EXCAVATION RESEARCH WITH CHEMICAL EXPLOSIVES

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INTRODUCTION

The U. S. Army Engineer Nuclear Cratering Group (NCG) is located at the Lawrence Radiation Laboratory in Livermore, California. NCG was established in 1962 and assigned responsibility for technical program direction of the Corps of Engineers Nuclear Excavation Research Program. The major part of the experimental program has been the execution of chemical explosive excavation experiments. In the past these experiments were preliminary to planned nuclear excavation experiments. The experience gained and technology developed in accomplishing these experiments has led to an expansion of NCG's research mission. The overall research and development mission now includes the development of chemical explosive excavation technology to enable the Corps of Engineers to more economically accomplish Civil Works Construction projects of intermediate size. The current and future chemical explosive excavation experiments conducted by NCG will be planned so as to provide data that can be used in the development of both chemical and nuclear excavation technology. In addition, whenever possible, the experiments will be conducted at the specific sites of authorized Civil Works Construction Projects and will be designed to provide a useful portion of the engineering structures planned in that project.

Currently, the emphasis in the chemical explosive excavation program is on the development of design techniques for producing specific crater geometries in a variety of media. Preliminary results of two such experiments are described in this paper; Project Pre-GONDOLA III, Phase III, Reservoir Connection Experiment; and a Safety Calibration Series for Project TUGBOAT, a small boat harbor excavation experiment.

IMPORTANCE OF CHEMICAL EXPLOSIVE EXPERIMENTS

The use of explosives for excavation 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. All of the foreseeable nuclear applications (1, 2) involve designs more complex than simple cratering under level terrain in a relatively dry medium. Specifically, aggregate production would be most ideally done under a topographic configuration that would maximize the volume of aggregate produced and make its recovery easiest. Ejecta dam construction would involve directed blasting techniques which would have to be uniquely tailored to the specific dam site. Canals and harbors will most often involve water saturated media or cratering under water. Canals and other cuts for land vehicle traffic will involve row cratering through varying terrain. All applications can involve unique geology, either layered and steeply dipping or in media for which no experience exists. Because it is infeasible to conduct enough nuclear experiments to develop the necessary engineering design techniques for each of the applications envisioned with the variety of geologic, hydrologic, and topographic features that can prevail, it will be necessary to derive this technology by a different route. One approach being taken to make the jump between a few cratering experiments and engineering design of complex applications uses computer calculations of the dynamic cratering process (Terhune, LRL). From an engineering standpoint, the ideal result of this program would be a set of design curves that would give the necessary emplacement information for each application and a set of physical site conditions prevailing. However, the current capability of the calculational technique is limited to two dimensions. Thus the set of curves, when they become available, will be limited to single-charge cratering in applications with an axis of symmetry. As indicated previously, these applications are the exception rather than the rule. In most real projects the use of this valuable calculational technique will still require an additional ingredient usually termed "engineering judgment". The use of engineering judgment implies experience of some related nature. It is this related experience that NCG is attempting to gain by using chemical explosives in relatively large concentrated charges in real construction projects.

Actually the chemical explosive excavation experiments contribute more than is implied by the previous statement. Though direct scaling from chemical explosive experience to nuclear explosive excavation cannot be done because of differences in the explosives' performance, (initial and subsequent pressures, temperatures and times) it is understanding how the cratered medium responds to a high shock loading and the nature of the gas cavity expansion that becomes important for predicting nuclear crater dimensions in the medium. If experimental cratering with chemical explosives in a medium can duplicate results of the calculational technique, based on a knowledge of the material properties, then it is more likely that nuclear cratering predictions for that medium made by the calculational technique will be valid.

It is within this framework of experience that adds to the empirical cratering application data and at the same time provides a laboratory for the computational technique that NCG's current chemical explosive test program is conceived.

THE RESERVOIR CONNECTION EXPERIMENT

The Reservoir Connection Experiment, executed in October 1969, was the last major experiment in the Pre-GONDOLA series of experiments. 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. (3, 4). Yields have ranged from 64 to 2000 pounds per charge. All of these experiments were peripheral to the main row-charge experiment at the site which is shown in Figure 1 prior to the reservoir connection detonation. This photograph shows the 20-ton Pre-GONDOLA I single-charge craters, (5), the Pre-GONDOLA II row at the left center, (6), and the Pre-GONDOLA III, Phase II connecting row at the right center. (7). Project Pre-GONDOLA I, four 20-ton cratering detonations, executed in the fall of 1966, 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, executed in June 1967, 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. During postshot engineering properties investigations, a wide trench was cut through the side lip and holes drilled into the rupture zone. The trench can be seen on the far side of the crater. 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 of the single-charge crater radius. Because the specific depth of burst (and consequently the crater radius-determined spacing) could not be established until some spacing was set, the design involved an iterative process starting with spacing based on the average depth of burst for the whole alinement and ending with spacing determined by actual depths of burst of adjacent charges. This charge configuration gave a very smooth, large crater which connected to the Pre-GONDOLA II crater. The Pre-GONDOLA III, Phase II row was executed during October 1968.

The last major experiment in the Pre-GONDOLA series was executed on 6 October 1969. This was Pre-GONDOLA III, Phase III, Reservoir Connection Experiment. In this experiment, five charges of varying yield and depth were placed (Figure 2) and simultaneously detonated to provide a connecting channel between the long crater shown in Figure 1 and the Fort Peck Reservoir. A varying terrain row cratering experiment of this scale had not been carried out previously. To complicate matters, a connection had to be made to the existing crater that would not leave a large amount of material blocking the channel. At the other end of the row, the objective was to connect directly to the reservoir with a minimum height end lip so that postshot excavation would not be necessary before water would fill the crater. The channel was designed to accommodate a navigation prism 67 ft. wide and 4 ft. deep at a water level of 2238 ft. The channel cross section was assumed to be hyperbolic with slope angles of 30°. No row crater enhancement was assumed in the design.

A preshot view of the crater showing construction activity is shown in Figure 3. Just after the detonation, Figure 4, water started to fill the crater. The water filling action, Figure 5, took about nine minutes. The final view, Figure 6, shows what the crater looked like when filled to the reservoir level. A composite of several sequential pictures taken of the detonation and resulting crater are shown in Figure 7. In one of these water can be seen spilling over the end lip into the crater. Crater profiles, center line and cross sections, are shown in Figure 8. The crater width at water level varies from a minimum of 100 feet to a maximum of 200 feet. The depth of water in the crater varies from a minimum of 13 feet to a maximum of 39 feet except at the entrance where the depth is approximately seven feet. The length of the water-filled portion of the crater is approximately 1370 feet. 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. In Figure 9 a tugboat is shown in the crater to provide some concept of scale.

KAWAIHAE SMALL BOAT HARBOR

Interest in the explosive excavation of harbors has generated the most current chemical explosive cratering project being conducted by NCG. This is Project TUGBOAT. (8). 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 Congressionally authorized small boat harbor so that some benefit would be obtained from the expenditure of the R&D funds. This site is in Kawaihae Bay on the west side of the Island of Hawaii (Figure 10). The project is planned for execution in three phases. Phase I, executed 4 to 7 November 1969, was a cratering and safety calibration series of detonations. Phase II is planned as a row and an array detonation(s) of nominal 10-ton charges designed to excavate a berthing basin and entrance channel.

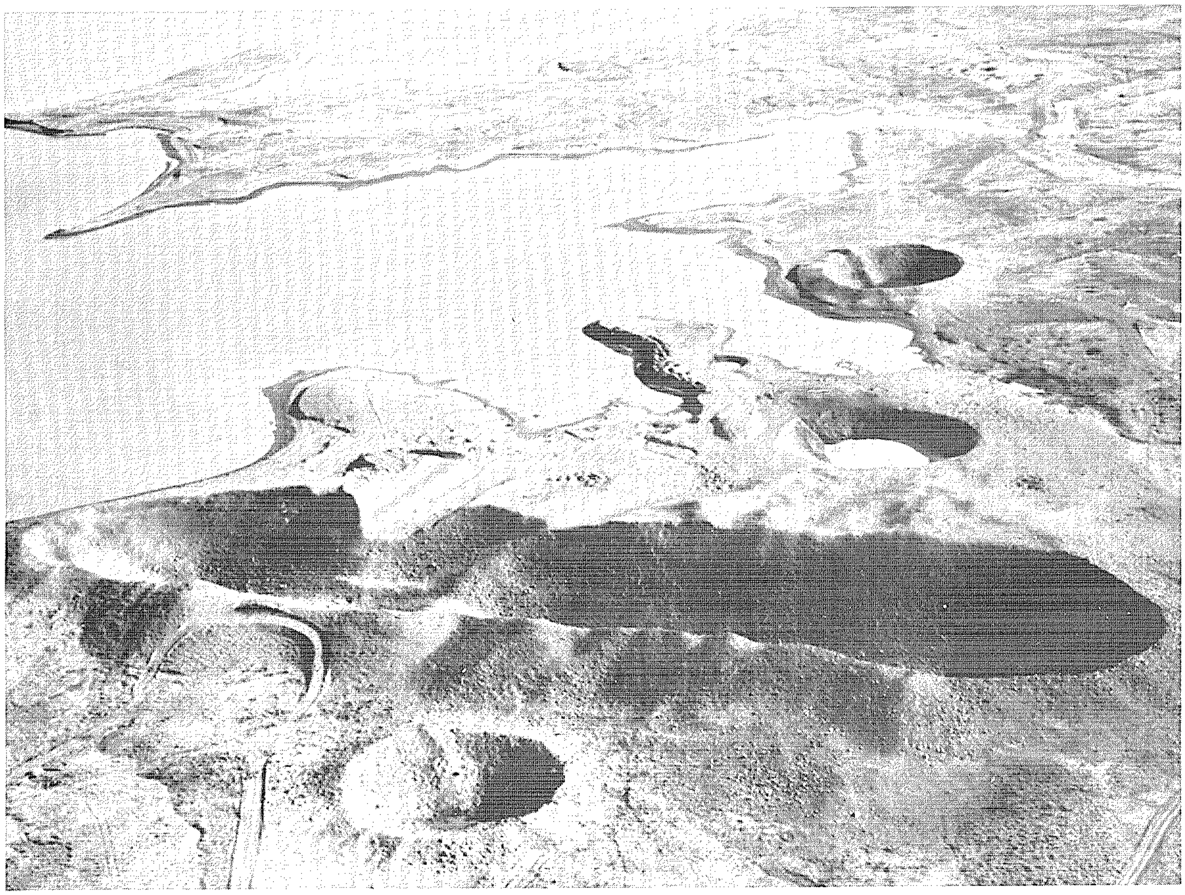

Figure 1. Pre-GONDOLA 20-ton single-charge craters and connecting row crater prior to execution of the reservoir connection experiment.

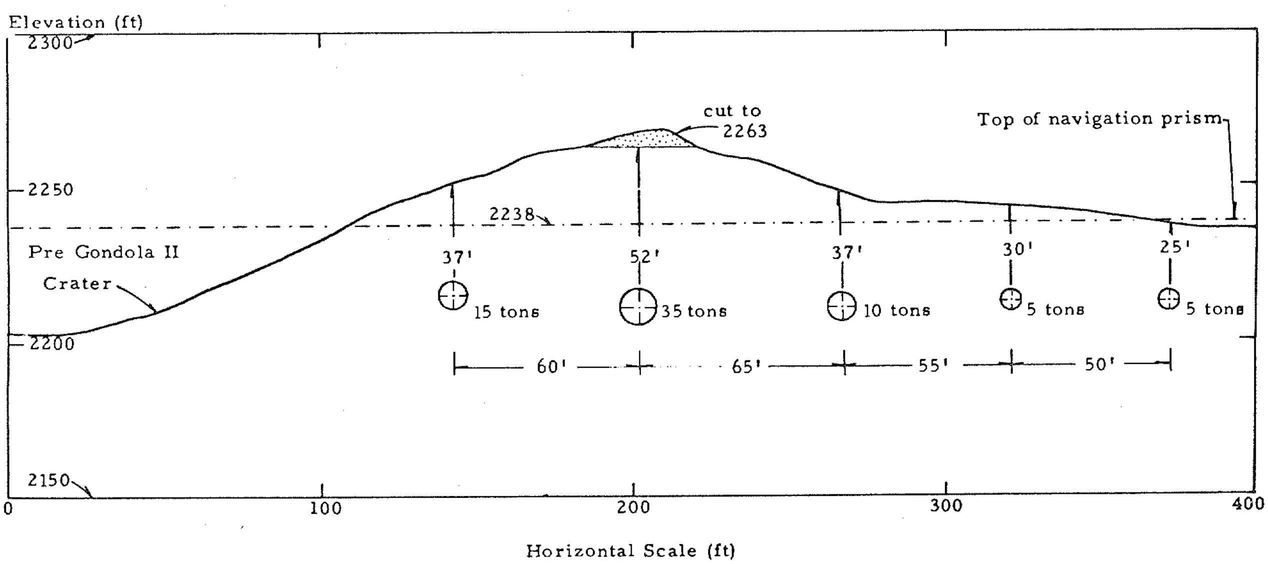

Figure 2. Centerline section drawing of the reservoir connection experiment, Pre-GONDOLA III, Phase III, showing charge depths, spacings and yields.

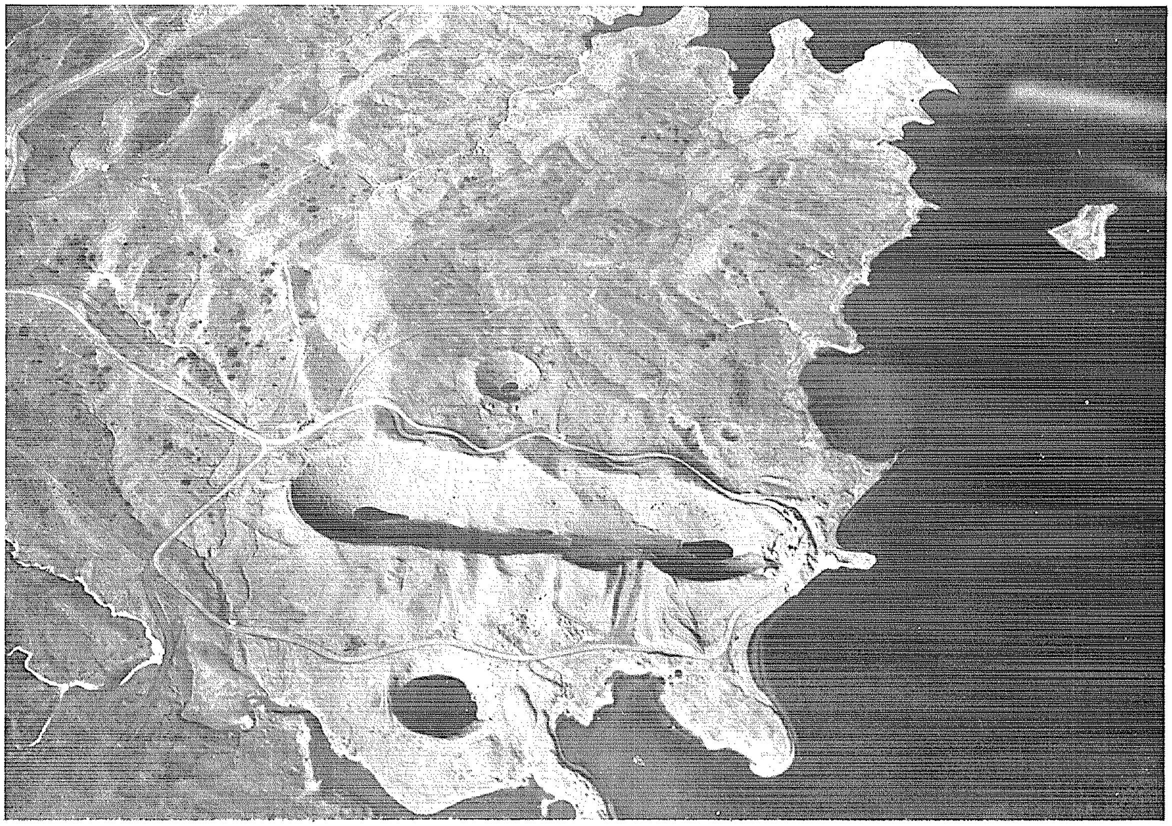

Figure 3. Preshot view of the Pre-GONDOLA III, Phase III, Reservoir connection experiment.

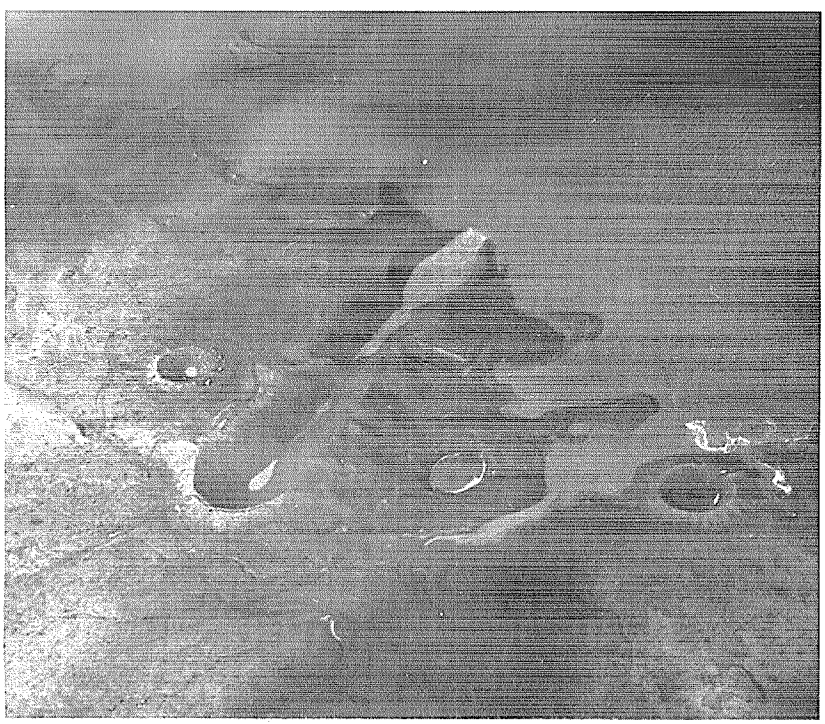

Figure 4. Connection experiment crater immediately following the detonation showing water starting to fill the crater.

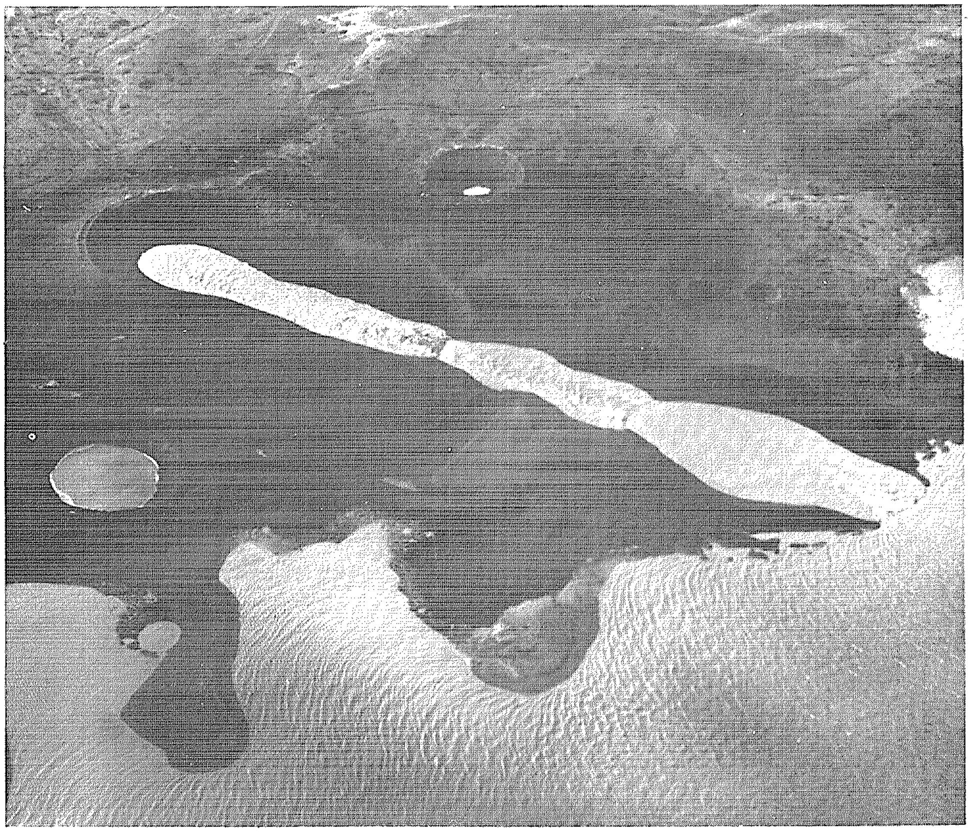

Figure 5. Reservoir connection experiment crater filling with water.

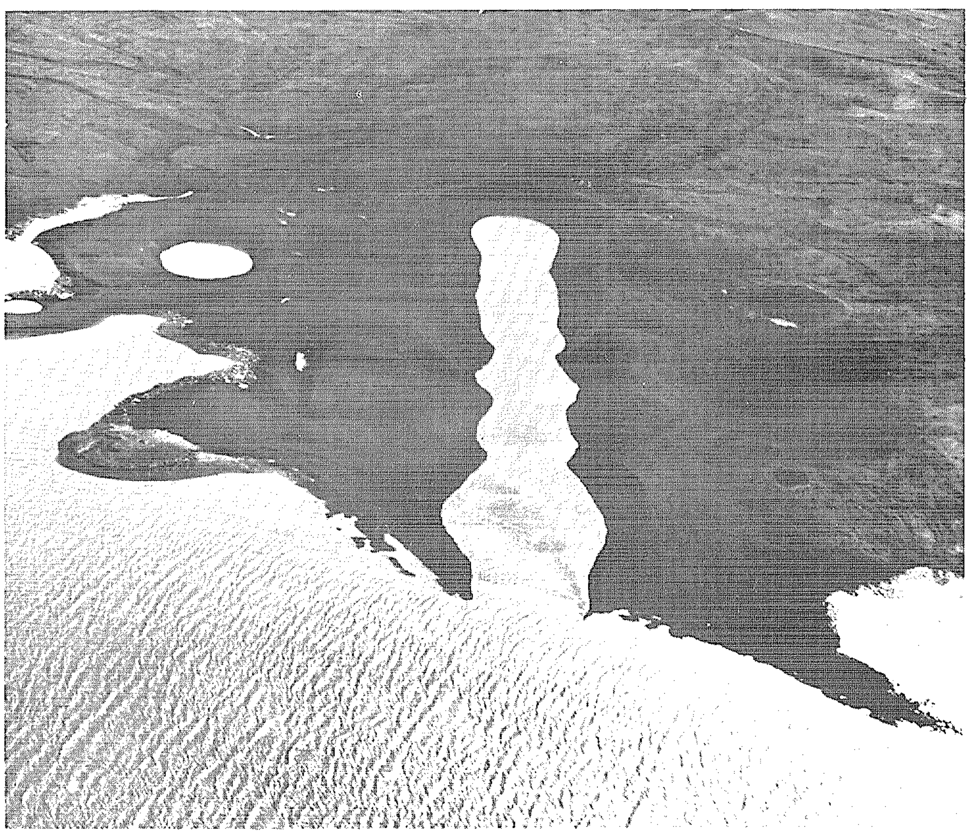

Figure 6. Reservoir connection experiment crater after water filling action was complete. Total filling time was about nine minutes.

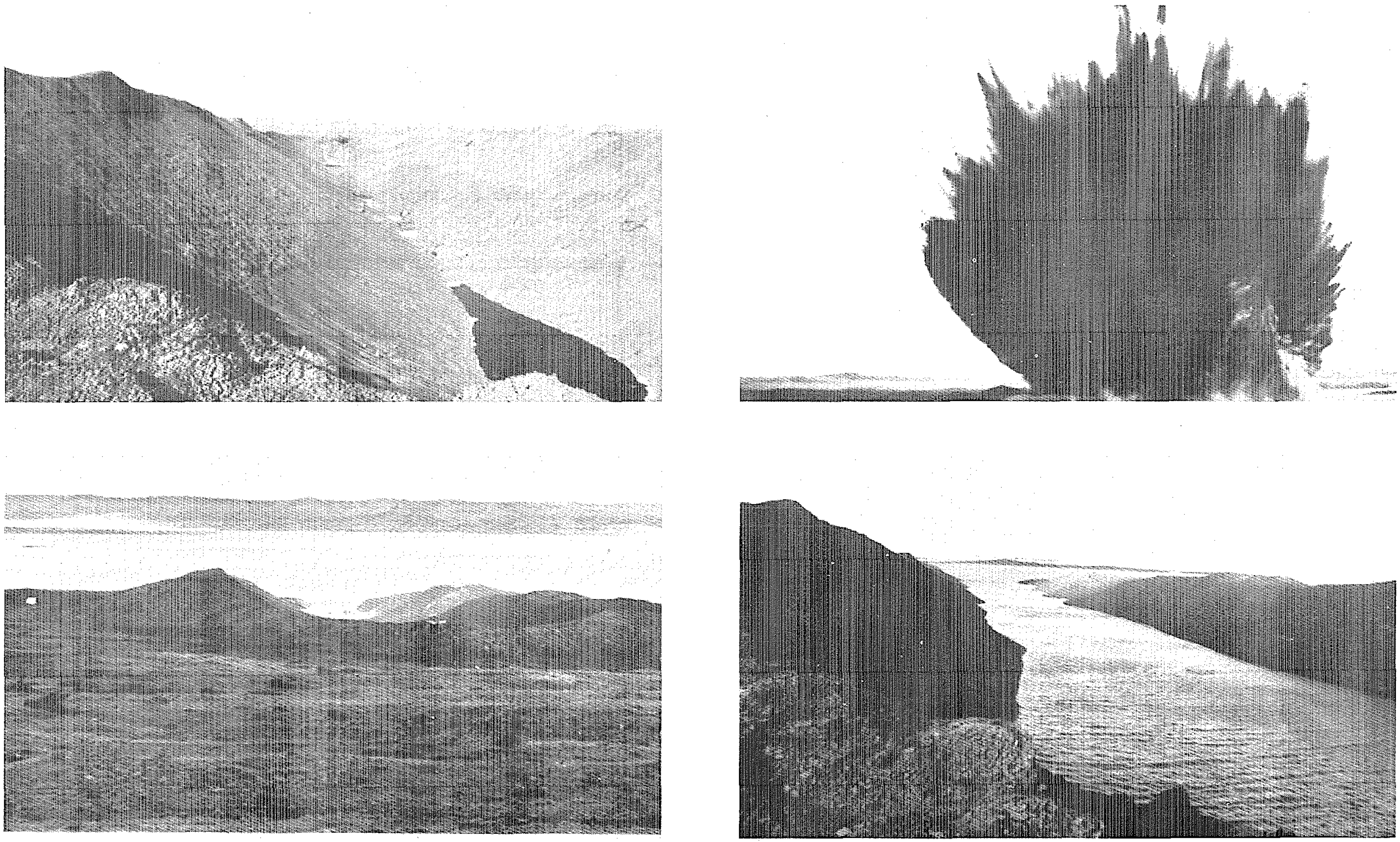

Figure 7. Sequential photos of the Reservoir connection experiment detonation and resulting crater.

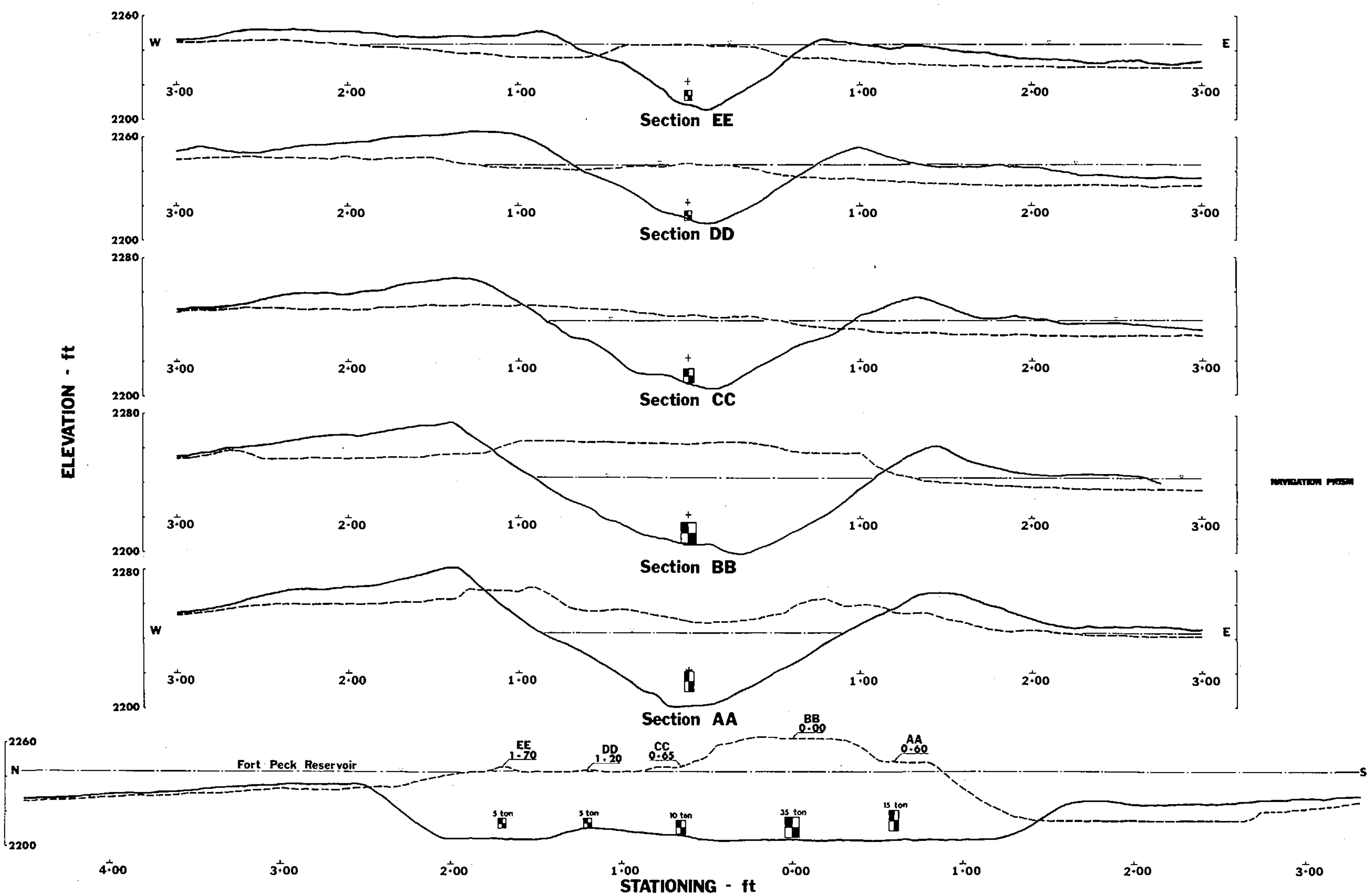

Figure 8. Centerline profile and cross sections, Reservoir connection experiment.

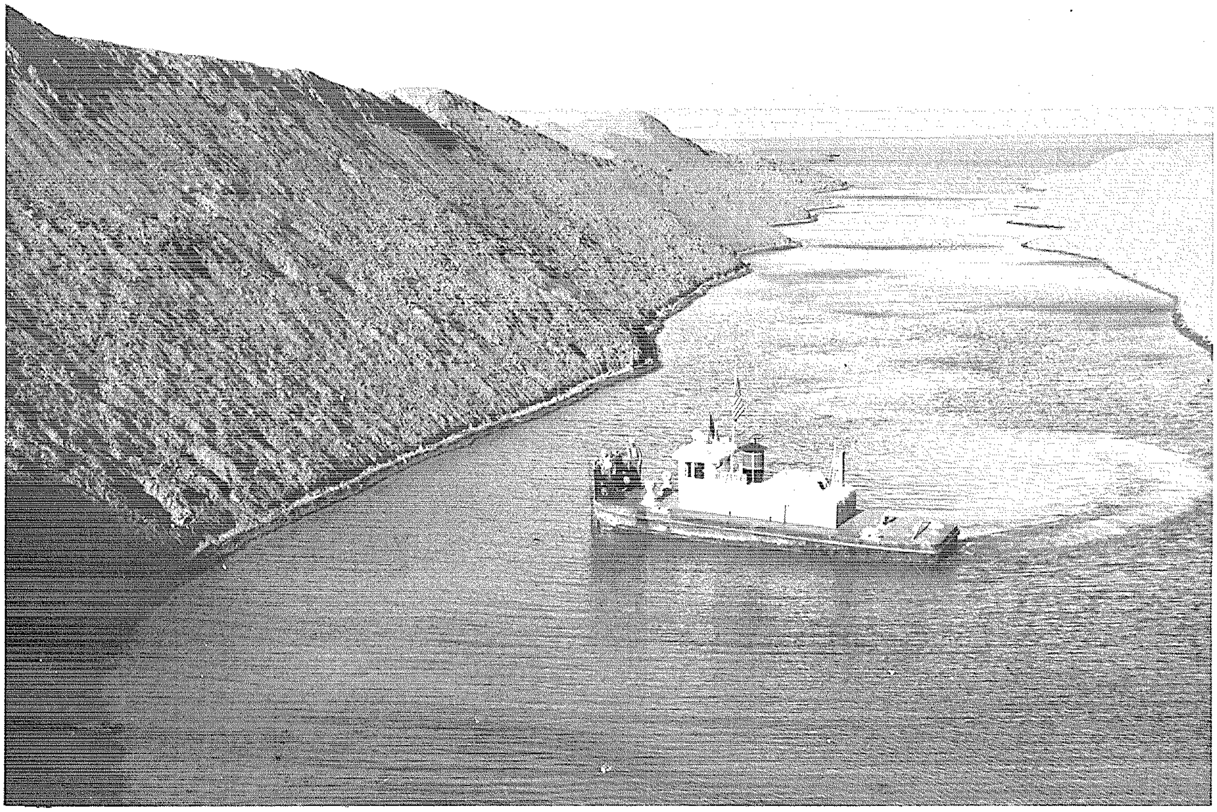

Figure 9. View of the Pre-GONDOLA crater with a tugboat in the channel.

Figure 10. Project TUGBOAT site in Kawaihae Bay on the west side of the island of Hawaii.

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 one-ton and one 10-ton. The one-ton charges were placed at depths ranging from 16 to 24 feet below mean lower low water level. The ten-ton charge was buried at 41 ft. below mean lower low water at what was predicted to be optimum for crater radius. This program was intended to provide crater dimension and safety data as a function of both depth of burst and yield.

The site medium is a coral limestone extending to 70 feet or more in depth and overlain by six to ten feet 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 which could be used as the core for a breakwater. After laboratory testing data was obtained for the coral, it was evident that there might be some surprises. The porosity of the material ranged from 37 to 64 percent, and the compressive strength was variable and ranged from 760 to 1738 lbs/in^2. This 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 one-ton and ten-ton craters. Profiles of the craters are shown in Figures 11, 12 and 13. A profile of the ten-ton crater is shown in comparison to a dry land crater in Figure 14. 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.

Because the radii for these craters are so large and do not significantly change over the range of depths of burst in the 1-ton series, a cratering curve has not been plotted. The parameter chosen for row and array charge design is the radius over which a relatively flat bottom occurs. The project calls for a minimum channel depth of 12 ft. For the 10-ton Echo calibration detonation (Figure 13) the average radius over which a minimum 12 ft. depth occurs is estimated to be approximately 60 ft.

The design problem for the berthing basin is primarily one of assuring a relatively smooth bottomed crater with a minimum depth of 12 ft. NCG's test modeling facility at the Lawrence Radiation Laboratory has been modified to do one-pound tests in saturated sand and in saturated sand overlain by four inches of water. A few tests have been conducted in the test pit since the Project TUGBOAT, Phase I tests and interestingly enough the craters are similar in shape to those observed in saturated coral. Several array charge detonations have been done at very wide spacing. These tests show the best results when the spacing is approximately twice the radius of the flat bottomed portion of the single-charge craters.

The preliminary redesign of the harbor entrance channel and berthing basin is shown in Figure 15. The berthing basin design uses four 10-ton charges spaced 120 ft. apart in a square array. This four-charge-square array provides more berthing space than was provided by the original design which used 10 charges in two parallel rows of five each. Some overdepth was desirable in the outer portion of the entrance channel and therefore these charges were spaced a little closer at 100 ft. This design requires the use of eight ten-ton charges in the entrance channel.

With this redesign of the entrance channel and berthing basin the project can be accomplished with 60% of the total yield specified in the original design. The savings from the reduction in emplacement construction and amount of explosives needed is expected to cover the additional cost of building a

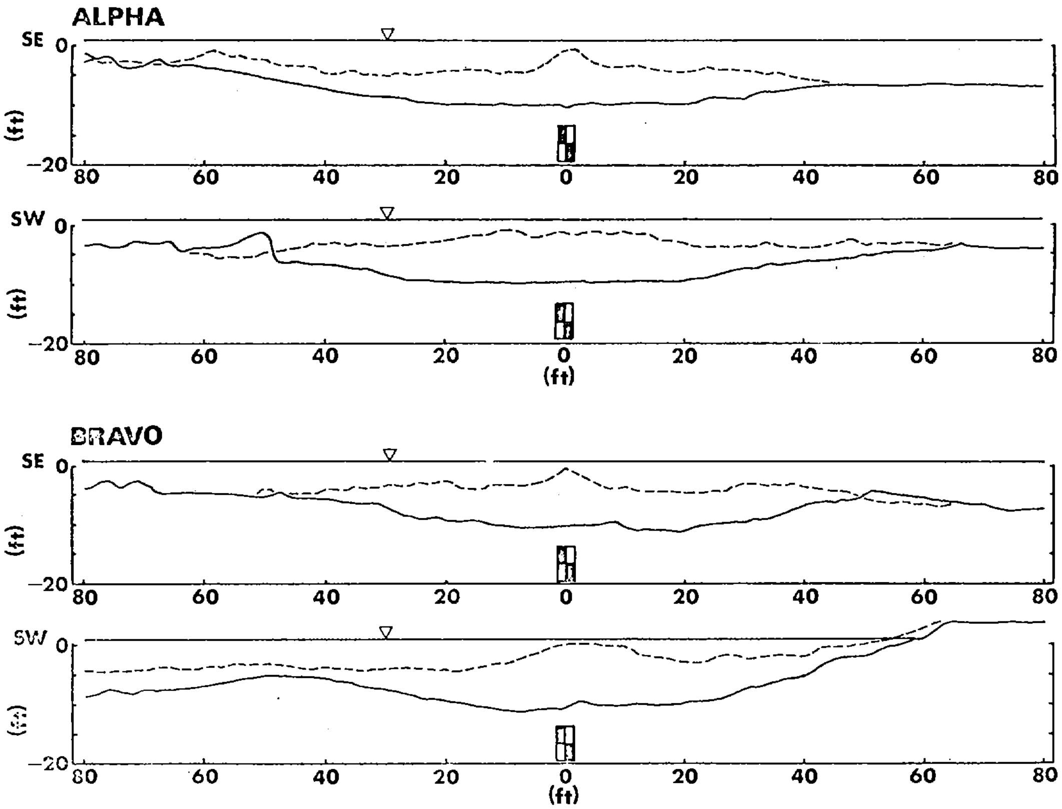

Figure 11. Project TUGBOAT, Phase I: ALPHA and BRAVO crater cross sections.

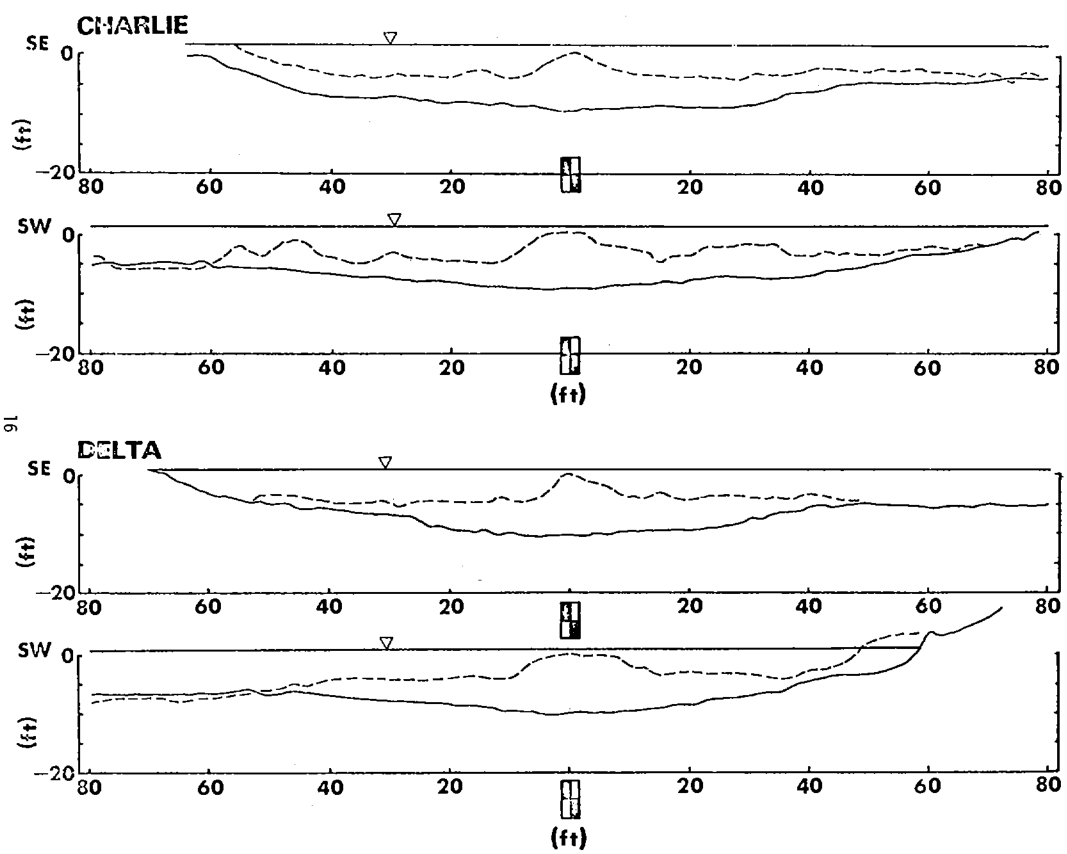

Figure 12. Project TUGBOAT, Phase I: CHARLIE and DELTA Craters.

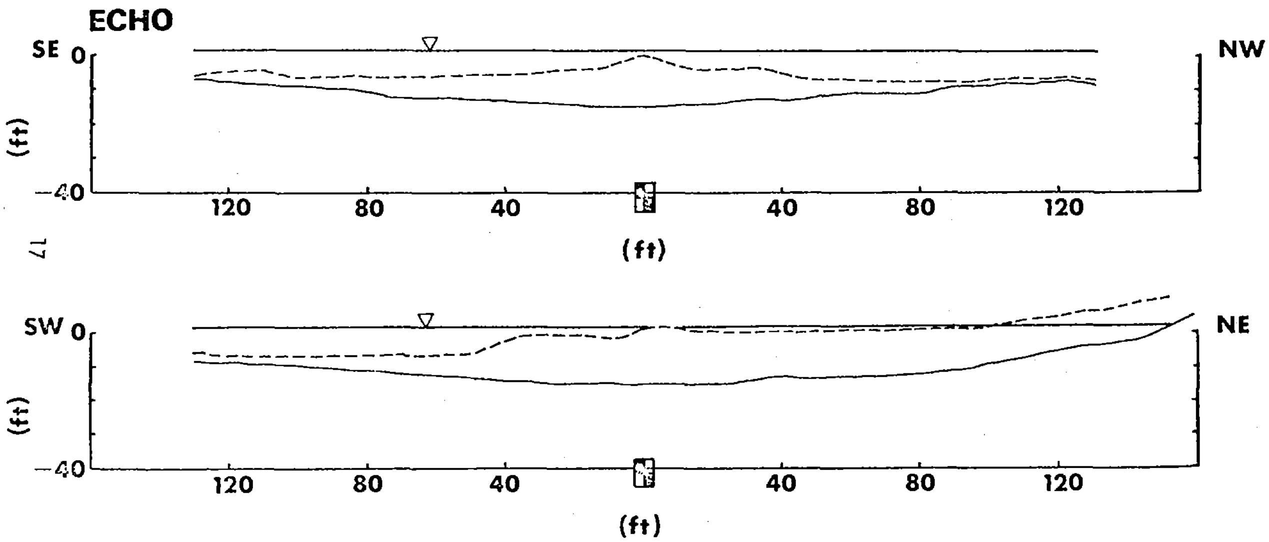

Figure 13. Project TUGBOAT, Phase I: ECHO crater cross section.

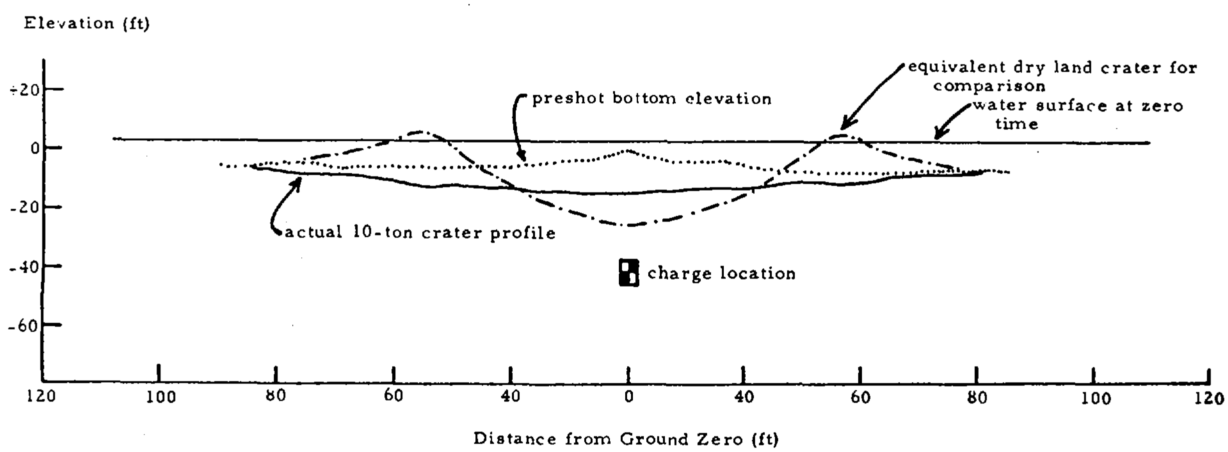

Figure 14. Profile of Project TUGBOAT, Phase I, 10-ton crater shown in comparison to an equivalent yield dry land crater.

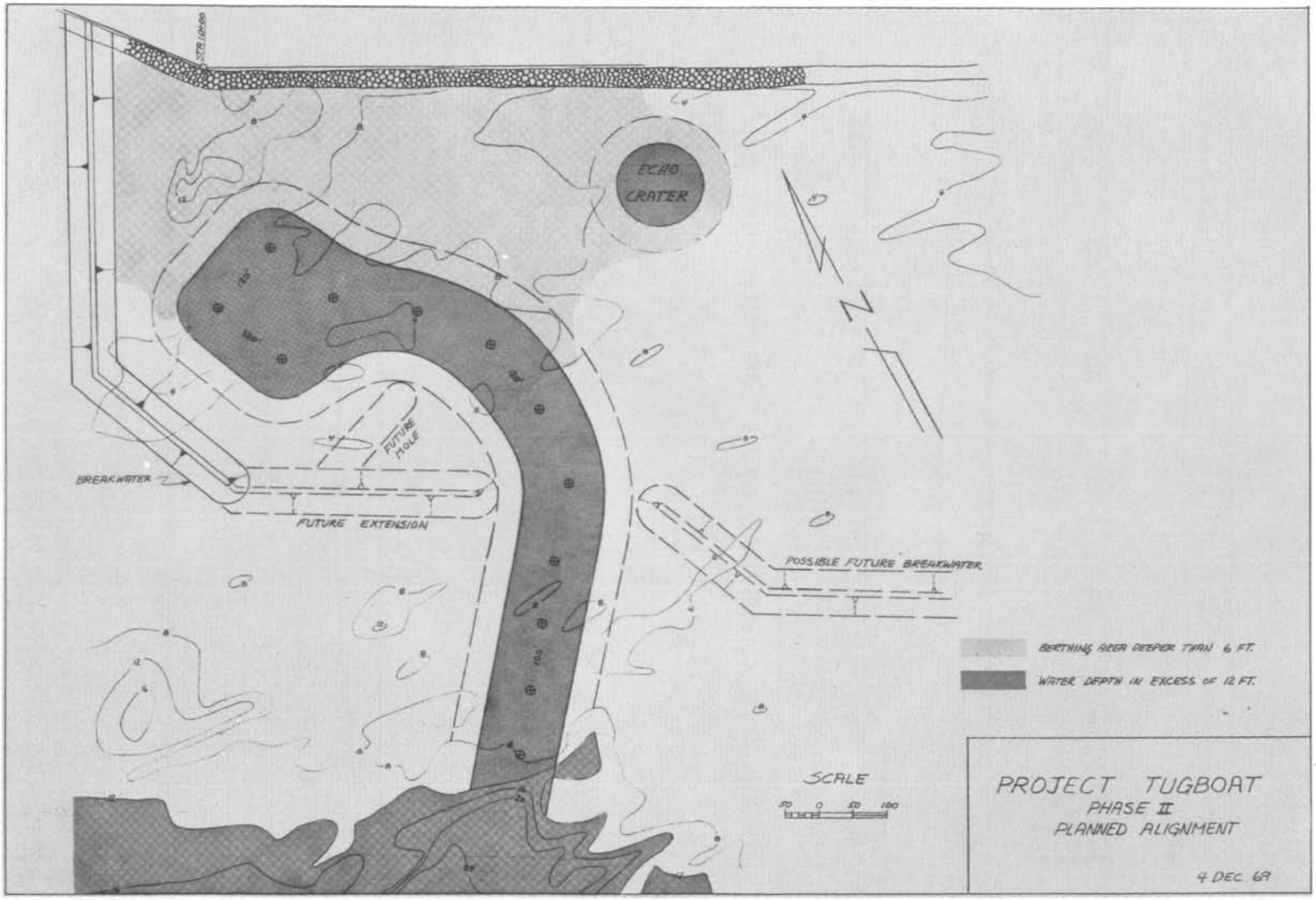

Figure 15. Project TUGBOAT revised design for Phase II, berthing basin and entrance channel excavation.

breakwater which will place a structural load on the near-crater area, something not yet attempted although necessary for many projected uses of explosive excavation, protect the cratered area for postshot material properties investigations and provide needed protection to the eventual harbor area.

FUTURE EXPERIMENTAL WORK

NCG plans to continue to conduct chemical explosive experiments in conjunction with Authorized Civil Works Projects to develop experience in all explosive excavation applications. As these experiments are conducted it is expected that the attendant publicity will generate wide interest and new projects, while at the same time making this new construction method acceptable as a routine alternative to be considered in the initial design phase of all large earthmoving projects.

The next major experiment under consideration involves the removal of a portion of Wayanda Ledge from the Sergius Narrows in Southeastern Alaska. Wayanda Ledge is an underwater rock mass which restricts navigation in a channel with existing very high tidal currents. The current general concept is to explosively remove a portion of the rock mass, depositing the broken rock in the deep portion of the channel. Site reconnaissance is under way at this writing. The material has been classed as a hard rock and will provide experience in excavation of a hard rock underwater. During a site calibration program at least one detonation will be planned to investigate the harbor concept originally planned for Project TUGBOAT; that is, a detonation in a competent medium in shallow water where the lip would provide protection for a harbor facility inside the crater.

NCG is also considering applying the experience in linear channel excavation to a river diversion and railroad relocation project in conjunction with the Trinidad Dam construction in southeastern Colorado. The required diversion channel is approximately 1700 ft. long. The depth of the cut required is approximately 38 ft. Several sidehill cuts are required for the railroad relocation. The medium at the site is classed as a low to moderate strength sandstone. This project will provide cratering calibration of a new medium (sandstone) and will provide practical experience in row excavation through slightly varying terrain and in connecting row design.

SUMMARY

As a result of the technology gained in NCG's experimental cratering work in the Plowshare Program, its mission has been expanded to include developing chemical explosive excavation technology. This mission is being accomplished by conducting chemical explosive experiments as part of Authorized Civil Works Construction Projects. Two recent experiments are contributing to this technology; Pre-GONDOLA III, Phase III, Reservoir Connection Experiment and a calibration series as part of Project TUGBOAT.

The Pre-GONDOLA tests, conducted over a period of four years, have produced data on excavation of weak saturated materials and on row crater formation characteristics and row crater connections. The most recent phase of the Pre-GONDOLA series was completed in October 1969, culminating in a reservoir-connection shot which created a linear channel connecting a previously excavated row crater to the Fort Peck reservoir. The channel connection resulted from detonation of five charges ranging in yield from five to thirty-five tons; the total charge was seventy tons.

Project TUGBOAT is designed to provide a portion of a planned small craft harbor in Kawaihae Bay, on the northwest coast of Hawaii. The project is being executed in three phases. Phase I was executed in November 1969; it consisted of five calibration shots in a coral medium overlain by several feet of water. The first four shots, at one-ton yield, produced craters very similar in shape and size to each other but very wide and shallow when compared to dry land experience. The craters had no lips. A single ten-ton detonation provided a scaling point for crater dimensions and for safety program measurements. The results of Phase I shots have been used to design the Phase II detonation of twelve ten-ton charges for entrance channel and berthing basin excavation, scheduled for April 1970. Because the craters were much larger than predicted, the project will be accomplished with about half the amount of explosives in the original design.

Future planned experiments include an underwater navigation hazard (rock) removal, river diversion channel excavation, and sidehill cuts for railroad relocation.

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