The Corps of Engineers Nuclear Construction Research Activities

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Program activities of the U. S. Army Corps of Engineers Nuclear Cratering Group include (a) cratering calibration of various geologic media and development of techniques to provide a desired crater geometry with chemical explosive detonations; (b) joint planning of and technical participation in Atomic Energy Commission nuclear excavation experiments; (c) development of data on the engineering properties of nuclear craters; (d) development of chemical and nuclear explosive construction technology for civil works; (e) engineering studies of nuclear construction feasibility; and (f) joint CE/AEC civil works nuclear construction experiments.

NCG has executed seven major chemical explosives cratering experiments to provide cratering calibration of dry alluvium, dry basalt, rhyolite, and water-saturated clay shale. Recently completed was a reservoir connection experiment at Fort Peck, Montana, and the cratering and safety calibration detonations for a small boat harbor excavation experiment in Kawaihae Bay on the Island of Hawaii. Nuclear crater engineering properties field investigations have recently been completed in which a trench was excavated through the lip of the crater and the material screened and weighed. Investigations are planned for some of the more recently executed nuclear cratering experiments. Estimates of true crater volume and radiation logs in drill holes on two other projects have been used as a basis for development of a technique for predicting the expected exposure dose rates in nuclear craters.

Four conceptual nuclear construction applications have been identified as having significant potential for accomplishment: (a) nuclear quarrying to produce rockfill or aggregate; (b) nuclear harbor construction; (c) nuclear ejecta dam construction; and (d) nuclear canal or roadbed cut excavation. The nuclear quarry has been identified as the most direct application of present technology. The large nuclear harbor at a remote site is one of the most attractive prospects for nuclear excavation.

•THE U. S. Army Corps of Engineers (CE) and the U. S. Atomic Energy Commission (AEC) have been engaged in a joint research program since 1962 to develop the basic technology necessary to use nuclear explosives in conjunction with the construction of large-scale civil engineering projects.

Under the agreement for the joint research program, the AEC is primarily responsible for nuclear explosive development, execution of nuclear cratering experiments, and development of methods for predicting the size and shape of nuclear craters. The major AEC effort in this research program is accomplished by the Lawrence Radiation Laboratory in Livermore, California. The Corps of Engineers is primarily responsible for execution of corollary chemical explosive cratering experiments, technical participation in and assistance in the planning of the AEC's nuclear cratering experiments, and development of the requisite engineering and construction data to be used as the

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basis for using nuclear explosives for construction purposes. The U. S. Army Engineer Nuclear Cratering Group (NCG) is located at the Lawrence Radiation Laboratory and is responsible for technical program direction effort of the Corps.

In addition to this joint research effort with the AEC in nuclear explosive construction, the mission of NCG has recently been expanded to include research aimed at the use of chemical explosives for projects of intermediate size. This mission has grown out of the experience gained in our chemical explosive cratering experiments. The chemical explosive experiments currently being accomplished by NCG are intended to provide experience and data useful in both the joint program with the AEC and NCG's expanded mission in the use of chemical explosives in construction.

The basic concept of nuclear construction (1) involves the subsurface detonation of nuclear explosives either to break up and eject large quantities of rock and/or soil and by so doing produce excavations that may be used as engineering structures, such as channels, harbors, dams, or spillways, or to simply break up rock to produce a quarry. The primary advantage in using nuclear explosive methods rather than conventional construction methods is economy. The nuclear cratering experience to date indicates that there is a significant potential for using nuclear explosives to accomplish large-scale construction projects at considerable savings in cost and time.

The use of nuclear explosives for construction involves more than merely producing craters or mounds of rock. One must be able to predict the geometry of the crater or, better still, produce a desired geometry to fit a specific application. In addition, one must know the extent of the disturbance to the media that has occurred immediately adjacent to the crater for those applications involving use of the crater as an engineering structure. Also, it is necessary to have detailed knowledge of nuclear explosive characteristics and handling and emplacement requirements as well as an understanding of the extent and safety implications of airblast, ground shock, and residual radioactivity effects that occur as a result of nuclear cratering detonations. The objective of the nuclear excavation research program is to develop the technology required to address these areas of interest.

The NCG program activities include (a) cratering calibration of various geologic media and development of techniques designed to provide a desired crater geometry with chemical explosive detonations; (b) joint planning of and technical participation in AEC nuclear excavation experiments; (c) development of data on the engineering properties of nuclear craters; (d) development of civil works chemical and nuclear explosive construction technology; (e) accomplishment of engineering studies of nuclear construction feasibility; and (f) execution of joint CE/AEC civil works nuclear construction experiments.

This paper summarizes the scope of NCG research activities and discusses the results of the most recent programs.

CRATER GEOMETRY

There are basically two approaches that have been developed to date for predicting crater dimensions. One approach involves computer calculations of the mound and cavity growth used in conjunction with a freefall, throwout model that gives a reasonable estimate of the crater radius and ejecta boundary. The second approach involves empirical scaling relationships.

The Plowshare Division of the Lawrence Radiation Laboratory has developed the SOC (spherical, one-dimensional) and TENSOR (cylindrical, two-dimensional) computer codes that numerically describe the propagation of a stress wave of arbitrary amplitude through a medium (2, 3). These codes are Lagrangian finite-difference approximations of the momentum equations that describe the behavior of a medium subjected to a stress tensor in one (SOC) and two (TENSOR) dimensions. The code calculations handle both the initial shock wave, which creates spall velocities, and the gas acceleration phase. The end product of the TENSOR code calculations is a chronological history of the cavity and mound growth resulting from an underground explosive detonation. The code calculation runs until the particle velocities no longer increase significantly from cycle to cycle. At this point, a freefall, throwout model calculation is used to determine the mode of deposition of that material which has been given sufficient velocity to pass the original ground surface. The ballistic trajectory of any given mass determines its final position on the surface. The throwout model calculation permits one to estimate crater radius and the maximum range to which significant material is thrown by the detonation. An estimate of the crater depth may also be made by considering the stability of the cavity walls and the bulking characteristics of the material that falls back into the crater opening.

The second crater geometry prediction approach involves the use of scaling laws that relate crater dimensions for some reference energy yield to crater dimensions for any energy yield. The reference nuclear yield normally used is 1 kiloton (kt), which is approximately equivalent to the energy released by the explosion of 1 kiloton (2,000,000 lb) of TNT. The results of cratering experiments to date have led to the development of an empirical scaling law based on a scaling exponent of 1/3.4 (4). Figure 1 shows cratering curves (based on the empirical 1/3.4 scaling relationship) that relate apparent crater radius and apparent crater depth to the depth of burst for detonations in hard rock and desert alluvium (1). Similar crater prediction curves (chemical explosives only) have been developed for clay shale (Fig. 2).

EXPERIMENTAL CRATERING PROGRAM

The NCG chemical explosive cratering experiments are designed to calibrate new geologic media for crater dimensions and to serve as forerunners to nuclear experiments in the same or similar media. They are also used to develop techniques of explosively achieving a desired crater geometry. In the case of Project Tugboat and other chemical explosive projects under consideration, they are intended to provide a useful portion of a planned civil works project. One or more of the craters produced in each new medium have been conventionally excavated during post-shot investigations and holes drilled in and around the craters to study the properties of the material immediately surrounding the apparent crater. In those cases deemed appropriate, ground shock and airblast effects have been measured. Radioactive tracer studies have been accomplished in an attempt to compare radioactivity venting from single and multiple-charge events. In short, the chemical explosive experiments continue to provide pertinent data in an expedient and relatively inexpensive manner. The chemical explosive cratering experiments, therefore, do complement the large-yield nuclear cratering experiments.

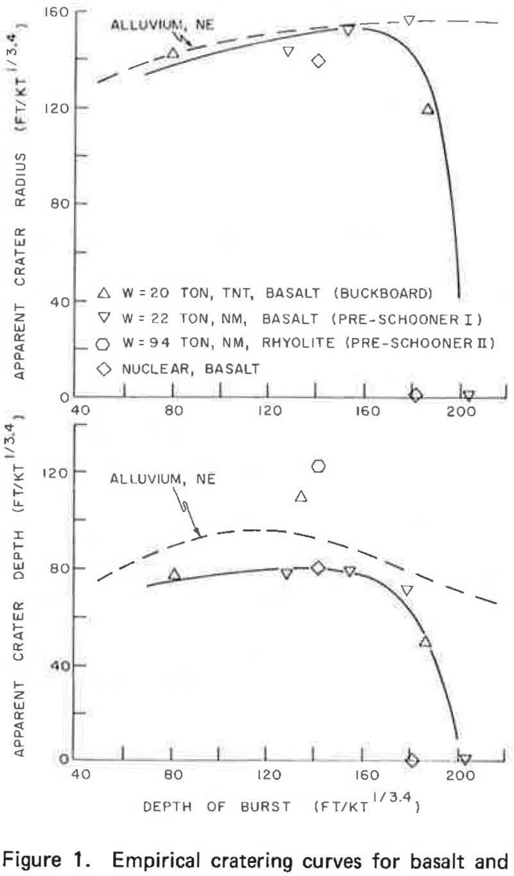

Figure 1. Empirical cratering curves for basalt and desert alluvium.

NCG has executed seven major chemical cratering experiments to date. They are Pre-Buggy I, Pre-Schooner I, Pre-Schooner II, Pre-Gondola I, Pre-Gondola II, Pre-Gondola III, and Phase I of Project Tugboat. All of these experiments except for the last phase of Pre-Gondola III and Tugboat have utilized the liquid explosive nitromethane in spherical containers or cavities. In Phase III of Pre-Gondola III and in Tugboat, an aluminized ammonium nitrate

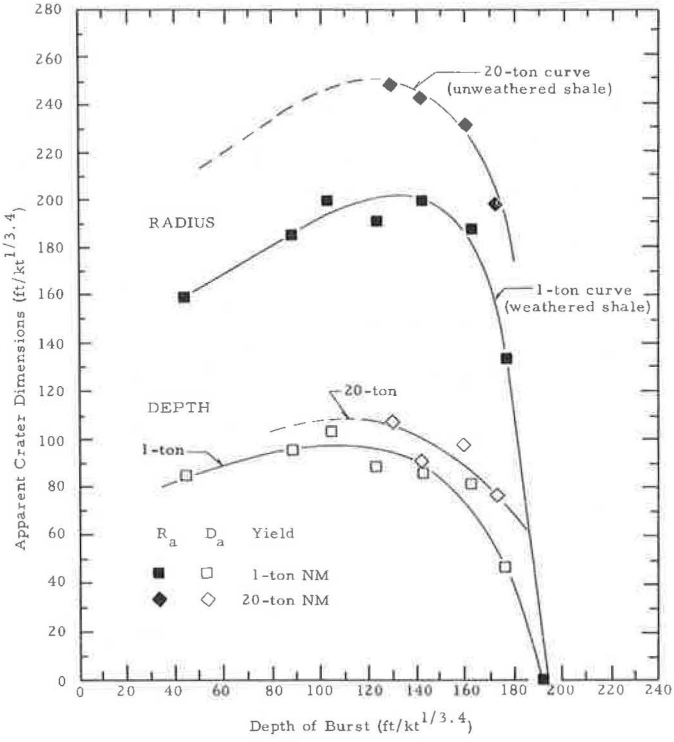

Figure 2. Empirical chemical explosive cratering curves for clay shale.

slurry explosive was used. Yields have ranged from 1,000 pounds per charge to approximately 100 tons per charge.

Project Pre-Buggy I (5) was conducted in alluvium at the Nevada Test Site and included both the detonation of single-charge cratering events and multiple-charge row cratering events. The purpose of this experimental series was to provide data for linear row crater geometry as compared to single-charge crater geometry and to establish design criteria for spacing and depth in row craters. Enhancement in depth and width of the row craters compared to single-charge craters was found. As anticipated, spacing and depth parameters were found to be very interdependent in determining final crater geometry. A spacing of one single-charge crater radius at about optimum depth produced relatively smooth uniform linear craters with no significant cusping. This series was followed by Pre-Buggy II, which further defined row-charge cratering parameters and provided design criteria that assisted in the design of Project Dugout, a chemical row-charge experiment in basalt, and the 5 kt nuclear row-charge cratering experiment, Project Buggy (February 1968).

Project Pre-Schooner I (6) was a series of four 20-ton single-charge chemical cratering events detonated at varying depths of burst in a dry basalt at the Nevada Test Site. These events established an empirical cratering curve for a hard, dry rock. Project Pre-Schooner II (7) was a nominal 100-ton single-charge cratering event in a rhyolite medium in the Bruneau Plateau area of southwestern Idaho. The data from the Pre-Schooner events have been used in the design of the nuclear cratering events Sulky, Cabriolet, Buggy, and Schooner.

The Pre-Gondola experiments were designed to provide crater geometry data in a weak, saturated clay shale. The site selected for these experiments is located adjacent to the Fort Peck Reservoir, Fort Peck, Montana. A number of experiments have been conducted at the site during the past three years. These have included small-scale experiments in single, row, and array emplacement configurations (8, 9). Yields have ranged from 64 to 2,000 pounds per charge. All of these experiments were peripheral to the main row charge experiment at the site, which is shown in Figure 3 prior to the last row charge detonation. This photograph shows the 20-ton Pre-Gondola I single charge craters (10), the Pre-Gondola II row at the left center, (11) and the Pre-Gondola III Phase II connecting row at the right center (12). Project Pre-Gondola I, four 20-ton cratering detonations, provided data on the variation of crater dimensions in clay shale with respect to depth of burst. The Charlie crater was partially filled in by the Pre-Gondola II five-charge row and is located at the extreme left of the long row crater. Pre-Gondola II consisted of two 40-ton charges and three 20-ton charges spaced at approximately 80 feet and buried at 150 ft/kt$^{1/3.4}$ (48.8 to 59.9 ft). All five charges were detonated simultaneously to give the linear channel. A wide trench was cut through the side lip and holes drilled into the rupture zone. Pre-Gondola III Phase II provided the longest portion of the crater and consisted of seven charges, 30 tons each, all buried at the same elevation but with variable spacing between charges. Four of the charges were spaced at an average single charge crater radius. The remaining three charges were spaced at 0.6 times the single charge crater radius. That is, the spacing between charges varied and was dependent on the average of the single charge crater radii that would result from the two adjacent charges if detonated separately as single charges. This charge configuration gave a very smooth, large crater that connected to the Pre-Gondola II crater. The Pre-Gondola I single charge detonations were executed during the fall of 1966, the Pre-Gondola II row during June 1967 and the Pre-Gondola III Phase II row during October 1968.

The last major experiment in the Pre-Gondola series was executed on October 6, 1969. This was Pre-Gondola III Phase III, Reservoir Connection Experiment. In this experiment, five charges of varying yield and depth were so placed and simultaneously detonated to provide a connecting channel between the long crater shown in Figure 3 and the Fort Peck Reservoir. A centerline section drawing showing individual charge yields and locations is shown in Figure 4. Figure 5 shows the preshot view of the crater. Just after the detonation, Figure 6, water started to fill the crater. The water filling action, Figure 7, took about 9 minutes. The final view, Figure 8, shows what the crater looked like when filled to reservoir level. The crater width at water level

Figure 3. Pre-Gondola 20-ton single-charge craters and connecting row crater prior to execution of the reservoir connection experiment.

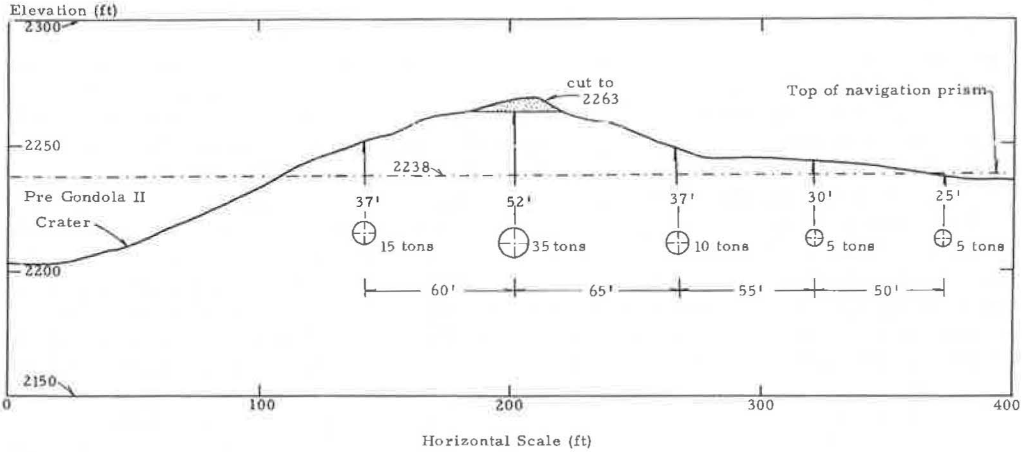

Figure 4. Centerline section drawing of the reservoir connection experiment, Pre-Gondola III, Phase III, showing charge depths, spacings, and yields.

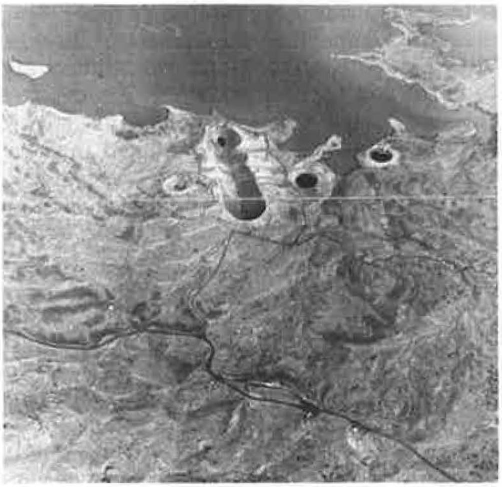

Figure 5. Preshot view of the Pre-Gondola III, Phase III reservoir connection experiment.

varies from a minimum of 100 ft to a maximum of 200 ft. The depth of water in the crater varies from a minimum of 13 ft to a maximum of 39 ft, except at the entrance where the depth is approximately 7 ft. The length of the water-filled portion of the crater is approximately 1,370 ft. Although this work was totally experimental, it was very successful and graphically illustrates two proposed applications of large-scale explosive excavation, an inland harbor and a canal.

Interest in the explosive excavation of harbors has generated the most recent chemical explosive cratering project being conducted by NCG, known as Project Tugboat. This explosive excavation experiment is designed to investigate the general concept of producing a harbor basin in shallow water in a near-shore environment. The site for the experiment was picked to coincide with the site of a planned small boat harbor so that some benefit would be obtained from the expenditure of the research and development funds. This site is in Kawaihae Bay on the west side of the Island of Hawaii (Fig. 9). The project is planned for execution in three phases. Phase I, executed November 4-7, 1969, was a cratering and safety calibration series of detonations. Phases II and III are planned as row or array detonations of nominal 10-ton charges designed to excavate a berthing basin and entrance channel.

Experience in cratering in a completely saturated medium overlain by water is almost nonexistent. Because of this, five detonations were included in the Phase I program, four each 1-ton and one 10-ton. The 1-ton charges were placed at depths ranging from 16 to 24 ft below mean low water level. This program was intended to provide crater dimension and safety data as a function of both depth of burst and yield.

Figure 6. Reservoir connection experiment crater immediately following the detonation, showing water starting to fill the crater.

Figure 7. Reservoir connection experiment crater filling with water.

Figure 8. Reservoir connection experiment crater after water-filling action was complete.

Figure 9. Site for the planned Kawaihae small boat harbor. The harbor is to be located in the coral reef area in the upper right quadrant of the picture.

The site medium is a coral limestone extending to 70 ft or more in depth and overlain by 6 to 10 ft of water. The original concept for explosively excavating a harbor in this material assumed that the crater formation process would be similar to that experienced in previous dry-land experiments and that a crater lip would form that could be used as the core for a breakwater. After laboratory testing data were obtained for

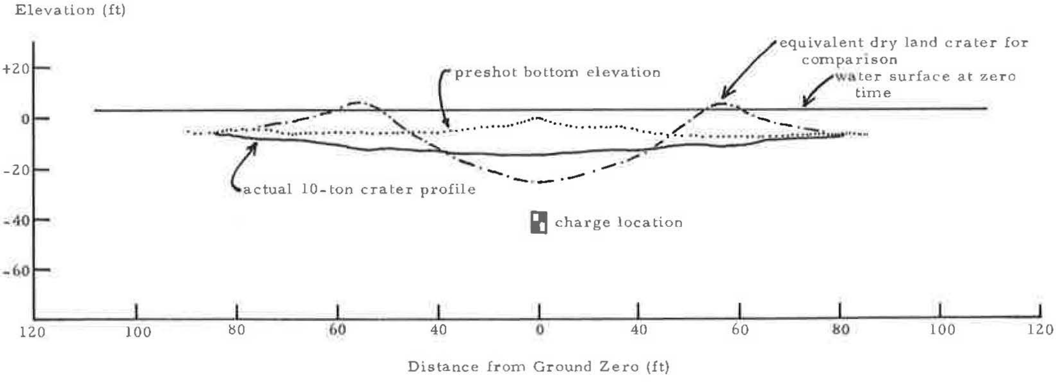

Figure 10. Profile of Project Tugboat, Phase I, 10-ton crater shown in comparison to an equivalent-yield dry-land crater profile.

the coral, it was evident that the concept might be somewhat in error. The porosity of the material ranged from 37 to 64 percent, and the compressive strength was variable and ranged from 760 to 1,738 psi. The data strongly indicated that the material would be compacted in the cratering process and very little ejecta would be available to form a lip that would extend above water. This indeed was the case for both the 1-ton and 10-ton craters. A profile of the 10-ton crater is shown in comparison to a dry land crater in Figure 10. As can be seen, there were no lips. The total apparent crater volume seems to result from crushing and compaction of the coral. The crater shape is more desirable for creating a harbor than that originally contemplated based on dry land experience in that it is very broad and of shallow depth. On the basis of these calibration results, it is currently estimated that the harbor basin and entrance channel can be accomplished with about half the amount of explosives called for in the original design. At this writing, data analysis is still proceeding.

ENGINEERING PROPERTIES OF NUCLEAR CRATERS

NCG technical participation in AEC nuclear cratering experiments has included crater measurements, a joint long-range fallout monitoring and interpretation program with the U. S. Public Health Service and the Lawrence Radiation Laboratory, and post-detonation excavation and drilling of the crater fallback, ejecta, and rupture zones for engineering properties investigations.

Engineering properties investigations at the nuclear cratering experiment sites have been performed by NCG in a manner similar to those developed in the postshot excavation and drilling of the chemical explosive craters. These studies are intended to provide information that will permit an evaluation of the usefulness of the crater as an engineering structure or of crushed and broken rock as usable quarry rock.

A nuclear detonation in soil or rock produces significant changes in the media surrounding the visible crater. To assess the engineering usefulness of the crater, one must be able to predict the extent and physical characteristics of the zones of disturbance created by the detonation. The nature of these zones affects such engineering considerations as stability of crater slopes, foundation conditions in the vicinity of the excavation, and seepage and drainage in the media altered by the detonation. A significant portion of the nuclear excavation research program, therefore, is devoted to determination of how nuclear cratering detonations affect the immediate geologic environment and the impact of cratering formation phenomenology on the stability of crater slopes.

The results of nuclear crater properties investigations to date indicate that the disturbed zones surrounding the crater may be categorized as follows (Fig. 11):

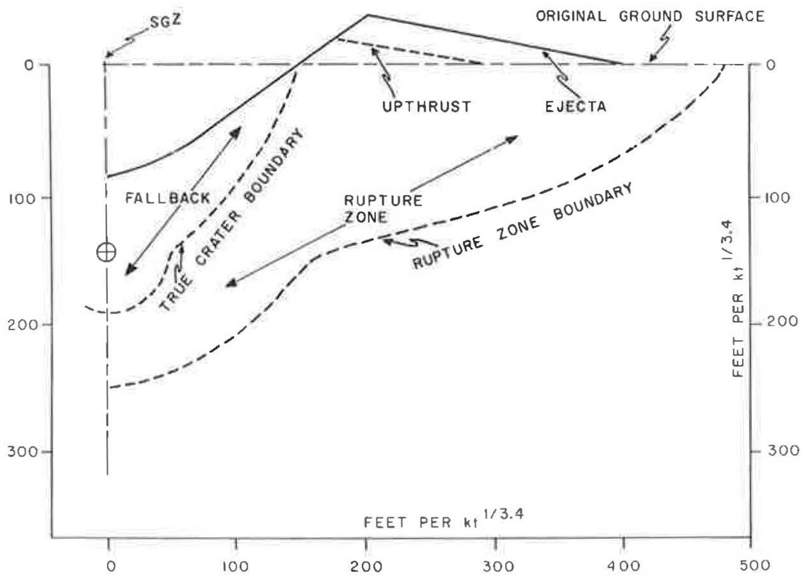

Figure 11. Cross section of typical crater in hard rock showing zones of disturbance.

The apparent crater is defined as that portion of the visible crater which is below the preshot ground level.

The true crater is defined as the boundary (below preshot level) between the loose, broken, disarranged fallback material and the underlying material that has been crushed and fractured but has not experienced significant vertical displacement or disarrangement.

The fallback consists of materials that have experienced significant disarrangement and displacement and have come to rest within the true crater.

The rupture zone is that zone extending outward from the true crater in which stresses created by the detonation have caused fracture and crushing of the material. In this zone, displacements and changes in density are evident but the material remains basically coherent in contrast to the disarranged fallback materials.

The elastic zone is that zone extending beyond the rupture zone in which no fissures, cracks, or permanent displacement of material are evident. Strong earth motions are propagated through the elastic zone to great distances.

The ejecta consists of material thrown out above and/or beyond the true crater.

In order to analyze effectively the potential engineering behavior of an excavation produced by nuclear explosives, one must be able to predict with reasonable accuracy the following geometric and physical characteristics of the various crater zones:

1. Geometry of the apparent and true craters;
2. Geometry, effective porosity, bulk density, permeability, and in situ strength characteristics of the rupture zone, fallback, and ejecta;
3. Particle size of the fallback and ejecta; and
4. Degree and orientation of blast fracturing in the rupture zone.

Techniques for predicting apparent crater geometry have been described in preceding sections of this paper. The general shape of the rupture zone for craters produced by nuclear explosives buried in the optimum depth of burst region is shown in Figure 11 (13).

The comparison of preshot in situ block or grain size with the particle size of the ejecta and fallback for the craters investigated to date has shown a fairly close correlation. In a moderately to highly fractured rock medium, the preshot in situ block size has a significant influence on the fallback/ejecta sizes. There are also indications that increasing depths of burst may tend to increase the percentage of coarse particles. As a rock medium becomes more massive (i.e., spacing between joints and fractures greater than 3 to 5 ft), the degree of control of in situ block sizes on fallback and ejecta sizes becomes less pronounced.

Information from investigations completed to date indicates that the bulking factor of the fallback and ejecta material (ratio of preshot bulk density) will be within the range of 1.1 to 1.6 for hard rock media.

The limit of blast fracturing and the outer boundary of the rupture zone are coincident. Comparison, to date, between the limit of bulking (zone of increased effective porosity) and the limit of blast fracturing indicates that their envelopes are also nearly coincident. Both the intensity of blast fracturing and bulking decrease with distance from the true crater boundary. The observed concentrations of blast fracturing and relatively high effective porosity appear to extend along boundaries between different rock types.

Postshot field investigations of the Cabriolet nuclear crater (2.3 kt at 171 ft in rhyolite/trachyte) have recently been completed (14). A trench was excavated through the lip of the crater and the material screened and weighed. The measured bulk density of the ejecta was 124 lb per cu ft, giving a bulking factor of 1.10. The true crater radius was estimated at 210 ft. This is about 18 ft larger than that predicted by Figure 11. The maximum uplift of the rupture zone observed in the excavated trench was 14 ft.

Because of the high cost of obtaining this kind of information for the large nuclear craters planned for execution in the research program, NCG has initiated an effort to develop the capability to obtain the required information by large-diameter core drilling of the fallback, ejecta, and rupture zone. The initial effort will be to develop a disintegrating grout that can be used during coring operations but can be easily separated later from the cored material to permit determination of a size gradation curve and bulk density measurements.

Techniques have not been developed that would enable one to predict accurately the permeability and in situ strength characteristics of the fallback, ejecta, and rupture zone. The development of the required additional prediction techniques and the refinement of the existing techniques as discussed here are being accomplished under the research program.

NCG STUDIES OF ENGINEERING FEASIBILITY

Studies of the feasibility of using nuclear explosives for specific civil works projects serve three purposes. First, they provide a feedback to the research program of specific problem areas encountered in real applications. Second, because they are being accomplished by engineers in the Corps Districts throughout the United States, they are serving to train a large pool of talent in this new technology. Third, they serve to develop experiments that may be used in conjunction with the construction of actual civil works projects to demonstrate the viability of nuclear excavation.

The primary purpose for the studies has changed from the initial one, which was to identify specific problems that could be solved in the research program, to identifying specific projects that could be accomplished using nuclear explosives. Twelve studies of specific civil works project applications have been completed or are near completion. They have included studies of spillway nuclear excavation, canal nuclear excavation, nuclear quarrying, creation of dams with nuclear explosives, and nuclear harbor excavation.

During the course of these studies, many problem areas were identified. One problem identified early concerned nuclear explosive emplacement construction. Studies were initiated to determine the best techniques and the costs of drilling large-diameter (>30 in.) emplacement holes in varying geologic media (15). Also initiated were studies of methods and costs of constructing emplacement holes in disturbed materials in and near existing nuclear craters for extending a nuclear excavation (connecting charge) or modifying an existing crater (triple row technique, second pass emplacement). A study was also initiated on conventional excavation techniques for use in conjunction with nuclear excavation projects (16).

Early in the feasibility study effort it became apparent that an analytical technique for predicting gamma radiation exposure rates in the nuclear crater and lip area as a function of time was needed. In most of the projects studied there was a need to reenter the crater area as early as practical to carry out conventional construction activities. A prediction technique has been developed (17) that assumes mixing of the radionuclides produced with a portion of the volume of material making up the true crater volume. A significant conclusion of this work is that, for cratering detonations at optimum depth of burst, reentry times decrease as explosive yield increases. This conclusion is shown in Figure 12. The assumptions made to arrive at this prediction are that the fission portion of the nuclear explosive yield is 3 kt and does not change with yield and the gamma-emitting induced radionuclides that contribute to the exposure rate in the crater are the same as those given in AEC Classification Bulletin WNP-11 for radionuclides present in the radioactive cloud and fallout from a Plowshare cratering detonation. Also, induced radionuclides in cloud and fallout are in the same ratio to the total produced as the fission products given in WNP-11 are to 3 kt assumed for the explosive. The dose rate assumed safe for reentry is 2.5 mR/hr. With expected improvements in explosive design, it is predicted that entry can be made to a megaton-yield crater with proper rad-safe control approximately 3 weeks following the detonation.

NUCLEAR CONSTRUCTION APPLICATIONS

The potential use of nuclear methods of construction (18) covers a wide range of projects. It is reasonable to anticipate that nuclear explosives could be used advantageously in the construction of such water resource projects as navigable waterways, dams, harbors, storage reservoirs, or spillways. In addition, nuclear-excavated cuts could be incorporated in highway and railroad construction to provide rights-of-way through mountainous or precipitous terrain. A rather basic application of nuclear construction techniques would involve the detonation of a nuclear explosive at a relatively deep depth of burst to produce aggregate for use in the construction of dams, breakwaters, and other rockfill structures.

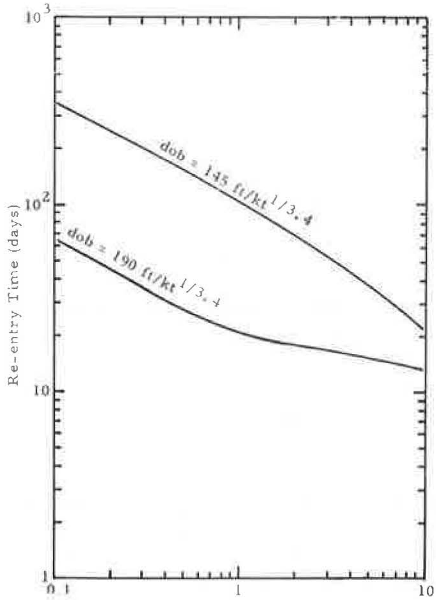

Figure 12. Predicted reentry time into the gamma radiation field in the nuclear crater ejecta and fallback region as a function of total nuclear explosive yield for two depths of burst.

The following paragraphs describe those nuclear applications which are considered to have the greatest potential for use in the construction of large-scale civil works projects.

Nuclear Quarrying

The subsurface detonation of a nuclear explosive has potential for producing a large volume of broken rock at a low unit cost. The basic concept in using nuclear explosives for quarrying purposes is to detonate the device at such a depth that the quantity of broken rock is maximized and the distance to which the rock is ejected is minimized. In order to facilitate removal of the rock after the detonation and to facilitate subsequent operations of the quarry, a sloping terrain configuration appears to be the most advantageous topographic environment for nuclear quarrying projects.

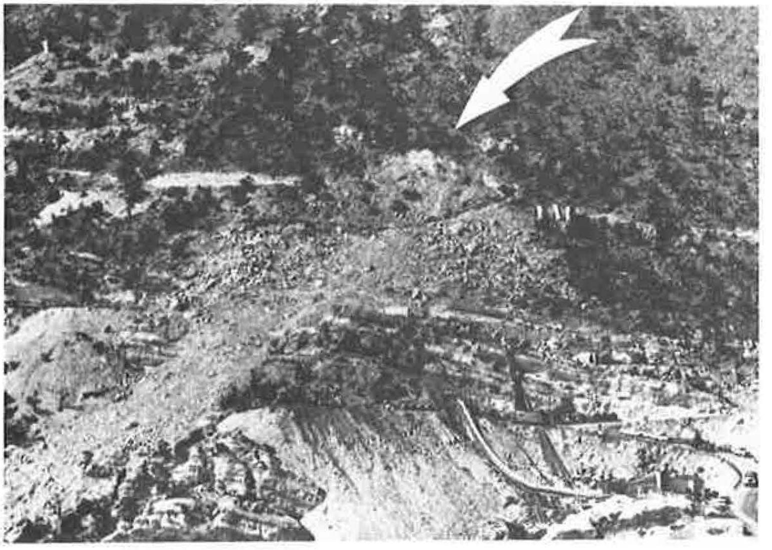

Figure 13. Neptune postshot configuration.

Several of the nuclear cratering experiments that have been executed to date have provided information of significant value in developing nuclear quarrying technology. The Neptune Event was a 115-ton nuclear detonation at a depth of 85 ft under a 30-deg slope in 1958. The resulting postshot configuration is shown in Figure 13. About 34,000 cubic yards of material were ejected downhill as a result of this detonation.

In December 1964, the Sulky Event (85 tons nuclear at a depth of 90 ft under level terrain) was detonated in basalt at the Nevada Test Site. The resulting configuration (Fig. 14) was a mound of rock that projected above the preshot ground surface rather than the classical crater.

As currently envisioned, nuclear quarrying projects would involve detonation of a nuclear device under sloping terrain at a depth of burst similar to that used in the Sulky detonation. The broken rock resulting from such a detonation could be removed with reasonable ease and used as rockfill for dams, breakwaters, or other construction projects requiring large quantities of aggregate. A concept of a nuclear quarry in operation is shown in Figure 15.

Figure 14. Sulky Event.

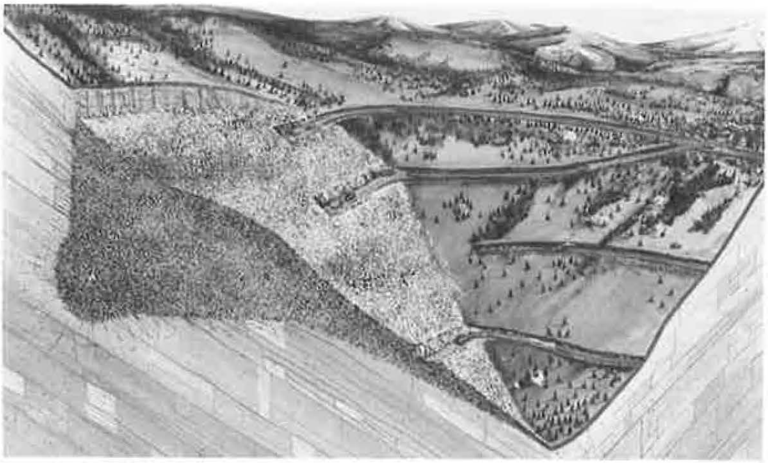

Figure 15. Nuclear quarry concept.

Nuclear Ejecta Dam

A potential nuclear construction application that appears to be quite feasible involves the detonation of a nuclear explosive in the wall of a canyon to eject material across the canyon and thereby create a water storage embankment. In addition to the material actually ejected into the canyon, it is reasonable to assume that some material would collapse from the region immediately above the true crater boundary and add to the total volume of embankment material.

The technique of using explosives to create dams across canyons has been successfully demonstrated by the Soviet Union. The detonation of 2,000 tons of chemical explosive in a narrow, steep-walled canyon on the Vakhsh River in Tadzhikistan resulted in a 2.6 million cu yd rock-fill dam.

In addition to the nuclear detonation itself, consideration must be given to the practical engineering aspects of the dam construction such as an impermeable embankment seal, settlement of the ejecta material, and seepage through the embankment. It is

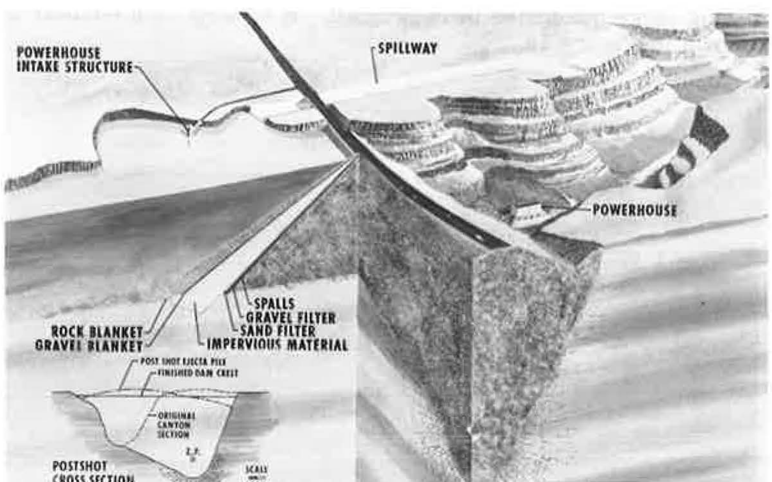

Figure 16. Nuclear ejecta dam concept.

Figure 17. Harbor excavation concept.

planned that these engineering problems would be investigated in a chemical explosive experiment on a smaller scale that would precede a nuclear experiment. The concept of a nuclear ejecta dam is shown in Figure 16.

Nuclear Harbor

The concept of using nuclear explosives to produce protected water areas of sufficient depth to facilitate entry, unloading, and exit of deep-draft vessels has been considered for several years. The crater formation process, in addition to creating an excavation of the required depth, results in the formation of a crater lip that may well function as a breakwater to protect the harbor area from wave action. The nuclear construction aspect of the harbor may involve the detonation of a single explosive to produce the harbor area itself as well as the detonation of a row of explosives to excavate the entrance channel. A concept of this application is shown in Figure 17.

The conventional engineering and construction aspects of harbor design that must be considered in conjunction with the nuclear aspects are most important. Loading and unloading facilities must be constructed as well as areas for cargo clearance and vessel anchorage.

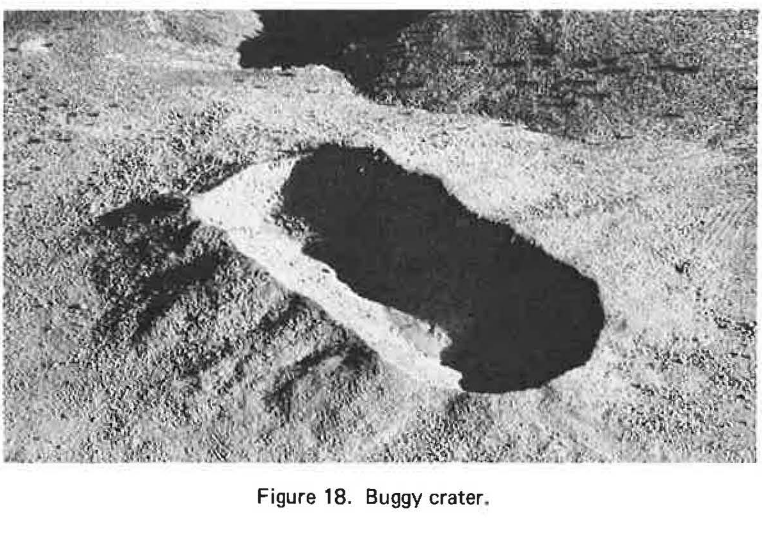

Figure 18. Buggy crater.

Figure 19. Model of transisthmian sea-level canal nuclear excavation showing results of first-pass detonations.

Nuclear Excavated Cuts

A series of nuclear explosives may be detonated simultaneously in a row to produce a linear crater. The linear crater may be used, in turn, as a navigable water way or canal or as a right-of-way for a highway or railroad through mountainous terrain.

The Buggy Event, March 12, 1968, consisted of the simultaneous detonation of five 1.1-kt nuclear explosives and resulted in a linear crater approximately 900 ft long, 250 ft wide, and 60 ft deep. The postshot configuration of the Buggy crater is shown in Figure 18.

Figure 20. Artist's sketch of a nuclear-excavated canal through the Darien region of eastern Panama.

The most widely known potential application of nuclear explosives in the excavation of a navigable waterway is the proposed construction of a sea-level canal through the Central American isthmus. The excavation of such a canal by nuclear methods would involve the detonation of a series of linear craters rather than a single linear crater. The total nuclear yield for the excavation across the entire isthmus would be excessive for safety reasons if detonated all at one time. Figure 19 shows an alignment across the Central American isthmus subsequent to the detonation of the first series of linear craters. The second pass of detonations would produce linear craters that would connect to those produced during the first pass and thereby result in a continuous sea-level waterway from the Atlantic to the Pacific Oceans. A concept of a portion of the completed nuclear-excavated sea-level canal along an alignment in the Darien region of Panama is shown in Figure 20.

The Nuclear Cratering Group is currently developing nuclear excavation designs for proposed sea-level canal alignments in conjunction with the current Atlantic-Pacific Interoceanic Canal Studies.

Other potential uses of nuclear-excavated cuts include the construction of spillways at a site remote from a dam, river diversion channel, or reservoir outlet canals.

SUMMARY

The NCG program activities include (a) cratering calibration of differing geologic media and testing of techniques designed to provide a desired crater geometry with chemical explosive detonations; (b) joint planning of, and technical participation in, AEC nuclear excavation experiments; (c) development of pertinent data on the engineering properties of nuclear craters; (d) development of civil works chemical and nuclear explosive construction technology; (e) accomplishment of engineering studies of nuclear construction feasibility; and (f) execution of joint CE/AEC civil works nuclear construction experiments.

The chemical explosive tests conducted thus far have provided empirical data for the design of the nuclear experiments Sulky, Cabriolet, and Buggy. The Pre-Gondola experiments have provided cratering experience in a wet clay shale and in the row charge and connecting row charge techniques.

Engineering properties investigations of nuclear craters are providing data that will be used as a basis for assessing the suitability of a nuclear crater for the engineering applications presently contemplated.

Four conceptual nuclear construction applications have been identified as having a significant potential for accomplishment: (a) nuclear quarrying to produce rockfill or aggregate; (b) nuclear ejecta dam construction; (c) nuclear harbor construction; and (d) nuclear canal excavation. The nuclear quarry has been identified as the most direct application of present technology.

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