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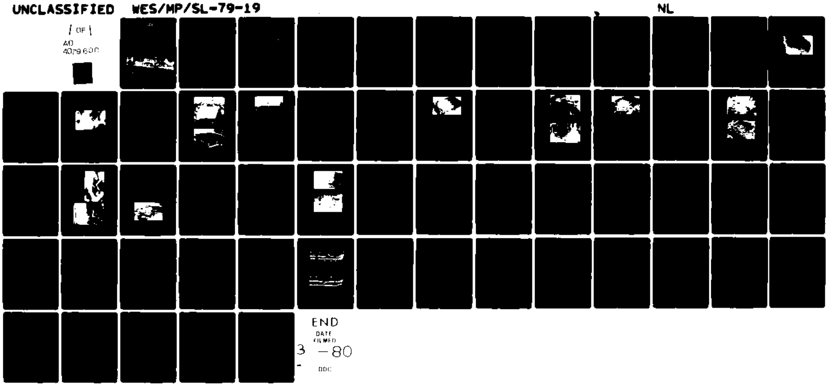

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FEASIBILITY OF USE OF SIMPLE MODELS TO TEST EXPLOSIVE CRATERING OF ROADS ON SLOPES IN ROCK

by

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Cratering charges were detonated in unstemmed shafts drilled in test beds fabricated of bricks, in order to explore whether such beds might offer a simple approximate way to model the cratering behavior of jointed rock. One-pound TNT charges were fired in four beds on level ground and one on a slope. Scaled depth of burst ranged from 1.1 to 1.7 ft/lb$^{1/3}$ (0.44 to 0.67 m/kg$^{1/3}$).

In two beds where bricks were close-packed but not cemented, rubble mounds rather than apparent craters were formed. The beds appeared to be so over

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20. ABSTRACT (continued).

permeable that the pressure of the explosion gases was rapidly dissipated and much of the gases' energy was effectively wasted.

In cemented beds on level ground, smaller apparent craters resulted than were predicted from published cratering curves for dry rock. In a cemented bed on a hillside, much more damage and material movement occurred than for a comparable bed on level ground.

The small apparent craters produced may have been caused in part by the vertical joints in the beds, which may have induced vertical trajectories of ejecta particles. Excavated true craters in cemented beds were square-shaped with flat floors, conforming to previously published descriptions of true craters in horizontally bedded, vertically jointed rock.

The brick beds modeled fresh, unweathered rock with widely spaced joints. No such fresh, massive rock has been present at known field test programs where subsurface charges have been fired and apparent craters studied. Also, in being unstemmed, the brick shots differed from most reported cratering tests. The brick cratering results appear to compare realistically with nature, in view of the test conditions. Therefore, the technique should be useful for studying cratering behavior in jointed rock in various topographic configurations, where approximate answers are acceptable.

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PREFACE

This study was authorized as part of the In-House Laboratory Independent Research (ILIR) Program for FY78, and was conducted under Project 4A161101A91D, Task 02, Work Unit 126. The study was planned in May and June 1978. Three test explosions were conducted in July 1978; two additional explosions were fired in September 1978. The tests were performed at the U. S. Army Engineer Waterways Experiment Station (WES) explosives test facility adjacent to the Big Black River in Warren County, Mississippi.

Mr. Colin C. McAneny, geologist, Structures Laboratory, WES, conceived, organized, and managed this study and prepared this report. Several persons of the Structures Laboratory staff offered constructive suggestions. Messrs. Leo F. Ingram and James L. Drake aided in formulating the concept of the study and discussing its implementation. Among the several WES personnel involved in executing the project, Mr. William Washington deserves special recognition for his continuing reliability, ingenuity, industriousness, and enthusiasm. Others who gave particular services included Messrs. John Shaler, Steve Lent, Hugh Wilson, Byron Armstrong, Wallace Gay, Sherman Price, and Jack Conway. Review of the manuscript by Mr. L. K. Davis is appreciated.

The Commander and Director of WES during the period of this study was COL John L. Cannon, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
degrees (angular)	0.0175	radians
feet	0.305	metres
$ft/lb^{1/3}$ (scaled charge depth of burst)	0.397	$m/kg^{1/3}$
gallons (U. S. liquid)	3.79	cubic decimetres (litres)
inches	25.4	millimetres
miles (U. S. statute)	1.61	kilometres
pounds (mass)	0.454	kilograms
pounds (force) per square inch	6890	pascals
tons (2000 lb, mass)	907	kilograms

FEASIBILITY OF USE OF SIMPLE MODELS TO TEST EXPLOSIVE CRATERING OF ROADS ON SLOPES IN ROCK

PART I: INTRODUCTION

Background

1. In military operations, obstacles and barriers are used to hinder the movement of an enemy force. One significant type of obstacle is a crater excavated explosively in a road. So long as this crater is large enough, steep enough, and properly placed, it will have the desired barrier effect. Before firing the demolition charge, however, the commander must be sure that the crater will have these attributes.

2. Explosion-produced craters in soil give no great problem in prediction. Although soils vary greatly, they differ from rock in one distinct feature: they are penetrable. Thus, shafts in which to place demolition charges can be sunk rapidly with explosive shaped charges, and standardized procedures have been developed for cratering of roads on soil (Headquarters, Department of the Army, 1971).

3. Cratering of rock presents a more difficult problem. Since rock is not penetrable, demolition charges require preconstructed emplacement shafts. Existing experience indicates that in rock cratering, structural features--i. e., joints and other surfaces of weakness such as bedding planes--have a dominating influence on cratering. These features, however, vary from site to site. Rock is of great practical military importance, because many good tactical obstacle sites, where topography prevents a bypassing, are in mountainous areas where rock is common. Yet cratering experience in rock is relatively sparse, and information on local geological structural features has been recorded only rarely (Rooke et al., 1974; Müller and Carleton, 1977; Johnson et al., 1971; USAEWES, EERL, 1972). Field testing of cratering in rock is difficult and expensive.

4. One way to circumvent the high cost of cratering field tests

in rock would be to perform cratering tests in small-scale models. However, in practical fact, sophisticated models are themselves expensive. But there are many untested rock-cratering situations--combinations of rock, overburden, geometry, and topography--where even general information as to cratering behavior is lacking. It is possible that such information could be obtained by tests in simple models, cheaply fabricated out of readily available materials. The goal of this study was to ascertain whether this is a reasonable possibility.

5. Bricks offer a readily available, low-priced material that is physically similar to rock and easy to work with. The geometrical way in which bricks are stacked offers an opportunity, in a gross way, to simulate rock structure. The use of different bonding materials between bricks offers an opportunity to simulate, grossly, rock separation surfaces of various characters. Using these simple materials, one might be able to construct economical rock models close enough to reality to give meaningful cratering results. To determine whether the technique was worth serious consideration, however, required actually building some models and testing them.

6. A literature search early in the study revealed that two previous programs had used a similar modeling approach. In the mini-budget SUGARSHOT test series, a cherry-bomb firecracker was exploded on a bed of stacked sugar cubes (Melzer, 1970). The directions of both ejecta and true-crater development were controlled by the jointing in sugar-cube bed. The same effect was demonstrated in the more formal BRICKPILE series, which used C-4 explosive charges and beds of small square ceramic bathroom tiles (Terlecky et al., 1971). Since these series were not concerned with craters as obstacles, the charges were set on the test-bed surface or only slightly indented into it, rather than being buried.

7. Tiles were considered for use in the present study, but they were rejected in favor of bricks. This matter is discussed in Appendix A.

Purpose and Scope

8. The purpose of this study was to determine whether beds of bricks might offer a useful method for modeling the cratering behavior of jointed rock masses. Five test beds were constructed of bricks and blasted with cratering charges. The apparent craters were measured, and the loose brick rubble was excavated to permit measurement of true craters. An attempt was made to judge the validity of the modeling method by comparing the results with previous cratering experience reported in the literature.

PART II: TEST PROGRAM

General

9. The test program was conducted at the Big Black Test Site (BBTS), an explosive testing facility operated by the Waterways Experiment Station about 10 miles* southeast of Vicksburg, Mississippi. Five test explosions were detonated in solid beds of bricks. Charges of TNT were fired in open shafts drilled into the beds. Three tests were conducted in beds with level surfaces. After the results of these shots had been assessed, two more beds were built and blasted, one on level ground and one with a sloping surface.

10. Variables among the five test beds, besides bed topography, included brick stacking pattern, cementation, and charge depth of burst. The shots were viewed visually, and high-speed motion pictures were taken of the last two shots. All test results were recorded photographically and by survey measurements along two diameters through the craters. The rubble was excavated at each bed, and the excavated true craters were then examined and surveyed.

Test Bed Construction

11. Each test bed was built in an excavated pit. For the first three beds, pits were dug by a backhoe into native soil on level ground in the north part of the BBTS reservation. Pits were dug to a depth of about 4 ft. Self-leveling concrete was poured in the bottom of each pit to give a level floor. Eight days later, the first brick bed was constructed.

12. In each pit, a circle of 3.6-ft (1.1-m) radius was scribed on the concrete floor. The first course was then placed by laying bricks within and out to this circle. Another course was placed on top of it, then another, and so on, until the entire cylinder had been placed.

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 3.

In each succeeding course, bricks were placed directly in alignment with the bricks in the course below, so that the finished cylinder had the structure of a rock mass with continuous joints in two perpendicular sets. Care was taken to keep the bricks snugged against each other, so that the joints would be of minimal thickness. A view of a partially constructed test bed is shown in Figure 1.

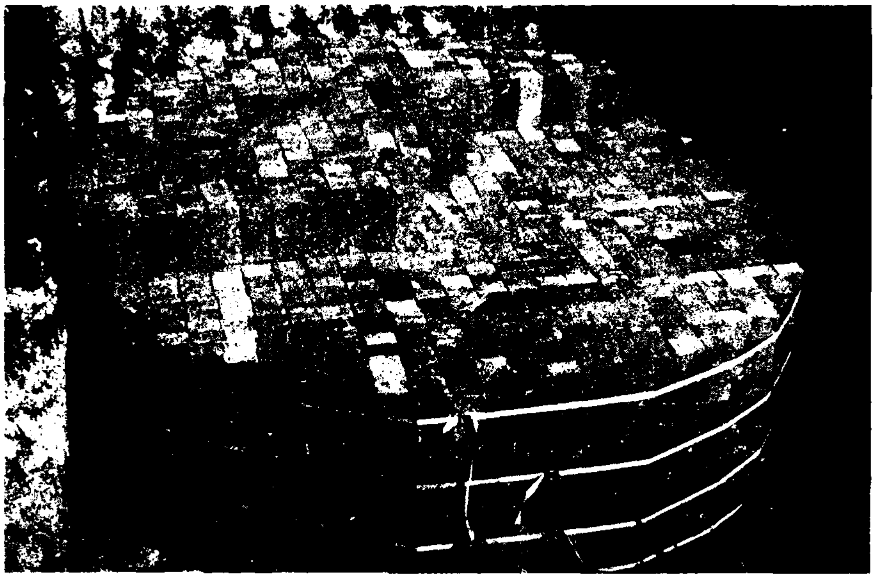


Figure 1. Bed 2, partially constructed

13. In order to describe brick orientation, a system of nomenclature for the brick axes was adopted. The long axis was designated a, the short axis c, and the intermediate axis b. This system is illustrated in Figure 2.

14. The first three test beds differed from one another with regard to stacking pattern and cementing. Two beds were constructed with the c axis vertical, and one with the a axis vertical. Bed 1 was constructed with the c axis vertical, without cement. Bed 2 was constructed with the a axis vertical, without cement. Bed 3 was constructed with the c axis vertical, with cement. A summary of particulars of all five test beds is given in Table 1.

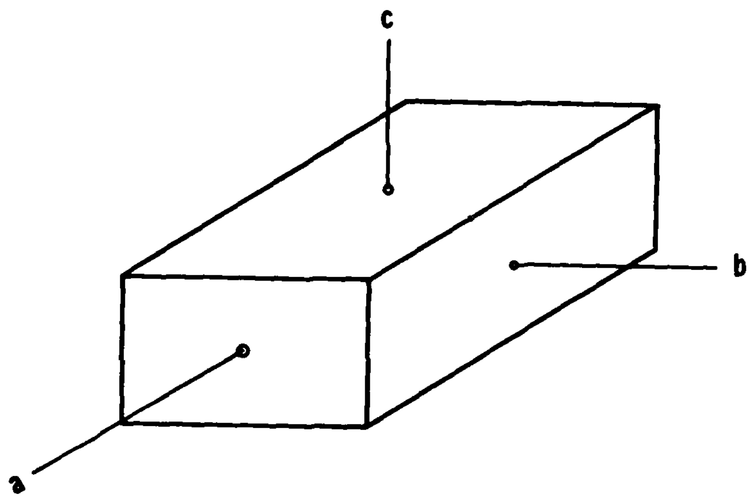


Figure 2. Brick-axis nomenclature used in this report

15. The bricks used were paving bricks furnished by Tri-State Brick and Tile Company of Jackson, Mississippi. They were solid rectangular blocks without indentations. Nominal dimensions were 7-3/8 by 3-3/8 by 2-1/4 in. Stated tolerances were plus or minus 3/32 in. for all dimensions, but it appeared that most bricks were quite close to the nominal dimensions. Three tests on specimen bricks gave specific gravity as 2.15 and crushing strength as 10,100 psi (7×10^7 pascals).

16. The intended purpose of the cementing material was merely to alter the joint-surface properties from the uncemented condition, so as to induce different phenomenology. No particular bond strength or other property was sought. Several possible bonding substances were considered, including glue, paraffin, molten sulphur, paint, whitewash, and grease. Cement slurry was selected because it was easy to work with and readily available.

17. The slurry was mixed according to the following: 28 lb of water, 14 lb of dry portland cement, and 1.5 lb of powdered bentonite per batch (13 kg, 6.5 kg, 0.7 kg, respectively), the dry ingredients being thoroughly mixed before addition of water. The slurry had a pea-soup consistency. Care was taken to keep it agitated at all times,

to prevent settling out of solids and consequent inconsistencies. In constructing the cemented beds, bricks were dipped individually in slurry just before being placed (Figure 3). When a course had been laid, slurry was poured over the top and worked into the cracks with a paint roller, in an attempt to get all interstices completely cemented. The cement in bed 3 cured for ten days before the bed was blasted, and that in beds 4 and 5 for 6 weeks.

Figure 3. Cemented bed 3 under construction. Brick was dipped in cement slurry, in pail, before being placed

18. After construction of beds 1, 2, and 3, the pits were backfilled with ordinary concrete, vibrated to insure compaction. The concrete cured for two days before the charge-emplacement shafts were drilled and for nine days before the explosive charges were fired. On shot day, the concrete had acquired an average crushing strength of 1770 psi (1.2×10^7 pascals).

19. Emplacement shafts were drilled in the centers of the brick beds with a BX diamond coring bit, using a portable electric-powered drill with water circulation. Shaft diameter was 2-3/8 in. (60 mm). Beds 1 and 2 were saturated with water before drilling in order to induce the drill cuttings to exit the bed rather than becoming lodged in

the interstices. The beds absorbed 142 and 146 gallons of water, respectively (538 and 553 litres). After the emplacement shafts were drilled, a satellite shaft was drilled near the periphery of each bed, the beds were drained, and the satellite shafts were backfilled with concrete.

20. Beds 4 and 5 were constructed after beds 1, 2, and 3 had been blasted and excavated and thus benefited from the experience of beds 1-3. Bed 4 was built by reconstructing bed 1 as a cemented bed. Bed 1 was excavated down to clean and undamaged bricks. Cement slurry was poured on the floor and worked in. The bed was given all the slurry that it would absorb. Thereafter, as the bed was raised, a saturating amount of slurry was poured on each course and worked in.

21. Bed 5, the last one to be built and tested, modeled a side-hill cut roadway. It was built in a pit cut into the side of an embankment, as shown in Figure 4. Figure 5 shows the bed during construction, and Figure 6 shows it completed and ready for blasting. It was a cemented bed, rectangular in plan, with a sloping front conforming to the slope of the embankment, about 30 deg or 58 percent. The brick c axes were vertical and a axes parallel to the embankment contour.

22. The foundation of bed 5 was a level floor of tamped soil. The bed was made only 15 courses high, rather than the 19 courses used in beds 1 and 3, as it was believed that the bottom few courses could be omitted without seriously affecting cratering phenomena. The bed sat 2-1/2 ft (0.8 m) out from the back wall of the pit and 1-1/2 ft (0.5 m) in from each side. The space was backfilled with tamped soil as the bed was raised, in about 1-ft (0.3-m) lifts. Concrete floor and sides would have been preferable for comparability with the other test beds. However, complicated form work would have been required, and it was decided to use the simpler soil approach. An uphill slope adjacent to the simulated cut roadbed was omitted, as it was presumed that the bed itself and the lower slope would be more significant in the cratering process.

23. The emplacement shaft was located 1.71 ft (0.521 m) (six bricks) in from the outer edge of the top bed surface. Water

Figure 4. Pit dug in side of embankment prior to building of bed 5

Figure 5. Test bed 5 partially constructed

Figure 6. Test bed 5 completed and ready for blasting. One-pound TNT charge sits next to emplacement shaft

circulation was maintained during drilling of the shaft, but the water level in the shaft fell rapidly after completion of drilling, indicating a leaky bed.

Firing and Test Documentation

24. The explosive charges were cast TNT cylinders with integral tetryl boosters. They were initiated with commercial instantaneous electric blasting caps. Total charge weights were 1.05 ± 0.02 lb (0.477 ± 0.009 kg). Charge dimensions were 5-5/8 ± 1/8 in. in length by 2-3/16 ± 1/8 in. in diameter (0.143 ± 0.003 m by 0.0556 ± 0.0032 m). All charges were detonated in open holes with no stemming. This was in conformance with military practice, where road-demolition shafts have only a manhole cover between the explosive charge and the atmosphere. Depths of burst (DOB), both actual and scaled, are listed in Table 1.

25. Reference stakes were driven beyond the test beds to establish north-south and east-west survey lines parallel to the brick axes. Survey profiles were run along these lines before and after each shot

and after excavation of the true crater. Before shots 1, 2, and 3, the bed surfaces were spray-painted with different colors, to assist in distinguishing ejecta from the various beds. High-speed motion pictures (500 frames per second) were taken of shots 4 and 5.

PART III: RESULTS

Bed 1

26. Bed 1 was constructed of uncemented bricks stacked with the c axis vertical. The charge, weighing 1.07 lb, was buried at a depth of 1.67 ft, and thus at a scaled depth of 1.63 $ft/lb^{1/3}$ (0.486 kg, 0.509 m, 0.65 $m/kg^{1/3}$). For details of bed construction, see Tables 1 and 2. Bed 1 was the first to be blasted, followed by bed 2 and bed 3. In all cases a great amount of straight-up ejection was noted.

27. Bed 1 produced a "RETARC"--a rubble mound--rather than the expected crater, as shown in Figure 7. The mound was slightly asymmetric, being high to the west and northwest. There was a slight amount of ejecta to the north and south, that is, parallel to the long joints (the a axes). The appearance of the mound gave the impression of a cratering shot at which the charge had been buried too deeply. There was a concentration of small broken rubble at the very center of the mound. The true-crater lip was visible around the edge of the rubble. The intact bricks immediately outside the true crater had been thrust upward slightly (less than 1 in.). The continuous rubble field was completely contained within the circle of the original brick bed. There was an absence of painted surfaces in the central mound, while conversely both painted and charred surfaces were common in the ejecta. There were some radial cracks in the concrete surrounding the brick bed, principally on the north and south sides where the thickness of concrete was least.

28. The true crater was excavated by hand several days after the shot. The survey profiles of the rubble mound and the excavated true crater are shown in Figure 8. The dimensions of mounds and craters are given in Table 2. The mound was elongate in the north-south direction, and thus parallel to the a (long) axis of the bricks.

29. In excavating the true crater, some judgment was required in deciding what rubble pieces to remove. A piece sitting at an odd angle, with no apparent regular relation to its neighbors, was removed; one

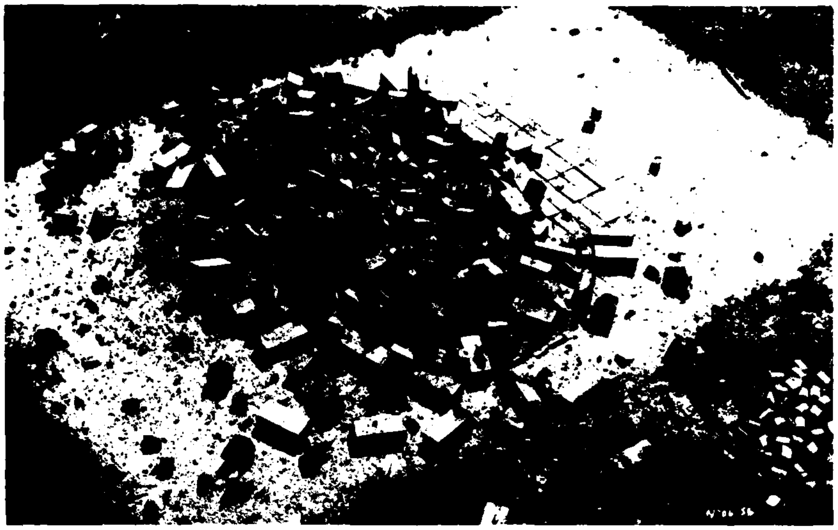


Figure 7. "RETARC" (rubble mound) formed in bed 1

sitting in its original orientation, even though it was quite loose, was left in place. The final crater was roughly square with roughly vertical, jagged walls. Figure 9 shows the appearance of the final pit floor, and Figure 10 is a view of the final excavated crater.

Bed 2

30. In bed 2 the bricks were stacked with the a axis vertical. A single course was thus 0.61 ft thick (7-3/8 in.) (0.187 m), and there were six of them in the cylinder. The emplacement shaft was 1.93 ft deep (0.589 m), and thus penetrated slightly into the fourth course of bricks. DOB was 1.70 ft (1.67 ft/lb$^{1/3}$) (0.519 m and 0.66 m/kg$^{1/3}$).

31. Firing of charge 2 gave another RETARC, with a very compact mound of rubble (Figure 11). To the eye, the mound appeared more circular in outline than that of bed 1; and surveys confirmed this: the bed 2 mound measured 6.3 by 5.2 ft (1.9 by 1.6 m), with the longer dimension being north-south, or parallel to brick dimension b (Table 2). The north and south sides of the bed showed a rebound effect, with the east-west joints opening up to 1/2- , 3/4- , and even 7/8-in. (0.022-m) widths. No such effect appeared on the north-south joints. As at bed 1,

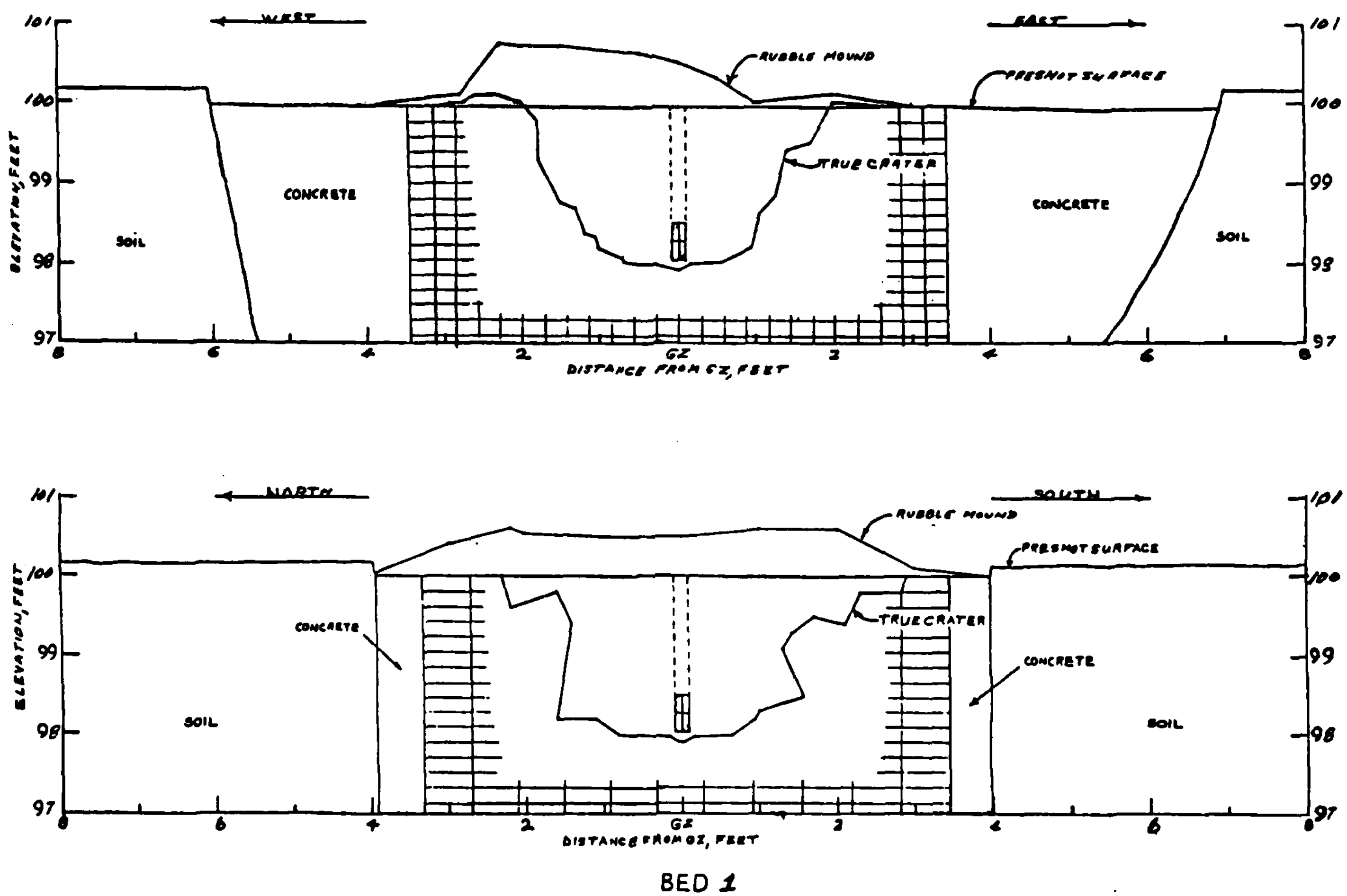


Figure 8. Preshot, postshot, and postexcavation profiles of bed 1

Figure 9. Excavated crater floor in bed 1

Figure 10. Excavated true crater in bed 1

Figure 11. "RETARC" (rubble mound) formed in bed 2

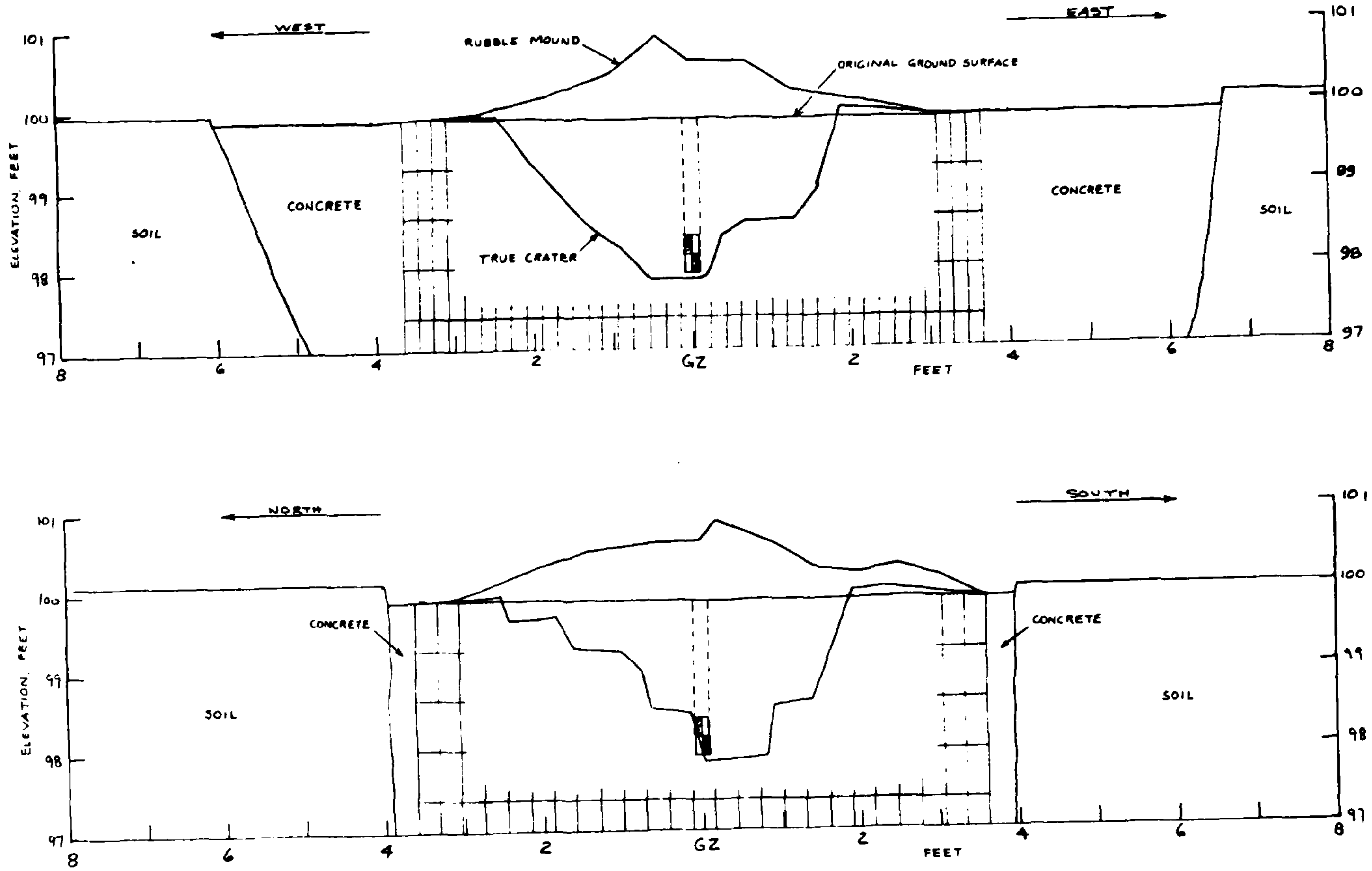
there was quantitatively very little ejecta beyond the test pit limits. Again there were radial cracks in the concrete north and south of the shot; one extended out into the soil.

32. Figure 12 shows the surveyed profiles of both the rubble mound and the excavated true crater. The true crater was narrower and more V-shaped than at bed 1. There were keyways in the east, north, west, and south directions; that is, one or two bricks in the surface course had been dislodged directly out from the center in the orthogonal directions (the directions parallel to the joints). This effect had also been noted at bed 1. A view of the final excavated true crater is shown in Figure 13.

Bed 3

33. Bed 3 was the third shot to be fired. In all geometrical respects, the bed was the same as bed 1. DOB was 1.67 ft (1.64 ft/lb$^{1/3}$) (0.509 m, 0.65 m/kg$^{1/3}$). In bed 3, however, the bricks were cemented. The results of the shot were qualitatively different from those of the first two.

34. This test also produced a RETARC, but a laterally wider one



BED 2

Figure 12. Preshot, postshot, and postexcavation profiles of bed 2

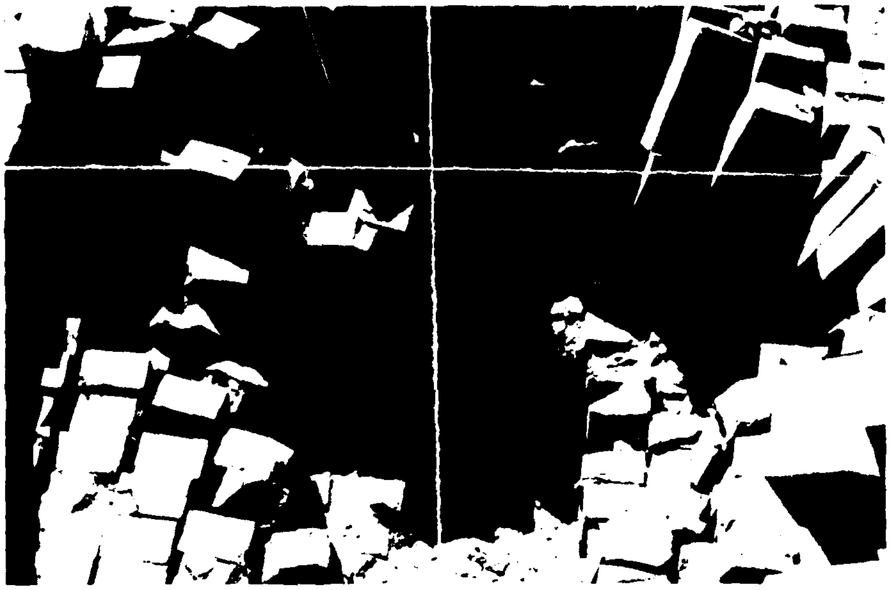


Figure 13. Excavated true crater in bed 2

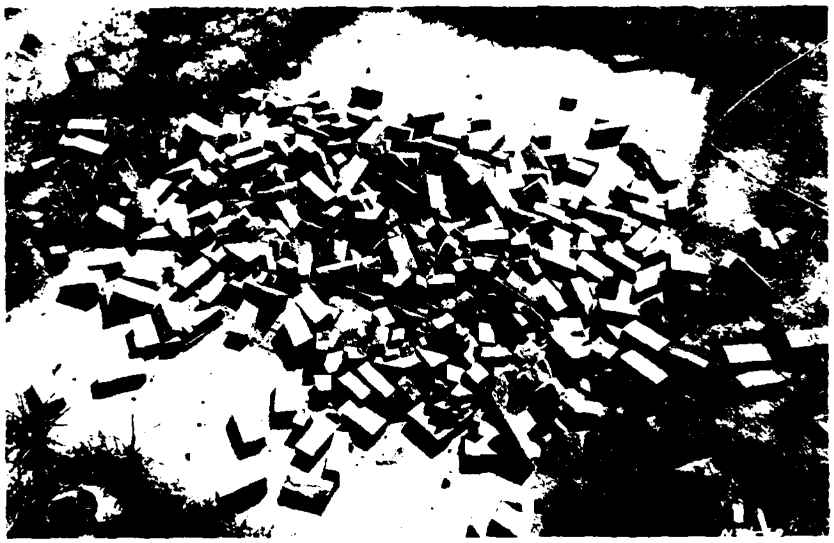


Figure 14. Rubble mound with small apparent crater in bed 3

with a small apparent crater in the middle of the rubble (Figures 14 and 15). There was slight but noticeable preferential ejection in the north and south directions (the brick a axes). As compared with beds 1 and 2,

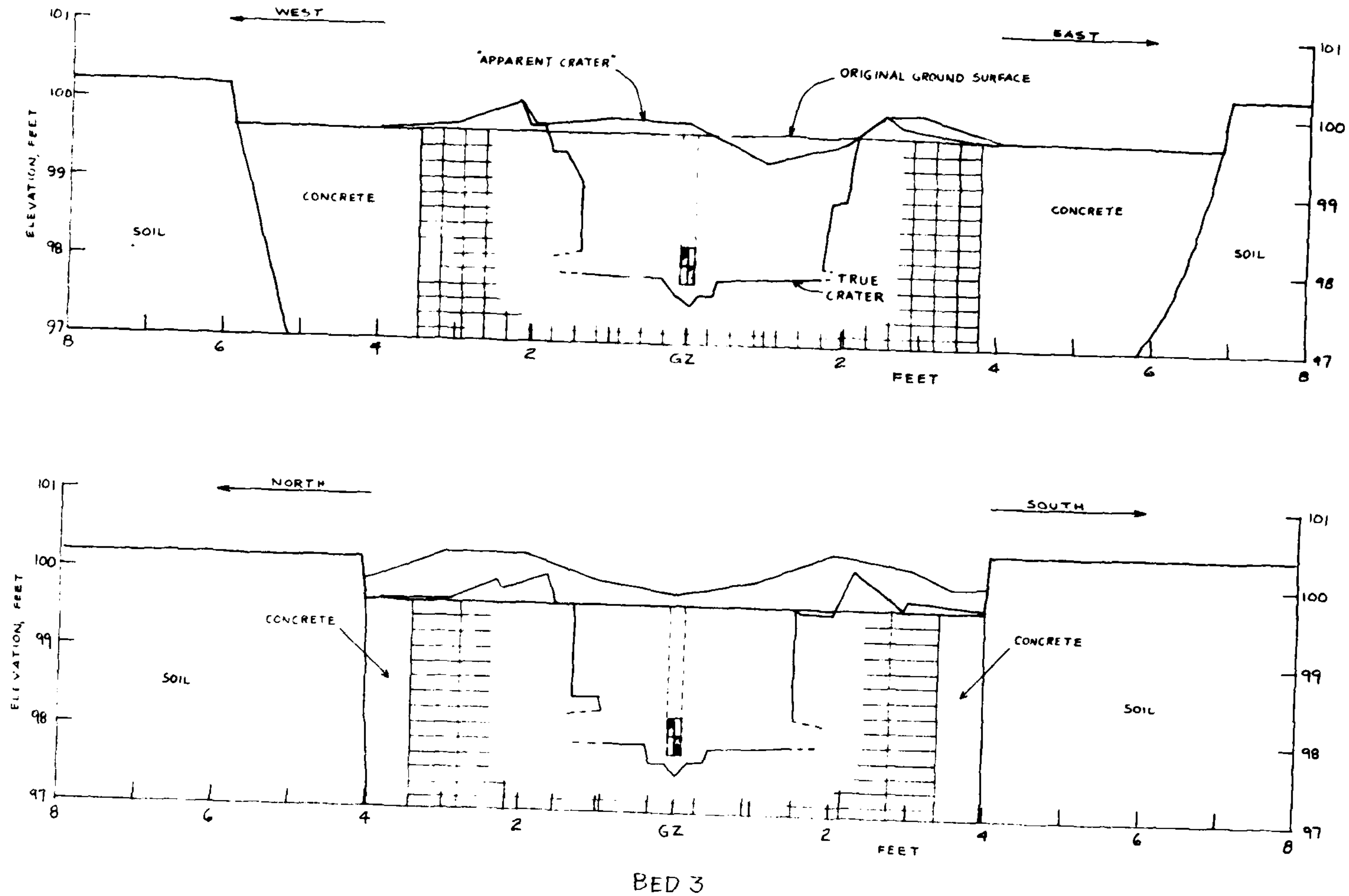


Figure 15. Preshot, postshot, and postexcavation profiles of bed 3

there were notably more integral bricks as rubble fragments, and fewer broken and splintery pieces. A distinct upthrust of 2 in. and more (0.05 m) was noted around the true-crater lip, visible through the rubble. One major east-west crack occurred in the concrete monolith at both ends of the test bed. The rubble mound (dimensions given in Table 2) was larger in area than that at bed 1. It was elongate in the north-south direction, apparently controlled by the orientation of the a axis of the bricks. The true-crater outline appeared nearly circular, and in fact it proved to be slightly wider east-west than north-south (Table 2).

35. During excavation of the true crater, the fact that the bed was cemented made judging the true-crater boundary slightly easier than at beds 1 and 2. As excavation proceeded, more fragments that were entirely broken were encountered as the level of the charge was approached, six or seven courses below the top surface. The excavation finally produced a square crater with a level floor on top of the tenth course of bricks. There was a square pit in the exact center, where the two bricks immediately adjacent to the bottom of the charge had been pulverized (Figure 16).

36. A remarkable upthrust phenomenon was noted at bed 3. The explosion gases appeared to have worked their way in between courses 9 and 10, and lifted course 9 and everything above it. The result was a deep overhang on all four sides of the final crater below course 9 and above the floor-forming course 10. On the four walls this vertical upthrust was measured from the floor as follows: north, 5.5 in.; west, 3.5 in.; south, 4.25 in.; east, 1.5 in. (0.14, 0.09, 0.11, and 0.04 m, respectively). The upthrust is particularly well shown in Figure 17, but can also be seen in Figure 16.

Bed 4

37. Bed 4 was a cemented reconstruction of bed 1. It was thus comparable in structure to bed 3. However, in bed 4, the charge was fired at a depth of 1.10 ft (0.336 m); scaled depth was 1.08 ft/lb$^{1/3}$ (0.43 m/kg$^{1/3}$).

Figure 16. Square pit in center of flat floor of true crater in bed 3. View is toward west wall

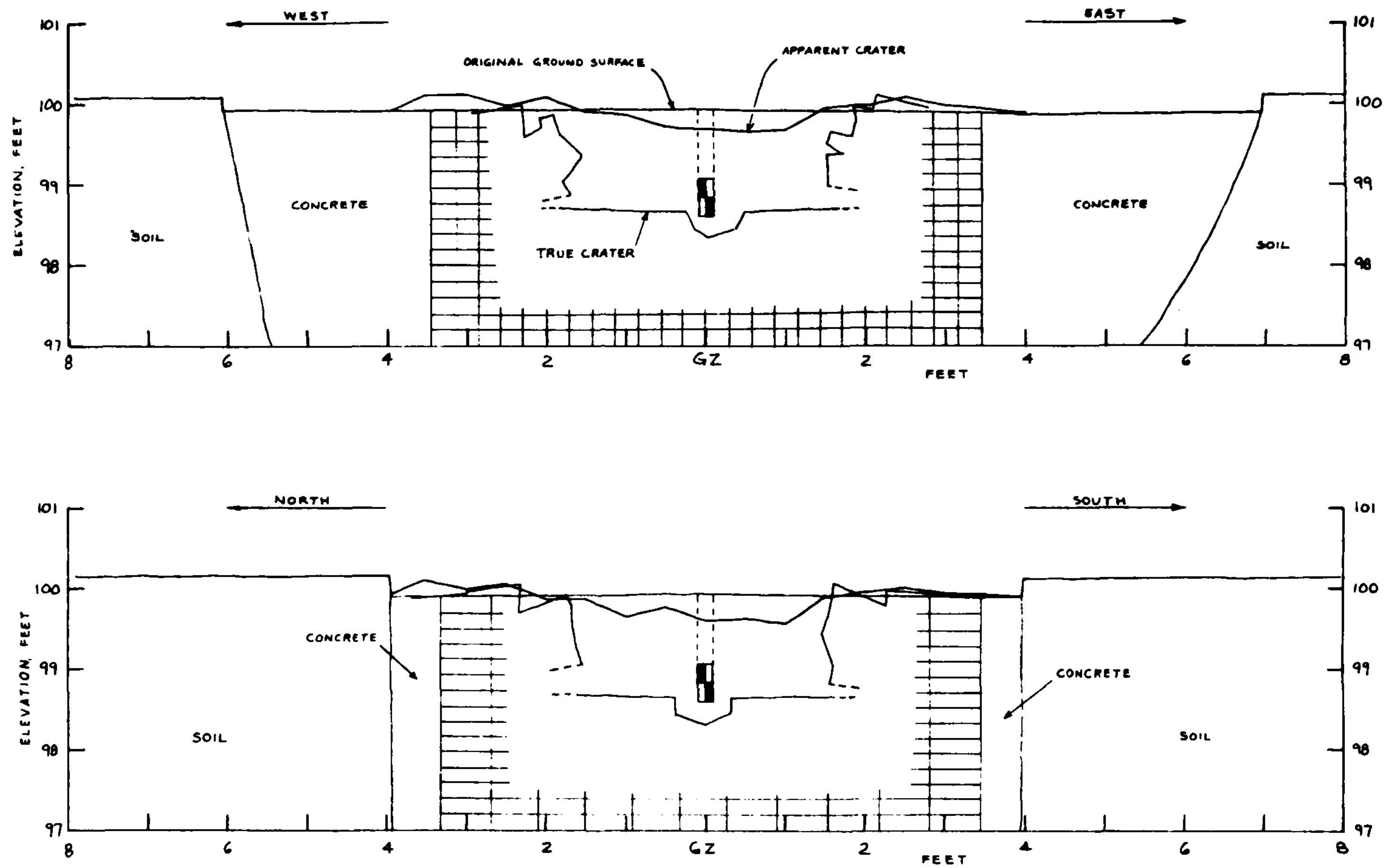
Figure 17. Upthrust beneath course 9 in north wall of true crater in bed 3

38. The test in bed 4 appeared to produce much more ejecta than previous shots. The ejecta was also more laterally dispersed than before, with the farthest piece landing more than 300 ft (90 m) from the test bed.

39. Nevertheless, a large crater was not produced, and no large quantity of ejecta was deposited either near or far from the shot site (Figure 18). A shallow but distinct apparent crater was formed, with a distinct upthrust all around. A slightly greater than average ray of ejecta was deposited to the south and southwest, but there was no continuous ejecta or rubble field anywhere except within the crater boundary itself. The apparent crater was wider north-south than east-west (parallel to the brick a axes), as shown in Figure 19 and Table 2. The true-crater lip was clearly visible, and nearly square. There appeared to be more broken bricks close in than there had been at bed 3.

40. The excavated true crater was square, with a flat floor on top of brick course 7. There was a semisquare hole in the center, where the explosion had pulverized the two immediately adjacent bricks of course 7; but instead of being full square, as at bed 3, the northeast corner was truncated; the brick material here was ragged but intact and could not readily be dislodged with a screwdriver. There was a distinct

Figure 18. Apparent crater formed in bed 4



BED 4

Figure 19. Preshot, postshot, and postexcavation profiles of bed 4

upthrust and overhang at the base of course 6, on all four sides of the crater, as there had been at bed 3. These overhangs are indicated in the true-crater profiles in Figures 15 and 19. The greater detail in Figure 19 than in Figure 15 represents only a more detailed survey at bed 4, not an actual difference in detailed crater shape.

41. The film record of shot 4 documented the striking preponderance of straight-up ejection, despite the apparent abundance of lateral ejecta noted while watching the shot. The height to which ejecta was thrown was not measured. Material that flew straight up, of course, fell straight back and filled the crater, producing the shallow apparent crater recorded in Figure 19.

Bed 5

42. Bed 5 was a side-hill cemented model founded on a tamped-soil floor and confined by tamped-soil backfill. The charge was fired at a depth of 1.67 ft and scaled depth of 1.65 ft/lb$^{1/3}$ (0.509 m and 0.66 m/kg$^{1/3}$) in a shaft placed 1.71 ft (0.521 m) back from the edge of the slope.

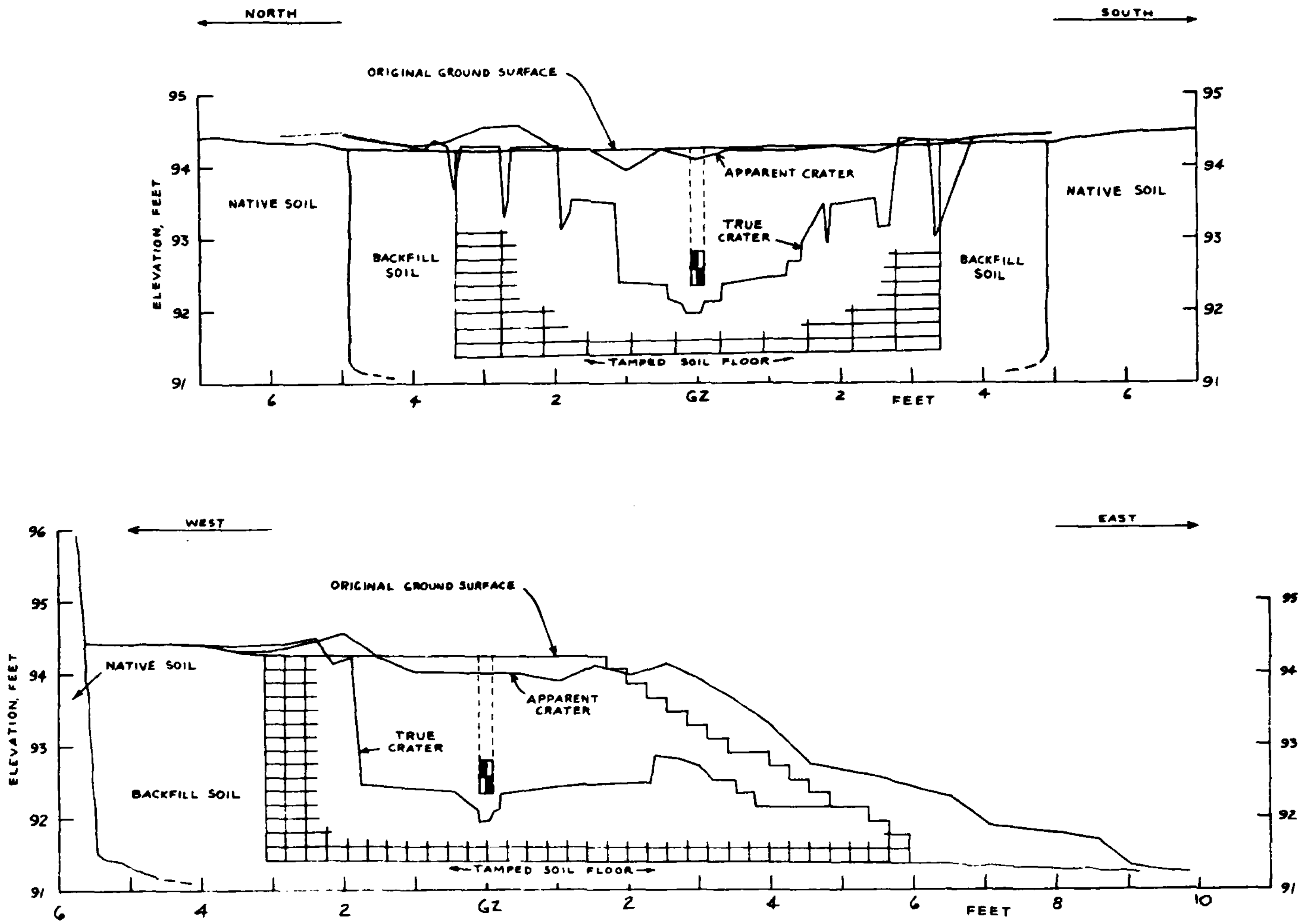
43. When charge 5 was fired, visually observed ejection was primarily straight up and straight out of the hill. The rubble (Figures 20 and 21) was predominantly composed of intact bricks. Broken brick fragments were concentrated at and immediately downhill from the ground-zero location. Some bricks were deposited on top of the embankment, directly uphill from the blast. A small apparent crater was formed (Figure 22). As the east-west profile in Figure 22 shows, the major effect of the blast was to shift material in a downhill direction. Along both sides of the bed the bricks rebounded from the soil walls, an effect visible in Figure 21. Individual bricks in the outer rows underwent shearing motions with regard to one another. Some loose bricks fell into the void between the soil wall and the edge of the bed.

44. At the front of the model, the three bottom layers of bricks (below the first "step"; see Figure 22) appeared to be intact. Above that the model was broken up along joints. This general-distress effect

Figure 20. Bed 5 after blasting, viewed from east (downhill)

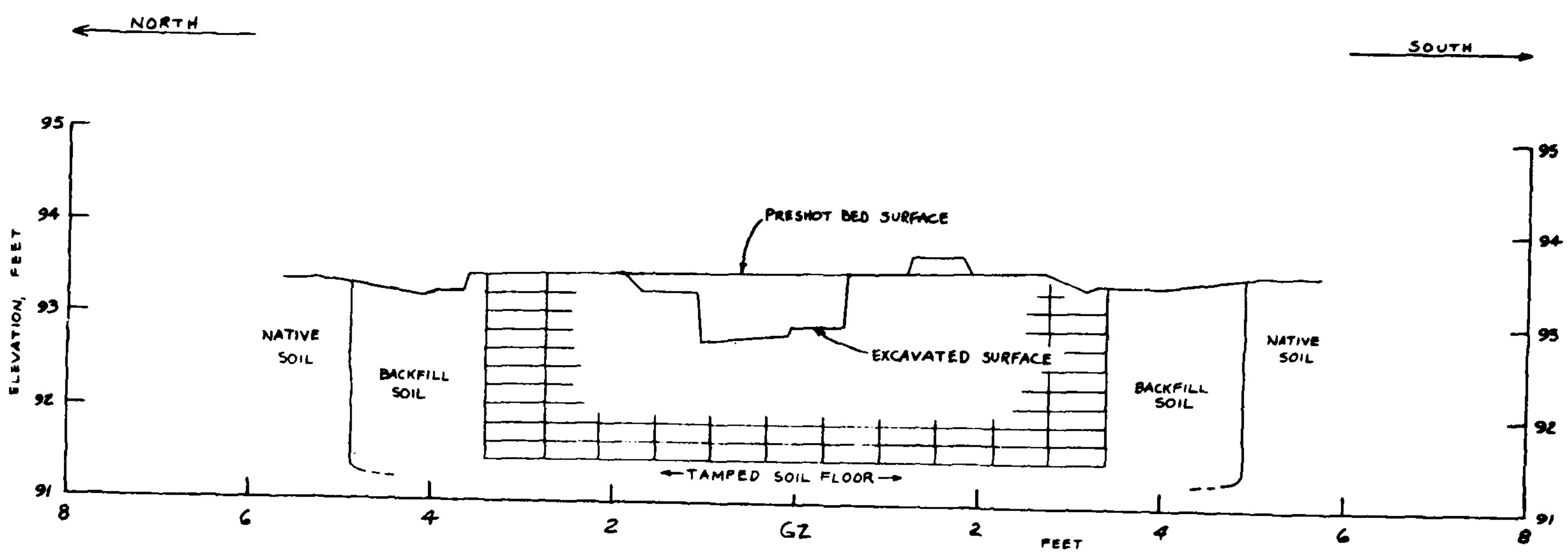
Figure 21. Bed 5 after blasting, viewed from above (top of embankment)

had not been noted in the flat-ground beds. The greater ejection and greater general distress at bed 5 were undoubtedly due to both the sloping bed and the weaker soil confinement. It is not known which of these factors had the greater effect. It seems logical that the weaker confinement may have contributed to the distress within the bed but that



BED 5

Figure 22. Preshot, postshot, and postexcavation profiles of bed 5



BED 5

Figure 23. Postexcavation profile, bed 5, through saddle 2.9 ft east of ground zero

the greater ejection was probably due to the sloping geometry.

45. The bed was excavated to a true crater as indicated in Figures 22 and 23. The indistinctness of the true-crater boundary, discussed below, was well demonstrated. The true crater had a flat floor, elongated out of the hill; the elongation, thus, in this case was opposed to the orientation of the brick a axes. There was no upthrust at the base of the crater. The gases were evidently able to find relief by moving material out, and did not wedge in as they did in the confined cases of beds 3 and 4.

46. The high-speed camera malfunctioned at test 5, and no film record was obtained.

PART IV: DISCUSSION OF RESULTS

General

47. In essence, the brick-model tests produced either mounds or shallow craters that would be unsatisfactory as military obstacles. The shaft size, charge weight, and depth of the brick tests were chosen so as to form a scaled-down model of existing military demolition shafts. If the results could be directly scaled upward, they would imply that a cylindrical charge in an open hole in fresh orthogonally jointed and bedded rock, with no overburden, would fail to create a satisfactory crater obstacle. This would be true regardless of the depth of burst. Such a fact might have serious military implications. It is imperative, therefore, to examine to what extent the brick-model results predict inferior cratering in a full-scale situation.

Mechanism of Cratering

48. It is beyond the scope of this report to go deeply into the mechanism of cratering, but some discussion of it is necessary in trying to explain the brick-model results. Figure 24 (from Rooke et al., 1974) illustrates dimensions and nomenclature conventionally used in describing and discussing explosion craters. Two basic concepts are those of the apparent and the true crater. The apparent crater is the real one in the layman's sense: it is the depression that one sees after the dust has settled. The true crater is a concave surface outside of which the rock or soil, though ruptured, is still in its original orientation. The material within the true crater and below the apparent crater is termed fallback.

49. The true crater is more abstract than the apparent crater, and more difficult to define. In fact, several differing definitions have appeared in the literature. The best is probably the following, from Fisher (1968): "The true crater is defined as the boundary (below preshot ground level) between the loose, broken, disarranged fallback

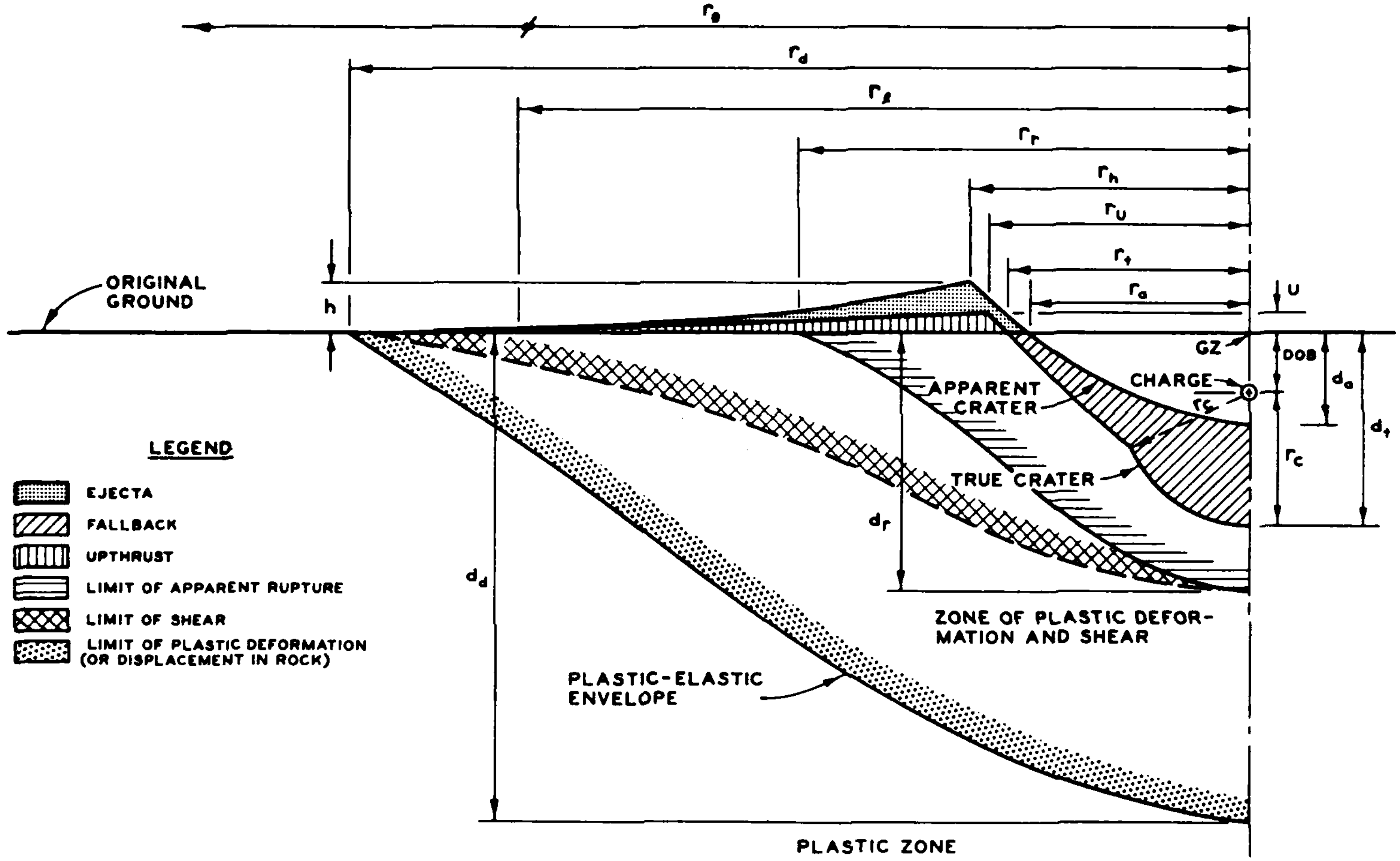


Figure 24. Conventional crater nomenclature (from Rooke et al., 1974)

materials and the underlying rupture zone material which has been crushed and fractured, but has not experienced significant displacement or disarrangement. The true crater boundary is not a distinct surface of discontinuity, but rather a zone of transition between rupture zone and fallback materials." This definition was kept in mind during the process of excavation of true craters in this test series.

50. It is the apparent crater that is available to act as an obstacle. The apparent crater presents a more sophisticated problem in origin than the true crater, because certain effects and phenomena enter into the formation of the apparent crater that do not affect the true crater. One of these is bulking. As material is fractured, disturbed, and moved, it is bulked, acquiring a larger total volume because of the interstitial spaces that are introduced. Another phenomenon is ejection. Production of an apparent crater demands creation of an empty volume, which in turn demands ejection--removal, and transportation elsewhere--of the material that was in the space to be vacated. It is conceivable that, because of bulking, no apparent crater would be produced even though some of the original material had been removed by ejection; a fraction of the former material, now bulked, could occupy the total former volume. <u>Satisfactory</u> ejection, for production of an apparent crater, implies two things: the material must be thrust out of the to-be-cratered volume in the first place, but it must also be thrown out with enough lateral component of motion to come to rest out to the side and not back within the crater boundary.

51. The brick-model tests failed to produce apparent craters because of insufficient ejection. This may have been insufficient ejection in the first place, or only insufficient lateral motion imparted to the ejecta. In any event, apparent craters were not formed by shots 1 and 2 and diminutive apparent craters were formed by shots 3 and 4. Shot 5, at which a marginal apparent crater was formed, must be considered a special case because of its unique topography.

Deviation of Results from Predictions

Predictions

52. Before shots 1, 2, and 3 were detonated, predictions were made for the dimensions of the resulting craters, using cratering curves for dry rock in Johnson (1971); see Figure 25. For the (identical) charge weights and DOB of tests 1 through 3, these curves predict a radius of 2.0 ft and depth of 1.0 ft (0.61 and 0.31 m). The curves apply to stemmed shots. Results of the Middle Course II cratering series (Sprague, 1973) suggested that unstemmed shots should give craters 10 to 20 percent smaller in linear dimensions than fully stemmed shots. Thus dimensions only slightly smaller than 2.0 ft and 1.0 ft were expected. The actual dimensions in all three tests differed radically from these expected values.

Deviations from predictions

53. The appearance of the beds after shots 1 through 3 was what would have been expected for scaled depths of burst considerably greater than the actual depths. Johnson (1971, Figure 4, p. 10) shows a rubble mound to be the expected result at depths of burst substantially greater than optimum. The observed brick-model results suggested the computation of a hypothetical "effective charge weight," using as a basis a scaled DOB that one might expect to have been the case judging from the appearance of the blasting results. Carrying out such a procedure gave "effective charge weights" of one-fifth to one-quarter the actual weights for beds 1 and 2. This suggested there was a great loss of effective energy.

Possible reasons for deviations

54. One credible reason why beds 1 and 2 departed so strongly from expected cratering was that they were so gas-permeable that the explosion gases dissipated rapidly and never had the chance to exert a maximum ejection effect. The intended purpose of using the bonding material at bed 3 had been to alter the joint strength properties from those at beds 1 and 2. It appears that the cement exerted a more fundamental, though unanticipated, influence, that of a sealant. By filling

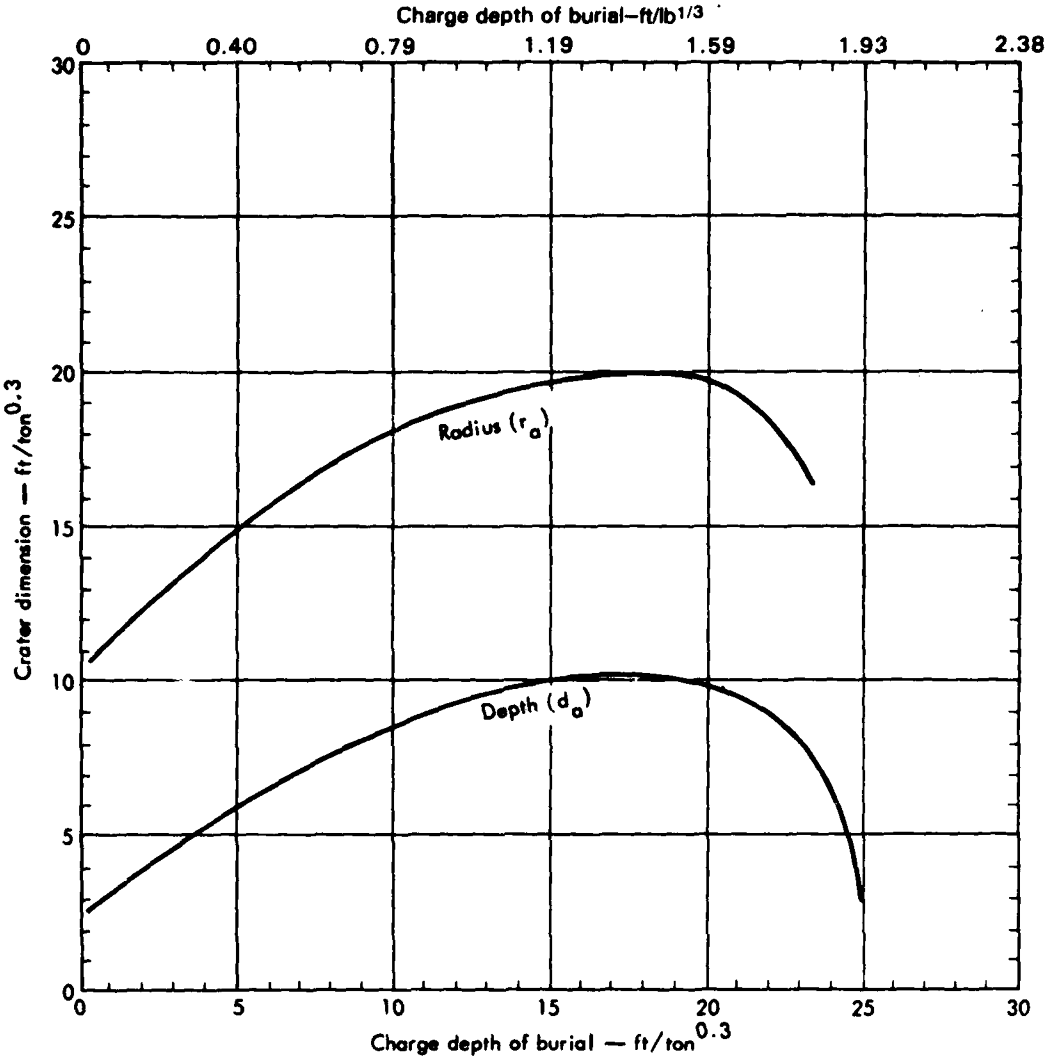


Figure 25. Crater dimensions scaled to 1-ton charges of TNT or equivalent buried in dry rock (from Johnson, 1971)

the joints and bedding planes, the cement rendered bed 3 impermeable, in contrast to the highly permeable beds 1 and 2. The explosion gases were apparently able to exert a productive cratering effect at bed 3 that did not occur at beds 1 and 2, where the gases were largely dissipated through the open joints and bedding planes. There was ample evidence in the form of soot deposition to indicate that explosion gases deeply permeated the joints in the beds.

55. Another likely cause of inferior cratering was the lack of stemming. This condition existed for all tests, while only beds 1 and 2 were gas-permeable. It is virtually certain that lack of stemming had an effect, but there is no evidence with which to quantify it.

56. Another contributing factor at all beds except No. 4 may have been an excessive DOB. From Figure 25, it can be observed that optimum scaled DOB would be 1.35 $ft/lb^{1/3}$ (0.54 $m/kg^{1/3}$), whereas the scaled DOB for shots 1, 2, 3, and 5 was 1.65 ± 0.02 $ft/lb^{1/3}$ (0.66 ± 0.1 $m/kg^{1/3}$). The scaled DOB at shot 4 was 1.08 $ft/lb^{1/3}$ (0.43 $m/kg^{1/3}$). This, though 0.27 scaled foot (0.11 scaled metre) shallower than optimum, should have given a crater depth 96 percent of the maximum, which would have been 1.00 ft (0.31 m). The overly deep shots at 1.65 $ft/lb^{1/3}$ (0.66 $m/kg^{1/3}$) should have given depths of 94 percent of the maximum, but since the curve descends steeply above 1.65, there is more chance for error towards the deep end of the curve.

57. Thus, it could be said that beds 1 and 2 had three detrimental factors against them (gas-permeable, unstemmed, and DOB too great), bed 3 had two (unstemmed and DOB too great), and bed 4 only one (unstemmed). If the predictive method is reliable, then the discrepancy between the expected depth of 1.0 ft and the actual depth of 0.3 ft at bed 4 must be ascribed to lack of stemming. In the opinion of the author, however, the predictive method is probably less than completely reliable. Had shot 4 been stemmed, the crater depth would have been greater, but probably not as great as predicted.

58. The uncemented condition was demonstrated to be an unrealistic model of real rock, as much of the pressure from the explosion gases was dissipated in the open joints. It is interesting, however, to note that the shot behavior of beds 1 and 2 was very different from the behavior predicted informally by several of the author's colleagues in the WES Structures Laboratory, who expected that "brick would be flying all over the county." The jointing in the beds was uniformly vertical, and the bricks were interlocked in a close-packed configuration, similar to a set of blocks in their carton when first brought home from the toy store. The first block is difficult to remove; once it is out, the

others are removed easily. Apparently this arrangement induced bricks to be heaved straight upward, so that they fell back directly into the excavated hole and built up a mound. In fact, the high-speed motion pictures of shot 4 showed a striking tendency for the ejected material to move nearly vertically. Thus, perhaps this is another detrimental factor against the brick beds: their structure. Prominent and easily sheared vertical joints tended to control the direction of ejection, to minimize the imparting of a lateral component to the ejecta motion, and thus to hinder apparent-crater formation.

Comparison with Previous Cratering Experience

Cratering literature

59. Cratering research has proceeded along several paths. Although there is abundant literature (see Rooke et al., 1974; Müller and Carleton, 1977), it is not extensive with regard to the specific case of cratering in fresh rock. Moreover, the brick-model tests did not duplicate any known cratering event or events, so that direct comparison, which would be the simplest procedure to interpret, is impossible.

60. A major avenue of cratering research has been in military programs, where concentrated explosive charges have been detonated in or on various media. In general, the results of near-surface military shots are not helpful in interpreting the brick-model results, because quite different cratering behavior results from near-surface explosions than from buried ones. Buried military shots are more nearly applicable. Extensive and carefully documented tests were conducted in granite and sandstone in the Underground Explosion Test Programs of both the U. S. Army Corps of Engineers (Engineering Research Associates, 1952; Engineering Research Associates, 1953) and the Colorado School of Mines (Colorado School of Mines, 1948). All shots in these programs were stemmed, however, and cratering studies involved true craters only; no apparent-crater information was recorded.

61. A limited area of military testing has studied the effect on

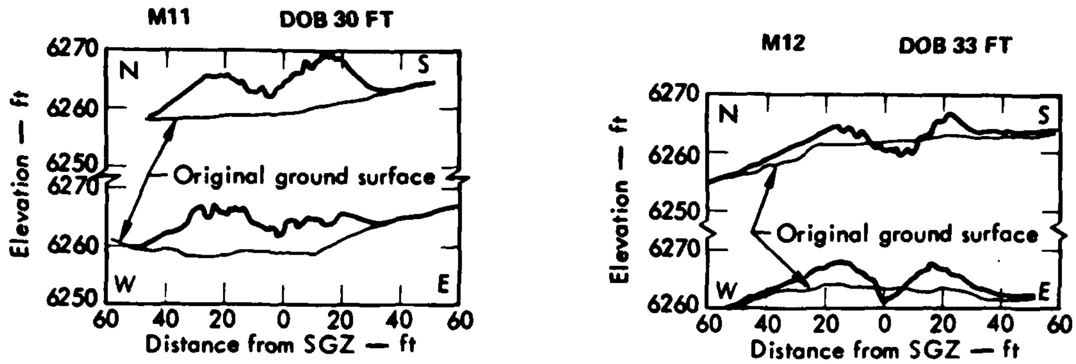
crater size of stemming versus an open charge hole. Unfortunately, most of these tests were performed in soft materials (e.g., Knudson et al., 1972). Only in the Middle Course II cratering series was rock present (Sprague, 1973), and in most of the tests of that series, competent rock was overlain by overburden, or weathered and fractured rock, or both. The Middle Course II series is discussed further below.

62. Another set of cratering tests took place during the PLOWSHARE program, where the goal was to use cratering as a means of excavation for construction purposes. Reports coming from these efforts are only marginally useful, since the explosive charges were always stemmed and most of the testing was done wholly or partially in soil-like materials. One favorable aspect of this research was that apparent craters were the primary object of interest.

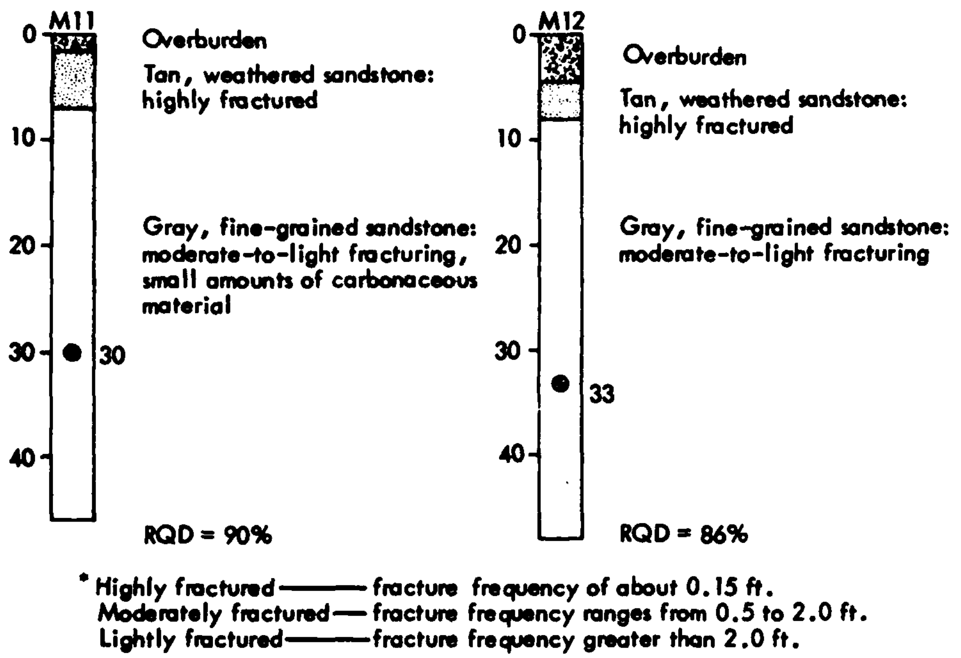
63. Still another avenue of cratering research has been in fundamental studies of rock breakage in the field of mining or quarrying. Here there has often been an effort to test fresh, unweathered rock, but stemming has been used and true, rather than apparent, craters have been studied.

Specific comparisons

64. The literature thus gives no direct and scant close analogy. The closest analog probably consists of two shots fired during the Middle Course II cratering series in 1971 at Trinidad, Colorado. Shots M11 and M12 were both 1-ton spherical charges fired in unstemmed 3-ft-diameter emplacement holes. Figure 26 (after Sprague, 1973) indicates the emplacement conditions and the cratering results for these two shots. Shot M11 was fired at a scaled DOB of 2.22 $ft/lb^{1/3}$ and M12 at 2.62 $ft/lb^{1/3}$ (0.88 and 1.04 $m/kg^{1/3}$, respectively), so both charges were appreciably deeper than the brick-model charges. Both charges, however, were in and beneath a substantial thickness of competent rock with only a thin cover of weak rock and overburden. Physically, therefore, the emplacement conditions approached those of the brick models. As shown by Figure 26, one shot produced a mound and the other a diminutive apparent crater. Other open-hole shots in the Middle Course II series, where the scaled DOB was closer to those of the brick models,



a. CRATERING RESULTS



b. LITHOLOGIC COLUMNS

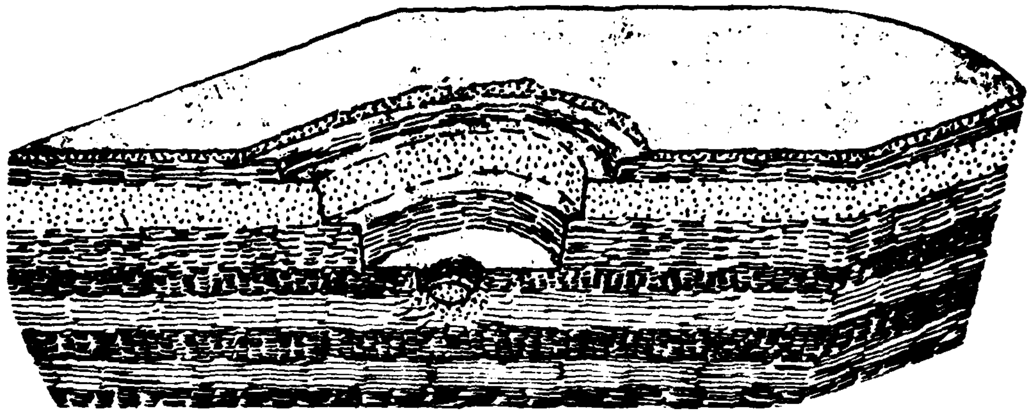
Figure 26. Cratering results and lithologic columns at shots M11 and M12, Middle Course II cratering series. Both charges were one-ton spheres of an aluminized ammonium-nitrate water-gel explosive in unstemmed 3-ft-diameter emplacement shafts (after Sprague, 1973)

were emplaced under substantial thicknesses of weathered rock and overburden, and thus were less adequately modeled by the brick beds. Their cratering results do not seem inconsistent with the brick-bed results, however, interpreted in the light of the physical differences.

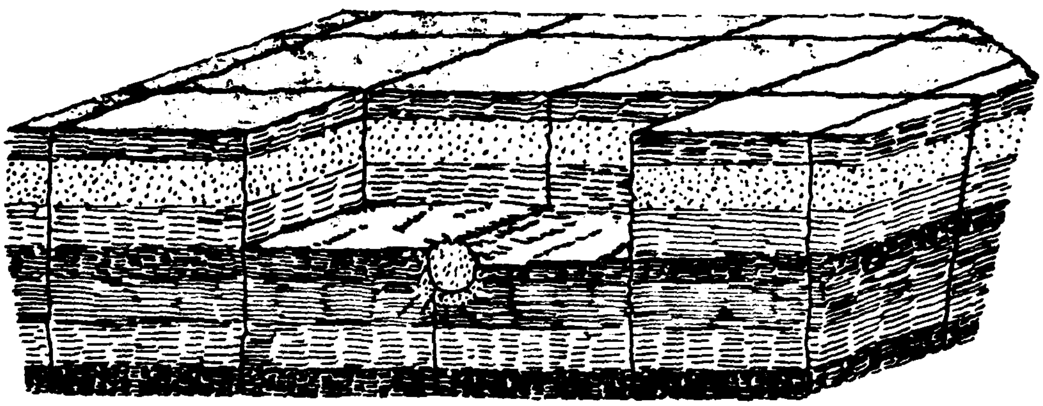
65. The shape of explosive craters in bedded and jointed media has been discussed by Gnirk and Pfleider (1968). They state (p. 325): "For explosive crater formation in a rock mass with both horizontal bedding planes and vertical joint systems, the shape of the crater may approximate a rectangular parallelepiped" (see Figure 27). The shapes of the true craters of beds 3 and 4 agreed remarkably well with this description.

Validity of Modeling Method

66. The question remains whether the brick-model test method is scientifically sound. This implies an examination of the question of scale modeling, as applied to cratering tests. Such an examination in detail is beyond the scope of this report, but such analyses are available in the literature. In effect, it appears (Danés discussion following Johnson, 1963) that cube-root scaling is satisfactory for that part of the cratering process where gravity is not a factor. This includes detonation, fracturing, and gas acceleration of ejected particles. Gravity does enter into the trajectory of the ejected particles, and thus into apparent-crater formation. We may examine the direction in which the error from incorrect scaling of gravity should affect the model results. To scale properly for gravity would require increasing the gravitational field, as has been accomplished by L. K. Davis of WES (personal communication) in unpublished research on cratering in a centrifuge. Failing to scale gravity would mean that actual gravity at the model was too weak. Thus, ejected particles would feel an insufficient pull back to earth, would travel overly far, and would deposit an unduly wide pattern of debris. The expected prototype phenomenon would be a less widely dispersed ejecta population than the model population. The brick tests themselves produced slightly dispersed ejecta populations and associated poor apparent-crater development. The implication is that prototype-scale cratering in similarly structured material under



(A) Explosive Crater Formation in a Rock Mass with Horizontal Bedding.



(B) Explosive Crater Formation in a Rock Mass with Horizontal Bedding and Vertical Jointing.

Figure 27. The effects of horizontal bedding and vertical jointing in rock masses on explosive crater formation (from Gnirk and Pfleider, 1968; reprinted by permission)

similar burst conditions would be expected to yield very laterally restricted ejecta distributions and poor apparent craters.

67. Following this thinking, we may postulate a field cratering situation that would be well modeled by the brick tests. Considering beds 3 and 4, the best field analog would be the flat floor of a quarry where the rock is evenly and fairly thickly bedded and orthogonally jointed at moderate to wide spacings. See, for instance, Figure 28, which represents a 5-times scaled-up version of brickbed 3. If the bed 3 results predict well, the result of detonating the charge in the bed shown in Figure 28 would be a rubble assemblage fairly close in elevation to the preshot ground level, neither an appreciable apparent crater nor an appreciable mound. There would be some freshly broken blocks near the shot hole, but most of the rubble blocks would be bounded by joints and bedding planes. The rubble blocks would be rather large, about 1 by 1.5 by 3 ft (0.3 by 0.5 by 0.9 m). Excavation of the rubble would produce a square pit with steep or vertical sides and a flat bottom. To the author this seems like a reasonable expectation.

68. Blasting tests in models have been performed in the past, e.g. the ZULU II series (Bening and Kurtz, 1967) and rock tests by Johnson (1963). Those in sand beds and the like are efficient models only of soil-like materials, not of rock. Those in rock monoliths or concrete are better approaches to rock blasting, but they lack the essential factor of geologic structure. The discrete-element beds tested in this series are a step closer to reality than such monolith shots. They have some geologic structure, even if it be a highly specialized and simplified one. If blasting tests in models are to be carried out, the author believes that test beds constructed of bricks offer a more realistic analog to nature than cast monoliths.

69. Where detailed prediction with high confidence is the goal, there is doubtless no substitute for field testing at scales at or near one to one. The author does believe, however, that when properly used, the brick-modeling technique has its own value. If brick models were constructed with an appropriate effort to follow gross features of particular field test sites, and then subjected to detonations in

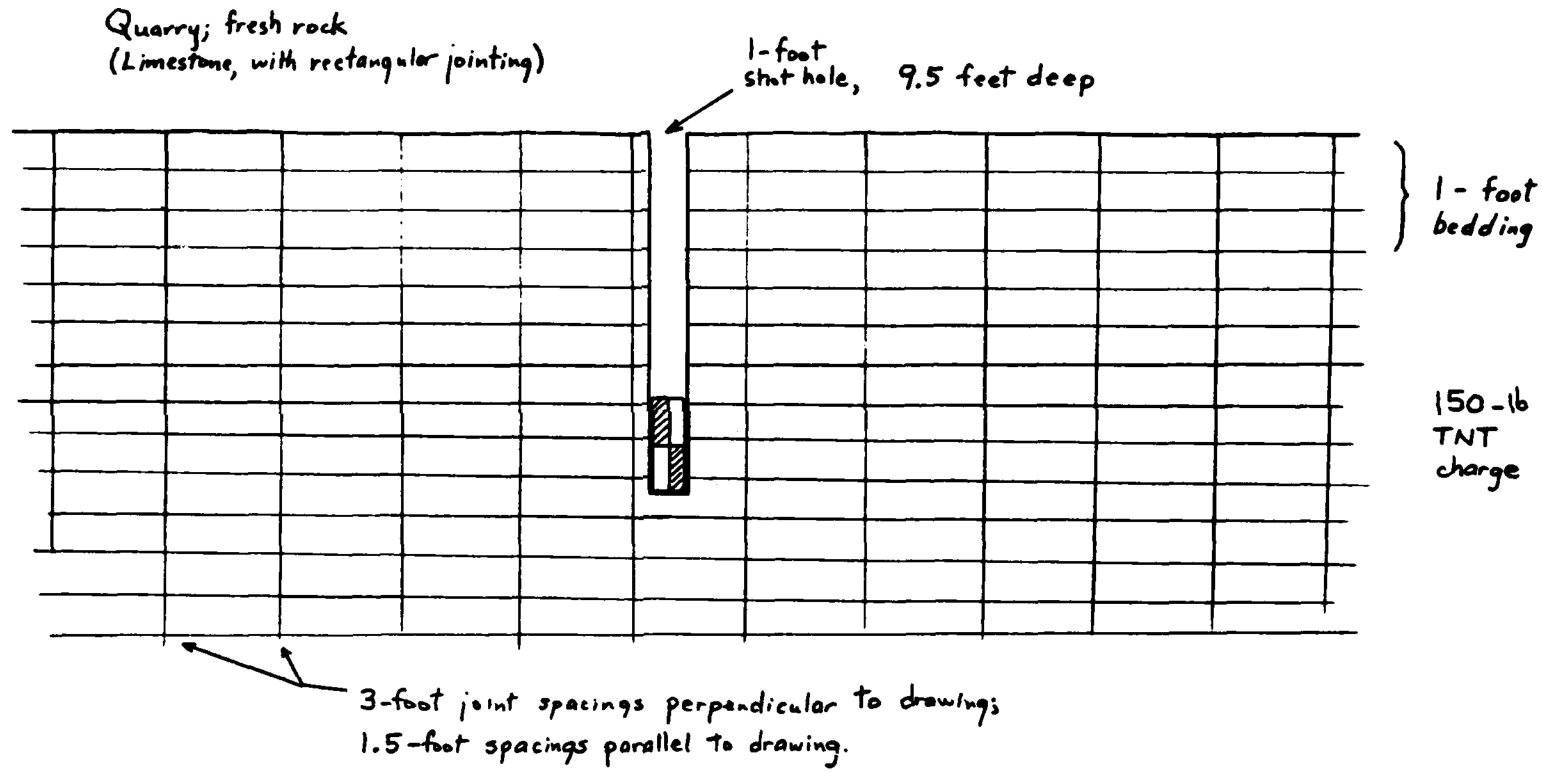


Figure 28. Representation of a realistic setting that would be directly modeled by brick test 3 at a 5:1 scale

duplication of specific field tests, a grasp of those effects that do model satisfactorily could be gained. Then other brick-model tests could be designed and conducted with some confidence in the meaning of their results. The conduct of field testing is generally costly, both to find and acquire the sites, and to carry out the test programs. In view of all these facts, the capability to design and build approximate sites at will, close to home, would have definite attractiveness.

70. As mentioned above, the shaft size, charge weight, and depth of the brick tests were chosen so as to model existing military demolition shafts. In fact, a road pavement is not constructed directly upon outcropping bedrock, but upon a granular subgrade, of some thickness, laid down on top of the rock. Moreover, even for minimal subgrade thickness, instances where the bedrock would be completely fresh, as well as massively bedded and jointed, would surely be rare. Thus, actual demolition shafts would rarely if ever be perfectly modeled by the brick beds of the test series. Nevertheless, the case modeled by these brick tests could be regarded as a limiting, unfavorable-for-cratering case toward which the real-world military situation might approach.

71. It is concluded that the model blasting results obtained on the cemented beds were realistic, and that the technique has been demonstrated to have value. The technique is, therefore, worth pursuing further.

Future Tests

72. One avenue of specific interest that could be investigated in a future simple series of brick-model tests would be whether inclined rather than vertical joint planes would tend to cause more favorable formation of apparent craters. In any cratering shot under level ground, the most favorable ejection direction is straight up. The vertical direction leads to the nearest free face and offers the path of easiest relief for the movement of material. In the level-ground brick-model tests this direction was also favored by two vertical joint sets.

The blasts produced a large amount of straight-up ejection with fallback filling the crater. It is an interesting question whether inclined joints would systematically lead to better throw-out. If they were found to do so, the technique of improving apparent-crater formation at real military sites by constructing artificial inclined joint planes might be worth serious investigation.

73. An interesting test would be to duplicate shot 1 or 2 or both with the brick beds saturated with water. More effective cratering would be expected because of the confinement of the explosion gases by the no-longer gas-permeable beds.

74. Tests could also be conducted in beds that incorporated overburden over bricks. In fact, all sorts of combinations of geometry and materials are possible.

75. The difference in confinement between the four level brick beds (beds 1-4) and the hillside bed (bed 5) showed up in greater bed distress at the latter, in the form of loosening of bricks adjacent to the crater. For an ideal comparison, bed 5 should have been concrete-enclosed; but operational difficulties of pouring concrete on a slope would persist. It might be better, therefore, if the series were to be redone, to build the level beds with tamped-soil floors and backfill. Alternatively the difficulties of concrete form construction could be accepted, and all tests conducted with concrete backfill.

Discrete Element Method (DEM)

76. A collateral point of interest in carrying out the brick-model cratering tests was that they might furnish test data for the algorithms of the Discrete Element Method (DEM). This computational technique uses Rigid (RBM), Simply Deformable (SDEM), or Breakable (RMBC) blocks to describe the response of a rock body to an event by applying appropriate laws of motion (Cundall et al., 1978). The technique may be applicable to the modeling of cratering in jointed rock. Since the structure and properties of the brick models were completely known, the results should offer an excellent opportunity for testing the DEM.

General Observations on Test Results

77. The preponderance of fractured brick at beds 1 and 2, in comparison with the other tests, probably arises from the fact that, being not tightly locked into position, as were individual bricks in the cemented beds, individual bricks were able to strain and jostle, and were thus more susceptible to being broken when hit by both the shock wave and the gas pressure from the detonation.

78. The importance of the explosion gases as a factor in cratering was clearly demonstrated, both by the inferior cratering results in the gas-permeable beds 1 and 2 and by the uplift phenomena noted in cemented beds 3 and 4. According to current conceptions in commercial blasting, the explosion gases are of vastly greater significance than the shock wave (personal communications, Richard A. Dick and Calvin J. Konya), although much importance was attached to the shock wave in older literature.

79. The simple sketch in Figure 24, with the true-crater boundary indicated as a sharp line, is misleading, as is the word "fallback," which implies that all the material inside the true crater has been heaved upward and has fallen back to its present position. In fact, the true-crater boundary may be a very gradational zone; and much of the "fallback" material may never have left its present vicinity. A particularly good description of these characteristics is given in Fisher (1968). The indistinctness of the true-crater boundary was noted in excavating all five brick beds. It was repeatedly necessary to make judgmental decisions whether a given brick should be removed or not, whether it properly lay inside or outside the "true crater."

PART V: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

80. Cratering results in cemented brick test beds appear reasonable when compared with results of previous field cratering tests, if all respective test details are taken into account. Accordingly, cemented brick test beds appear to be valid approximate models of jointed rock masses for the purpose of studying cratering behavior. Further tests are warranted.

81. The importance of the explosion gases was demonstrated. The test results were consistent with current beliefs in the field of blasting, which ascribe pre-eminent importance to gas pressures as opposed to the effects of shock.

82. Vertical joints in a brick or rock bed may inhibit apparent-crater formation, by inducing straight-up ejection, so that the ejected material falls directly back into the crater.

83. The published predictive curve for craters in dry rock (Johnson, 1971) is probably not accurate for unstemmed shafts in fresh, orthogonally jointed rock. Accordingly, full-scale demolition shafts in such rock may not yield the desired crater obstacles.

84. The shapes of the excavated true craters in the cemented brick beds closely resembled shapes previously described in the literature for true craters in horizontally bedded, vertically jointed rock. This agreement suggests that the beds were good models of such rock.

Recommendations

85. Since the brick-model cratering technique appears to have shown enough promise to warrant further checking, it is recommended that further test shots be conducted. Several possible directions in which to proceed are as follows:

- a. Perform cratering tests in cemented brick beds with level surfaces but with inclined bedding and jointing in the beds. These tests would examine whether superior lateral ejection, and thus better apparent craters, would result from cratering shots in rock with inclined geologic structure.

b. Perform a rerun of shot 1 (uncemented) with the bed saturated with water. This test would seek to verify whether gas permeability was the principal factor in the production of mounds rather than craters in the uncemented beds. For the same purpose, perform a second rerun of bed 1 with the bed saturated with a gel.

c. Perform reruns of shots 1, 3, and 4, but using stemming. These would seek to quantify the contribution of lack of stemming to the smallness of the craters in the present series.

d. Select from a literature search a few well-documented cratering shots in rock. Design brick beds to model the site conditions at these shots, including overburden and stemming as appropriate. Fire cratering charges in these beds and compare the results with the field cratering results. These tests would investigate the capability of the brick-modeling technique to produce cratering results that are faithful models of full-scale cratering events.

86. After the tests outlined above have been conducted, the results should be assessed. A decision should then be made as to what future tests, if any, using the brick-modeling technique would be interesting or profitable.

87. It is also recommended that an attempt be made to model the five tests of the present series with the DEM.

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TABLE 1. TEST-BED INFORMATION

BED NO.	BED DESCRIPTION	BRICK STACKING *	CEMENTING **	SHAFT DEPTH FT +	NUMBER OF BRICK COURSES: TOTAL	NUMBER OF BRICK COURSES: PENETRATED BY SHAFT	DEPTH OF CENTER OF CHARGE FT	CHARGE WEIGHT LB ++	SCALED CHARGE DEPTH FT/(LB)$^{1/3}$
1	Bricks placed in cylinder, approximately 7.2 ft diameter, 3.6 ft high (19 courses); founded on level concrete floor in dug pit; concrete backfill.	c axis vertical.	N	1.90	19	10	1.67	1.07	1.63
2	Same as bed 1, except: approximately 3.7 ft high (6 courses).	a axis vertical.	N	1.93	6	3.1	1.70	1.06	1.67
3	Same as bed 1.	c axis vertical.	C	1.90	19	10	1.67	1.05	1.64
4	Same as bed 1. Bed 4 was prepared by excavating bed 1 and rebuilding it with addition of cement slurry.	c axis vertical.	C	1.33	19	7	1.10	1.06	1.08
5	Sloping model built in cut into embankment. See figure 22. Compacted soil backfill.	c axis vertical. a axis parallel to hill contour.	C	1.90	15	10	1.67	1.03	1.65

Notes: * All stacking was one brick directly above another; no overlapping; continuous joints. Brick-axis nomenclature: a, parallel to long dimension (7-3/8 in.); b, parallel to intermediate dimension, 3-3/8 in.; c, parallel to short dimension (2-1/4 in.). See Figure 2.

** Cementing: N, no cementing agent; C, cement-slurry bonding agent. See text for description.

+ All shafts were 2-3/8 in. in diameter (drilled with BX diamond coring bit).

++ All explosive charges were TNT cylinders with integral cast-in-place tetryl boosters. Length: 5-5/8 ± 1/8 in.; diameter: 2-3/16 ± 1/8 in. Initiated by commercial electric blasting caps.

TABLE 2. DIMENSIONS OF CRATERS AND RUBBLE MOUNDS, BEDS 1-4

		Dimension (Feet)							
		Apparent Crater		Rubble Mound		True Crater		Apparent-Crater	True-Crater
Bed No.	Brick Orientation	NS	EW	NS	EW	NS	EW	Depth	Depth
1	a NS b EW c vertical	--	--	7.0	5.0	4.6	3.9	-0.5	2.1
2	a vertical b NS c EW	--	--	6.3	5.2	4.4	4.3	-0.7	2.0
3	a NS b EW c vertical	*	1.9	8.1**	6.8	3.6	4.0	-0.2	2.1
4	a NS b EW c vertical	3.7	3.0	---	---	4.6	4.2	0.3	1.6

Notes: * Not surveyed; see figure 15.

** Rubble mound at bed 3 was artificially constricted in NS direction because construction error placed top of bed about 0.6 ft below ground surface.

APPENDIX A: REASONS FOR SELECTING BRICKS IN PREFERENCE TO CERAMIC TILES

1. Considerable thought was given at the start of the program to using some material other than brick that would make it possible to work at a smaller scale. The only other rocklike product available in regular shapes was found to be ceramic bathroom tile. All other clay-tile products had shapes that would not permit complete packing of a given volume of space. Tabulated below are comparative properties of bathroom tiles versus bricks.

Tiles	Bricks
Smaller	Larger
Very oblate	Rectangular
Tetragonal	Orthorhombic
Denser	Lighter
Stronger	Less strong
Semivitreous, nonporous	More porous
Low coefficient of friction on joints	Higher coefficient of friction on joints
Flaw-free	Some contain incipient cracks and flaws
Faces are slightly beveled near edges	Faces meet at a sharp edge
Quite homogeneous	Somewhat heterogeneous

2. Bricks were selected for the following primary reasons. The bevels along the tile edges would make unrealistic "tubes" in a solid bed; the high-friction joints of bricks seemed more realistic; the orthorhombic symmetry of bricks gave more stacking-pattern options than the tetragonal symmetry of bathroom tiles; and bricks were judged probably easier to stack, requiring less painstaking effort, and involving less chance of a "jostle" accident.

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

McAneny, Colin C
Feasibility of use of simple models to test explosive cratering of roads on slopes in rock / by Colin C. McAneny. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1979.
51, [2], 1 p. : ill. ; 27 cm. (Miscellaneous paper - U. S. Army Engineer Waterways Experiment Station ; SL-79-19)
Prepared for Assistant Secretary of the Army (R&D), Department of the Army, Washington, D. C., under Project No. 4A161101A91D, Task 02, Work Unit 126.
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