Progress in Nuclear Excavation Technology

MILO D. NORDYKE, University of California, Lawrence Radiation Laboratory, Livermore, California; and
LOUIS J. CIRCEO, U. S. Army Corps of Engineers

Several experiments conducted during the past year in the Plowshare Program and other developments related to nuclear cratering are described. Newly developed cratering curves in alluvium and basalt rock are presented, based on several high-explosive cratering programs. Progress in the development of a theoretical model of cratering is summarized. Also described is a recent investigation into the phenomenology of subsidence craters produced by very deeply buried detonations in alluvium. High-explosive row charge detonations to produce channels are presented. Results from the Dugout experiment, the first row charge cratering detonation in rock, indicated that many of the concepts developed for row charges in alluvium are also valid in a hard rock medium.

Two investigations into the survival of craters under the action of natural and dynamic forces are described, and economics of nuclear excavation are presented using newly released AEC charges for nuclear explosives. Advancement in the development of low-fission thermonuclear explosives is expected to reduce radioactivity levels considerably below 1962 Sedan levels.

•THE PLOWSHARE Program was established in 1957 to investigate possible industrial applications of nuclear explosives. Currently under investigation are applications relating to excavation, mining, and isotope production. Large-scale excavation is perhaps the most promising use of nuclear explosives. The great energy released by a buried nuclear explosion shatters and imparts a sufficient velocity to the medium above the explosion not only to break up the medium, but also to eject it and produce a crater. A row of explosions spaced about one crater radius apart and detonated simultaneously will produce a ditch about the depth and width of a single crater. Such effects indicate a potential capability of nuclear explosives for excavating large quantities of material for the construction of harbors, canals, and highway and railway cuts. Deeper burial in a hard rock medium would produce large quantities of broken rock which could be used as aggregate.

Over the past 13 years a considerable body of data on explosive cratering has been developed for application to nuclear excavation projects (1). These data were obtained from ten cratering programs using chemical high explosives and seven nuclear cratering detonations. The types of media studied have ranged from marine muck to hard dry basalt, although most effort has been devoted to craters in desert alluvium and basalt at the Nevada Test Site. Considerable effort has also been devoted to the study, with chemical explosives, of the use of linear explosives and rows of point charges. Basic nuclear excavation technology has previously been discussed (2). This paper summarizes information acquired during the past year which has contributed toward nuclear excavation technology and industrial applications.

DEVELOPMENT OF NUCLEAR EXCAVATION TECHNOLOGY

Cratering in Alluvium

Table 1 summarizes most of the pertinent nuclear cratering data obtained since 1951. Not shown is a large amount of data obtained from explosions at much larger depths

Paper sponsored by Special Committee on Nuclear Principles and Applications.

TABLE 1

SUMMARY OF NUCLEAR CRATERING DATA FROM NEVADA TEST SITE

Shot Name	Medium	Yield (kt)	Depth of Burst (ft)	Dimensions of Apparent Crater			
				Radius (ft)	Depth (ft)	Volume (cu yd)	Lip Height (ft)
Jangle S	Alluvium	1.2 ± 0.1	-3.5[a]	45	21	1.65×10^3	—
Johnnie Boy	Alluvium	0.5 ± 0.2	1.75	61	30	5.3×10^3	10
Jangle U	Alluvium	0.2 ± 0.1	17	130	53	3.7×10^4	8
Teapot ESS	Alluvium	1.2 ± 0.1	67	146	90	9.6×10^4	20
Sedan	Alluvium	100 ± 15	635	604	320	6.6×10^6	15-100
Danny Boy	Basalt	0.42 ± 0.08	110	107	62	3.6×10^4	15-30
Neptune[b]	Tuff	0.115 ± 0.015	100	100	35	2.2×10^4	—

[a]Detonated 3.5 ft above surface. [b]Detonated 100 ft beneath a 30-deg slope.

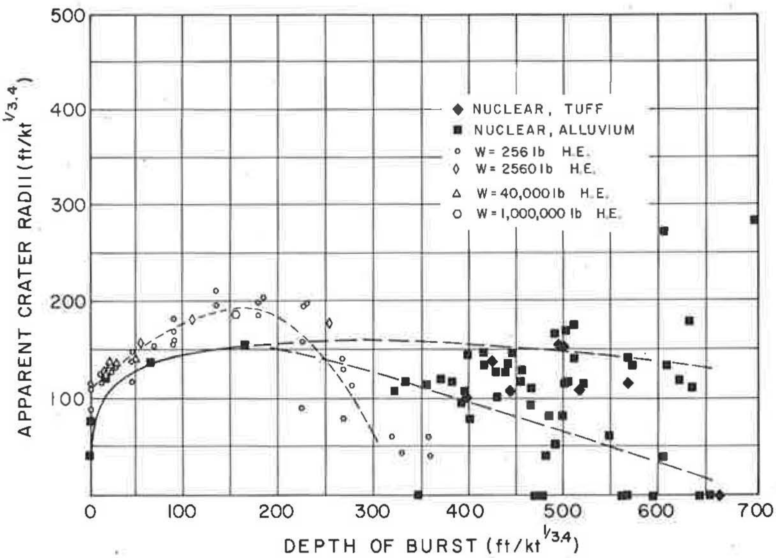

Figure 1. Plot of chemical high explosive (H.E.) and nuclear explosive apparent crater radius data vs depth of burst; NTS desert alluvium, $W^{1/3.4}$ scaling.

of burst. Nuclear and chemical explosive data points for desert alluvium have been plotted in Figures 1 and 2. The dashed curves are the last-square fits of the 256-lb chemical explosive data. Nuclear data are shown by the solid curves. The difference between the curves for the chemical explosive and those for nuclear explosive data is attributed to the variation of explosion phenomena between nuclear and chemical explosives (3).

Much data have also been obtained from the nuclear weapons tests conducted at the Nevada Test Site over the past several years. When a large nuclear explosion is detonated at a depth of burial much deeper than optimum, a large underground cavity is formed which ultimately collapses, resulting in a large subsidence crater at the surface of the ground. Figure 3 shows a schematic cross-section of such a crater as reconstructed from postshot drill-hole information. Figure 4 is a photograph of a typical subsidence crater a few seconds after it has collapsed. The data points for a large number of these subsidence craters whose scaled depths of burial vary from 300 to 700 ft/kt$^{1/3.4}$ have been plotted in Figures 1 and 2. In some cases, the detonation point was located in weakly cemented tuff; in others, it was located in alluvium. In all cases, the

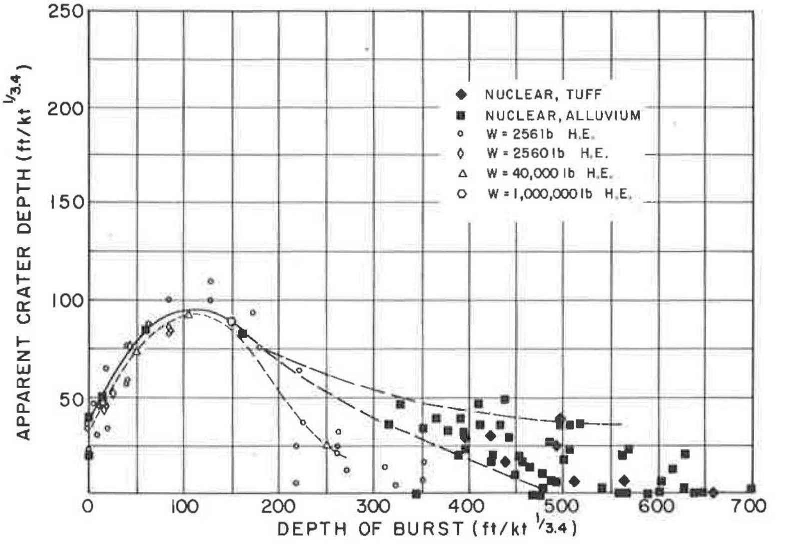

Figure 2. Plot of chemical high explosive (H.E.) and nuclear explosive apparent crater depth data vs depth of burst; NTS desert alluvium, $W^{1/3.4}$ scaling.

major portion of the collapse chimney region was in alluvium. The nature of the medium surrounding the detonation point is indicated.

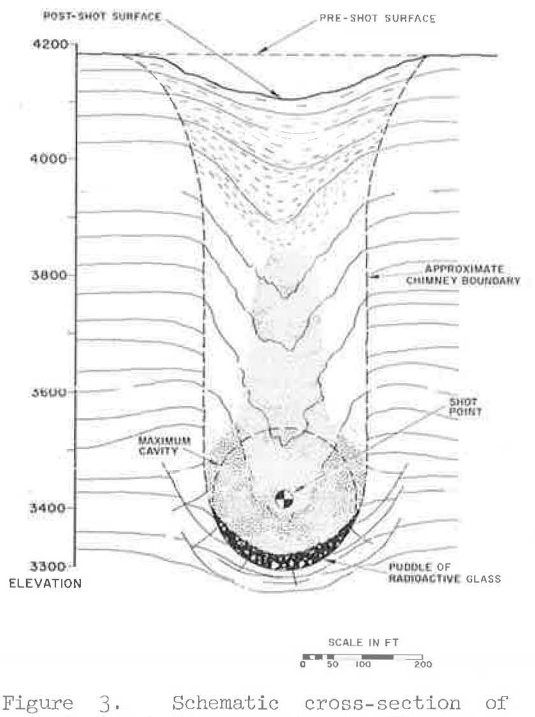

Figure 3. Schematic cross-section of typical subsidence crater in alluvium.

These subsidence cratering data for large-yield explosions have had a significant effect on our predictions of the size craters expected at large depths of burial in desert alluvium. It should be noted that subsidence craters are only expected in a medium such as desert alluvium where no bulking during collapse is observed. In a rock-type medium where bulking does occur, the volume of the underground cavity would not be transmitted to the surface as it is in alluvium, but would be distributed throughout the chimney region in the form of voids between the broken rock. With deep burial, the collapse region would, in fact, not even reach the surface of the ground.

Cratering in Basalt

To obtain cratering data for hard rock that would be useful to the Plowshare Program, Project Buckboard was undertaken in the summer of 1960. This program consisted of ten 1,000-lb and three 40,000-lb detonations in basalt (4). The site was a basalt-topped mesa in the Forty-Mile Canyon area on the west side

Figure 4. Aerial view of typical subsidence crater taken several seconds after collapse.

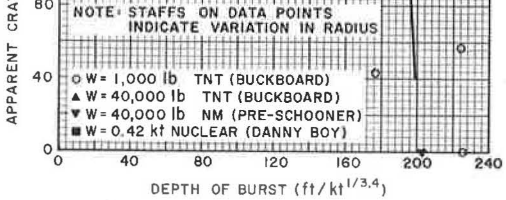

Figure 5. Plot of chemical high explosive (H.E.) and nuclear explosive apparent crater radius data vs depth of burst; basalt, $W^{1/3.4}$ scaling.

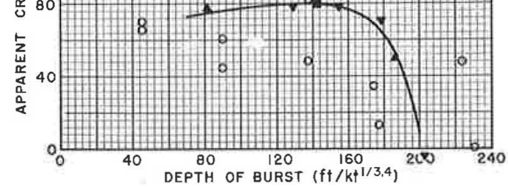

Figure 6. Plot of chemical high explosive (H.E.) and nuclear explosive apparent crater depth data vs depth of burst; basalt, $W^{1/3.4}$ scaling.

of the Nevada Test Site. These data are plotted in Figures 5 and 6. Visual observation of the craters led to the conclusion that 1,000-lb charges in a hard rock such as basalt do not result in meaningful apparent crater data. The apparent craters for the 40,000-lb charges, however, appeared to be much more relevant. It should be mentioned that the crater resulting from the intermediate shot at 136 ft/kt$^{1/3.4}$ was half in cinders and half in solid basalt. The effect of this on crater dimensions was somewhat difficult to estimate, but the unusually large dimensions of this crater relative to the other craters made this data point appear somewhat anomalous.

In an effort to obtain more and better data in basalt, a cratering program was undertaken in the spring of 1964 by the U.S. Army Engineer Nuclear Cratering Group (5). This program, called Pre-Schooner, was conducted at the same site as the Buckboard series and consisted of four 40,000-lb shots using the liquid chemical explosive, nitromethane. These data are also plotted on Figures 5 and 6.

Shown in Figures 5 and 6 are curves fit to these data. The 1,000-lb crater data and the data point for the anomalous Buckboard crater at 136 ft/kt$^{1/3.4}$ were given essentially no weight. Comparison of the 1,000-lb and the 40,000-lb crater data does not allow derivation of an empirical scaling exponent for basalt, but it does indicate that a scaling such as $W^{1/3.4}$ is adequate.

Row Charge Data

Alluvium.—Since Plowshare is interested in the utilization of craters for purposes such as canals and railroad and highway cuts, we are interested in the effects not only of point charges but also of rows of charges detonated simultaneously.

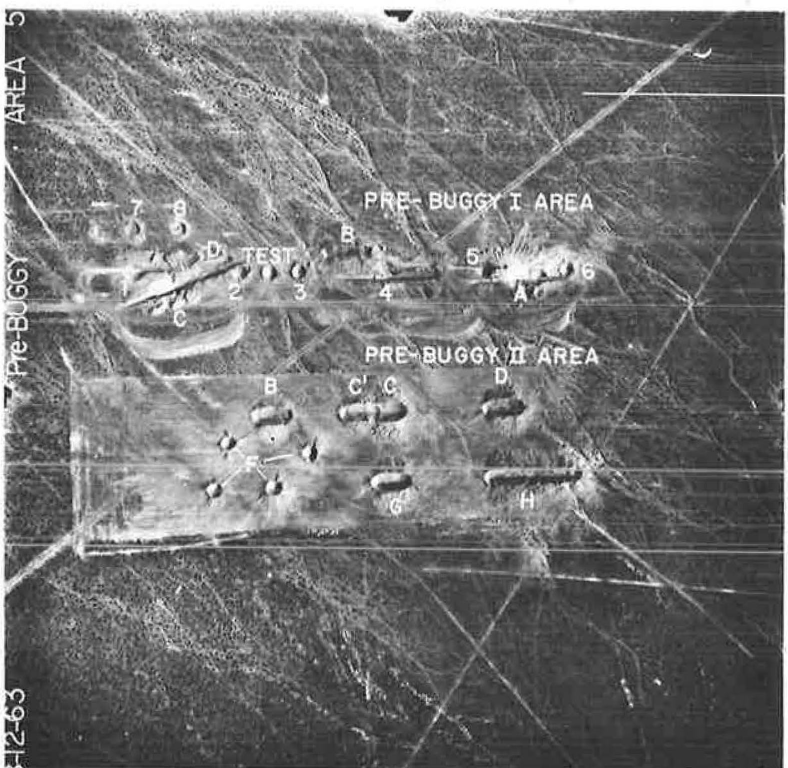

Figure 7. Vertical aerial view of Pre-Buggy crater in Area 5, NTS.

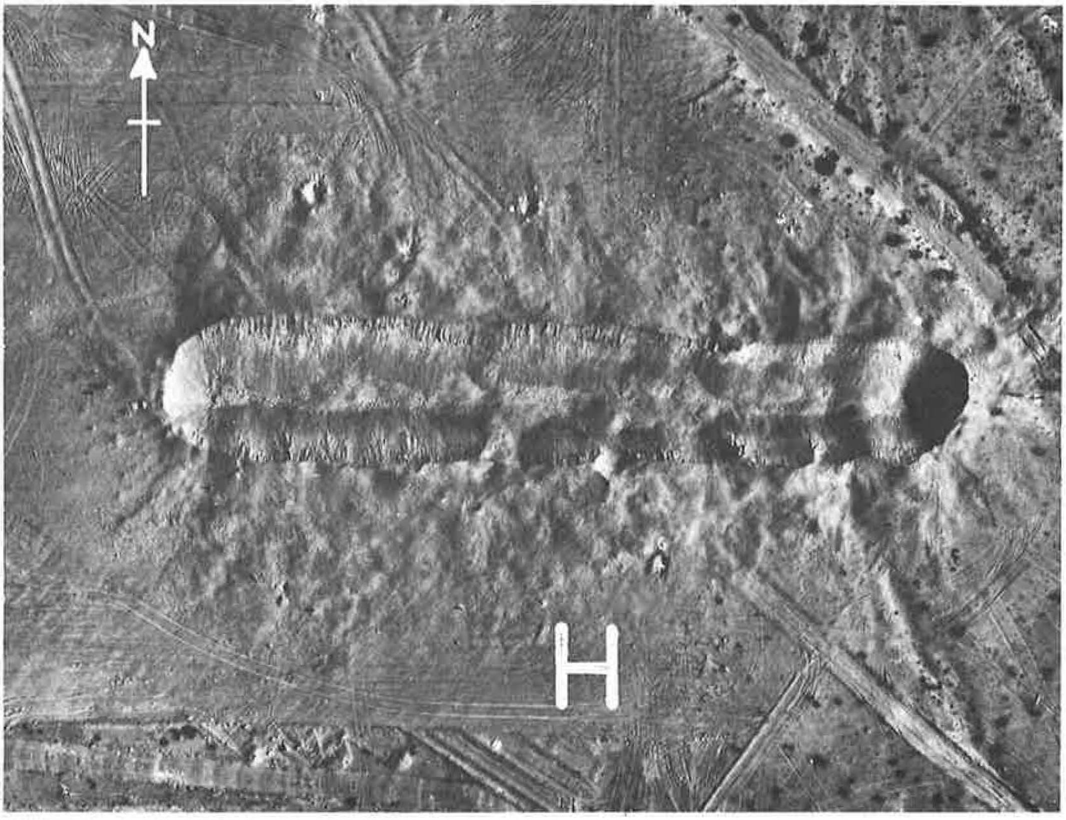

Figure 8. Vertical aerial view of Pre-Buggy crater H, showing effect of change of spacing from 1 radius spacing on the left to $1\frac{1}{2}$ spacing on the right.

In 1963, the U. S. Army Engineer Nuclear Cratering Group conducted the Pre-Buggy Program (6), consisting of a number of cratering shots utilizing 1,000-lb charges of nitromethane. Each detonation consisted of five charges in a row detonated simultaneously. In an extension of this program in July 1963, conducted by the Lawrence Radiation Laboratory and termed Pre-Buggy II (7), these cratering data were extended to two unique geometries: (a) two craters connected end-on in an attempt to explore the problem of connecting two craters, and (b) 13 charges using the same depth of burst but three different spacings. The Pre-Buggy area is shown in Figure 7. The two connecting craters are shown in the Pre-Buggy II area and are labeled C′ and C. The 13 charges with three different spacings are labeled row H.

The purpose of these row cratering experiments was to determine: (a) the effect on crater dimensions of variation in the spacing between charges, (b) the effect of spacing on the irregularity or cusping in the crater, and (c) the shape of the lip relative to the lip obtained with point charges, on both the sides and the ends of the crater. The conclusions can be summarized as follows:

1. Use of a spacing equal to approximately a single crater radius results in a smooth-sided crater with apparent dimensions about 10 to 20 percent larger than expected on the basis of single charge data;

2. Use of a spacing of about 1.25 times a single crater radius results in a ditch with dimensions approximately equal to those expected from single charges; and

3. Use of a spacing of 1.5 times a single crater radius results in a crater which is somewhat smaller than a single crater radius and quite irregular in cross-section.

These three spacings were used for row H, and the effect of the various spacings can be seen in Figure 8, an aerial view of row H, Pre-Buggy II.

The other significant conclusion from these cratering programs is that when four, five, or more charges in a row are fired simultaneously under conditions that result in a uniform ditch, the lips on the sides of the crater are approximately 50 to 100 percent higher than would be expected from single crater lips, whereas the lip on the end of the crater is virtually nonexistent in alluvium. This effect, of course, is extremely

Figure 9. Dugout crater.

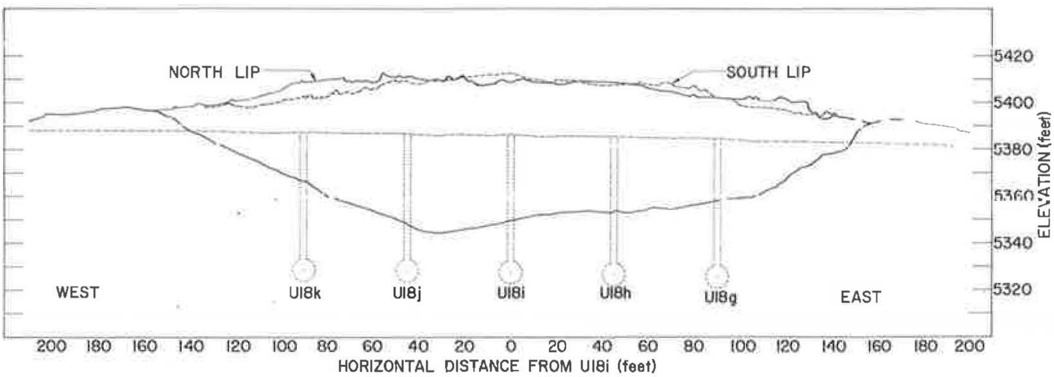

Figure 10. Cross-section and plan view of crater resulting from Dugout detonation.

significant when one is discussing the concept of making a long channel where it is necessary to connect a number of ditches.

Basalt.—Since most nuclear excavation applications will be in hard rock, it is regarded as extremely important to extend row charge data to that medium. In June 1964, the Dugout experiment, the first row cratering experiment in hard rock, was conducted on Buckboard Mesa at the Nevada Test Site (8). This project consisted of five spheres, each containing 40,000 lb of nitromethane.

The center of each sphere was about 59 ft below the ground surface, corresponding to a scaled depth of burst of about 185 $W^{1/3.4}$. The charges were spaced 45 ft apart, which corresponded to a spacing of slightly less than one crater radius. Five additional emplacement holes were drilled on line with the experiment to determine the damage incurred by emplacement holes adjacent to cratering explosions.

The crater resulting from the detonation is shown in Figure 9, and a plan and cross-section view is shown in Figure 10. The average width of the center 60 percent of the crater is 136 ft. The average depth of the crater is 35 ft, and the length is 287 ft. The average lip height above the original ground surface is about 24 ft along the sides of the crater and 12 ft on the ends. The apparent crater has a volume of about 21,000 cu yd.

The Dugout experiment produced several interesting conclusions regarding row cratering in a rock medium. Assuming that the 45-ft spacing is equivalent to the spacing of a single crater in this location, an enhancement of greater than 30 percent is seen in the crater dimensions of width and depth. This is similar to the enhancement observed in the Pre-Buggy series. The lip height along the sides was about 65 percent of the crater depth, also similar to Pre-Buggy. However, the lips on the ends were somewhat greater than those observed in alluvium. Perhaps the most significant results are that the simultaneous detonation of a row of explosives will produce a linear channel with no cusps and that many of the concepts developed for row charges in alluvium appear to also be valid in a hard rock medium.

Engineering Developments

Over the past several years, several nuclear detonations have taken place at the Pacific Proving Grounds at Eniwetok and Bikini Atolls. Many of these shots were surface and near-surface bursts which resulted in craters, some of considerable size. Figure 11 shows three of the Pacific craters. The two large craters, Mike and Koa, were produced by high-yield detonations, and the small crater, Seminole, was a low-yield shot. The Mike crater is over 1 mi in diameter.

In April 1964, a study was conducted at Eniwetok Atoll to investigate the long-term effects of wave action and weathering on craters (9). This study has indicated that no major changes have occurred in the craters, except for considerable silting up of the large craters shown in Figure 11. Minor slope failures have occurred and wave action has eroded the above-water lips of some craters. However, the craters have significantly altered the geomorphic balance of wave action, erosion, and deposition in the area. Burial at optimum depth will result in higher lips, steeper slopes, and more protection from external weathering conditions.

In another study, an investigation is being conducted into the ability of cratered slopes to survive ground shock from adjacent detonations. The 100-kt Sedan crater was instrumented and photographed in conjunction with a nearby underground detonation to observe the slope reaction to the seismic shock. Preliminary results indicate that portions of the crater received ground shocks in excess of 1.0 g. Only minor slope failures occurred, all in sections previously considered unstable, indicating that cratered splopes can withstand considerable ground shock from adjacent detonations. This becomes important when joining or extending nuclear channels. Only an insignificant amount of the rockfall resulting from these minor slope failures rolled to the bottom of the crater where a roadway would ordinarily be located in a nuclear-excavated highway cut.

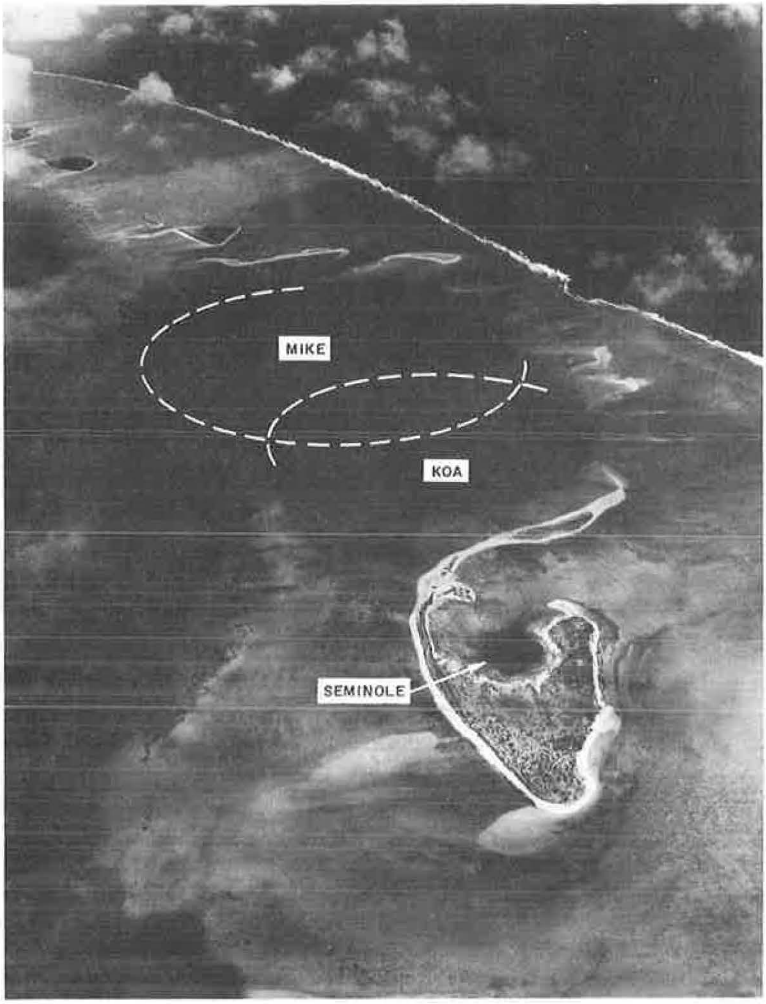

Figure 11. Craters produced by near-surface detonations at Pacific Proving Grounds, Eniwetok Atoll.

Theoretical Calculations of Cratering Mechanics

In an effort to develop a more fundamental understanding of the cratering process and the interaction of the various parameters encountered in nature, considerable effort has been devoted to the development of a theoretical calculation of the cratering process. Present work is based on a two-phase model (3) which considers first the hydrodynamic growth of a spherical cavity resulting from the explosion. When the rarefaction would be expected to return to the cavity from the earth's surface, this model is no longer valid. The second phase of the cavity growth is the so-called gas-acceleration phase resulting from the adiabatic expansion of the cavity in the upper hemisphere with a resultant long-term acceleration of the overlying medium.

The first phase is calculated on a one-dimensional hydrodynamic plastic-elastic computer code called SOC (10). The output from this code establishes the initial conditions of the cavity size, cavity pressure, and particle velocity of the medium between the cavity and the ground surface that are required for the second phase of the calculation.

For this second phase, the overburden material is assumed to be a homogeneous, incompressible, viscous fluid. The upper cavity surface is subdivided into elemental surface areas, and mass zones are defined which subtend these areas. By applying Newton's Second Law with simple empirically calibrated frictional force to each mass element and assuming that the cavity gas behaves adiabatically, the cavity evolution, mound development, and the formation of the lip through upthrust are numerically simulated.

These calculational models have been applied (11) to the 0.5-kt chemical cratering explosion, Scooter, and have reproduced observed ground motions extremely well. In addition, the models have been used to calculate a 0.5-kt chemical explosive source at a variety of depths of burst. Assuming a reasonable angle of repose for alluvium of 45 deg, crater radii for scaled depths of burst from about 30 to 200 $ft/kt^{1/3.4}$ have been predicted which compare very favorably with observed crater radii for chemical explosives in alluvium. Further, the apparent crater depths for shallow depth of burst craters have been reasonably well calculated.

RELATED DEVELOPMENTS

Nuclear Device Charges

The AEC has encouraged industry and other groups to participate in the Plowshare Program by analyzing the possible uses of nuclear explosives in their specific fields.

TABLE 2

ESTIMATED UNIT COSTS OF EXCAVATION IN HARD ROCK

Yield (kt)	Projected Charge ($)	Depth of Burial (ft)	Cost of Emplacement Hole[a] ($)	Operations and Safety Cost[b] ($)	Total Cost ($)	Apparent Crater Dimensions			Unit Cost ($/cu yd)
						Diameter (ft)	Depth (ft)	Volume (cu yd)	
10	350,000	280	84,000	200,000	634,000	540	155	660,000	0.96
100	460,000	550	165,000	300,000	925,000	1,070	310	5,160,000	0.18
2,000	600,000	1,330	400,000	500,000	1,500,000	2,580	750	72,220,000	0.02

[a]Assuming drilling costs of $300/ft.
[b]Varies greatly from one site to another; for this comparison a typical cost averaged over a number of charges in a row has been assumed.

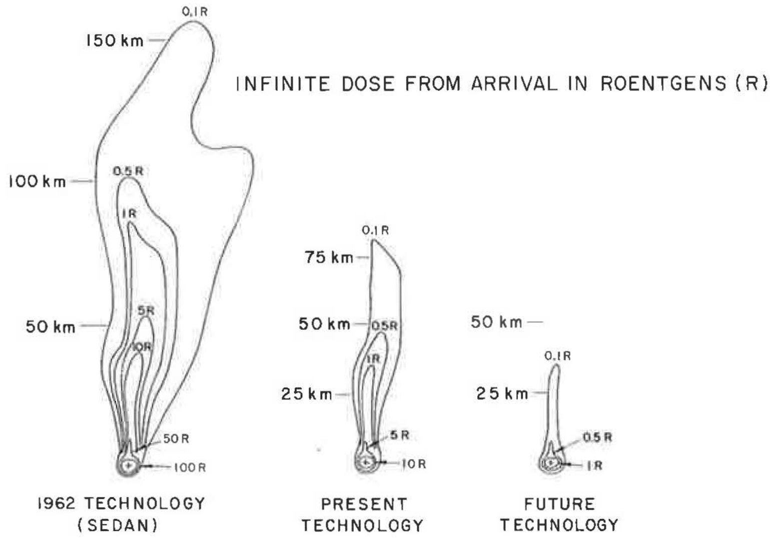

Figure 12. Estimated technological advances to be made in fallout deposition of radioactive debris from 100-kt nuclear cratering detonation.

To allow such investigations, the Commission in 1958 released, within the limits permitted by national defense and security, a schedule of cost estimates for nuclear explosives and related services, including safety studies.

Since that time, improvements have been made both in the design of nuclear explosives and in their emplacement, as well as in the technology of the explosion and its effects. One of the most significant technological advances has been in the development of thermonuclear explosives with very low fission yields.

Consequently, in 1964 the AEC revised its estimates and now projects a charge of $350,000 for a nuclear explosive with 10-kt yield and $600,000 for a nuclear explosive with 2-megaton yield (12). Interpolations may be made for other yields based on a line drawn between these two charges (13, Fig. 13). These charges cover nuclear materials, fabrication and assembly, and arming and firing services. Significant related services which are not covered by these projected charges are safety studies, site preparation including construction of holes, transportation and emplacement of the devices, and support. Costs of safety studies, which were included in the 1958 charges, have not been included in the new charges since they can be accurately estimated only for each individual situation.

It is expected that these projected charges are sufficiently representative of the future situation to warrant their use in feasibility studies. Although the projected charges might be used as a basis for discussion of costs to be assumed by the AEC in such projects, it should be recognized that the costs to be assumed by the AEC as finally negotiated might be significantly different from the projected charges.

Using these charges and assuming related excavation costs, it is significant to note the estimated costs of nuclear excavation. As shown in Table 2, excavation in the 10-kt range produces unit excavation costs which are competitive with conventional excavation costs. However, using larger yields, the unit cost is reduced rapidly to a few cents per cubic yard in the megaton range. This emphasizes the great economic benefits to be derived from nuclear explosive techniques for large-scale excavation.

Radioactivity

As mentioned previously, recent technological advances have developed thermonuclear explosives with very low fission yields. In addition to economy in device charges, reduced fission yields greatly decrease the amount of radioactivity produced. This will significantly increase the radiological safety of nuclear excavation.

Figure 12 illustrates the advances being made in this area. The 1962 fallout pattern is based on the Sedan event. The infinite dose is that which downwind residents would receive, assuming continuous residency following a 100-kt nuclear detonation. The roentgen contour is approximately equal to the maximum lifetime dose allowed to the general population by the Federal Radiation Council.

As seen in Figure 12, the range to the 0.5-roentgen isodose line for a cratering explosion like Sedan would be about halved if present explosives had been used. Use of nuclear explosives and emplacement techniques which will be developed in the foreseeable future will effect an even more dramatic reduction of such a fallout pattern. These reductions mean that the amount of radioactive material in future fallout patterns from a 100-kt cratering explosion will be about a factor of 100 less than the amount in the 1962 Sedan fallout pattern.

SUMMARY

A large quantity of cratering data has been obtained over the past 13 years in a number of media. One medium in particular, NTS desert alluvium, has been exhaustively explored with both chemical explosive point charges, nuclear point charges, and chemical explosive row charges. One other medium, basalt, has been explored to a lesser extent with large-yield chemical explosive charges, and cratering curves have been determined. These two media, in general, are expected to bracket most types of media to be encountered in nature; therefore, the range of crater dimensions to be expected for many nuclear excavation projects will, in all probability, fall between these two types of media. The Dugout experiment, the first row charge cratering ex-

periment in hard rock, indicates that many of the concepts developed for row charges in alluvium are also valid in a hard rock medium.

Two investigations into the survival of craters under the action of natural and dynamic forces indicate that craters are not severely affected by wave and water action over long periods and that cratered slopes can survive large seismic forces without experiencing serious slope failures.

A theoretical model of explosive cratering is being developed, based on a hydroelastic-plastic model and a late-phase gas-acceleration model. Results to date are very encouraging and indicate an ability to duplicate both observed surface motions and empirical crater dimension curves for alluvium.

Nuclear excavation costs in hard rock are estimated to be competitive with conventional excavation in the 10-kt range, rapidly decreasing to a few cents per cubic yard in the megaton range. Advancement in the development of low-fission thermonuclear explosives in the near future is expected to reduce radioactivity levels 100-fold below 1962 Sedan levels.

In all, many significant developments have occurred during the past year which have brought nearer the fulfillment of such applications as Project Carryall and the construction of a new sea-level Isthmian Canal by nuclear methods.

REFERENCES

1. Nordyke, M. D. Cratering Experience with Chemical and Nuclear Explosives. Proc. 3rd Plowshare Symposium, Lawrence Radiation Lab., TID-7695, April 1964.
2. Nuclear Excavation, 1963. Highway Research Record No. 50, 1964. 53 pp.
3. Nordyke, M. D. On Cratering: A Brief History, Analysis and Theory of Cratering. Lawrence Radiation Lab., UCRL-6578, Aug. 1961.
4. Vortman, L. J., et al. Project Buckboard, Final Report. Sandia Corp., SC-4675(RR), Aug. 1962.
5. Spruill, J. L. Project Pre-Schooner, Crater Measurements. U. S. Army Engineer Nuclear Cratering Group, PNE-502, Nov. 1964.
6. Graves, E., et al. Project Pre-Buggy, Scope of Chemical Explosive Cratering Experiment. U. S. Army Engineer Nuclear Cratering Group, PNE-300, May 1963.
7. Spruill, J. L., and Videon, F. F. Project Pre-Buggy II, Apparent Crater Studies. U. S. Army Engineer Nuclear Cratering Group, PNE-315, Nov. 1964.
8. Nordyke, M. D., et al. Project Dugout, Technical Director's Summary Report. Lawrence Radiation Lab., PNE-600, Jan. 1965.
9. Circeo, L. J., and Nordyke, M. D. Personal communication.
10. Butkovich, T. R. Calculation of the Shock Wave from an Underground Nuclear Explosion in Granite. Proc. 3rd Plowshare Symposium, Lawrence Radiation Lab., TID-7695, April 1964.
11. Knox, J. B., and Terhune, R. W. Calculation of Explosion of Explosion-Produced Craters—High Explosive Sources. Lawrence Radiation Lab., UCRL-7738, Rev. I, Oct. 1964.
12. Frank, W. J. Characteristics of Nuclear Explosives. Proc. 3rd Plowshare Symposium, Lawrence Radiation Lab., TID-7695, April 1964.
13. Hansen, S. M., and Toman, J. Aggregate Production with Nuclear Explosives. Highway Research Record No. 107, 1966.