the ILIR single-charge events; overpressures recorded perpendicular to the VS simultaneous row charges are shown in Fig. 56(b). The overpressure level of $+0.065 \text{ lb/in.}^2$, which is a reasonable threshold for damage to average-size residential windows, is also indicated in these figures.

It may be noted in Fig. 56 that typical ΔP values exceeded 0.065 lb/in.^2 only at ranges very close to blast center ($R = 100$ to 700 ft). Ground shock is an overwhelmingly predominant damage effect at ranges this close to the explosive, and local missile throwout also presents a possible hazard. Thus, it is evident that airblast overpressures from deep mound-

ing events are comparatively small and do not normally constitute a limiting safety factor. This result is in agreement with preshot expectations.

In some cases observed overpressures were lower than the predictions. The CS-1 simultaneous row event produced peak overpressures only slightly higher than those seen for comparable ILIR single-charge detonations (the single charges were about 60 lb heavier than the individual charges in the CS rows). The low overpressures for CS-1 may have been partly caused by incomplete detonation; a noticeable "valley" in the middle of the positive-phase pulse seen off-the-end of the row would indicate a low-order detonation of charges near the row center. The overpressures for CS-2 were less than those for the single-charge events,

Table 7. Seismic vibration data.

Experiment	Total weight of explosive, lb	Range, ft	Peak particle velocity, in./sec			Remarks
			Radial	Vertical	Transverse	
VS-1	1505	1208	0.55	0.28	0.55	
		2375	0.047	0.035	0.035	
		5776	— ^a	0.013	0.022	
		7742	0.0076	— ^a	0.0056	
VS-2	1547	1306	0.43	0.19	0.28	
		2469	0.035	0.028	0.024	
		5853	0.016	0.0067	0.011	
		7852	0.0063	0.0020	0.0035	
VS-3	1477	1420	0.50	0.17	0.25	
		2575	0.043	0.028	0.031	
		5940	0.016	0.0083	0.017	
		7969	0.0063	0.002	0.0035	
CS-1	948	1030	0.45	0.23	0.33	
		2193	0.038	0.020	0.022	
		5579	0.0096	0.005	0.0063	
		7921	0.0043	0.0017	0.0030	
CS-2	948	1371	0.12	0.044	0.094	Six identical charges detonated individually at 25-msec intervals
		2528	0.0094	0.0071	0.0071	
		5896	0.0029	0.0014	0.0030	
		7921	0.0013	0.00041	0.00068	
ML-1	2726	1565	0.37	0.13	0.31	Firing: 286 lb at 0 msec, 578 lb at 50 msec, 1890 lb at 150 msec
		2678	0.031	0.017	0.024	
		5979	0.011	0.0065	0.017	
		8086	— ^b	0.0018	0.0034	
ML-2	2917	1546	0.43	0.11	0.30	Firing: 544 lb at 0 msec, 780 lb at 50 msec, 1659 lb at 150 msec.
		2661	0.024	0.024	0.026	
		5966	0.013	0.0040	0.0166	
		8069	0.0057	0.0015	0.0030	

^aRecord obscured by noise.^bEquipment malfunction.

demonstrating the efficacy of interchange delays in reducing airblast to single-charge levels. Overpressures measured off the end of the CS-2 row were higher than the perpendicular overpressure from the same row, primarily because airblast gages were located off the concluding end of the row (i.e., last charge detonated), causing the individual charge pulses to overlap and reinforce slightly.

Certain unexpected effects were discovered during the airblast investigation. For deeply buried events the airblast due to venting at presplit panels or from exposed detonating cord may exceed the airblast at close ranges from the main charges. Event ML-1 provided an example of significant presplit pulses. The high-frequency pulses from detonating cord appear to attenuate rapidly with

Fig. 54. Ground-surface seismic vibration measurements: scaled velocity vs range, for 56 recorded events at Project Lost Creek.

range and are difficult to separate from other airblast effects. It has been found that close-range overpressures may be reduced by covering the detonating cord

with soil or sand and by judicious choice of orientation.

Some of the unusual airblast effects are attributed to topographic irregularities near the detonation site. Double pulses observed at several gage stations were caused by reflections at the edge of a very steep ravine. Such reflections may grossly distort the pulse shape, affecting the measured positive-phase impulse and even the amplitude. Terrain irregularities also made it impossible to emplace gages exactly perpendicular to or off the end of the rows in several cases. Avoidance of extremely rough terrain whenever possible would simplify the interpretation of records and produce higher quality airblast data for future experiments. Local topographic features are expected to be much less important for large-scale events in which the array size is larger than the local irregularities.

The Lost Creek airblast study achieved its objectives and provided the data necessary for predicting airblast from deep mounding events. Some aspects related to close-range airblast from detonating-cord and presplit detonations require further investigation.

Fig. 55. Typical overpressure vs time histories for some Lost Creek events.

Fig. 56. Peak positive overpressures Δp as a function of range R from SGZ; typical single-charge (ILIR) and row-charge (VS) events.

Discussion of Results

This section discusses the experimental results and mounding in general. Specific topics, such as blasting results, fragmentation, and velocity gage records, are discussed first. More general topics, such as stress wave attenuation, measurement of rock distress, explosives, and design criteria for mounding excavations are discussed later in the section.

BLASTING RESULTS

One effect shown at Project Lost Creek was the insufficient bulking produced by detonation of a single 200-lb charge, buried at mounding depth, to allow the rock to be excavated. This was evidenced for two of the ILIR detonations and for the charges at the ends of the rows in ML-1, where the corners of the pit could not be dug out. This would probably not be the case for very large mounding charges, of the order of tons, where equipment would have better access to the broken rock. For sufficient bulking to allow the rock to be excavated, the reinforcing effect or enhancement of other charges in a row was required.

The scaled depths used at Project Lost Creek were substantially greater than any previously tested by EERL or NCG. An exception was Project Mini Mound⁷; but only one scaled depth of burial was used at Mini Mound, and the effect of variations in depth was not addressed. Previous EERL-NCG investigations have been concerned with depths in the cratering range, and such mounding as occurred was incidental.

Blasting results at Project Lost Creek confirmed the well-known fact that geologic conditions exert an intimate control over blasting results. Evidence for this included the dominance of columnar jointing over presplit fracturing at ML-2, the difficulty in producing a presplit face in the upper weathered fractured rock in the IL-1 and IL-2 area, and the superiority of blasting results in the west portion of ML-1, where firm rock was shallow, over those in the east portion, where overburden was present.

Formation of the ridge of unbroken rock between the two rows of ML-1 may have been abetted by the escape of some of the explosive energy from the main charges in the direction of the buffer zones. Examination of film of the ML-1 detonation, however, shows no visible evidence of venting from the main charges through the buffer zones. Such a phenomenon would probably have been accompanied by a directed-blasting effect, the rubble produced by the presplit and buffer zone detonations being thrust outward by the force of the main blast. The result of such an effect would be a concentration of mounded rubble at the sides of the experiment, in the direction of the presplit and buffer-zone panels. Little if any such directed blasting effect was noted at ML-1. It is more probable that the inter-row spacing of 1.7 R was too large. At ML-2, however, such a directed blasting effect may have contributed to the V-shaped configuration of rubble within the ML-1 trench. A better design might have put the ML-2 charges slightly deeper.

It is reasonable to suppose that cusping would be observed along the bottom of a mounding-row excavation between the individual charge locations, unless the charges were very close together. It was hoped that such an effect might be found in the VS excavations; however, the equipment available for excavation in these pits was not capable of sufficiently scouring the bottom to reveal such cusping. A track-mounted backhoe capable of going down into the pit, or a clamshell, would have enabled the examination of such an effect.

The well-formed presplit faces achieved at the IL-3 test panels with inclined drill holes reflected the firm rock at the site, the favorable geometry afforded by the inclined holes, and the buffer-zone arrays, which allowed the rock in front of the presplit faces to be excavated. The results of the IL-3 test panels showed that certain buffer-zone patterns, spacings, and loadings were compatible with preservation of a presplit face. They did not show what the configuration of an effective buffer zone should be for the purpose of stress wave attenuation. Furthermore, it is believed that buffer-zone test panels are futile by themselves; they involve subjective judgment as to how much fracturing or what kind of fracturing would act as a good buffer for attenuating the stress wave. Moreover, it is not known which parameter to control: stress, strain, particle velocity, displacement, or the venting of gases. The observation of fracturing at depth is a practical impossibility. Either the rock cannot be exposed, or if it is exposed, the act of exposing it is certain to disturb it. It would be desirable to conduct a program of calculations using

hydrodynamic codes describing stress wave propagation through rock to determine the desirable properties of a buffer zone.

Presplitting was successful along the west wall of ML-1. However, trimming was also successful in the firm fresh rock at IL-8 (see Appendix G), which was similar to the rock on the west side of ML-1. Trimming was unsuccessful along the side of VS-1; it can only be speculated how well presplitting might have done had it been attempted at that location. Presplitting was largely unsuccessful at shallow depths in the IL-1 test panels and at other sites where a surface layer of weathering along fractures was present, as it was at VS-1. In the author's judgment, the evidence from Project Lost Creek was too sparse to suggest with any degree of assurance whether trimming or presplitting offers a more promising way to construct final slopes in conjunction with mounding blasts.

The powder factor of the mounding-row detonations ranged from 0.51 to 1.02 lb/yd³ with an average of 0.82 — weighted with respect to total weights of explosive (see Table 5). The powder factor for conventional blasting at the NPP test quarry, as computed from data in Ref. 14, was approximately 1.10. Thus mounding at Project Lost Creek had a slightly lower powder consumption per cubic yard than the conventional blasting. The fragmentation was slightly coarser, however, as discussed below, so that the two effects tend to compensate each other.

CS SERIES — EVALUATION OF SEQUENTIAL DETONATION

Because of the failure of CS-1 to detonate properly and fully, no direct compar-

ison of dimensions, powder factor, shock, and seismic effects between CS-1 and CS-2 is possible. The evidence regarding the incomplete detonation of CS-1 included excavation experience, film records, close-in subsurface velocity records, and airblast records. All of these corroborate one another.

It is interesting to compare the close-in subsurface velocity records of CS-1 and CS-2 (see Table 6). At the close-in gage, the highest single particle velocity was recorded from the fourth Charge C of CS-2, one of the two charges closest to the gage. Had all six charges of CS-1 fired instantaneously and fully, certainly its close-in gage should have experienced a peak velocity at least equal to that from a single charge at CS-2. Apparently the four end charges (two end, two next-to-end) on CS-1 detonated normally, yet the combined effect of these was only 75 in./sec as against 96 in./sec from Charge C and 54 in./sec from Charge D of CS-2. This comparison shows that the closest charges to the gage exert an overriding effect in comparison with those further away. Notably, at the far-out gage, the peak velocity from CS-1 was four times greater than the velocity from any single CS-2 charge. The seismic vibrations generated by CS-1 were greater than those from CS-2 by a factor of two to three. Presumably, this difference would have been somewhat greater had all the charges in CS-1 detonated high-order.

In the absence of a direct comparison of the mounding effectiveness of the simultaneous and sequential modes of detonation, it may be remarked that the sequential mode produced very satisfac-

tory mounding results with demonstrably lower shock and seismic effects except at a range of 20 ft. Accordingly, use of the sequential mode may be judged acceptable, and probably desirable in any application in which seismic limitations play a prominent role.

FRAGMENTATION

As a comparison with the fragmentation produced by the mounding blast at Project Lost Creek, gradation curves representing rock from the test fill placed by NPP in 1967 are shown in Fig. 57. This rock came from the NPP test quarry between elevations 2500 and 2450. It had been blasted in a rectangular 10- X 12-ft pattern of 3½-in. blast holes loaded with 3 to 3½ lb of dynamite per foot and fired with several delays. It had been loaded, hauled by dump truck, dumped, spread by dozer in 2-ft lifts, each of which was compacted with two passes of a D-8 dozer. A total of three lifts were placed, to give a 6-ft embankment. This had then been trenched with a backhoe, and one truckload had been hauled to the North Pacific Division laboratory where these gradation curves were determined by sieving. The curves are steep, indicating poorly graded or well-sorted material. Median sizes ranged from 3 to 5 in.

The median size of the mounded rock from Project Lost Creek was 7 to 12 in. The median size of the rock from the NPP test fill was thus notably smaller than that of the mounded rubble. Some of this difference must be attributed to secondary breakage during handling of the test fill material; how much, however, is an open question.

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Fig. 57. Gradation curves for rock test fill material from NPP test quarry.

It is concluded that the fragmentation produced by mounding at Lost Creek was slightly coarser than that produced by conventional blasting. This conclusion is supported by the observation of comparatively fine, uniform breakage at the ML daylighting shot.

No differences in fragmentation were noted in the three explosives used at Project Lost Creek. The differences that were noted were attributable to the natural fracture pattern. A massive rock bed was noted at CS-1, and the fragments there were coarser than elsewhere. The great bulk of the mounded rubble was composed of block sizes consistent with the fracture patterns observed when the 10-in.-diameter explosive emplacement

holes were visually logged. Differences in fragmentation were also attributable to proximity to an explosive charge. For example, finer fragmentation was noted and documented near Charge D of VS-1. The finer fragmentation observed at the ML daylighting shot was associated with distribution of explosives within the rock and with the high powder factor (about three times that of ML-1).

At several places, sizable blocks were noted after the mounding blasts, but the blocks showed incipient cracks, as shown in Fig. 35. When moved by the bulldozer, these blocks readily broke into smaller fragments. This experience contrasted with the experience at Project Mini-Mound (Ref. 7, p. 58; also personal observations

by the author), where large blocks of massive sandstone produced by mounding blasts tenaciously remained intact even though handled many times by the bulldozer.

The purpose for which rock fragmentation is desired must, of course, be kept in mind. Mounding as practiced at Project Lost Creek proved to be eminently successful for the purpose of producing rock fill at the Lost Creek quarry site. Probably this would be the case in other appropriately jointed or fractured rock. In a massive unfractured rock, however, mounding with concentrated explosive charges might well produce many large boulders that might be unacceptable for their intended use. In such an event, it might be required that the blasting system be modified to include satellite holes, decking charges, or both.

Mention may be made of the practical difficulties involved in getting a valid size distribution by the point-counting method. The method is believed to be a valid substitute for a screen and sieve analysis, provided the rubble surface sampled is truly representative of the deposit as a whole. This latter constraint is of vital importance. It had been planned at Project Lost Creek to make point counts at strategic locations during the excavation process as the mounds were removed and the subsurface rubble dug away. Thus details of fragmentation at different places in the experiments could be monitored. This monitoring was not done because of the use of the bulldozer as the principal tool for excavation at Lost Creek. The dozer blade and tracks produce secondary breakage. The dozer also tends to slur

over the surface of the rubble, introducing a certain amount of fine blocks and particles. The gradations referred to in this report represent samples of rubble in which this slurring and comminuting effect of the bulldozer was not present, or was present in what was judged to be a minor degree.

VELOCITY GAGE RECORDS

The ILIR program showed that where there was a presplit panel between the main charge and the gages, the presplit detonation itself generated higher amplitudes than the main charge at both the near and far gages. Attenuation of peak velocities from the main charge by a buffer zone, over and above that resulting from the presence of a presplit panel, was not demonstrated. There were no observable differences in the effects of the different buffer-zone patterns. There was scatter in the data, the sample was small, and the gages were so placed that a portion of the stress wave could bypass the buffer zone; however, the existing data (horizontal velocity in the radial direction) did not demonstrate the effectiveness of a buffer zone over and above that produced by a presplit plane in significantly reducing the stress wave amplitude from the main charge.

The rock immediately beyond the controlled blasting panels was subjected to higher particle velocities by the panels themselves than by a single main charge. The question should be considered whether this would be the case for a row of charges. The ML-1 experiment did measure particle velocities from a row-charge with a presplit panel and buffer

zone between the row and the gages. However, the gages were placed at a 20-ft depth, while the average main-charge depth was 13.5 ft and the bottoms of the presplit and buffer zone panels were between 13 and 14 ft deep. The gages could not be placed at a shallower depth because of overburden and rock conditions. It is probable that the gages received the stress wave directly from the main charges with little or no attenuation by the controlled blasting panels. Therefore, the ML-1 data shown in Table 6 do not answer the above question.

The close-in subsurface velocity records from the two CS mounding rows have already been discussed. As mentioned, the peak velocity at a very close-in gage is probably caused by the charges closest to the gage. For gages farther out, more superposition occurs so that at some distance all the individual charges in a row contribute substantially to the measured effect.

The highest particle velocities from row charges were recorded at the VS series, which had the greatest total charge weights. The peak velocities recorded from VS-3 at both the 20-ft and 50-ft gages were higher than their respective counterparts from VS-2 but lower than those of VS-1. The mound and excavation size of both VS-1 and VS-2, of course, greatly exceeded that of VS-3. This is an interesting anomaly the significance of which is not understood. A detailed study of the close-in subsurface velocity data from the various mounding-row experiments, in terms of scaled distances, different explosives, and other possible factors, is beyond the scope of this report.

BOREHOLE PHOTOGRAPHY

The results of the borehole photography program were disappointing. On the film records it was very difficult to see very fine cracks, which would represent newly formed blasting fractures. The borehole photography results confirm the results of the water-pressure-testing program, discussed below, which show blast-induced fracturing to be limited generally to the upper portions of the rock. Because of the cost of the program and the disappointing results, borehole photography is not recommended for future investigations of this sort.

PERMEABILITY TESTING

The permeability testing resulted in a qualitative picture of the blast-induced fracturing. It did not, however, reveal precise boundaries of increased permeability zones, nor did it allow exact comparisons of given hole intervals before and after blasting. Greater precision than was achieved could have been attained by more painstaking repositionings of the packer and retestings to obtain equal flow rates. It is questionable how much of the extra effort would have been warranted. For purposes of these simple tests, the single-packer system employed was quite adequate. A double-packer system, as is commonly used to isolate sections of a borehole, would have been more cumbersome to use, and it is believed that little additional information would have been obtained.

For future tests of this sort, it is suggested that a gravity-feed, constant-head system be tried. Such a system would be

cheaper and simpler, and could be used without a pump. Flows would be smaller, but by careful water quantity measurements, good accuracy should be attainable. More accurate knowledge of the operating head would be a desirable feature. The throttling system used to maintain a constant delivery pressure in the pumped system was crude and subject to error.

STRESS AND DAMAGE MEASUREMENT

The objective of the subsurface velocity measurement program was to quantify one of the parameters associated with damage to rock. Increased permeability was used as an indicator of damage. The subject of what constitutes damage or distress to the rock is a difficult one. The ultimate criterion for an excavated slope is whether the slope will be stable after its excavation. The stability of slopes is a complex subject in its own right, well beyond the scope of this report.

In addition to the methods used to observe blast-induced damage at Project Lost Creek, certain other possibilities may be mentioned. Preshot and postshot core drilling in the region of interest close behind the presplit face could be performed, and comparisons made between the condition of the core with regard to fracturing. When a presplit face has been excavated, as at the ML experiment, horizontal coring into the face, carried far enough back in to assure a sampling of virgin rock, might show a progressive decrease in fracturing. The preshot fracture condition would have to be determined, of course,

from vertical boreholes. In-situ methods of rock testing, such as jacking, might show differences in rock strength or elasticity that could be correlated with blasting damage.

EXPLOSIVES

The reasons for using three blasting agents at Project Lost Creek were mentioned earlier in this report, as was the fact that the slurry blasting agents actually delivered did not meet the desired specifications.

In terms of fragmentation, no difference could be ascribed to the three blasting agents used at Project Lost Creek. In terms of mound size and amount of rock broken, ANFO was clearly the best of the three blasting agents and Slurry B the worst. This ranking, established by the results of the VS series, was confirmed by the single-charge IL-9 detonations (see Appendix G). In future mounding detonations in this medium, therefore, ANFO would have to be preferred over either of the two slurries used here.

It would be desirable to know the properties of the three explosives contributing to their relative performance. Regrettably, the Lost Creek results throw little light on the question. An examination of the properties of the three explosives shown in Table 3 shows no correlation whatever with observed performance, with the exception that the least effective explosive, Slurry B, had the lowest detonation velocity. Results of this project are not, therefore, generally applicable to specifying explosives for mounding.

MOUNDING-ROW DESIGN

The method by which the ML-1 double-mounding-row excavation was designed has been described. To recapitulate, the procedure consisted of the following steps (refer to Fig. 58 for dimensional quantities):

(1) Select the width of the excavation:
 $L = 78$ ft.

(2) Select in-row charge spacing:
 $S = 18$ ft.

(3) Select buffer-zone widths: $B_1 = 4$ ft, $B_2 = 7$ ft.

(4) Choose W_t , the true crater width, on the basis of the portion of the VS-1 pit that was judged to have had the optimum spacing (near Charge D). At this location $k = 5.1$ and $W_t = 2.8$ DOB.

(5) Select $M = 0.85 W_t$, the row-separation distance.

(6) Determine lateral dimensions:
 $L = 78$ ft $= B_1 + 0.5 W_t + M + 0.5 W_t + B_2$
 $= (B_1 + B_2) + 1.85 W_t$

$$78 = 11 + 1.85 W_t;$$

so that $W_t = 67/1.85 \approx 36$ ft and $M = 0.85 W_t \approx 31$ ft.

(7) Determine DOB:

$$\text{DOB} = \frac{W_t}{2.8} = \frac{36}{2.8}$$

Fig. 58. General layout of first lift of ML-1.

13 ft (13.5 ft was actually used).

(8) Select Y:

$$\text{DOB} = k \sqrt{\frac{Y}{S}}$$

$$13.5 = 5.1 \sqrt{\frac{Y}{18}}$$

$$Y = 125 \text{ lb.}$$

The key steps in this design procedure were the selection of the relation $W_t = 2.8$ DOB from VS-1 (step 4), and the selection of M as $0.85 W_t$ (step 5).

In retrospect, because of the mound of material left in the center of the ML-1 excavation, a smaller row separation, M , in terms of W_t , is deemed appropriate, and judgment suggests that $M = 0.7 W_t$ would be better than $M = 0.85 W_t$.

Examination of the geometry of the VS-2 excavation, and specifically of the relation between W_t and DOB at the optimum section (see Fig. 19) shows that:

$$W_t = 2.4 \text{ DOB.}$$

Similarly for VS-3 (Fig. 21):

$$W_t = 1.6 \text{ DOB.}$$

Considering all three VS rows, it appears that the true-crater width varied from a maximum of:

$$W_t = 2.8 \text{ DOB in VS-1,}$$

to a minimum of:

$$W_t = 1.6 \text{ DOB in VS-3.}$$

Therefore, the corresponding ML-1 row-separations for the above range of W_t would be:

$$M = 0.7 W_t = 0.7 \times 2.8 \text{ DOB} = 0.7 \\ \times 2.8 \times 13 = 25.5 \text{ ft using VS-1,}$$

to

$$M = 0.7 W_t = 0.7 \times 1.6 \text{ DOB} = 0.7 \\ \times 1.6 \times 13 = 14.5 \text{ ft using VS-3.}$$

In comparison, the actual row separation used in ML-1 was:

$$M = 0.85 W_t = 0.85 \times 2.8 \text{ DOB} = 0.85 \\ \times 2.8 \times 13 = 31 \text{ ft.}$$

In retrospect, M was too large in ML-1 and probably should have been about 25 ft.

For a future design, the following step-by-step procedures are recommended. The following equations, in addition to those already stated, will be used (refer to Fig. 58 for dimensional quantities):

$$W_t = f \times \text{DOB},$$

where f is a factor between 1.6 (VS-3) and 2.8 (VS-1);

$$L = 2B + W_t + (N-1) M,$$

where N is the number of rows and B is the width of a controlled blasting zone.

(1) Determine required width of excavation.

(2) Select lift height, H.

(3) Select the width of the zone at either side of the excavation, B, that will accommodate side slopes and/or controlled blasting.

(4) Set depth of burial of mounding charges, DOB, equal to H.

(5) Determine W_t and the factor f, which should be between 1.6 and 2.8 in accordance with the results of the VS series. The f may be determined by executing a series of VS-type experimental rows, or an average f value of 2.2 may be used.

(6) Determine the row separation, M, from the relation:

$$M = 0.7 W_t \\ (\text{or } M = 0.7 \times f \times \text{DOB}).$$

(7) Select the number of rows. Refer to Fig. 59; use the following relation and adjust N to the nearest integer value:

$$N = \frac{L - 2B - W_t}{M} + 1.$$

(8) Adjust dimensions to conform to the integer value of N.

(9) Determine the factor k for use in the relation $\text{DOB} = k (Y/S)^{1/2}$; this may be done by executing a series of VS-type experimental rows, or, an average value of 5.1 may be used.

Fig. 59. Generalized layout for multiple-row, multiple-lift excavation.

(10) When the above relation (step 9), is used, with DOB and K known, S and Y can be solved for in terms of one another; construct a table of compatible S and Y values.

(11) It will probably be convenient to select Y, from considerations such as seismic limitations on charge size or available drill diameters; having selected Y, select the compatible value of S.

(12) The constraint must be observed that S be not too great relative to other dimensions as to produce a cusped, rather than a smooth, excavation. The following limitation should be observed:

$$S \leq 0.7 W_t$$

A numerical example of this procedure is given below:

Let the following dimensions apply:

$$L = 78 \text{ ft}$$

$$B = 5 \text{ ft}$$

$$H = 18 \text{ ft}$$

The step-by-step procedure is as follows:

$$(1) L = 78 \text{ ft.}$$

$$(2) H = 18 \text{ ft}$$

$$(3) B = 5 \text{ ft.}$$

$$(4) \text{DOB} = H = 18 \text{ ft.}$$

$$(5) f = 2.2 \text{ (assumed); } W_t = f \times \text{DOB} = 39.6 \text{ ft.}$$

$$(6) M = 0.7 W_t = 27.7 \text{ ft.}$$

$$(7) N = \frac{78 - (2 \times 5) - 39.6}{27.7} + 1 = 2.03, \text{ say } N = 2.$$

$$(8) M = \frac{L - 2B - W_t}{N - 1} = 28.4 \text{ ft.}$$

$$(9) k = 5.1 \text{ (assumed).}$$

(10) $18 = 5.1 \sqrt{Y/S}$; therefore the following values of Y and S are compatible:

<u>Y</u>	<u>S</u>
50	4.0
100	8.0
150	12.0
200	16.0
250	20.0
300	24.0
350	28.1

(11) A suitable charge size for 10-in. diameter holes is $Y = 200 \text{ lb}$; spacing therefore will be $S = 16 \text{ ft}$.

(12) Since S is not greater than $0.7 W_t = 27.7 \text{ ft}$, the constraint of step 12 is not violated.

Our design parameters are then as follows, in summary:

Charge weight = 200 lb

Depth of burial = 18.0 ft

Charge spacing = 16 ft

Row separation = 28.4 ft

No. of rows = 2

This design procedure has been developed empirically on the basis of experience at Project Lost Creek. A quasi-analytical approach to mounding-row design is given in Appendix D. The two procedures give approximately equal design parameters. Both, for instance, would design the 14-ft-deep ML-1 cut, if it were to be excavated anew, with three rather than two mounding rows. The empirical method is somewhat simpler to use; however, either an assumed k would have to be used or a VS-type mounding test row would have to be blasted at a new site. The method outlined in Appendix D is based on single-charge parameters; consequently, it is theoretically possible to compute the appropriate value of k for a new explosive and rock combination, by

a series of single-charge mounding calibration shots.

The use of the quantity "DOB" in designing blasts implies the use of relatively compact charges (values of L/D ratio below some upper limit). The L/D ratios of the mounding charges at Project Lost Creek are given in Appendix B. Most mounding charges had L/D ratios between 3 and 9, four were greater than 9, and two were greater than 10. The above design procedure should be used only with caution or not until specific testing is accomplished if L/D ratios greater than about 10 are involved.

In some situations the design of mounding blasts may be governed by seismic limitations. A millisecond-delay mode of detonation may be employed when necessary to stay within prescribed blast-effect limits. The seismic effects of blasting are discussed in detail in Ref. 18.

EVALUATION OF MOUNDING AS A BLASTING SYSTEM

The distinction between mounding as tested at Lost Creek and conventional blasting consists of two factors. First,

for the major tests at Lost Creek, the L/D ratio ranged between 3 and 13, while for conventional blasting it is generally 40 to 80 or more. Second, in mounding, the free face toward which breakage is induced is the horizontal ground surface, while in conventional blasting, it is the vertical or inclined edge of a bench.

The results of the ML experiment prove that mounding is indeed a technically feasible system for use in producing a structural excavation, if used in conjunction with controlled blasting to control the side slopes. Whether mounding offers significant advantages over conventional blasting practice cannot be stated at this point.

Fundamental to this question is the matter of cost. It is assumed that overall drilling and blasting costs will diminish with increasing hole and charge size. It has not been considered meaningful to analyze cost data from Project Lost Creek, because the project was experimental in nature and on a small scale, and also because the contractor worked on an equipment-hire basis, which is not a common type of construction contract.

Summary and Conclusions

A program of blasting experiments was carried out in the basaltic andesite rock at Project Lost Creek to investigate the concept of mounding and to examine the effectiveness of controlled-blasting techniques. This program comprised three main series, the VS, CS, and ML series, and several supplementary experiments. Several technical programs

were carried out in conjunction with the test blasts. Principal objectives of the program were:

- (1) Defining design criteria for mounding detonations.
- (2) Examining the fragmentation achieved by mounding blasts.
- (3) Comparing the mounding effectiveness of three different explosives.

(4) Examining the effectiveness of certain controlled blasting techniques for stress wave reduction.

(5) Testing the suitability of mounding as a blasting system for producing rock fill.

Design criteria arrived at are summarized in three equations relating charge depth for individual mounding charges, DOB, charge weight, Y , in-row spacing, S , row separation distance, M , and mounding-row excavation width, W_t :

$$\begin{aligned}W_t &= 2.8 \text{ DOB (for VS-1)} \\ \text{DOB} &= k (Y/S)^{1/2} \\ M &= 0.7 W_t.\end{aligned}$$

Further testing or experience will be required to ascertain the applicability of the design equations to other geological media than that of the Project Lost Creek test site.

The basaltic andesite at the Lost Creek site broke when blasted by mounding charges to give relatively uniform small block sizes with a median diameter of 7 to 12 in. and few blocks greater than 2 ft in size. The fragmentation was determined primarily by the prevailing natural fracture pattern. There were suggestive, though not conclusive, indications that mounding gives slightly coarser fragmentation than conventional blasting in the same material.

Of the three mounding explosives tested, ANFO proved to be the most effective, and Slurry B the least effective, in terms of total amount of rock broken. No correlation could be drawn between mounding performance and known properties of the explosives. Slurry B, the least effective mounding explosive,

resulted in higher close-in subsurface peak velocity measurements than Slurry A, for reasons that are not clear. Program objectives regarding evaluation of explosives were not met, inasmuch as the two slurry explosives delivered by the site contractor did not have the explosive properties specified by EERL. It is believed that, if explosives with the specified properties had been supplied, they would have performed considerably better than those used.

The limited data from the project¹ indicate that controlled blasting panels do exert an attenuating effect on subsurface horizontal peak velocity close to a mounding blast. The buffer-zone measurements in this experiment did not show an additional reduction beyond that exerted by the presplit plane. The sparsity and scatter of the data and less-than-optimum gage placement indicate that further investigation is warranted.

Mounding blasts with L/D ratios between 3 and 13 were shown to produce satisfactory rock fill at the Lost Creek quarry site. It is judged that similar results could be expected in other prefractured rock, but that the technique needs to be tested further in a massive and unfractured formation. Changes in the design procedures might be necessary to accommodate larger L/D ratios, decking of charges, or satellite holes to achieve satisfactory fragmentation.

Ground-surface seismic motions recorded during Project Lost Creek were within the range of predictions made before the project. Differences in seismic motions that could reliably be correlated with presence or absence of controlled-blasting panels surrounding a

mounding blast were not observed.

The airblast results proved the efficacy of the system for monitoring airblast overpressures of low amplitude.

Before-and-after permeability testing gave a simple measure of rock fracturing due to blasting. A similar but even simpler test using gravity flow rather than pumping is suggested for future trial.

A mounding-row test with a sequential mode of detonation of the mounding charges gave satisfactory results in terms of degree and quantity of rock breakage, and produced lower intermediate-range ground-surface seismic-vibration effects than a comparable row detonated instantaneously. A direct comparison in terms of quantity of broken rock between the two modes of detonation was not pos-

sible because of low-order detonation of some of the charges in the instantaneous row.

The results of a few trimming tests carried out during the project varied with site geology and rock history (i.e., whether the rock had been subject to nearby prior mounding blasting). It was not possible to judge whether presplitting or trimming offers a better means of producing a final slope in a mounding excavation. However, presplitting was successfully used in the ML-1 and ML-2 experiments.

Finally, successful completion of the two-lift ML structural excavation demonstrated that mounding, in conjunction with presplitting and buffer zones, does offer a technically feasible means of producing a structural excavation.

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Appendix A

Project Organization

AGENCIES AND PERSONNEL:

(1) R. L. LaFrenz, LTC, USA	(15) E. Breckel, A. Breckel
(2) W.C. Day, Deputy Director (Civil)	(16) W. Stocker, Technician, Geology Section
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(5) G. E. Lakeman, SP5, USA	P. M. Spencer, Technician
(6) J. Isaacson, Construction Representative, NPP	Instrumentation Services Division, WES
(7) T. D. Jangula, SP4, USA	(19) J. D. Day, Section Chief
J. E. Shaler, SP4, USA	T. P. Williams, Technician
(8) R. E. Martin, Area Engineer,	Weapons Effects Laboratory, WES
Rogue River, USCE-NPP	B. B. Redpath, Geophysicist
(9) Oregon Crane Service, Medford, Oregon.	(20) J. D. Dishon, SP4, USA
Field Superintendent: C. A. Lanfear	(21) J. D. Dishon
(10) C. C. McAneny, Geologist	(22) T. M. Tami, Physicist
(11) J. E. Sagen & B. Hann, Party Chiefs, NPP	E. D. Allen, SP5, USA
(12) WAC Corporation, Eugene, Oregon;	(23) C. M. Snell, Physicist
Under contract to NPP	H. A. Washburn, SP4, USA
(13) Photogrammetry Section, NPP	
(14) E. Breckel, Driller, NPP	
A. Breckel, Driller, NPP	
B. W. Henderson, Geologist, NPP	
W. N. White, Geologist, NPP	

Fig. A1. Organization and personnel, Project Lost Creek.

Appendix B

Charge Configurations

Table B1. Charge configurations – Project Lost Creek.

Experiment	No. of charges	Charge weight, lb	Mean L/D ratio	Explosive(s)	Depth (avg), ft	Scaled depth	
						ft/lb ^{1/2}	ft/lb ^{1/3}
VS-1	7	215	8.2	200 lb ANFO 15 lb boosters	17.7	1.20	2.96
VS-2	7	221	5.2	210 lb Slurry A 11 lb boosters	17.9	1.20	2.96
VS-3	7	211	5.8	200 lb Slurry B 11 lb boosters	17.8	1.22	2.99
CS-1	6	158	3.9	150 lb Slurry A 8 lb boosters	15.6	1.24	2.89
CS-2	6	158	3.7	150 lb Slurry A 8 lb boosters	15.6	1.24	2.89
ML-1	14	135	5.4	125 lb ANFO 10 lb boosters	13.5	1.16	2.63
ML-2 A-F	10	315	8.6	300 lb ANFO 15 lb boosters	17.3	0.98	2.54
G-K		161	3.2	150 lb ANFO 11 lb boosters	14.9	1.17	2.74
IL-4M	1	221	5.3	210 lb Slurry A 11 lb boosters	17.8	1.19	2.94
IL-5M	1	221	5.3	210 lb Slurry A 11 lb boosters	17.8	1.19	2.94
IL-7	1	200	17.1	(five 40-lb cratering charges)	17.8	1.25	3.04

Appendix C

Laboratory Testing of Rock Drill-Core Specimens

Specimens of basaltic andesite rock from eight NX core borings, holes Q-35 through Q-42, were tested by the North Pacific Division Laboratory (NPD), Corps of Engineers, Troutdale, Oregon. The properties tested, and the test results, are listed in Tables C1 and C2. The hole locations are listed in Table C3. Core from a ninth hole, Q-43, which was located out of the blasting area and was of a different rock (a vesicular andesite), was tested for moisture content only. Hole depths ranged from 25 to 40 ft.

Test specimens were selected to represent sound and stained rock. Sound rock was regarded as that which was intact, generally unweathered, and with or without visible healed fractures. Stained rock was that which was weathered with or without visible incipient fracture. Because of the weathered and fractured nature of the rock, difficulty was experienced in getting the desired number of sound core specimens. Some specimens selected as "sound" showed internal unhealed or altered fractures after test, and therefore were reclassified as stained. As a result the desired number of sound core specimens was not obtained for balanced representation for all holes.

Test procedures are summarized below.

(1) Specific Gravity, Absorption, and Porosity. Specimens were oven-dried at 105°C for 24 hr, soaked for 7 days, weighed saturated-surface-dry and in water, dried for 7 days at 105°C, and

weighed. The method of determining the specific gravity and absorption is essentially ASTM-C 127. The method for determining porosity was that outlined in Ref. C1. Basically, the porosity was computed by dividing the absorbed water by the external volume of the specimen.

(2) Moisture Content. Specimens were weighed before and after oven-drying to a constant weight at 105°C. In the case of the waxed specimens, the cores were weighed immediately after removal of the wax.

(3) Unconfined Compressive Strength, Static Modulus of Elasticity, and Poisson's Ratio. Specimens were prepared and tested in accordance with ASTM-C 2938-71, Standard Method of Test for Unconfined Compressive Strength of Rock Core Specimens. Specimen end surfaces were ground to the required planeness tolerance by means of a metal lathe equipped with a milling-grinding attachment. Tests were made in a 440,000 lb capacity BLH hydraulic testing machine fitted with false platens as required by the test method. Load was applied at the rate of 25 to 50 lb/in.²/sec for the weaker to higher strength rock, respectively.

Static moduli and Poisson's ratios were computed from the tangential strains at approximately 40% of the ultimate stress. The strain was measured by means of SR-4, Type A-1 electric resistance strain gages bonded in pairs at mid-height on diametrically opposite sides, one pair parallel to and the other normal to the vertical axis.

Table C1. Test results for sound NX drill core specimens from EERL test blasting program, Lost Creek quarry.^a

Core drill hole No.	Depth, ft	Natural water content, %						Mois- ture ^c content at test, %	Static tests				Dynamic tests			Scratch ^d hardness	Remarks
			Specific gravity			Absorp- tion, %	Po- rosity, %		Com- pressive strength, lb/in. ²	Modulus of elastic- ity, E _s × 10 ⁻⁶ lb/ in. ²	Pois- sons ratio	Tensile strength, lb/in. ²	Modulus of elastic- ity, E _{dyn} × 10 ⁻⁶ lb/ in. ²	Longi- tudinal velocity, V1 × ft/ sec			
			Bulk dry	Bulk SSD	Appar- ent												
Q-35	8.4-8.8	—	—	—	—	—	—	0.5	36,800	8.58	0.25	—	—	—	(1)	Shear cone at 70 deg from horizontal	
	11.6-12.0	—	2.64	2.66	2.69	0.6	1.69	—	—	—	—	—	—	—	—	—	
	17.4-18.0	0.6	—	—	—	—	—	0.3	37,300	7.90	0.25	—	—	—	(1)	Shear cone at 70 deg from horizontal	
	22.0-23.8	—	2.62	2.65	2.70	1.1	2.87	—	—	—	—	—	—	—	—	—	
Q-36	7.7-8.1	—	—	—	—	—	—	0.2	35,600	8.71	0.26	—	—	—	(2)	Shear cone at 70 deg from horizontal	
	18.3-19.3	0.7	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
	22.5-23.5	—	2.63	2.65	2.69	0.8	2.17	—	—	—	—	—	—	—	—	—	
Q-37	9.5-10.2	—	2.62	2.54	2.69	1.0	2.60	—	—	—	—	1945	9.66	17,650	(2)	—	
	16.4-17.0	0.6	—	—	—	—	—	0.4	32,840	8.57	0.23	—	—	—	(1)	Shear cone at 73 deg from horizontal	
	24.1-24.9	0.8	—	—	—	—	—	—	—	—	—	1410	9.30	17,320	(1)	—	
Q-38	9.0-10.0	—	2.62	2.65	2.69	1.0	2.50	—	—	—	—	—	—	—	—	—	
	10.9-11.6	1.1	—	—	—	—	—	—	22,590	8.20	0.21	—	—	—	—	Shear cone at 63 deg from horizontal	
	19.5-20.5	—	2.61	2.64	2.70	1.2	3.23	—	—	—	—	—	—	—	—	—	
	23.0-24.0	—	—	—	—	—	—	—	—	—	—	1335	9.55	17,770	(1)	—	
Q-39	5.0-5.6	—	—	—	—	—	—	0.3	—	—	—	—	8.78	17,010	—	—	
	9.5-10.1	—	2.60	2.64	2.70	1.5	3.95	—	—	—	—	—	—	—	—	—	
	10.4-11.2	0.6	—	—	—	—	—	0.4	34,030	8.61	0.24	—	—	—	(1)	Shear cone at 70 deg from horizontal	
	17.3-17.8	0.7	—	—	—	—	—	—	28,560	8.55	0.24	—	—	—	(1)	Shear cone at 74 deg from horizontal	
	18.3-19.5	—	2.64	2.66	2.70	0.8	2.00	—	—	—	—	—	—	—	—	—	
	23.0-24.0	—	—	—	—	—	—	—	—	—	—	—	9.53	17,720	—	—	
	24.0-25.0	—	—	—	—	—	—	—	—	—	—	630	9.47	17,660	(1)	—	
Q-40	11.2-12.3	1.1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
	14.6-15.1	—	—	—	—	—	—	0.3	30,000	7.36	0.22	—	—	—	(1)	Shear cone at 72 deg from horizontal	
	23.0-24.0	—	2.64	2.66	2.70	0.8	2.09	—	—	—	—	—	—	—	—	—	
Q-41	10.3-11.3	—	2.66	2.68	2.71	0.7	1.86	—	—	—	—	—	—	—	—	—	
	19.3-19.8	—	—	—	—	—	—	0.4	—	—	—	—	10.75	18,890	(1)	—	
	28.0-29.0	—	2.65	2.67	2.71	0.8	2.03	—	—	—	—	—	—	—	—	—	
Q-42	11.0-12.0	—	—	—	—	—	—	—	—	—	—	1740	10.08	18,400	—	—	
	14.5-15.2	—	—	—	—	—	—	—	—	—	—	2005-1210 ^e	7.03	15,290	(1)-(2)	—	
	18.8-19.7	—	—	—	—	—	—	—	—	—	—	—	9.95	17,710	—	—	
	22.0-23.0	—	2.63	2.65	2.69	0.9	2.35	—	—	—	—	—	—	—	—	—	
	24.3-25.0	0.7	—	—	—	—	—	0.4	34,050	8.86	0.24	—	—	—	—	Shear cone at 72 deg from horizontal	
Average		0.8	2.63	2.65	2.70	0.9	2.45	0.3	32,420	8.37	0.24	1470	9.41	17,550			

^aSound core specimens include rock with and without visible healed fractures.^bNatural water content obtained from waxed core specimens.^cMoisture content obtained from specimens after test.^dScratch hardness test rated as follows: (1) Cannot be scratched with common pen knife, (2) can be scratched with great difficulty with pen knife.^eCore specimen tested twice: first break occurred in lighter brown rock near end (1210 lb/in.²), second break occurred in darker rock near center.

Table C2. Test results for stained NX drill core specimens from EERL test blasting program, Lost Creek quarry.^a

Core drill hole No.	Depth ft	Natural water content, %							Static tests				Dynamic tests		Scratch ^d hardness	Remarks	
			Specific gravity			Absorp- tion, %	Po- rosity, %	Water content at test, %	Com- pressive strength, lb/in. ²	Modulus of elastic- ity, Es × 10 ⁻⁶ lb/ in. ²	Pois- son's ratio	Tensile strength lb/in. ²	Modulus of elastic- ity, Edyn × 10 ⁻⁶ lb/ in. ²	Longi- tudinal velocity, V _l × ft/ sec			
			Bulk dry	Bulk SSD	Appar- ent												
Q-35	0. -1.0 5.7-6.2	— —	2.56 —	2.61 —	2.70 —	2.1 —	5.29 —	— 0.5	— 21,720	— 7.34	— 0.14	— —	— —	— —	— —	(1)	Shear along healed joint 50 deg from horizontal- vertical splitting. ^f
	11.6-12.0	—	—	—	—	—	—	0.3	—	—	—	—	4.48	13,230	(1)		
	13.0-14.0	—	—	—	—	—	—	0.2	—	—	—	—	7.01	15,890	—		
	14.0-15.0	—	—	—	—	—	—	0.4	—	—	—	240	5.18	13,230	—		
Q-36	2.0-3.0 7.0-7.5 18.3-19.3	— 0.5	2.56 — —	2.61 — —	2.71 — —	2.2 — —	5.53 — —	— — 0.3	— — —	— — —	— — —	— — —	— — 6.15	— — 14,530	— — —	—	
	21.5-22.5	—	—	—	—	—	—	0.3	—	—	—	—	8.53	17,110	—		
	22.5-23.5	—	—	—	—	—	—	0.2	—	—	—	—	9.02	17,730	—		
Q-37	2.1-3.6 3.4-4.0	— —	2.52 —	2.58 —	2.68 —	2.4 —	6.02 —	— —	— 16,520	— 9.20	— 0.24	— —	— —	— —	— —	(2)	Shear at altered joint 63 deg from horizontal. ^f Shear at altered soft, tan joint, 45 deg from hori- zontal.
	6.4-7.0	—	—	—	—	—	—	—	16,170	8.03	0.45	—	—	—	(2)		
	15.0-16.0	—	—	—	—	—	—	0.4	—	—	—	380	9.24	17,260	—		
	23.3-23.9	1.1	—	—	—	—	—	—	—	—	—	—	—	—	—		
Q-38	5.3-6.0	—	—	—	—	—	—	0.5	18,310	9.06	0.26	—	8.91	17,620	(1)	Shear at altered soft, tan joint 70 deg from hori- zontal.	
	15.0-16.0 17.7-18.3	— 1.5	2.52 —	2.58 —	2.69 —	2.4 —	6.17 —	— —	^e 2,260	— —	— —	— —	— —	— —	— —		—
Q-39	1.1-2.8 8.0-8.9	— —	2.63 —	2.66 —	2.71 —	1.1 —	2.85 —	— 0.3	— —	— —	— —	— —	5.34	13,260	—	—	
Q-40	8.5-9.5 9.9-10.5 12.6-13.4	— — —	2.57 — —	2.62 — —	2.69 — —	1.7 — —	4.48 — —	— 0.3 0.3	— — 11,000	— — 2.65	— — 0.07	— — —	— — —	— — —	— — —	(1)	Shear along dark brown altered joint 70 deg from horizontal Shear at altered joint 74 deg from horizontal.
	17.2-18.1	0.9	—	—	—	—	—	—	22,740	8.58	0.22	—	—	—	(2)		
Q-41	11.8-12.3	—	—	—	—	—	—	—	18,390	9.38	0.23	—	—	—	(1)	Vertical splitting — shear healed joint at 60 deg from horizontal. ^f Shear at altered soft, tan joint, 77 deg from hori- zontal.	
	18.2-19.3	0.9	—	—	—	—	—	—	11,650	5.56	0.12	—	—	—	(1)		
	23.1-23.9 32.0-33.0 36.0-36.8	0.7 — 0.7	— — —	— — —	— — —	— — —	— — —	— 0.3 0.4	— — 17,160	— — 9.57	— — 0.24	— — —	— 7.51 —	— 15,730 —	— — —	(2)	Shear along joint 45 deg from horizontal. ^f
Average		0.9	2.56	2.61	2.70	2.00	5.06	0.3	17,080	7.71	0.21	310	7.14	15,560			

^aOriginal stained core specimens were selected to include rock discolored and/or with visible incipient fractures; selected sound cores that exhibited unhealed internal fractures after testing are also reported as stained cores.

^bNatural water content obtained from waxed core specimens.

^cMoisture content obtained from specimens after test.

^dScratch hardness test rated as follows: (1) Cannot be scratched by common pen knife, (2) can be scratched by common pen knife with great difficulty.

^eUltimate strength not included in average.

^fAltered joint material soft, generally greenish-yellowish-tan, some dark brown, scratched with fingernail.

Table C3. EERL core borings.

Hole No.	EERL designation	Coordinates		Collar elevation	Depth, ft	Remarks
		N	E			
Q-35	IL-5C-A	369,467.2	1,418,290.4	2548.5	25.4	IL-5 Experiment - North side
Q-36	IL-5C-B	369,456.2	1,418,324.8	2544.2	25.5	IL-5 Experiment - East side
Q-37	IL-4C-C	369,496.5	1,418,344.0	2545.9	25.3	IL-4 Experiment - South side
Q-38	IL-4C-D	369,505.1	1,418,308.9	2550.6	25.5	IL-4 Experiment - West side
Q-39	IL-4C-A	369,540.6	1,418,318.1	2552.6	25.4	IL-4 Experiment - North side
Q-40	IL-4C-B	369,531.3	1,418,353.0	2549.6	25.4	IL-4 Experiment - East side
Q-41	ML-1C	369,795.5	1,418,602.2	2541.6	40.1	ML-1 Experiment - West side
Q-42	-	369,376.5	1,418,153.3	2562.0	30.0	Exploratory hole to site CS series
Q-43	-	369,442.8	1,418,077.0	2568.6	30.9	Exploratory hole to site CS series

After test, specimens were examined for internal fractures, type of failure, and angle of shear cone and hardness by knife blade scratch noted. A megascopic description of test specimens may be found by referral to specimen depths in the drilling logs made by Portland District geologists during drilling operations. Moisture content at time of test was also determined for selected specimens by the aforementioned method.

(4) Tensile Strength. Specimens were tested for tensile strength in a 60,000-lb Riehle hydraulic testing machine by the method outlined in ASTM-D 2936, Standard Method of Test for Direct Tensile Strength of Rock Core Specimens. An epoxy resin was used to bond the core specimens to the metal caps. The epoxy resin was allowed to cure approximately 24 hr before testing. Only sound specimens were selected for test. However, two that failed at internally altered fractures were reclassified as stained and replaced by two additional sound specimens.

(5) Dynamic Modulus of Elasticity and Longitudinal Velocity. Dynamic moduli of elasticity were computed for core

specimens from fundamental transverse frequencies determined by the method and equipment, including a cathode-ray oscilloscope and frequency counter, as described in ASTM-C 215. Specimen length-to-diameter ratios ranged from 2.5 to 4.6. Twelve sound core specimens were requested for testing. Of the 20 core segments of sufficient length available, 10 were classified as sound and 10 as stained by visual examination and/or test value.

Longitudinal velocities were computed from the following formula, which appeared in Ref. C2:

$$V_1 = \sqrt{\frac{E(1 - \mu)}{\rho(1 + \mu)(1 - 2\mu)}}$$

where:

V_1 = longitudinal velocity

E = dynamic modulus of elasticity

ρ = mass density

μ = Poisson's ratio

The test results presented in

Tables C1 and C2 are discussed below.

(1) Moisture Content. Of the 17 waxed specimens received for moisture content

determination, 9 were classified as sound and 7 as stained. The sample from drill hole Q-43 is reported separately. Average moisture contents were as follows:

<u>Rock condition</u>	<u>No. of specimens</u>	<u>Moisture percent</u>
Sound	9	0.8
Stained	7	0.9
Q-43	1	3.0

The after-test specimens averaged 0.3% moisture content for both the sound and the stained specimens. The core had been stored inside the laboratory for 60 to 90 days prior to test.

(2) Specific Gravity, Absorption, and Apparent Porosity. Average bulk specific gravity for the stained rock was 2.56 and for the sound rock, 2.63. Apparent specific gravities were the same. Absorption and porosity of the stained rock were about double those of the sound: 2.0 and 5.06%, respectively, for the stained, vs 0.9 and 2.45% for the sound.

(3) Unconfined Compressive Strength, Static Modulus of Elasticity, and Poisson's Ratio. Nineteen specimens were selected for test, 13 as sound and 6 as stained. Four of the specimens initially classified as sound failed along internal altered fractures and were therefore reclassified as stained (footnote a of Table C2). Compressive strengths for the sound core ranged from 22,590 to 37,300 lb/in.², averaging 32,420 lb/in.². For the stained the range was 11,000 to 22,740 lb/in.², with an average of 17,080 lb/in.². One extremely low-strength specimen, Q-38 (17.7-18.3) at 2,260 lb/in.² was excluded from the average.

Static moduli and Poisson's ratios for the sound core were very consistent,

ranging from 7.36 to 8.86 with an average of 8.37×10^6 lb/in.² and 0.21 to 0.26 with an average of 0.24, respectively.

For the stained core, values were more varied with a low of 2.65, a high of 9.57, and an average of 7.71×10^6 lb/in.². Poisson's ratios were 0.07 to 0.45, and averaged 0.21. The reason for variation in the static moduli and Poisson's ratio values is location of the SR-4 strain gages on the core specimens. If the gage was located in an area of sound rock of a specimen of generally unsound rock, the low indicated strain would result in an apparent high modulus or erratic Poisson's ratio. It follows that if the gage was bonded in an area of softer, unsound rock or across a seam, the reverse would be true. Although care was taken in selection of gage locations on each core specimen, this condition could not be avoided in many of the unsound rock specimens.

Hardness of all samples varied between that which cannot be scratched with a pen knife blade and that which could be scratched with a pen knife blade only with difficulty. The core specimens were predominantly in the first group, with some areas of lighter color in the second. However, material in the altered joints exposed by failure was much softer, being easily scratched with a fingernail.

(4) Tensile Strength. Tensile tests were requested on sound rock core only. However, when examination of two low-strength specimens after test revealed that the failure took place at internal altered fractures, they were reclassified as stained and reported as such. The tensile strength of the sound rock ranged

from a low of 630 lb/in.² to a high of 2005. The average strength of the six specimens was 1470 lb/in.². One 0.7-ft-length of core was tested twice. The first failure took place at 1210 in a lighter brown portion of core and the second at 2005 in a darker area. The two stained specimens averaged 310 lb/in.²

(5) Dynamic Modulus of Elasticity and Longitudinal Velocity. These values were very consistent for the sound rock specimens, averaging 9.41×10^6 lb/in.². The high was 10.75 and the low was 7.03. Eight of the ten specimens had dynamic moduli greater than 9.00×10^6 lb/in.². Results were more varied for the stained rock cores with a high of 9.24, a low of 5.34, and an average of 7.14×10^6 lb/in.². Since longitudinal velocities were computed from moduli of elasticity, the values are in the same order. For the sound rock they averaged 17,550 ft/sec, with a high of 18,890 and a low of 15,990. The average for the 10 stained specimens

was 15,560 ft/sec, the high being 17,730 and the low 13,230.

Photographs of specimens before and after test are shown as Figs. C1 through C5.

Fig. C2. Representative core specimens for dynamic modulus of elasticity and longitudinal velocity tests; specimens for tensile strength tests were selected from cores classified as sound by dynamic tests.

Fig. C1. Representative core specimens for compressive strength and static modulus of elasticity tests.

Fig. C3. Core specimens after tensile strength tests.

Fig. C4. Core specimens after compressive strength and static modulus of elasticity tests.

Fig. C5. Additional core specimens after compressive strength and static modulus of elasticity tests.

References

- C1. Standardized Tests for Determining the Physical Properties of Mine Rock, U.S. Department of Interior, Bureau of Mines, Rept. RI-3891 (1946).
- C2. D. U. Deere and R. P. Miller, Engineering Classification and Index Properties for Intact Rock, Air Force Special Weapons Center, Kirtland Air Force Base, N. Mex., Rept. AFWL TR-65-116 (1966), p. 98.

Appendix D

Design of Mounding Rows

By Bruce B. Redpath

The concept of mounding, investigated in the Project Lost Creek experimental series, was an outgrowth of the throw-out cratering research conducted by EERL and its predecessor, the USAE Nuclear Cratering Group. Cratering involves the use of compact explosive charges called "point-charges"; i.e., charges that are concentrated in a sphere or in a compact cylinder, as distinguished from the relatively long, cylindrical charges employed in conventional drilling and blasting. The point charge concept permits the definition of quantities such as a scaled depth of burial, and in general, permits the scaling of all crater dimensions by some power of the charge weight; i.e.,

$$\text{Dimension} \propto Y^p$$

(where Y is weight of charge).

It was empirically determined for throw-out cratering that the crater dimensions produced by a single buried charge scaled approximately as the charge weight raised to the $1/3.4$ -power.^{D1} This empirical scaling exponent falls between the $1/3$ -power, which would be required by dimensional analysis without a consideration of the force of gravity, and the $1/4$ -power, which can be theoretically derived for cratering in a gravitational field. In the case of a single mounding charge (i.e., a charge buried too deeply to eject rock from the true crater, as depicted in Fig. 3), it is believed that the $1/3$ -power is adequate to predict (describe) how the effects and

crater dimensions vary with the charge weight because relatively little of the explosive energy is expended against the force of gravity.

Scaling laws were originally developed for single charges. When charges are combined in a linear row, the scaling laws are modified and the interaction of the charges must be considered. In a row-charge, we have to take into account how the effects of adjacent charges reinforce or enhance each other when they are detonated simultaneously. We can express row-charge phenomena (or enhancement) in terms of what a single charge will do by itself; i.e., we can normalize row-charge effects to single-charge effects. To do so we must also be able to express the placement or positioning of the charges in a row in terms of single-charge placement parameters.

Going back to the concept of a single point-charge buried at mounding depth, we can assume that there is an "optimum" scaled depth where the term "optimum" refers to the best combination of the volume and degree of rock breakage. In other words, where the primary objective is to break the most rock for later excavation, there will be an optimum depth of burial for a given charge weight, and it can be expressed in the units of $\text{ft/lb}^{1/3}$. The optimum depth will be difficult to determine experimentally, for there is bound to be some tradeoff between the volume of broken rock and how well it is broken. The optimum depth will also

depend on the type of rock and the type of explosive.

When a charge is buried at the optimum depth for mounding (i.e., optimum from the standpoint of subsequent rock excavation), the extent or surface radius of the roughly conical zone of broken rock can also be scaled to the charge weight. For simplicity we can use the radius of the true crater formed by the charge as a measure of rock breakage. In summary, we will assume that a single charge does have an optimum depth of burial, and that we can define a true crater radius for this depth. These two assumptions are necessary to proceed with the design of a row of mounding charges.

Because of a gap in our current mounding technology, we will rely on some empirical row-charge laws derived from throw-out cratering experiments^{D2} and hypothesize some rules for rows of mounding charges.

In throw-out cratering, it has been reasonably well established that the crater produced by a row of charges can be reproduced by a row of smaller charges, buried at the same depth as the original charges, but spaced closer together. The principle is simply that it takes a given amount of explosive energy to break and move (i.e., eject) a given amount of rock. The empirical rules were quantified by expressing both the dimensions of the row crater and the spacing of the charges in terms of single-charge parameters. That is, the dimensions of a row-crater are expressed in terms of single-charge dimensions, and the amount by which the depth or width of a row crater is larger than the depth or diameter of a single-charge crater (pro-

duced by a charge equal in weight to one of the charges in the row) is referred to as "enhancement." The spacing of the charges in a row is expressed in terms of the radius of the optimum single-charge crater. Specifically, if a row-crater has a width " W_a " and a depth " D_{ar} ," then the enhancement is defined as the quantity:

$$e = \frac{W_a}{2R_a} = \frac{D_{ar}}{D_a},$$

where R_a and D_a are the optimum radius and depth of the single crater that would be produced by one of the charges in the row. We can extend this definition to true crater dimensions by writing:

$$e = \frac{W_t}{2R_t}, \quad (D1)$$

where W_t is the width of the true crater, and R_t is the radius of the true crater formed by a corresponding charge weight.

It was experimentally determined for throw-out cratering that the enhancement factor is related to the charge spacing by:

$$e^2 = \frac{1.4}{S/R_a}, \quad (D2)$$

where S is the spacing between charges. Note that this expression implies a degradation of row-charge dimensions if the charges are spaced farther apart than $1.4 R_a$. The concept of enhancement requires that the depths of burial of charges in a row must be greater by the amount of enhancement, than the optimum depth of burial of an equal-weight single-charge. In order to extend the use of Eq. (D2) to rows of mounding charges, we simply substitute the true-crater radius, R_t , for R_a . At this point it is speculative to assume that the numerical factor of 1.4

in Eq. (D2) is valid for mounding charges, but we will do so for the present.

We can now make the following statement about depth of burial:

$$\text{DOB} = e \cdot \text{dob} \cdot Y^{1/3}, \quad (\text{D3})$$

where:

DOB = absolute depth of burial of a mounding charge in a row

e = enhancement of the row crater dimensions relative to true single crater dimensions.

dob = optimum scaled depth of burial for a single mounding charge

Y = charge weight of a row charge.

Equation (D3) is simply a statement about crater geometry; if charges are spaced closer together and we get some enhancement of their effects, then their individual optimum depths of burial should be increased by the amount of the enhancement.

We now restate Eq. (D2) using the true crater radius:

$$e^2 = \frac{1.4}{S/R_t}, \quad (\text{D4})$$

which can be rewritten as:

$$e^2 = \frac{1.4}{S/(r_t Y^{1/3})}, \quad (\text{D5})$$

where r_t is the scaled value of the optimum true-crater radius for a charge weight Y. Taking the square root of both sides of Eq. (D5) we have:

$$e = \sqrt{1.4} r_t^{1/2} \frac{Y^{1/6}}{S^{1/2}}. \quad (\text{D6})$$

Substituting this into Eq. (D3) we obtain:

$$\text{DOB} = \sqrt{1.4} r_t^{1/2} \frac{\text{dob} Y^{1/6} Y^{1/3}}{S^{1/2}};$$

i.e.,

$$\text{DOB} = \sqrt{1.4} r_t^{1/2} \text{dob} \left(\frac{Y}{S} \right)^{1/2}. \quad (\text{D7})$$

This equation suggests that the depth of burial should scale as the square root of the linear charge density, which is consistent with dimensional analysis. The scaled values of r_t and dob in Eq. (D7) will depend on the type of explosive and the rock; in a particular case the first three terms on the right-hand side of Eq. (D7) can be combined into a constant; i.e.,

$$\text{DOB} = k \left(\frac{Y}{S} \right)^{1/2}. \quad (\text{D8})$$

For the sake of example, we will proceed now to evaluate the constant in Eq. (D8) by assuming some reasonable values for r_t and dob.

Using the units of pounds and feet, suppose

$$r_t = 2.0 \text{ ft/lb}^{1/3}$$

at a

$$\text{dob} = 2.7 \text{ ft/lb}^{1/3}.$$

We would then have:

$$\text{DOB} = \sqrt{1.4} \times 2.0^{1/2} \times 2.7 \times \left(\frac{Y}{S} \right)^{1/2};$$

i.e.,

$$\text{DOB} = 4.5 \left(\frac{Y}{S} \right)^{1/2}. \quad (\text{D9})$$

If our assumptions about r_t and dob are correct, and if the factor 1.4 in Eq. (D4) is valid, then Eq. (D9) could be used to compute the correct depth of burial for a charge weight Y at a spacing of S . However, we must impose an important constraint, derived from throw-out cratering, that charge spacing, S , cannot exceed $1.4 R_t$. For example, if we are using 200-lb charges spaced 16 ft apart, then they should be buried at a depth given by:

$$\begin{aligned} DOB &\approx 4.5 \left(\frac{200}{16} \right)^{1/2} \\ &\approx 15.9 \text{ ft,} \end{aligned}$$

and in no case should the spacing be greater than

$$1.4 R_t = 1.4 \times 2.0 \times 200^{1/3};$$

i.e.,

$$S \leq 16.4 \text{ ft.}$$

Assuming that an equation similar to Eq. (D8) is valid, we could also reverse the procedure above and use empirical evidence to compute the constant in the equation. For instance, if our observations of the VS-1 results suggest that the 18-ft spacing produced the best results, remembering that $Y = 215$ lb and $DOB = 17.8$ ft, we have:

$$k = \frac{DOB}{(Y/S)^{1/2}},$$

so that

$$\begin{aligned} k &= \frac{17.8}{(215/18)^{1/2}} \\ &\approx 5.15. \end{aligned}$$

The observation that this value of k is greater than the value $K = 4.5$ in our example above might indicate that either the factor of 1.4 in Eq. (D4) is too low, or that r_t or dob are actually higher than the values used in the preceding example, or a combination of all three. Again for the sake of example, let us increase the charge spacing factor from 1.4 to 1.5, assume that $dob = 2.7 \text{ ft/lb}^{1/3}$ is still reasonable, and use the factor of $k = 5.15$ based on the VS-1 results to back-figure a new value for r_t :

$$\begin{aligned} r_t &= \left(\frac{5.15}{\sqrt{1.5 \text{ dob}}} \right)^2 \\ &= \left(\frac{5.15}{\sqrt{1.5 \times 2.7}} \right)^2 \\ &\doteq 2.4 \text{ ft/lb}^{1/3}; \end{aligned}$$

this would also mean that the spacing between charges should not exceed

$$\begin{aligned} S &\leq 1.5 \cdot r_t \cdot Y^{1/3}, \\ &\approx 1.5 \times 2.4 \times 215^{1/3} \\ &= 21.6 \text{ ft.} \end{aligned}$$

These values are reasonable; there is information from Project Lost Creek that supports the value of r_t being near $2.4 \text{ ft/lb}^{1/3}$, and certainly VS-1 did mound satisfactorily when the spacing was of the order of 20 to 24 ft.

We can now outline some general design procedures, and using the numbers above, give an example of how to design a multiple-row mounding detonation.

Assume that we want to excavate a 150-ft-wide cut using charges that weigh approximately 150 lb, and further, that we want to remove the rock in 20-ft lifts. What should the depth of burial be, how

many rows do we need, and what should the charge spacing be?

We can begin by postulating several design criteria: the depth of burial should be equal to the lift height and the rows should be separated by approximately $1.5 (W_t/2)$, and be located a distance of about $W_t/2$ from the sides of the excavation.

The 20-ft lift height will correspond to the optimum depth of burial for a particular charge weight, and this charge weight becomes the basis of our design. Remembering that we are using $2.7 \text{ ft/lb}^{1/3}$ as optimum dob, we can compute the nominal charge weight by:

$$Y = \left(\frac{20}{2.7}\right)^3$$

$$Y_s = 406 \text{ lb.}$$

Eventually our enhancement rule will be applied to replace the 406-lb charges with 150-lb charges, but first we will compute the number of rows required to excavate the full width of the spillway.

Our guidelines for the arrangement of the row-charges across the excavation are depicted in Fig. D1 where the separation between rows is approximately $1.5 W_t/2$ and the side rows are located a distance $(W_t/2 + B)$ in from the excavation boundaries.

B is the width of a zone that will act as a buffer zone and that will allow for controlled blasting such as presplitting. For this example, B will be assumed to be 5 ft. According to Fig. D1 we therefore have:

$$L = (N - 1) 1.5 W_t/2 + 2 W_t/2 + 2B;$$

therefore:

$$N = \frac{\left[\frac{4(L - 2B)}{W_t} - 1\right]}{3} \quad (\text{D10})$$

For a charge weighing 406 lb and spaced at $1.5 R_t$, we have

$$\begin{aligned} W_t &= 2R_T = 2r_t Y^{1/3} \\ &= 2 \times 2.4 \times 406^{1/3} \\ &= 35.54 \text{ ft.} \end{aligned}$$

Consequently,

$$\begin{aligned} N &= \frac{\left[\frac{4(150 - 10)}{35.54} - 1\right]}{3} \\ &= 4.92. \end{aligned}$$

Because we must have an integer number of rows, we round N up to 5 and proceed to compute the actual separation, D, between rows as:

$$D = \frac{L - (W_t + 2B)}{N - 1} \quad (\text{D11})$$

$$\begin{aligned} D &= \frac{150 - (35.54 + 10)}{4} \\ &= 26.1 \text{ ft} \end{aligned}$$

Fig. D1. Generalized cross section of mounding excavation, first lift.

At this point we have 5 rows of 406-lb charges spaced at $1.5 R_t$ ($= 1.5 \times 17.77 = 26.66$ ft) with the rows separated by 26.1 ft. The last remaining step is to reduce the individual (406-lb) charge weights to 150 lb by close spacing and the corresponding enhancement. The amount of enhancement required will simply be:

$$e = \left(\frac{406}{150} \right)^{1/3}$$

$$= 1.39;$$

so that the charge spacing will be:

$$S/R_t = \frac{1.5}{e^2}$$

$$= 0.77,$$

and R_t for a 150-lb charge is:

$$R_t = r_t Y^{1/3}$$

$$= 2.4 \times 150^{1/3}$$

$$= 12.75 \text{ ft.}$$

Therefore, the charge spacing, S , will be

$$S = 0.77 R_t$$

$$= 0.77 \times 12.75$$

$$= 9.8 \text{ ft.}$$

We have now replaced the rows of 406-lb charges spaced 26.66 ft apart with rows of 150-lb charges spaced 9.8 ft apart. Note that the linear charge density along each row has not changed; i.e.,

$$\frac{406}{26.66} = \frac{150}{9.8} = 15.3 \text{ lb/ft.}$$

Our final pattern will consist of 150-lb charges distributed in a 9.8×26.1 -ft grid. Assuming a lift height of 20 ft, a "powder factor" can be computed as

$$P.F. = \frac{150 \times 27}{9.8 \times 26.1 \times 20} \text{ lb/yd}^3$$

$$= 0.79 \text{ lb/yd}^3.$$

Even though we have reduced the charge weight to 150 lb, the separation between rows is still correct because of enhancement. Our required enhancement was 1.39, and we see that the nominal separation of:

$$1.5 W_t/2 = 1.5 e R_t$$

$$= 1.5 \times 1.39 \times 12.75$$

$$= 26.6 \text{ ft,}$$

which is, as we expected, practically the same as the value of $1.5 W_t/2$ we calculated for the 406-lb charges.

In retrospect, the design of the ML-1 experiment was not in accord with the design concepts that we have just outlined, and a redesign on the basis of these concepts will serve as another example.

We will maintain several of the properties of the ML experiment as constraints to be met by a new design:

(a) Width at ground surface ($= L$)
 $= 78 \text{ ft}$

(b) Charge spacing in ML-1 rows
 $(= S) = 18 \text{ ft}$

(c) The number of rows in ML-1 will be two, with only one row in ML-2. All other parameters will change in response to our design concepts. Because we are specifying that there will be only two rows in the first lift, rather than specifying the depth of the first lift, we

will have to reformulate Eq. (D10) to obtain an expression for W_t ; i.e.,

$$W_t = \frac{4(L - 2B)}{3N + 1}, \quad (D12)$$

where $N = 2$, as stated, and we will let $B = 7$ ft. Therefore,

$$\begin{aligned} W_t &= \frac{4(78 - 14)}{7} \\ &= 36.6 \text{ ft}, \end{aligned}$$

and because

$$W_t = 2R_t$$

$$R_t = 18.3$$

and because

$$R_t = r_t Y^{1/3} \quad (r_t = 2.4 \text{ ft/lb}^{1/3})$$

$$\begin{aligned} Y &= \left(\frac{18.3}{2.4} \right)^3 \\ &= 442 \text{ lb}. \end{aligned}$$

The depth of burial will be:

$$\begin{aligned} \text{DOB} &= \text{dob } Y^{1/3} \quad (\text{dob} = 2.7 \text{ ft/lb}^{1/3}) \\ &= 2.7 \times 442^{1/3} \\ &= 20.6 \text{ ft}. \end{aligned}$$

If we were to use 442-lb charges, they would have an in-row spacing of $1.5 R_t$ or 27.4 ft; however, because we are constraining our spacing to be 18 ft, we have to adjust the charge weights downward to conform to this lesser spacing. We can do this easily by maintaining the same linear charge density along each row. If Y is the appropriate charge weight for an 18-ft spacing, then

$$\frac{442}{27.4} = \frac{Y}{18};$$

therefore,

$$\begin{aligned} Y &= \frac{18 \times 442}{27.4} \\ &= 290 \text{ lb}. \end{aligned}$$

The separation between rows is given by Eq. (D11):

$$\begin{aligned} D &= 78 - (36.6 + 14) \\ &= 27.4 \text{ ft}. \end{aligned}$$

For the first lift, then, we have a pattern of two rows of 290-lb charges on an 18- $\times$ 27.4-ft grid and buried at 20.6 ft.

Reference to Fig. D2 will indicate that the dimensions of the second lift are, assuming 1H:4V slide slopes, a 5-ft bench, and a 7-ft buffer zone as in the first lift,

$$\begin{aligned} L_2 &= 78 - (2 \times 5) - (2 \times 5) \\ &= 58 \text{ ft}. \end{aligned}$$

The 7-ft buffer zone in the second lift means that

$$\begin{aligned} W_t &= L_2 - 2b \\ &= 58 - 14 \\ &= 44 \text{ ft}; \end{aligned}$$

Fig. D2. Mounding excavation example, giving transverse and vertical dimensions.

therefore,

$$R_t = 22 \text{ ft,}$$

and

$$Y = \left(\frac{22}{2.4}\right)^3$$
$$= 770 \text{ lb,}$$

and

$$\text{DOB} = 2.7 \times 770^{1/3}$$

$$= 24.8 \text{ ft.}$$

Once more assuming that we are using an 18-ft spacing, we compute the new charge weight for ML-2 as we did for ML-1; i.e.,

$$\frac{770}{1.5 \times 22} = \frac{Y}{18}$$

$$Y = 420 \text{ lb.}$$

References

- D1. M. D. Nordyke, On Cratering. A Brief History, Analysis, and Theory of Cratering, Lawrence Livermore Laboratory, Livermore, Calif., Rept. UCRL-6578 (1961).
- D2. B. B. Redpath, "A Concept of Row Crater Enhancement," in Proc. Symposium on Engineering with Nuclear Explosives, Las Vegas, Nev., 1970 (American Nuclear Society, 1970), pp. 1679-1691.

Appendix E
Particle Size Gradation Curves

Fig. E1. Particle size distribution, VS-1 pit near Charge D.

Fig. E2. Particle size distribution, VS-2 mound.

Fig. E3. Particle size distribution, VS-3 mound.

Fig. E4. Particle size distribution, CS-1 mound.

Fig. E5. Particle size distribution, CS-2 mound.

Fig. E6. Particle size distribution, ML-1 mound.

Fig. E7. Particle size distribution, ML-2 rubble.

Appendix F

Airblast Measuring System, Data, and Analysis

By H. A. Washburn and C. M. Snell

INTRODUCTION

Buried detonations in unsaturated media usually produce two distinct airblast pressure pulses. The initial or ground-shock-induced pulse is caused by the upward spall velocity of the ground surface above the explosion. The second or gas-vent-induced pulse follows when the explosive cavity gases vent to the surrounding atmosphere. The gas-vent pulse is relatively strong for shallow detonations, but is rapidly suppressed and lags further behind the ground-shock pulse as scaled depth of burial increases. The ground shock pulse becomes dominant (larger in amplitude) for deeply buried mounding events and for most detonations in saturated media. At very great scaled depths of burial, the gas-vent pulse disappears completely.

The damage-causing potential of the airblast from a given event is determined by the amplitude or peak overpressure of the dominant pulse. Peak overpressures of 4.5 mbar (0.065 lb/in.^2) are likely to cause some damage to average-size residential windows. The amplitude of an overpressure pulse is a function of the range from SGZ (Surface Ground Zero: the geographic point directly above a buried explosive charge), energy yield of explosive, type of explosive, depth of burial, surrounding medium, stemming of the charge, and ambient atmospheric conditions. The peak overpressure " ΔP " of the pulse generally attenuates with

range "R" approximately as $R^{-1.0}$ to $R^{-1.3}$. The effects of charge yield and ambient atmospheric pressure may be predicted by simple scaling laws. The remaining factors may be investigated experimentally by holding most emplacement parameters constant and varying one factor (i.e., depth of burial, or explosive type). For row charges, the overpressure is also influenced by the number of charges in the row, the intercharge separations, the intercharge time delays (if any), and the angle from the row at which airblast is measured. For simultaneous events, overpressures are generally greatest perpendicular to the row axis, and least off the end of (parallel to) the axis. These effects are likewise subject to experimental elucidation. The Lost Creek events provided an excellent opportunity to acquire airblast data for deeply buried single and row-charge detonations utilizing several types of explosives.

DESCRIPTION OF AIRBLAST SYSTEM

The airblast overpressure-time histories for all major Lost Creek mounding detonations were measured by a newly acquired system capable of recording low-amplitude pressure pulses. The instrumentation consisted of five Dynasciences Model P7 variable-reluctance differential-pressure transducers installed at various distances from detonation sites and in two principal directions from the areas of the row-charge

detonations. The gages were one arm of an AC bridge excited by a 3-kHz signal, and the output was demodulated, amplified, and recorded on a CEC P-119 oscillograph, with backup recording on a Sangamo 3200 tape recorder performed on most of the tests. The electronics were designed and operated by personnel from the Instrumentation Services Division of WES, except for the ML-2 detonation, for which the Dynasciences Model CD 32 carrier demodulators were used with only oscillograph recording. All gages were connected by shielded cable to the electronics and recorders in the Control-Point trailer. The zero-time fiducial and Irig B Time Code* were also recorded. The experimental layout is shown in Fig. F1.

PRESHOT PREDICTIONS

Predictions were made using the methods presented in Refs. F1 and F2 (referred to hereafter as theoretical predictions), and the empirical results of some of the Trinidad detonations, primarily B-8 (Ref. F3). The theoretical predictions for a 200-lb charge with DOB = 18 ft and for the two directions from a 7-charge row at optimum spacing are plotted in Fig. F2. The prediction obtained from the Trinidad B-8 detonation scaled to a 200-lb charge is included in Fig. F2 for comparison.

*Irig B Time Code refers to a standard 1000 Hz electronically generated time code described in Ref. F4. Irig time signals were not recorded for Event ML-2 due to unavailability of the signal generator.

EXPERIMENTAL SETUP

Measurements were made on the detonations designated VS-1, VS-2, VS-3, IL-4, IL-5, IL-7, CS-1, CS-2, ML-1, and ML-2, and on two tests of primacord. The primacord tests were performed (1) to determine the effect that covering the cord with soil had on airblast suppression, and (2) to estimate expected overpressure levels from detonating primacord. These experiments were implemented because earlier measurements indicated that primacord contributed significantly to the close-range airblast pulses from deeply buried events.

DATA

The measured peak overpressures from the ten major events and the primacord

Fig. F1. Modular layout of airblast data acquisition system.

tests, and the integrated positive phase and negative phase impulses from several of the major events, are summarized in Tables F1 through F5. Tabulations for the major events give the event identification, number of charges and configuration (for rows), weight of explosive per charge, type of explosive, depths of burial, and spacing (for rows). The data compilations list the airblast gage number and maximum overpressure range

for each gage, range (from charge SGZ, or the center of the row, or the nearest main charge SGZ), azimuth from the row axis for row events (0 deg corresponds to the axial direction off the end of the row), time of first detected pulse arrival, peak positive overpressures with identifications where possible, times of positive peaks, integrated positive phase impulses, negative peak overpressure excursions, times of negative peaks, integrated negative

Fig. F2. Peak airblast overpressure predictions for Project Lost Creek.

Table F1. Single detonations.

Station: range, lb/in. ²	Dis- tance from SGZ, ft	Azimuth from SGZ, deg	Time of first pressure arrival, sec	Peak (+) pressure, lb/in. ²	Time of (+) peak, sec	Positive phase impulse, lb/in. ² - msec	Peak (-) pressure, lb/in. ²	Time of (-) peak, sec	Negative phase impulse, lb/in. ² - msec	Eleva- tion W.R.I. SGZ, ft
A. Detonation IL-4 (210 lb Slurry A; DOB = 17.8 ft)										
135 ± 0.1	476	195	0.4135	0.0037 0.0035	0.417 0.428	0.018 0.0	-0.0011 -0.0014 -0.0016	0.422 0.452 0.468		-16
136 ± 0.1	739	135	0.646	0.0061 0.0023	0.6475 0.654	0.013	-0.003	0.651		-21
137 ± 0.2	314	198	0.2698	0.0085 0.0045	0.2713 0.2835	0.025	-0.0044 -0.0033	0.277 0.309		-14
138 ± 0.2	not used									
139 ± 0.3	~142	60	0.1283	0.033 0.0065	0.1298 0.1388	0.074	-0.025	0.134		-13
B. Detonation IL-5 (210 lb Slurry A; DOB = 17.8 ft)										
135 ± 0.1	393	190	0.3498	0.0118 0.0035	0.3505 0.3635	0.053	-0.003	0.358		-17
136 ± 0.1	712	130	0.6392	0.0070 0.0041	0.640	0.022	-0.0023	0.6805		-20
137 ± 0.2	266	185	0.2343	0.034 0.015	0.237 0.245	0.091	-0.024	0.241	-0.067	-14
138 ± 0.2	517	130	0.4643	0.0053 0.0050	0.4654	0.020	-0.0028	0.509		-63
139 ± 0.3	144	48	0.130	0.054 0.020	0.131 0.138	0.107	-0.034	0.135	-0.070	-1
C. Detonation IL-7 (150 lb AN and 50 lb TNT; DOB = 17.8 ft)										
135 ± 0.1	523	185	0.446	0.0104 (p) 0.0109 0.0202 (gv)	0.450 0.458 0.492		-0.0053 -0.0090	0.464 0.508		-18
136 ± 0.1	811	135	0.707	0.0032 (p) 0.0077 0.0099 (gv)	0.710 0.716 0.749		-0.0097	0.784		-23
137 ± 0.2	306	190	0.250	0.032 (p) 0.030 0.032 (gv)	0.252 0.260 0.293		-0.0141 -0.0153 -0.0177	0.256 0.265 0.310		0
138 ± 0.2	625	135	0.5375	0.0025 (p) 0.0063 0.0108 (gv)	0.548 0.584		-0.0091	0.613		-66
139 ± 0.3	139	85	0.121	0.124 (p) 0.042 0.089 (gv)	0.123 0.130 0.153		-0.051 -0.022 -0.044	0.128 0.133 0.171		-2

p = probable primacord peak; gv = gas vent pulse.

Table F2. Row detonations VS-1, VS-2, and VS-3.

Station; range, lb/in. ²	Distance from Row center, ft	Closest main charge hole, ft	Azimuth from row axis, deg	Time of first pressure arrival, sec	Peak (+) pressure, lb/in. ²	Time of (+) peak, sec	Positive phase impulse, lb/in. ² - msec	Peak (-) pressure, lb/in. ²	Time of (-) peak, sec	Negative phase impulse, lb/in. ² - msec	Eleva- tion W.R.I. SGZ, ft
A. Detonation VS-1 (7 charges of 200 lb ANFO each; DOB = 16.3 to 18.0 ft; spacing = 12 to 24 ft)											
135 ± 0.1	475	422	-7	0.361	0.0184 .0101 .0087 .0094 .0101	0.3648 .3752 .3838 .3942 .4229	0.519				44
136 ± 0.1	583	—	99	0.511	.0561 .0765	.5134 .5162	0.88	-0.0115 -0.0161 -0.0150	0.5369 0.5468 0.5781	-0.81	14
137 ± 0.2	268	216	-3	0.169	.0498 .0267 .0185 .0221 .0195	.1717 .1816 .1911 .1988 .2306	1.14				27
138 ± 0.2	273	—	103	0.238	.110 .134	.2421 .2445	1.65	-0.016 -0.032	0.2827 0.3154	-1.33	-39
139 ± 0.3	273	—	103	0.238	.106 0.132	.2403 0.2440	1.73	-0.016 -0.028	0.2828 0.3161	-1.27	-39
B. Detonation VS-2 (7 charges of 200 lb Slurry A; DOB = 17.8 to 17.9 ft; spacing = 12 to 24 ft)											
135 ± 0.1	447	395	-6	0.3388	0.0262 .0108 .0092 .0038	0.3430 .3542 .3684 .3812	0.380				33
136 ± 0.1	767	—	95	0.6637	.0695 .0030 .0022	.6664 .6798 .6904	0.474	-0.205 -0.0156	0.6769 0.6979	-0.372	28
137 ± 0.2	321	268	-5	0.2277	.044 .021 .0145 .009	.2321 .2430 .2580 .2687	0.590				15
138 ± 0.2	560	—	90	0.4842	.1015 .063 .019 .0225	.4851 .4900 .4962 .5021	0.593	-0.009 -0.022	0.4953 0.5142	-0.578	4
139 ± 0.3	366	—	87	0.3147	.116 .107 0.077	.3153 .3187 0.3255	1.04	-0.028	0.3388	-0.751	-39
C. Detonation VS-3 (7 charges of 200 lb Slurry B; DOB = 17.8 to 17.9 ft; spacing = 12 to 24 ft)											
135 ± 0.1	452	399	-6	0.3444	0.0109 .0118 .0062 .0065 .0050	0.3461 .3501 .3687 .3731 .3880	0.375	-0.0055	0.5015		74
136 ± 0.1	830	—	78	0.7133	.0248 .0287 .0203 .0038	.7181 .7231 .7268 .7415	0.437	-0.009 -0.0089	0.7520 0.7728	-0.42	40
137 ± 0.2	336	284	-12	0.2430	.0220 .016 .015 .0115 .0135	.2450 .2488 .2573 .2664 .2718	0.514	-0.006 -0.008	0.3505 0.3815		3
138 ± 0.2	575	—	72	0.4863	.0285 .0320 .0300 .0250 .0173	.4880 .4930 .4987 .5064 .5125	0.606	-0.009 -0.011	0.5275 0.5380	-0.568	4
139 ± 0.3	398	—	62	0.3251	.023 .027 .034 .032 0.021	.3266 .3328 .3379 .3440 0.3523	0.791	-0.0135	0.3920	-0.934	-39

|| = in direction along row axis; ⊥ = in direction perpendicular to row axis.

Table F3. Row detonations CS-1 and CS-2.

Station; range, lb/in. ²	Distance from Row center, ft	Closest main charge hole, ft	Azimuth from row axis, deg	Time of first pressure arrival, sec	Peak (+) pressure, lb/in. ²	Time of (+) peak, sec	Positive phase impulse, lb/in. ² - msec	Peak (-) pressure, lb/in. ²	Time of (-) peak, sec	Negative phase impulse, lb/in. ² - msec	Eleva- tion W.R.I. SGZ, ft
A. Detonation CS-1 (6 charges of 150 lb Slurry A; DOB = 15.6 ft; spacing = 16 ft)											
135 ± 0.1	406	368	19	0.328	0.0100 .0049	0.3435 .3805	0.39	-0.0058	0.4323	-0.59	-12
136 ± 0.1	905	—	74⊥	.786	.0083	.8015	0.22	-0.0041	.8895	-0.23	-21
137 ± 0.2	154	116	13	.1025	.0196 .0154	.1162 .1482	1.15	-0.0136	.202	-1.27	-8
138 ± 0.2	722	—	79⊥	.6335	.0087	.645	0.33	-0.0048	.735	-0.17	-65
139 ± 0.3	343	—	100⊥	0.2945	0.0145	0.306	0.48	-0.48	0.374	-0.35	-38
B. Detonation CS-2 (6 charges of 150 lb Slurry A; DOB = 15.4 to 15.7 ft; spacing = 16 ft)											
135 ± 0.1	430	390	-6	0.3905	0.0070 0.0062	0.4172 .445	—	-0.0043	0.5072	—	-21
136 ± 0.1	878	—	45	.7895	—	.0025 .0030	0.802 .8263	-0.0018	.9202	—	-15
137 ± 0.2	202	163	-11	.188	—	.0161 .0123	.1977 .2192	-0.0087	.3113	—	-17
138 ± 0.2	688	—	49	.625	0.0028	.0026 .663	0.645	-0.0025	.7625	—	-59
139 ± 0.3	280	—	63	0.2505	.0045 0.0070	.259 0.3000	—	-0.0038	0.404	—	-32

|| = in direction along row axis; ⊥ = in direction perpendicular to row axis.

Table F4. ML-series detonations.

Station; gage	Distance from Array center, ft	Nearest presplit charge, ft	Nearest main charge, ft	Azimuth from row axis, deg	Initial arrival time, ^a sec	Peak overpressures, lb/in. ²						Eleva- tion W.R.I. SGZ, ft
						Pre- split, 1 peak	Pre- split, 2 peak	Buffer zone, 1 peak	Buffer zone, 2 peak	Main charge, 1 peak	Main charge, 2 peak	
A. Detonation ML-1 (presplits; buffer zones; 14 charges; 125 lb ANFO; delays used)												
135 E-2	1068	1031	1054	76⊥	0.834	0.018	0.0136	0.005	0.0042	0.0155	0.0065	30
136 E-8	916	862	864	16	.7075	.0077	.0092	.0069	.0088	.0120	.011	-2
137 P-9	739	703	725	80⊥	.5495	.037	.023	.0143	.0125	.0164	.0245	22
138 P-8	497	460	481	89⊥	.3445	.164	.098	.089	.089	.085	.051	12
139 E-7	268	215	217	23	0.128	0.045	0.023	0.024	0.023	0.030	0.049	-18
B. Detonation ML-2 (presplits; buffer zones; 10 charges; 75 lb to 300 lb ANFO; DOB = 10.4 to 17.8 ft)												
135	1033	1005	1033	77⊥	0.7810	0.0082	0.0118	0.0038	0.002	0.0057	NA	47
136	918	833	844	15	.6823	.0066	—	.0081	.0078	.0058	NA	13
137	674	649	674	85⊥	.516	.0260	.0353	.00442	.00645	.0181	NA	41
138	415	392	415	93⊥	.287	.0514	0.0677	.021	0.0562	.0737	NA	39
139	245	169	165	-3	0.1815	0.0180	—	0.0193	—	0.0225	NA	-23

^aTimes are not accurate since they are measured relative to an arbitrary zero time — no fiducial on this shot.

⊥ = in direction perpendicular to row axis; || = in direction along row axis; NA = not applicable.

Table F5. Primacord test results.

Detonation description: One, 50-ft long loop (2 lengths, 3 ft apart), 25-grain primacord uncovered; another loop 20 ft away with 3-4 in. of local material, 150-msec delay between the two; another similar array using 50-grain E-cord.

Station	Approximate distance from SGZ, ft	Approximate azimuth from row axis, deg	Peak overpressure from uncovered 25-grain cord, lb/in. ²	Peak overpressure from covered 25-grain cord, lb/in. ²	Ratio of uncovered to covered 25-grain cord	pressure from uncovered 50-grain cord, lb/in. ²	Peak overpressure from covered 50-grain cord, lb/in. ²	Ratio of uncovered to covered 50-grain cord
135	720	90	0.0109	0.00208	4.5	0.0238	0.00366	6.5
136	480	0	.0078	.0052	1.5	.0199	.0133	1.5
137	485	90	.0104	.00168	6.2	.0177	.00266	6.6
138	350	90	.0183	.0049	3.7	.0498	.00865	5.8
139	200	90	0.044	0.0116	3.8	0.102	0.0186	5.5

phase impulses, and elevation of the gage location with respect to charge or row SGZ - + (plus) elevations are higher than SGZ; - (minus) elevations are lower than SGZ. The tabulated airblast data are plotted against range from SGZ (or from the row center, or from a specified charge location, for the row events) in Figs. F3 through F11. The preshot theoretical predictions are also plotted for comparison in several figures.

INTERPRETATION OF RESULTS: PULSE SHAPES AND PEAK OVERPRESSURES

VS Series

Each VS shot consisted of seven, 200-lb charges at average DOB's of 17.8 ft. The only difference between shots was the explosive used. The prediction curves given in Fig. F6 are for seven charges of 200-lb each, optimally spaced, with DOB's of 18 ft.

To interpret the plot of peak overpressures, one needs to understand the

dependence of peak overpressures on the angle from the row axis. The distance from a row center at which equal peak overpressures occur is expected to approximately define an ellipse. Standard procedure for airblast predictions is to make peak predictions for the two directions, parallel to the row axis (off the end of the row) and perpendicular to the row axis, as measured from the center of the row. The peak overpressures at angles between these two directions will then fall between these values. At Lost Creek it was not convenient to put the gages exactly along the axial or perpendicular directions for all row detonations. Therefore, whereas VS-2 had its "perpendicular" gages within 5 deg of being 90 deg from the row axis, VS-3 had its "perpendicular" gages at about 60, 70, and 80 deg from the row axis. Thus, the very low "perpendicular" values in Fig. F6 for VS-3 are due partly to this discrepancy. Directional effects can also be seen in the waveform of the

pulses; for VS-2, the "perpendicular" pulse appears to be very much like that from a single charge, and for VS-3, as the angle from row axis becomes smaller, the waveform becomes more like that seen off the end of a row. This effect will later be analyzed in detail by using a superposition principle to determine the entire pulse waveform at any angle and distance.

Peak ground-shock-induced overpressures for VS-2 were slightly higher than

those for VS-1, and much higher than those for VS-3 (Fig. F6). Since the three events were similar in configuration (charge weight and number of charges), the observed airblast differences indicate corresponding differences in peak surface spall velocities. It appears probable that VS-2 produced the greatest peak spall velocities at the ground-air interface, while the velocities for VS-1 and VS-3 were successively lower. Such variations may be attributed to differences in

Fig. F3. Peak overpressures from IL-4 and IL-5 detonations.

the explosive used for the three events, or to variations in the local medium characteristics. Differences in the effectiveness of the three explosives are believed to be the dominant factor in this case. The comparative impulse plots in Fig. F7, however, indicate higher positive phase impulses for VS-1, with lower (and comparable) impulse values for VS-2 and

VS-3. A better indication of the relative energy releases for the three explosives will be obtained by calculating energy fluxes at each gage. Further studies of this type are now in progress.

The enhancement factors used in predicting peak overpressures from row charges (Refs. F1 and F5) are determined by comparing VS-2 with IL-5,

Fig. F4. Positive phase impulses for IL-4 and IL-5 detonations.

since these two events used Slurry A explosive and gave consistent attenuation lines. These detonations indicate that $B = 1.0$ and 0.37 , for overpressures perpendicular and parallel to the row axes, respectively, when using the best fit to the data at 400 ft. Since the P_1 decayed with $R^{-0.9}$, P_{11} with $R^{-1.5}$, and P_{sc} with $R^{-1.3}$, the enhancement exponents will change with the range chosen for the determination. Preshot predictions were made using $B = 0.75$ and 0.5 , respectively.

ILIR Series

IL-4 and IL-5 were similar single-charge events of 210 lb of Slurry A at a DOB of 17.8 ft. The single-charge detonation IL-7 consisted of 150 lb of AN in canisters at a DOB of 17.8 ft.

IL-7 was different from the other two events in that it cratered. This can clearly be seen in the airblast records, where the strong late-time gas-vent pulse indicates venting, characteristic of cratering events. Also on the IL-7

Fig. F5. Peak overpressures for IL-7 detonation.

record, an initial high-frequency peak is observed, which attenuates very rapidly (as approximately $R^{-1.9}$). This peak is assigned to the primacord detonation. The ground-shock-induced peak arrives next, followed by the gas-vent pulse; both attenuate approximately as $R^{-1.1}$.

The IL-4 and IL-5 peak overpressures show considerable scatter; however, they fall within the range of predictions, displaying a slightly faster decay rate (approximately $R^{-1.2}$ to $R^{-1.4}$) than ex-

pected. The second peak at the close-in gages reported for these two events is actually just the first peak of the oscillatory pressure curve (the restoring pulse) usually observed following a dominant ground-shock-induced pulse; no other physical significance is assigned to it. Initially, it was suggested that, since an echo was detected from equipment working in certain areas of the quarry site, a similar effect might be observed from the detonations. Peaks like the "second

Fig. F6. Peak overpressures from VS-1, VS-2, and VS-3 detonations.

peak" for IL-4 and -5 cannot be assigned to such an echo. From the distances involved, the time separation of the echo from the initial pulse would be a minimum of 0.1 to 1 sec, and consequently the amplitude of the echo would be a small fraction of the original pulse, whereas the two peaks reported here are less than 0.01 sec apart. The two more distant gages on IL-5 and the farthest gage on IL-4 exhibited a different waveform: the first two peaks were actually much closer together than those for the close-in gages.

This relationship indicates that the second peaks are reflections from the sides or the bottom of the ravine situated between these gages and the shots. Gage 138 was located near the edge of the ravine for IL-5, and showed two peaks of nearly the same amplitude very close together. This gage was also considerably below SGZ elevation, thus explaining the low peak pressure level (Fig. F3).

The positive-phase impulses measured for IL-4 and IL-5 represent quite well-defined lines of $R^{-1.1}$ attenuation. Again,

Fig. F7. Positive phase impulses for VS-1, VS-2, and VS-3 detonations.

from Fig. F4, the effect of the position of gage 138 on the IL-5 detonation is quite apparent. Reflections increase the positive phase impulse, as would be expected.

The peak overpressures and impulses for IL-5 are consistently greater than for IL-4. The reason for this effect is uncertain, since both had equal amounts of explosive, equal DOB's, and similar geologic media. This effect indicates either that IL-5 was a higher-order explo-

sion than IL-4 or that the buffer zones around IL-4, which had been fired before the events had partially fractured the medium above the main charge, resulting in a poorer coupling of the explosive with the near-surface rock and giving a lower spall velocity. Maximum spall velocity for IL-5 was about 20 to 40 ft/sec as measured from high-speed film. Predictions were made using estimated velocities of 60 to 80 ft/sec.

Fig. F8. Peak overpressures from CS-1 and CS-2 detonations.

CS Series

CS-1 was a simultaneous detonation of six 150-lb charges at a DOB of 15.6 ft and a 16-ft spacing. CS-2 was a sequential detonation (25-msec delays) of the same charge configuration.

Comparing Figs. F3 and F8 shows that CS-1 produced peak overpressures only

slightly higher than the single-charge detonations, and CS-2 actually gave lower peaks. Since there was no primacord on the ground surface for the CS series, it seems likely that the peaks for the single-charge tests, which used primacord, were produced by a combination of primacord and surface spall. Separation of the two

Fig. F9. Peak overpressures from ML-1 detonation (circled symbols are for points along direction of row axis).

contributing factors is not possible at the present time.

For both events, the peak overpressures fell below predictions, and thus the oscillograph deflections, especially for CS-2, were very small, making the measurements less accurate. Comparison of the pulse shape for the farthest gage off the end of the CS-1 row with the pulse shape for similar simultaneous detonations (such as the VS series) reveals a noticeable "valley" in the middle of the first positive-phase pulse, indicating low-order or no detonation for one or more charges near the center of the row, specifically, the third and fourth charges from the gage end (south end). CS-2 pulse shapes off the end of the row indicate a low-order detonation of about the

Fig. F10. Peak overpressures from ML-2 detonation (circled symbols are for points along direction of row axis).

second sequenced charge. The interval between CS-2 peaks for the gages off the end of the row are actually about the same or smaller than for CS-1. This is because the sequence starts at the north end of the row and works toward the gages, and the 25-msec-delay and 16-ft-spacing combination gives an arrival-time sequence similar to that for CS-1, with the order reversed. The fact that the peaks

Fig. F11. Peak overpressures from primacord tests (circled symbols represent values obtained along primacord line axis direction; uncircled symbols are from points along direction perpendicular to this axis).

off the end of CS-2 were larger than those perpendicular to the row indicates that some reinforcement occurred due to superposition of adjacent charge pulses. The occurrence of overlap and possible superposition can also be deduced from Fig. F10, which shows the times of arrival plotted against the distance of the gages from the center of the row. The arrival times off the end for CS-1 are earlier than those perpendicular to the row, because of the initial arrival at each gage off the end is from the nearest charge (instead of the center of the row). For CS-2, all arrival times are later than for CS-1, and those off the end are about the same or later than those perpendicular to the row. The reason they are not noticeably later is that the "perpendicular" gages are actually only about 45 to 60 deg off axis. The discrepancy between arrival times for the gages off the end of the rows indicates that initial arrival for CS-2 is from the first sequenced detonation (rather than the "nearest" charge in the row).

Because of the small oscillograph deflections, no impulses were measured graphically. Impulse and energy for CS-1 will be determined later by digitized data analysis techniques and a computer reduction program. A comparison of energy could indicate the extent of low-order detonations on CS-1.

MS Series

This series was an experiment to determine the feasibility of using multiple lifts in quarry excavation. ML-1 consisted of presplit lines, buffer zones, and two rows of seven 125-lb charges each. ML-2 was at the bottom of the

ML-1 excavation; it also used presplit and buffer-zone charges, and a single 10-charge row of 75- to 300-lb charges plus a small array of charges at one end of the row. Since impulses will be more meaningful when assigned to particular detonations, impulse data reduction will be completed later with the above-mentioned computer routine.

ML-1 had a sequential firing of the presplits at 0 time, buffer zones at about 50 msec, and the main charges at about 150 msec. The closest gage perpendicular to the row axes revealed arrivals of the pulse peaks in the following order (west presplit arbitrarily chosen as 0 msec): (1) west presplit, 0, (2) east presplit, 62 msec, (3) west buffer zone, 74 msec, (4) east buffer zone, 120 msec, (5) west main charge row, 178 msec, (6) east main charge row, 195 msec. Each peak is distinct and clearly identifiable. With the known separation of the rows and an approximate acoustic velocity of 965 ft/sec, it is found that the buffer zone was actually fired at 70 msec and the main charges at 155 msec. For the closest perpendicular gage, the first presplit peak was the largest, and all other assigned peaks were about the same level. The east buffer zone had a noticeable gas vent, implying stemming failure, as did both main charge rows.

Perpendicular gages 135 and 137, at longer ranges, showed the same general pulse shape, with the usual dispersion-caused broadening. The higher frequency presplit and buffer-zone peaks decayed more rapidly than the main charge pulses, as would be expected. Some scatter of the peak-overpressure decay lines is due to the superposition of positive pulses on

the negative phases of preceding pulses.

The gages off the end of the rows give a better indication of the relative amplitude of each peak, because each row is about the same distance from the gage. Peak identification is not simple, because each pulse is actually a row pulse, and thus the pulse waveform consists of several extended row-type pulses followed by other superimposed row pulses. The result is a continuous "noisy"-looking wave with several positive- and negative-going pulses. Source identification is accomplished by using expected times of arrival.

It appears that most charges fired effectively. The main row detonation did not produce the largest airblast pulse for the close-in stations, where the presplit pulse predominated.

The waveform for ML-2 was slightly more complex. The closest gage perpendicular to the rows displayed distinct peaks for all detonations, but several additional peaks, which became unnoticeable at longer ranges, also appeared. Two of these peaks appeared at 9 and 16 msec after the first presplit pulse. These are probably either primacord peaks or reflections from the sides of the excavation. The identifications given to the other pulses indicate a buffer-zone detonation at 62 msec and main charge detonations at about 140 msec.

Again, superposition of the main-charge pulse and buffer-zone pulses on negative phases of previous pulses gives slightly misleading peak overpressures (plotted in Fig. F11). In spite of these uncertainties, it is evident that the attenuation rates on both ML-1 and ML-2 are very much faster perpendicular to the axis than off the end. Perpendicular,

the rate ranges around $R^{-1.8}$ to $R^{-2.8}$, whereas off the end it is closer to $R^{-1.2}$. The reason for rapid attenuation in the perpendicular direction is not clear.

ML-1 gives consistently higher overpressures both perpendicular and parallel to the rows. This difference could be partly due to ML-2 being "in a hole," although the total charge weight for ML-1 was also slightly larger.

Primacord Tests

The results of the primacord tests are given in Table F5. The yellow primacord of 50-grain strength gave approximately twice the peak deflections of the 25-grain E-cord. The test consisted of two 50-ft lengths of primacord about 3 ft apart (covered with 3 to 4 in. of soil) fired at zero time, and the same configuration about 10 ft away (uncovered) fired at 150 msec. Four gages were situated perpendicular to the long axis of these arrays, and one gage was off the end of these rows.

In the perpendicular direction, the average ratio of uncovered to covered cord peak overpressures for 25-grain E-cord was about 4.5; the ratio for 50-grain primacord was about 6.1. Off the end, the ratio at the one gage for both tests was only 1.5. The reason for the difference between ratios for the two directions is not clear, but the test indicates that airblast suppression by covering the primacord is effective only if the long axis of the primacord configuration does not point towards the direction of interest.

CONCLUSIONS

The airblast investigation produced generally high quality records. This

project thus satisfactorily tested the EERL airblast measuring system and confirmed our capability for making such measurements.

The data obtained increase our airblast prediction capability for small charge mounding detonations in basaltic andesite and similar rock media. The occurrence of low-order or misfired detonations might also be observed by means of the airblast pulse waveform. Thus, besides the usual safety aspect of airblast measurements, it is possible to evaluate explosion parameters.

For small-scale detonations, such as those considered here, the immediate topographic surroundings appear to have a noticeable effect on the shape and amplitude of the airblast wave. Accurate recording of pertinent terrain features and avoidance of irregular terrain whenever possible would aid data reduction. If primacord is used to fire small-sized detonations, then primacord must be taken into account when making the airblast predictions are made. The data needed to accomplish accurate predictions are not yet available.

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Appendix G

Minor Experiments

Several minor experiments were carried out at Project Lost Creek, most of which were designated with ILIR series numbers, although none were part of the original concept of the ILIR series.

ILIR-7: MILITARY EXPLOSIVE MOUNDING SHOT

As a test of the mounding efficiency of the standard Army cratering charge, in comparison with that of slurry blasting agents, a single mounding blast using the Army charges was carried out. The Army MO 39 40-lb cratering charge, an "off-the-shelf" type of explosive, is packaged in a canister 7 in. in diameter and 2 ft in length. It contains 30 lb of ammonium nitrate with an integral booster of 10 lb of TNT. The IL-7 charge was composed of five of these canisters end-to-end, resulting in a total length of 10 ft and a length-to-diameter ratio of 17 (Fig. G1). The center-of-charge burial depth was 17.8 ft, but the top of the charge was only 12.8 ft deep.

This detonation was instrumented to measure close-in subsurface ground shock, but a malfunction of unknown cause occurred in the recording system, and no records were obtained. Intermediate-range ground-surface seismic-vibration measurements were successfully made. Following the detonation, an attempt was made to dig out the broken material with the Gradall.

The IL-7 detonation threw considerable amounts of ejecta, leaving a small rubble-filled crater, 1 ft deep below the

original ground surface, rather than a mound. The Gradall dug into this rubble to refusal, which occurred at a depth of about 8 ft below the ground surface. Figure G2 shows the configuration of the apparent crater formed at IL-7, and the configuration of the experiment site after excavation. The small crater formed at IL-7 probably resulted from the shallow depth at which the upper end of the charge was buried.

ILIR-8: SMALL TRIMMING QUARRY

A small test quarry was opened up and its face repetitively trimmed backwards to study trimming techniques. A point of interest was to determine how great a burden could be trimmed with a given explosive loading. The quarry was situated in firm columnar-jointed rock east of the ML experiment and downhill from it (see Fig. G3).

The initial shot to form the quarry, designated IL-8A, comprised a presplitting blast and a "V-cut" pattern of delays (Fig. G3). The broken rock was excavated with a D-8 bulldozer. The working face was then trimmed back in three stages, the trimming blasts being designated IL-8B, IL-8C, and IL-8D, respectively. Details of loading for each detonation are given in Fig. G3.

The initial quarry detonation (IL-8A) produced a neat pile of broken rock, which was excavated by the D-8 bulldozer in 1 hr. The bottom failed to break near the face, however, and the bottoms of the

presplit holes were reloaded and fired ahead of IL-8B (note 3, Fig. G3). Each of the trimming blasts produced well-fragmented material and a clean vertical face. A view of the face after firing and excavation of IL-8B is shown in Fig. G4, and after IL-8D, in Fig. G5.

ILIR-9: SINGLE-CHARGE MOUNDING SHOTS

Late in the project it was decided to detonate three single 200-lb mounding charges of the three different blasting agents tested in the VS series. These tests were intended as a check on the

Fig. G1. Plan and sectional view, IL-7 detonation.

results of the VS series, in which varying mounding effectiveness had been shown by the three blasting agents. The

only effects measured were size of the mound produced and seismic ground-surface motions. The three detonations

(a) Section N85°W through IL-7 crater

(b) Section N5°E through IL-7 crater

Fig. G2. Sections through crater formed by IL-7 detonation.

were designated IL-9A (Slurry A), IL-9B (Slurry B), and IL-9C (ANFO).

An additional test performed was the detonation of twin charges of one of the

blasting agents in adjacent 6-in.-diameter blastholes, the combined weight of the two charges to equal approximately that of a single charge in a 10-in. hole. This

Fig. G3. Plan and sectional view, IL-8 quarry. (a) Plan. (b) Section AA'.

Fig. G4. IL-8 quarry face after first trimming detonation (IL-8B).

Fig. G5. IL-8 quarry face after third and final trimming blast (IL-8D).

test was designated IL-9D, and Slurry A was used. The details of the four detonations are shown in Fig. G-6.

The mounds resulting from the four IL-9 detonations confirmed the results of the VS-series. The largest mound was produced by ANFO (IL-9C). Next largest were the two mounds formed by Slurry A (IL-9A and IL-9D), and smallest was the mound formed by Slurry B (IL-9B). The topography of the four mounds is shown in Fig. G7, and sections through the mounds are shown in Figs. G8 through G11.

VS-1T TESTS: TRIMMING EXPERIMENTS IN VS-1 PIT

Following excavation of the VS-1 experiment, two attempts at trimming were made along the pit walls. One trimming pattern was drilled along the northwest edge in the vicinity of Charge E, the other in the south corner of the pit. The layouts and loadings of these patterns are shown in Fig. G12.

Neither test produced a clean face. At shallow depths at VS-1T(A) the rock

failed back to slightly behind the desired face, and rifts were formed in the rock 1 or 2 ft back from the newly formed pit lip. The detonation produced numerous large boulders (larger than 2 ft in diameter), some of which had drill holes running through them; evidently they were spalled from the upper portion of the rock. In the lower part of the detonation, the solid bedrock was unbroken and could not be excavated by the Traxcavator. VS-1T(B), in the south corner of the pit, likewise produced breakage to behind the desired face and a number of large boulders. In neither test was any trimmed face obtained.

The unfavorable factors for trimming at this site included both the layer of rock that was weathered along fractures and the fact that the rock had sustained the shock of the VS-1 mounding blast. The broken nature of the rock caused considerable difficulty in drilling and loading the blast holes. The lower part of the VS-1T(A) face probably could have been satisfactorily exposed had additional blast holes been used in front of the trim holes to break out the lower rock.

Fig. G6. Sectional views of IL-9A, IL-9B, IL-9C, and IL-9D experiments (single charges: no instrumentation).

Fig. G7. Four mounds from IL-9 series.

(a) Section E-W through IL-9B mound

Fig. G9. Sections through IL-9B mound.

(a) Section E-W through IL-9A mound

(b) Section N-S through IL-9A mound

Fig. G8. Sections through IL-9A mound.

(a) Section E-W through IL-9C mound.

(b) Section N-S through IL-9C mound.

Fig. G10. Sections through IL-9C mound.

(a) Section E-W through IL-9D mound.

(b) Section N-S through IL-9D mound.

Fig. G11. Sections through IL-9D mound.

(a) First trimming detonation (VS-ITA).

(b) Second trimming detonation (VS-ITB).

Fig. G12. Trimming experiments in VS-1 excavation.

Appendix H

Theoretical Justification for Point-Counting Method of Determining Rubble Size Gradation

Reference H1 describes a system of point-counting that may be used to determine the gradation of a rock rubble deposit produced by an explosive excavation event. This method is much cheaper and easier to use than collecting and sieving a sample of the deposit.

Size gradations of granular material are almost always based on sieve analyses. The latter are reported in terms of weight fractions of particles in given size ranges. For gradations from a simplified technique such as point counting to be generally accepted, they must be comparable to those determined on a weight basis.

Comparative tests in which sieving and point counting were carried out on the same material yielded very similar gradations (Ref. H1: Fig. 13). The question of why this correspondence should be true was mentioned but not otherwise addressed in Ref. H1. The following argument demonstrates why the point-counting method works.

It is essential at the outset that the term size be defined. As used herein, the size of a particle means the intermediate dimension of the smallest rectangular box that the particle could be fitted into exactly. So defined, this dimension is close to but not identical with the dimension sensed by a sieve. The questions of size and shape of irregular particles are discussed in Ref. H2.

A rubble deposit is composed of particles the sizes of which vary from

finest (less than 1/16-in.) to some maximum. The maximum in a given deposit might, for instance, be 4 ft. The particles are generally irregular in shape and lie together to form a fabric, a certain portion of which is voids.

The deposit may be homogeneous or heterogeneous; i.e., it may be composed of one type of rock or of more than one type. It may likewise be isotropic or anisotropic; i.e., its composition or fabric may be the same everywhere or it may vary systematically with direction, as in layering. The argument pursued herein is valid for homogeneous and isotropic rubble. The question of how much its validity fails in the case of heterogeneous or anisotropic rubble is discussed briefly below, but has not been examined in depth.

In a homogeneous deposit, the density of all particles is the same. Thus the weight of each particle is proportional to its volume. In an isotropic deposit, any traverse across or through it encounters the same assortment of rock blocks as any other. Thus in principle the blocks encountered in any traverse form a valid sampling of the deposit as a whole.

Given a rubble deposit, it is theoretically possible to sort all the blocks therein according to size. They could all be laid out in a line in order of size. Choosing certain sizes as cutoff points, we could divide our lineup of blocks into convenient size grades. Weighing the fragments in each grade, we could arrive

Fig. H1. Hypothetical stacking of cubic rubble blocks.

at a proportional distribution by weight. This is exactly analogous to a sieve analysis.

Operating on a given deposit, let us figuratively lay out all our blocks in order, as suggested above, and set up size grades. Let us then make two simplifying adjustments. First, let us convert each block from its actual size to the size of the median block in its grade. Then, let us adjust each block from its natural shape to the shape of a cube. Certain errors are introduced by these substitutions, but discussion of these errors is postponed until later.

Our deposit is now composed of a large number of cubic blocks of a finite number of sizes. Let us now stack these blocks into a close-packed configuration. In stacking, let us use cubes of a given size to compose each stack, and let us adjust our stacks to a common height. Also, let us arrange our stacks so that the smallest particles are at one end of our deposit, the largest particles at the other. Our deposit will now have been rearranged into a rectangular pile such as the one shown in Fig. H1. (Note: As drawn, the blocks in classes A and C are slightly distorted from cubes, for purposes of graphic simplification. In fact,

with a large number of blocks, by adjustment of dimensions in all three directions, a perfect or nearly perfect rectangular pile could be constructed.)

Let us now consider the results of two methods of mechanical analysis of the aggregation shown in Fig. H1, (a) by sieving, and (b) by point counting. Sieving will divide the material into the six classes A, B, C, D, E, and F. From geometry and the fact that all blocks are of equal density, it is obvious that the weights of these classes will stand in the proportions 4:6:6:6:6:3.

Consider now running a point count across the top of the deposit, from right to left or vice versa. Count points at any regular repetitive interval and assign each point to the size class of the block falling below it. The number of points assigned to each class will obviously tend to be proportional to the length of the traverse line underlain by the respective class. The more points taken (i.e., the smaller the sampling interval), the more closely the proportions approach their ultimate, correct value, which for the material in Fig. H1, is 4:6:6:6:6:3. Thus the two methods give identical results in this idealized case.

It is important to be aware of the simplifications introduced in this argument, and of the possible errors introduced thereby. Each real block was replaced by an equivalent-sized cube. The more the shapes of the real blocks depart from equidimensional, the greater is the error introduced herein. The more the actual fragments are tabular, platy, or "oblate" in shape, the more will the cubic substitution lead to overstated weights. The more needle-like or "prolate" the fragments, the more will the cubic substitution lead to understated weights. "Oblateness" is probably commoner in actual rubble blocks than "prolateness," so that the technique probably overestimates the effect of rocks that break to form flattish fragments.

Another simplification was the adjustment of all block sizes to median class sizes. This process should be self-compensating and should not introduce an appreciable error. The effect has not been studied exhaustively, however.

Fundamental to the point-counting technique, of course, is the requirement that the traverse or traverses selected are truly representative of the deposit as a whole. If the traverse does not "see" a representative assortment of blocks, the result cannot be correct. The number of sampling points, also, must be large enough to yield a significant result. These problems are of course fundamen-

tal and common to any problem of sampling of a population.

Within the limits posed by these uncertainties, the above simple demonstration shows that in the case of uniform rock that breaks into nearly equidimensional fragments, the mechanical analysis derived from point counting should approximate that derived from sieving the same material. It may be noted that the basaltic andesite rock at Lost Creek was quite uniform and broke into generally equidimensional fragments. It was thus very well-suited to the point-counting technique.

It may be mentioned that an unnecessary restriction in carrying out the point-counting technique is imposed in Ref. H1 where it is stated that the sampling grid should be larger than the largest block to be counted. The evident intent of this restriction is to prevent any single block from being counted more than once. The geometric argument advanced above, however, shows that the double or even triple (or more) counting of a large block is not an invalid step. The feature being measured by the point-counting technique is the area fraction underlain by blocks of a given size. So long as the traverse is truly representative, the one point out of 100 that falls on a certain large block produces the same information that four points out of 400 do, using a finer sampling grid.

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