TECHNICAL REPORT E-74-1

PROJECT TRINIDAD
EXPLOSIVE EXCAVATION OF RAILROAD CUTS 2 AND 3
BY MOUNDING AND DIRECTED BLASTING

Jerome E. Lattery

January 1974

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

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the Trinidad Dam and Lake Project. The first of the two experiments tested a charge array designed to break up material within a 19,000-yd³ cut to facilitate later removal of the material by mechanical means. The concept tested was mounding, a blasting technique in which charges are positioned with respect to the horizontal ground surface rather than a vertical bench face. The results from this experiment confirmed the applicability of empirical scaling methods to the design of an array of deeply buried charges. The second experiment was a directed blasting detonation that was designed to produce a 30,000-yd³ through-cut by cratering. This experiment tested a charge array design that had been developed by a combination of empirical scaling and kinematical methods.

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Jerome E. Lattery

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Preface

This report describes the two final experiments of Project Trinidad, a comprehensive series of experiments to determine the cratering properties of interbedded sandstones and shales and to confirm empirical parameters employed in explosive excavation design methods.

This report was prepared at the U.S. Army Engineer Waterways Experiment Station (USAEWES) Explosive Excavation Research Laboratory (EERL). Prior to 21 April 1972 EERL was the USAEWES Explosive Excavation Research Office (EERO). Prior to 1 August 1971 the organization was the USAE Nuclear Cratering Group.

The Directors of WES during execution of the experiments and preparation of this report were COL E. D. Peixotto and COL G. H. Hilt; the Directors of EERL were LTC R. L. LaFrenz and LTC R. R. Mills, Jr.

Abstract

This report summarizes the objectives, design, and results of two explosive excavation experiments performed as the final phase of Project Trinidad, a comprehensive series of tests to determine the cratering properties of interbedded sandstones and shales. The experiments were performed in September 1971 by the U.S. Army Engineer Waterways Experiment Station Explosive Excavation Research Laboratory. These final experiments were designed to excavate through-cuts for relocation of the Colorado and Wyoming Railroad at the Trinidad Dam and Lake Project. The first of the two experiments tested a charge array designed to break up material within a 19,000-yd³ cut to facilitate later removal of the material by mechanical means. The concept tested was mounding, a blasting technique in which charges are positioned with respect to the horizontal ground surface rather than a vertical bench face. The results from this experiment confirmed the applicability of empirical scaling methods to the design of an array of deeply buried charges. The second experiment was a directed blasting detonation that was designed to produce a 30,000-yd³ through-cut by cratering. This experiment tested a charge array design that had been developed by a combination of empirical scaling and kinematical methods.

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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: $K = (5/9) (F - 32) + 273.15$.

PROJECT TRINIDAD

EXPLOSIVE EXCAVATION OF RAILROAD CUTS 2 AND 3 BY MOUNDING AND DIRECTED BLASTING

Introduction

BACKGROUND

The two experiments described in this report were the final phase of Project Trinidad, a comprehensive series of explosive excavation experiments in interbedded sandstones and shales. The experiment series was conducted by the U.S. Army Engineer Waterways Experiment Station (USAEWES) Explosive Excavation Research Laboratory (EERL).

A basic mission of EERL is to develop techniques for excavating large quantities of earth and rock rapidly and economically by means of explosive energy. To the greatest possible extent, developmental experiments and demonstrations of the techniques are performed at the sites of authorized Corps of Engineers civil works projects and contribute toward completion of the project excavation work. The railroad cut experiments were performed at the Trinidad Dam and Lake Project and formed through-cuts for the relocation of the Colorado and Wyoming Railroad.

The earlier phases of Project Trinidad comprised a comprehensive series of experiments to determine the cratering properties of the interbedded sandstone and shale and to confirm empirical parameters employed in explosive excavation design. Cratering properties of the me-

dium were determined by a series of 1-ton single-charge detonations with charge burial depths ranging over the depths of practical interest. To compare their relative effectiveness, two types of explosive were used in this series. The experiments also included a number of row-charge cratering tests to confirm empirical relationships that prescribe charge spacings and burial depths for row charges. The final experiment in this earlier series was a double-row charge designed to produce a railroad cut.¹

SCOPE

This report provides an overall technical summary of the two railroad cut experiments. Included are descriptions of the charge array designs and the results from an engineering point of view. As contrasted with the experiments of earlier phases of Project Trinidad, these were designed primarily as applications of previously developed principles, rather than as fundamental developmental experiments. Although these experiments involved comparatively large tonnages of explosives in elaborate charge arrays, they were conceptually simple and were not heavily instrumented.

The primary technical objective of each of the railroad cut experiments was to test the performance of a particular explosive charge array. The first experiment, designated RR2, tested an array designed to break material within the intended excavation to facilitate removal of the material by mechanical means. A charge array of this type, referred to as a mounding charge array, produces results similar to those attained by conventional pattern blasting. (The significant differences between a mounding detonation and a pattern blast are the means by which charge sizes and positions are determined and the fact that a mounding

detonation is designed to break to a horizontal surface, rather than a bench or face.) The second experiment, RR3, tested a charge array designed to produce a crater the dimensions of which approximated those of the excavation that would have been performed by conventional means. Of particular interest were comparisons of predicted and actual cross sections of the broken volume (Experiment RR2) or crater (Experiment RR3).

Table 1 is a summary of parameters describing the overall dimensions of the excavations and the two charge arrays.

Table 1. Dimensions of Trinidad RR2 and RR3 experiments.

Designation, basic type	RR2 Mounding	RR3 Cratering
Excavation volume, yd ³	19,000	25,500
Excavation length, ft	520	520
Maximum excavation depth, ft	28	42
Total charge weight, tons	10.4	68.5
Number of charges	37	48
Minimum charge size, tons	0.2	0.5
Maximum charge size, tons	0.4	4.0
Crater volume, yd ³	—	28,600

Description of Project

SITE DESCRIPTION

The experiments were sited on the relocated alignment of the Colorado and Wyoming Railroad at the Trinidad Dam and Lake Project in Las Animas County, Colorado. Figure 1 is a map of the project area showing the relative locations of the damsite, relocated railway,

population centers, and the experiment sites. Three small towns in the vicinity of the experiment sites were within the reservoir clearing line and had been abandoned or demolished prior to the time the experiments were conducted. The remaining population centers nearest the sites were Jansen and Starkville, each being approximately 2 mi from the RR3

Fig. 1. Map of Project Trinidad vicinity.

site. The structures nearest the sites were the Corps of Engineers field office and the Trinidad Dam intake structure, both of which were about 1 mi from the Experiment RR3 site.

The two experiment sites were selected from the 23 through-cuts required along the 9-mi railroad relocation. Selection criteria included topography, excavation volume, proximity to man-made structures, type of material, and accessibility. The Experiment RR2 site was selected primarily for its slight sideslope and uniform depth of cut. The RR3 site, on the other hand, was selected for its steep sideslope and relatively deep depth of cut.

The RR2 site extends from Station 117+00 to Station 122+50 on the Albuquerque District Corps of Engineers railroad relocation plan; the RR3 site from Station 190+00 to Station 195+40 on the same plan.

The geologic stratigraphy of the RR2 site is shown in Fig. 2. The media at this site consist of shales, sandstones, siltstones, and coal in a complicated layering. The layers are reasonably persistent laterally except in the eastern third of the cut, where a fault crosses the alignment at an acute angle. The upper 10 ft of material consists of 2 ft of overburden and 8 ft of sandstones. The sandstones are of low strength and thinly

bedded, except for a persistent medium-strength bed of 3- to 6-ft thickness near the surface. Below the 10-ft depth, the material consists primarily of shales, siltstones, and coal.

For purposes of explosive excavation design, the medium at the RR2 site was considered to consist of dry, low-strength (less than 4000 psi) rock. Typical unconfined compressive strengths of its constituents were 500 to 1000 psi for the shales, 500 to 1500 psi for the siltstones, and 1000 to 4000 psi for the sandstones. Except for the coal, the media had a grain specific gravity of 2.7.

The RR3 site stratigraphy is shown in Fig. 3. The medium at the RR3 site had a complicated layered stratigraphy similar to that of the RR2 site.

For purposes of explosive excavation design, the entire volume of material at the RR3 site was also considered to be dry, low-strength (less than 4000 psi)

rock. The shales exhibited unconfined compressive strengths of 400 to 2400 psi, the sandstones had strengths of 1000 to 6500 psi, and the siltstones had strengths of 500 to 1000 psi. Although two sandstone layers had strengths greater than the upper limit of the low-strength category, they were only 2- to 4-ft thick and thus comprised a small fraction of the total material volume.

Except for the coal, the RR3 site media had a grain specific gravity of 2.7 and an average dry density of about 150 lb/ft³.

EXPLOSIVE CHARGES AND EMPLACEMENT

The explosive in both charge arrays was a mixture of prilled ammonium nitrate and 5.5% No. 2 fuel oil, a composition widely used commercially and known as ANFO. The two ingredients

Fig. 2. Stratigraphic cross section of the RR2 site.

Fig. 3. Stratigraphic cross section of RR3 site.

were mixed in a pump truck and poured into the emplacement holes.

Each charge was axially primed with a full-column string of Composition B high-pressure boosters. The boosters were initiated by detonating fuse arranged

in a conventional system of trunklines and downlines. In the charge array for the RR3 detonation the delayed charges had delay links at the primers with special 8-grain/ft downlines. In both charge arrays, the detonating fuse

system was fired by electric blasting cap.

The charges were placed in uncased holes drilled with a flight auger. Three hole diameters were used to accommodate the charge loads of 400 to 8000 lb per hole. Table 2 shows the hole diameters, charge weights, and approximate explosive column heights used. After placement of the primers and charge, each emplacement hole was fully stemmed with drill cuttings and soil.

TECHNICAL PROGRAM

The primary technical program activities were preshot and postshot mapping and surveying, and engineering properties investigations of the material and cratered areas. Other activities included high-speed motion picture photography of the detonations and measurements of ground motion and airblast effects.

The mapping and surveying consisted of detailed aerial photogrammetric surveys preshot and postshot at each site, supplemented by ground surveys. Contour maps of 1/600 scale with 2-ft contours were prepared for a 500- X 1000-ft area at each site. The differences between preshot and postshot topography revealed the apparent crater dimensions and aided observations of the disposition of ejected material.

Geologic and engineering properties investigations included preshot site explorations and postshot earthwork at the craters. Preshot investigations consisted of core drilling at each site to identify the media types and collect samples for laboratory testing. The postshot work included a pilot excavation at the

Table 2. Charge geometries.

Charge weight (lb)	Hole diameter (in.)	Column height (ft)	Height/diameter
400	12	9	9
500	18	5	3.3
800	18	8	5.3
1000	18	10	6.7
2000	36	5	1.7
3000	36	7	2.3
4000	36	10	3.3
5000	36	12	4.0
8000	36	19	6.3

RR2 site and crater shaping and grading at the RR3 site. The postshot particle-size distribution was sampled at both sites.

Photography included high-speed motion pictures of each detonation. The films were useful for surface motion measurements and furnished a general documentation of each detonation. For Experiment RR2, films were taken from positions west and north from the detonation. Standing targets were placed on the site to establish a distance scale on the films. On the RR3 experiment films were taken from positions east and north from the detonation site. Targets were placed over the end charges of each charge row and at selected positions over the charges. The former established distance scales on the films, and the latter marked locations on the surface for surface motion measurements.

Intermediate range ground motion and airblast effects were measured for both detonations. These measurements were conducted primarily to check predictions and to acquire legal documentation of the

effects. Ground motions were measured at two stations to determine peak motion amplitudes and attenuation with distance. On both detonations one ground motion station was located at the base of the

Trinidad Dam intake structure and the second at a position 1600 ft closer to the detonation. Airblast was measured at one station for the RR2 detonation and at three stations for the RR3 detonation.

Experiment RR2

OBJECTIVES

The basic objective of Experiment RR2 was to test a charge array designed to break, or mound, material within the planned excavation. The charge array tested was a double-row charge configuration of a design based on empirical scaling principles. In the development of explosive excavation techniques it represents an intermediate step between (1) charge array designs previously employed to form excavations by cratering with concentrated charges and (2) charge array designs used to fracture material with a pattern of columnar charges, as in conventional blasting practice. Since the experiment was intended primarily to determine the applicability of the scaling formulas, the design was kept simple and optimized neither cost nor ease of construction.

In a charge array of this type the design parameter most critical to production of a broken zone of uniform cross section is the spacing between charges within either row of charges. With optimum spacing, the width of the broken zone at positions between charges is equal to the broken zone width at the charge positions. Excessively wide spacings cause a reduction of crater width

(cusping) between charge positions; spacings too small cause excessive surface movement and throw. The main objective of this experiment was thus to verify the spacing parameter for a blast of practical production size. A second objective was to confirm the choice of scaled burial depth of the individual charges in the array. Optimum burial for mounding would produce satisfactory breakage with a moderate amount of surface movement.

EXPERIMENT DESIGN

In Fig. 4 the charge array plan is shown superimposed on a contour map of the natural terrain. Station positions of the charges, charge depths of burial, and charge weights are shown in Table 3. Three typical cross sectional profiles are shown in Fig. 5.

Development of the experiment design entailed (1) selecting appropriate scaling relationships for charge size, spacings between charges, and charge depth of burial, and (2) incorporating these relationships into a charge array that would conform to the variable cross-sectional geometry of the desired excavation. The scaling relations employed in the design for the RR2 Experiment were of the same form as those developed for designing

Fig. 4. Charge array for RR2 detonation.

row charges for cratering.² The general form of the relations is:

$$L = l_0 (y/y_0)^b,$$

where L is a scaled parameter for a charge of size, y , and l_0 is the value of the parameter for a reference charge size y_0 . For cratering phenomena that are little influenced by gravity an exponent, b , of $1/3$ is appropriate. The three scaling relations of this form employed in the RR2 design, written with numerical coefficients and units, are as follows:

$$\begin{aligned} \text{DOB} &= 35 y^{1/3} \text{ ft}, \\ S &= 42 y^{1/3} \text{ ft}, \\ W/2 &= 30 y^{1/3} \text{ ft}. \end{aligned}$$

In these equations, DOB is the depth of burial, y is the charge weight, S is the spacing between charges, and $W/2$ is the broken zone (crater) half-width at the ground surface. The unit of charge weight is a ton of TNT, which for purposes of this experiment was considered to be equivalent to a ton of ANFO.

The numerical coefficients were a matter of some judgment, because little quantitative information on mounding row charges existed at the time. The best

example of a mounding row charge was an experiment conducted by the USSR to determine the feasibility of raising a small dam by bulking the rock material in place.³ Other sources of information were a report of small-scale tests in soil with deeply buried single charges⁴ and an

extension of empirical formulas developed for row-charge cratering.²

In the latter case, the extension of cratering formulas consisted of generalizing the crater radius description to

Table 3. Charge emplacement data for RR2 detonation.

Station (ft)	Offset from RR centerline (ft)	Charge burial depth (ft)	Charge weight (ANFO) (lb)
117+37	3 north	21	400
117+62	5 north	21	400
117+87	6 north	24	500
118+14	8 north	24	500
118+43	8 north	24	500
118+72	9 north	24	500
119+01	10 north	24	500
119+30	10 north	24	500
119+59	10 north	24	500
119+88	10 north	24	500
120+20	10 north	28	800
120+55	10 north	28	800
120+90	11 north	28	800
121+22	11 north	24	500
121+49	11 north	21	400
121+74	11 north	21	400
121+99	11 north	21	400
116+94	15 south	21	400
117+19	18 south	21	400
117+44	18 south	21	400
117+71	15 south	24	500
118+00	14 south	28	800
118+35	14 south	28	800
118+70	13 south	28	800
119+05	12 south	28	800
119+40	12 south	28	800
119+75	12 south	28	800
120+10	12 south	28	800
120+45	12 south	28	800
120+80	12 south	28	800
121+12	11 south	24	500
121+39	11 south	21	400
121+64	11 south	21	400
121+89	11 south	21	400
122+14	11 south	21	400

(a) Cross section at station 118+00

(b) Cross section at station 119+50

(c) Cross section at station 121+00

Fig. 5. Typical cross-sectional profiles, Experiment RR2.

include the radius of the broken zone (true crater) for the case of charges buried at mounding depth. In cratering experiments it had been determined that charges within a simple row charge may be separated by a distance as great as 1.4 times the radius of the crater that any one of the charges would produce acting alone. Charges more closely spaced may be regarded as being equivalent to a continuous line charge, and crater dimensions vary as the inverse one-half power of the charge spacing. Parallel relationships were sought for rows of mounding charges. It was hypothesized that a maximum charge spacing definable in terms of broken zone radius should exist for mounding row charges, and that mounding row charges employing spacings within this maximum could be designed with formulations similar to those used for cratering row charges. A small-scale experiment was conducted near the RR2 site to ascertain the limits of spacings that might be employed in mounding row charges. Scaled spacings covered the range of from 1.0 to 2.0 times the broken zone radius. Although no maximum spac-

ing was clearly demonstrated, spacings in the midrange of those tried appeared to produce the best results with respect to rock fragmentation and broken volume per pound of explosive. A spacing of 1.4 times the broken zone radius was tentatively selected as suitable for mounding row-charge design. This particular spacing is the same as that employed for the cratering row charge design because the crater radius and broken zone radius are nearly equal for charges buried at optimum cratering depth.

Values of coefficients for the scaling relations used to design the charge array for Experiment RR2 were decided upon by subjectively considering the possible values from the several sources. The selected values are compared in Table 4 with those employed in the USSR experiment and those from other sources as noted.

The scaling parameters were applied graphically to the actual design of the charge array. The charge sizes and spacing between charges in both rows were determined by matching, as nearly as practicable, the theoretical broken

Table 4. Estimates of scaling coefficients for Experiment RR2 design parameters.

Parameter	Estimated values		Experiment RR2 design values
	USSR experiment	Other	
Charge burial depth	$34.4 y^{1/3.2}$	$40 y^{1/3^a}$	$35 y^{1/3}$
Half-width (radius of broken zone, $w/2$)	$26.5 y^{1/3.2}$	$28 y^{1/3^b}$	$30 y^{1/3}$
Spacing between charges	$44.7 y^{1/3.2}$	$42 y^{1/3^c}$	$42 y^{1/3}$

^aData in Ref. 4 imply optimum mounding depth is 2 to 3 times optimum cratering depth, which is $\sim 20 y^{1/3}$.

^bSingle-charge cratering data.

^cExtension of empirical row-charge cratering design formula.

zone profiles to cross sections of the cut taken at regular intervals along the alignment. The minimum charge size of 400 lb was the size necessary to produce a broken zone of requisite width in the double-row configuration. Because of the three-dimensional variability of the excavation, and the interrelated variables in the scaling relations, it was necessary to simplify the design by holding constant the spacing between rows. The interrow spacing selected was correct for 400-lb charges, but would have been too small for the larger charges. To correct this, the spacing between charges in both rows was extended 10% except where adjacent charges were each 400 lb.

A further consideration in the design is that the formation of the broken zone is independent of gravity. The broken zone associated with each charge is due primarily to a stress wave reflection phenomenon. Initial rock breakage and spalling at the ground surface occur when a strong compressional wave from the detonation of a charge is reflected at the surface as a tension wave. Material within a roughly conical volume delimited at the surface by this spalling phenomenon is heaved by the explosion product gases to leave a broken zone. Stress wave propagation is unaffected by gravity and stress wave reflection is symmetric about an axis normal to the reflecting surface. Consequently, the broken zone produced by the detonation of a charge is symmetric about this axis. In the charge array design, formation of the broken zone normal to the nearest free surface was anticipated, and charges were placed in such positions that broken zones formed normal to the nearest free sur-

face would be properly positioned with respect to the excavation boundaries and centerline.

RESULTS

The charge array for the RR2 experiment was detonated at 1115 hr, local time, on 18 September 1971. All 35 charges were detonated simultaneously.

Postshot inspection of the site revealed that relatively little permanent displacement of the ground surface had occurred. Although mixing of the various layers in the stratigraphic sequence had been expected, it was found that material near the surface had moved as a unit. Over a considerable area of the mound the thin layer of topsoil was found nearly intact on the coarsely broken sandstone layer. In Fig. 6 the photographs show the general postshot appearance of the surface. In general, the detonation created a slight depression on the south (uphill) side of the cut and created a low mound on the north (downhill) side.

Films of the detonation confirmed the relatively low rise and small lateral movement of the lofted material. Throughout the central 300 ft of the cut the surface material was lofted to heights of less than 30 ft. This low lofting indicates surface velocities of 45 ft/sec or less.

Table 5 shows the broken zone half-width, $W/2$, at various station positions. These dimensions are the horizontal distance from the alignment of each charge row to the apparent surface limit of breakage, as evidenced by cracks and discontinuities. At all station positions the broken zone was wider than predicted.

(a) North of centerline.

(b) South of centerline.

(c) West end.

Fig. 6. Experiment RR2 mound.

The average amount by which the measured half-widths exceeded the predicted half-widths was approximately 48%.

A pilot excavation was performed at the west end of the cut to determine the

(a)

(b)

Fig. 7. Pilot excavation work for Experiment RR2 in progress.

overall quality of rock breakage at depth. The western 100 ft of the cut was excavated vertically to subgrade and horizontally to the limit of breakage at the sides. Figure 7 shows the excavation work in progress. Some oversize rock was encountered at the surface, but underlying material was well broken and easily excavated. The particle size gradation was sampled during the pilot excavation work with the results shown in Fig. 8.

The remaining broken material is being excavated during the normal course of railroad relocation work. As of June 1973, approximately one-half of the entire volume had been excavated. The slopes on the sides of the cut are being formed at

Table 5. Broken zone half-widths, Experiment RR2.

Station	North side			South side		
	Half-width (ft)	DOB (ft)	Half-width DOB	Half-width (ft)	DOB (ft)	Half-width DOB
117+00	—	—	—	30	21	1.43
117+50	—	—	—	30	23	1.30
118+00	24	24	1.00	32	28	1.14
118+50	32	24	1.33	32	28	1.14
119+00	35	24	1.46	38	28	1.36
119+50	36	24	1.50	28	28	1.00
120+00	40	26	1.54	30	28	1.07
120+50	32	28	1.14	37	28	1.32
121+00	38	26	1.46	30	26	1.15
121+50	36	23	1.57	25	21	1.19
122+00	24	21	1.14	23	21	1.10

45 deg rather than the slope of 63 deg originally designed.

CONCLUSIONS

The overall results of the RR2 experiment confirmed the applicability of empirical scaling principles to the design of mounding charge arrays. The broken zone was of uniform width over most of its length without evidence of between-charge-position cusping or excessive cratering at the charge positions. The mound rise, although low, was uniform throughout the central region of the cratered area.

The broken zone half-width was greater than predicted. The assumed scaled half-width was $30 y^{1/3} \text{ ft/ton}^{1/3}$, or 0.857 DOB. The observed results indicate an average scaled broken zone half-width of $44 y^{1/3} \text{ ft/ton}^{1/3}$, or 1.27 DOB.

No allowances had been made in the design for the fact that a rock layer near the surface was much harder and stronger than the material at depth in which the charges were emplaced. Consequently, the surface velocity was low and generally poor breakage of the surface layer occurred. In a practical production

Fig. 8. Particle size gradation, Experiment RR2.

situation the remedy would have been to place decking charges or satellite charges in the hard layer. In this particular case,

however, such alterations to the charge array design would have compromised its research value.

Experiment RR3

OBJECTIVES

The objective of Experiment RR3 was to test a charge array for production of a through-cut in sloping terrain by directional throwout cratering (directed blasting). The charge array was designed to form a crater of overall dimensions comparable to those of an excavation that might be formed at the same location by conventional means. The unique feature

of this experiment was the employment of kinematics in addition to the more well-established empirical scaling method in the development of the experimental design. Charge weights and charge locations were determined in part by estimates of velocity and momentum imparted to masses of material. The overall performance of the charge array was assessed by comparing the actual vs predicted crater dimensions and ejecta distribution.

Fig. 9. Charge array for RR3 detonation.

EXPERIMENT DESIGN

The RR3 experimental design included four rows of charges in a three-dimensional array. Figure 9 shows the charge array superimposed on a contour map of the natural site terrain. The position, weight, and burial depth of each charge are shown in Table 6.

The charge array was designed to create a crater by a sequential detonation of two groups of charges. The first group of charges was the row charge on the downhill (north) side of the railway centerline. The second group included all charges in the three remaining rows. Charge weights and positions within each group were determined by empirical scaling methods. The degree of interaction between the two groups of charges was determined by considering the momentum of the masses of lofted material.

The empirical scaling method for designing row cratering charges comprises a few basic formulas for determining the charge size, the depth of burial, and the proper spacing between charges, as discussed in the preceding section. The method may be used to design a row charge that will produce a linear crater having the same cross section as a crater produced by one of the row member charges acting alone.² Although the basic method was developed for designing charge configurations intended to produce maximum apparent crater volume, the method has also been tested with other charge burial depths. (The RR2 experiment, discussed in the preceding section of this report, was a recent test of this nature.) This extension of the method is significant, because three of the four

rows of charges in the array for the RR3 experiment were placed at burial depths other than the optimum for crater volume. The purpose of employing a range of burial depths was to obtain certain particle velocities, as discussed below, in addition to attaining the desired cratering effects.

The directed blasting features of the experiment were designed with the aid of estimates of particle velocity. The model used for estimating velocities was simple, in keeping with the kinds of information available for devising the model and the uses to which the model was put. Although subsurface velocities were of primary interest, the available information described only surface velocities. It was thus necessary to assume that the surface velocities adequately describe subsurface velocities. The motion of particles in the interior of the mass of lofted material does vary, but the nature of this variation is known only slightly. It was necessary, therefore, that the motion of particles within broad regions could be regarded as constant with time and displacement. In the case of row charges the predicted crater area was bisected to define two regions of triangular cross section within which velocity was assumed constant. In the case of two parallel rows of charges, the assumed region of constant velocity was the rectangular prism between the two rows of charges. Invoking these assumptions results in a motion model depicting the lofted mass as prisms of material within which velocity is constant and equal to the surface velocity. This model is a serviceable, although tenuous, description of motion. Fortunately, more

Table 6. Charge emplacement data for RR3 detonation.

Charge identification number	Station (ft)	Centerline (ft)	Depth of burial (ft)	Charge weight, ANFO (tons)
101	190+85	5 north	22	0.5
102	191+16	5 north	27	1.0
103	191+53	5 north	30	1.5
104	191+96	5 north	38	2.5
105	192+42	5 north	46	4.0
106	192+81	5 north	47	4.0
107	193+20	5 north	46	4.0
108	193+68	5 north	40	4.0
109	194+15	5 north	32	2.0
110	194+52	5 north	26	1.0
111	194+83	5 north	20	0.5
112	195+11	5 north	20	0.5
201	191+38	17 south	30	1.5
202	191+67	17 south	39	2.0
203	192+00	22 south	48	2.5
204	192+35	27 south	47	2.5
205	192+70	28 south	47	2.5
206	193+03	27 south	42	2.0
207	193+33	25 south	37	1.5
208	193+61	23 south	36	1.5
209	193+89	18 south	34	1.5
210	194+14	19 south	30	1.0
301	190+52	21 south	16	0.5
302	190+77	25 south	19	1.0
303	191+08	26 south	22	2.0
304	191+38	29 south	21	1.0
305	191+67	31 south	24	1.5
306	192+00	32 south	25	2.0
307	192+35	40 south	27	2.0
308	192+70	44 south	28	2.0
309	193+03	44 south	23	1.5
310	193+33	42 south	21	1.0
311	193+61	39 south	19	1.0
312	193+89	34 south	19	1.0
313	194+14	31 south	18	0.5
314	194+40	27 south	20	1.0
315	194+68	25 south	19	1.0
316	194+94	22 south	16	0.5
401	191+60	56 south	17	0.5
402	191+85	60 south	17	0.5
403	192+10	64 south	17	0.5
404	192+35	68 south	17	0.5
405	192+60	71 south	17	0.5
406	192+85	71 south	17	0.5
407	193+10	71 south	17	0.5
408	193+35	68 south	17	0.5

detailed descriptions of motion were not required, because the most critical application of the model was in estimating relative rather than absolute momenta of lofted masses of material. Errors introduced by the simplifying assumptions could be expected to partially cancel.

The velocity magnitudes were computed as a function of charge depth of burial by an empirical formula describing observed surface velocities of a number of single-charge cratering detonations.⁵⁻⁷ The experimental data are shown plotted in Fig. 10 as maximum surface velocity vs scaled and normalized

depth of burial. The latter is normalized with respect to a medium having a specific gravity of 2.5. The curve shown is a least squares fit with each data point weighted by the cube root of charge size. A curve with equal weightings would be similar through the range of depths of burial of practical interest.

The relationship between velocity and depth of burial may be applied to row charges as well as single charges, provided the charges are spaced sufficiently close together to act as a line charge according to the empirical row-charge design formulas. The surface velocities

Fig. 10. Maximum surface velocity vs scaled charge burial depth.

for row charges satisfying this condition have been found to be nominally equal to the surface velocities produced by single charges having the same scaled depth of burial as members of the row charges.

The direction of surface velocity has been measured on fewer occasions than has the magnitude, and is less well-known. Charges deeply buried produce motion generally more vertical than do charges buried at shallow depths. Also, the material directly above a buried charge moves more vertically than material near the crater boundary, regardless of depth of burial. Although these trends are easily discerned, there is no tractable quantitative description of them. For purposes of the motion model developed here, the average motion of particles was estimated to be 30 deg from the vertical (or from the normal to the surface for charges buried under a sloping surface) for either single or row charges. The motion of material in the region between two parallel rows of charges was estimated to be vertical, or normal to the surface for parallel rows of charges under a sloping surface.

The foregoing principles and assumptions were applied to the experiment design in two ways. First, material within some regions required only sufficient velocity to carry it free of the crater. Estimates of velocity were made for these regions simply to confirm that the requisite initial velocities would be attained. The second application of motion estimates was more detailed. Material in some regions could be expected to move initially in such directions as either to fail to exit the crater or to come to rest on the wrong (uphill) side of the cra-

ter. In this case the motion model was employed to determine how motion could be altered by collisions between masses of material to attain a desired trajectory of the combined mass. Along with motion estimates, practical engineering constraints were imposed on the charge array design in determining relative positions of the charge rows and the number of rows to be employed at the various positions along the axis of the excavation. Of particular importance was the need to avoid excessive rock breakage and disruption on the uphill (south) side of the excavation.

The final design was developed by an iterative process in which cross sections of the excavation site were drawn and divided into elementary areas, such as those shown in Fig. 11. The particular configuration of four rows of charges in Fig. 11 evolved from an initial consideration of two rows. Of the four areas shown, Area III does not have a natural free surface as one boundary. The boundary indicated between Areas II and III is the transient boundary of the crater formed by the 100-row charge. Charges in the 100-row were detonated first, and a suitable time delay was introduced to permit stress wave passage and initial movement to occur to define the crater boundary before detonation of the remaining charge rows. The charges of the 200- and 300-row crater were positioned with respect to the predicted position of the 100-row crater.

Given the configuration shown in Fig. 11, material in Areas I and IV could be expected to move free of the crater without interfering with the motion of material from other areas. On the other

Fig. 11. Velocity vector diagram for Experiment RR3, Station 192+50.

hand, material in Area II would require a change from its initial motion to attain a suitable trajectory. This change was accomplished by a collision with the material of Area III. To estimate the outcome of the collision, a momentum vector was constructed for each area by multiplying its velocity vector by its cross-sectional area, the latter being proportional to mass per unit length along the row-charge axis. The resultant of the two momentum vectors was divided by the combined area to obtain a velocity vector for the combined mass.

A similar process was performed for cross sections taken at 50-ft intervals along the alignment. As the cross-sectional area of the excavation diminished in going from the center to either

end, the number of rows of charges required decreased from four to two. The empirical scaling method for designing row charges was then employed as an interpolation tool to replace the two-dimensional depictions of the required row charges at the cross sections with continuous row charges of requisite performance. A continuous row charge, in this context, is one in which all member charges are placed at the same scaled depth of burial. This step had been anticipated during consideration of the individual cross sections. Charge configurations amenable to this requirement of continuity were favored from the outset and could be made to satisfy all of the other design considerations with judicious lateral and vertical positioning of the charge rows.

In the final design the scaling parameters describing each of the four row charges were as listed in Table 7.

RESULTS

The charge array for the RR3 experiment was detonated at 1515 hr on 23 September 1971. The north row of charges was detonated first. The three remaining rows of charges were detonated simultaneously after a 0.1-sec delay.

The overall appearance of the crater is shown in Fig. 12, an aerial photograph taken from a position southwest of the site. Figure 13 is a contour map of the crater showing the predicted and observed crater outlines. The total crater

Fig. 12. Aerial photograph of crater, Experiment RR3.

volume of 28,600 yd³ compared favorably with the predicted volume of 30,000 yd³.

The crater cross section tended toward a flat-sided vee shape, rather than the concave bowl shape that was predicted.

Fig. 13. Predicted and observed crater outlines, Experiment RR3.

Table 7. Row-charge scaling parameters, Experiment RR3.

Charge row (see Table 5)	Scaled depth of burial (ft/ton ^{0.3})	Scaled spacing between charges (ft/ton ^{0.3})
100 (north side)	25	35
200	18	28
300	18	24
400 (south side)	20	30

Figure 14 compares the predicted and observed crater cross sections at Station 192+50, the approximate center of the cut. Figure 15 compares the crater and intended excavation cross sections at three positions along the alignment. The excessive deposition of material on the south slope of the crater indicates that the direction of motion of some material, probably that between the 300- and 400-rows, was more nearly vertical than expected.

At the east end, the crater was considerably narrower and shallower than predicted, and the cross-sectional area of the pile of ejected material far exceeded the cross section of the crater. Material had apparently moved laterally (i.e., in a direction along the excavation centerline)

from the central region of the cut and was deposited in the east end of the crater.

Surface velocities were inferred from high-speed motion pictures of the detonation. A photo target on the centerline at Station 193+00 exhibited a vertical velocity of 125 ± 15 ft/sec. A second target 30 ft uphill (south) from the centerline at the same station had a velocity of 150 ± 20 ft/sec. These velocities agree well with those used in the experiment design. However, the lofted material from between the third and fourth charge rows moved at velocities in excess of 200 ft/sec, velocities that were considerably greater than the predicted velocity of 140 ft/sec.

POSTSHOT EARTHWORK

The postshot earthwork consisted of shaping the crater to obtain suitable side-slopes and a flat, 40-ft-wide invert at grade. In the experiment design the side-slopes were two units vertical to one horizontal above elevation 6312, benched to slopes of two units vertical to three

Fig. 14. Comparison of predicted and observed crater cross sections, Experiment RR3.

Fig. 15. Comparison of crater and intended excavation cross sections, Experiment RR3.

Fig. 16. Comparison of crater and finished cut cross sections, Experiment RR3.

horizontal at lower elevations. However, examination of the crater and consideration of the nature of the material after the detonation suggested that a better slope configuration would be two units vertical to three horizontal overall. The crater was shaped to this configuration by remedial earthwork after the detonation.

The extent of earthwork performed during crater shaping is illustrated by the comparison of crater and finished-cut

cross-sectional profiles in Fig. 16. The particle size gradation was sampled during the work, and the distribution shown in Fig. 17 was found.

A total of 13,500 yd³ of material was removed from the crater, most of it from the south side. Two D8 bulldozers worked a total of 185 hr, including time for stockpiling boulders found outside the crater, and two 15-yd scrapers worked a total of 148 hr. The final appearance of the cut is shown in Fig. 18, a photograph taken from the east end.

Fig. 17. Particle size gradation, Experiment RR3.

CONCLUSIONS

The RR3 experiment has demonstrated the feasibility of using the directed blasting technique to aid in the design of charge arrays. The technique, when further developed, will be a valuable supplement to the empirical scaling method in designing explosive excavations of complicated geometry. The most important development required for further application of the technique would be a more detailed description of subsurface particle motion. Also useful would be suitable

Fig. 18. Finished RR3 cut.

criteria for determining an optimum number of charge rows for a given excavation cross section. However, such further developments could make the technique sufficiently complicated as to require digital computer solutions.

Experiment RR3 did not include tests to determine the compaction and settlement properties of the railway subgrade area. Such tests were not deemed necessary for this cut since thorough testing had been done in another cut formed by cratering in a similar medium 2 mi from RR3. The other cut was formed by the crater of an experimental blast design-

nated D4 (later RR1). An extensive series of tests, described in Ref. 1, were performed in the field and in the laboratory on rubble from the floor of the D4 crater. The basic conclusion drawn was that the material compacted by impact deposition forces would not be susceptible to large settlement or stability problems. The relative density of the crater floor material compared favorably with the density of material in engineered fills. Since the RR3 blast was similar in effect to the D4 blast, properties of the material at the RR3 site can also be expected to be similar.

Effects Measurements

GROUND MOTION

Ground motion predictions for the RR2 detonation were the same as the observed results from the C6 detonation of the Project Trinidad C-Series. The C6 detonation had a total charge weight of 10 tons, slightly less than the total charge weight in the charge array for the RR2 experiment. The prediction curve for peak particle velocity vs distance is shown in Fig. 19.

Ground motion predictions for the RR3 detonation were based on an empirical relation that gave a best fit to recorded motion data from previous experiments in the Trinidad series:

$$V = 1.68 \times 10^7 (N)^n W^{0.7} R^{-2.3},$$

where

V = peak surface velocity (cm/sec)

$$n = 0.014 R^{0.44}$$

W = weight of average charge in array (tons)

R = distance from ground zero (ft)

N = number of charges

The above relationship applies to the weight and number of charges detonated simultaneously; i.e., in the case of the RR3 detonation, the second group. The average charge weight in the group was $W = 1.19$ tons, and the number of charges, N , was 36. The prediction curve using these values of W and N is shown in Fig. 19.

Ground motion measurements were made at two stations in each of the two experiments. The measuring apparatus

consisted of two triaxial geophones and a six-channel recording galvanometer. One geophone was placed at the Trinidad Dam intake structure, and the second at a position 1600 to 1800 ft from the structure toward the detonation being observed.

The recorded ground motions were as indicated in Table 8. Due to instrumentation difficulties, the vertical motion component was recorded at only one station for each blast. At these locations it was stronger than the radial or transverse motion components. The observed peak vertical velocities are plotted in Fig. 19 with the prediction curves. Each of the data points falls above the associated curve. However, the disparity between the observed and predicted motion values

Fig. 19. Peak particle vertical velocity vs distance (prediction curves and observations).

Table 8. Seismic motion measurements.

Location		Distance from SG2 (ft)	Peak velocity (cm/sec)		
			Vertical	Radial	Transverse
RR2	West of dam intake tower	11,700	0.10	0.08	0.08
	Base of dam intake tower	13,300	No data ^a	0.024	0.028
RR3	West of dam intake tower	4,630	No data ^a	0.52	0.30
	Base of dam intake tower	6,420	0.61	0.44	0.20

^aMalfunctioning geophone.

is less than a factor of two, which is the nominal possible error of the prediction technique. A thorough discussion of ground motion measurements and predictions for both experiments, and others at the Trinidad Site, may be found in Ref. 8.

AIRBLAST

Airblast predictions for the two experiments were made by an empirical method using experimentally determined blast transmission factors.⁹ Since all of the charges for the RR2 detonation and most of the charges for the RR3 were buried at relatively deep scaled burial depths, the airblast transmission was low and the predicted airblast amplitudes were lower than for other cratering detonations of comparable size. The airblast predictions are shown as overpressure vs distance curves in Fig. 20. Two curves are shown for the RR3 detonation: one for directions perpendicular to the alignment, and a second for directions parallel to the alignment. Only one curve is shown for the RR2 detonation because the prediction technique is not sufficiently refined to

give airblast predictions as a function of azimuth for deeply buried charges.

Airblast gauges were operated at one location for the RR2 experiment and at three locations for the RR3 experiment. The gauge for the RR2 experiment was a mechanical self-recording type placed 3000 ft northeast of the detonation. The gauges for the RR3 experiment were

Fig. 20. Peak airblast overpressure vs distance (prediction curves and observations).

three units of a system of gauges set out for the Project Trinidad Middle Course II cratering experiments, which were being carried out concurrently with the railroad cut experiments.⁹

Two of the gauges were left in place at the Middle Course II Site, at distances of 8700 and 9200 ft east from the RR3 site. The third gage was moved to a position 2500 ft east from the RR3 site.

The measured peak overpressures are shown plotted with the prediction curves in Fig. 20. In the RR2 experiment, the overpressure at the gauge failed to exceed the gauge threshold sensitivity of 0.7 mbar. The overpressure at this point was either equal to the predicted value, or less by an indeterminate amount. The recorded peak overpressures for the RR3 experiment scattered about the prediction curve.

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