CONTINUOUS SEISMIC PROFILING STUDIES
OF THE PRESIDENT ROADS AREA,
BOSTON HARBOR, MASSACHUSETTS

by
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ABSTRACT

A high-resolution continuous seismic profiling system was used to study trends of sedimentation in the President Roads area of Boston Harbor, Massachusetts. Closely spaced survey lines were run with good navigational control.

The general sedimentary sequence in Boston Harbor consists of layered Pleistocene clays deposited on an uneven bedrock or till surface. The clay is overlain by Recent black mud over large areas. Layering in the clay tends to parallel the bedrock or till surface; no slumping has been found.

The President Roads area is generally characterized by good seismic penetration of the sediments; to the north or south, acoustic penetration is very poor or absent. The boundary of the region of good penetration has been partially delineated.

A fence diagram based on the survey lines has been prepared. Areas of thick, horizontally layered clays are sites from which long cores may be obtained in the future. In other places, where the layering is truncated at the water interface, a series of cores of moderate length could provide information about the complete sedimentary sequence.

Thesis Supervisor: Ely Mencher
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Introduction

During the late 1950's and early 1960's, Professor Harold E. Edgerton of the M.I.T. Department of Electrical Engineering obtained very good continuous seismic profiling (CSP) records in Boston Harbor with experimental equipment (Edgerton, 1963; Payson, 1963). The geological implications of these records provided much of the impetus for forming an informal group under the guidance of Professors Ely Mencher and Robert R. Shrock to study various aspects of sedimentation in the harbor. In 1964, National Science Foundation grant GP2628 was obtained to provide financial assistance for continuation of these studies as an educational program.

CSP studies were initially carried out on a reconnaissance scale. Donald Phipps (1964) correlated Yules' surveys of 1963-64 with earlier experimental CSP records and with information in the geological and civil engineering literature. These and subsequent broad surveys, as well as experience gained in testing acoustic devices in the harbor and in attempting to obtain cores, indicated that in the President Roads area and in the region of the Quarantine Rocks (south of Rainford Island) closely spaced CSP surveys would be a fruitful means of studying sedimentation.
Objectives of the Present Investigation

The main objective of the work undertaken in 1965 and reported herein was to obtain a detailed three-dimensional picture of the distribution of unconsolidated sediments in the President Roads area of Boston Harbor. In addition to the inherent interest of such an investigation, it was thought that the CSP results would help to plan an efficient program for obtaining core samples. Not only would sequences of horizontally layered sediments be sought as optimal locations for coring, but also core samples might be necessary to solve questions of interpretation of the CSP records.

The development of techniques for conducting a fine-scale CSP survey was another area of prime interest at the outset of the investigation. A simple method of providing adequate navigational control, techniques for processing the seismic recordings, and a means of presenting the results were all sought.

No research into instrumentation was planned. Rather, existing commercially available equipment was to be used. It was hoped, however, that systematic investigation of the President Roads area would help to establish this part of the harbor as a testing area for experimental equipment.

Extent of the Survey

The President Roads is a three square nautical mile area north of Spectacle and Long Islands and west of Deer Island and Long Island Head. Figure 1 shows the location of
Figure 1
CSP Reconnaissance in Boston Harbor
this area. In addition, major broad seismic survey lines of 1963-1965 are indicated.

During 1965, 164 continuous seismic profiling sections were run under good navigational control. The total distribution of these sections is shown in Figure 2. This investigation covers most of that part of the President Roads where acoustic penetration of the bottom occurs. It might appear, in view of our ignorance about the seventy-five square miles of Boston Harbor, that this survey grid is too fine. The scale of variation in the harbor, however, demands very closely spaced sections.

Continuous Seismic Profiling Equipment

The continuous seismic profiling apparatus used is a portable, short-pulse-length, high peak amplitude system manufactured by Edgerton, Germeshausen, and Grier, Inc. (Edgerton, 1963; Edgerton and Payson, 1964; Payson, 1963; Yules and Edgerton, 1964). Since its operation has been described elsewhere in some detail, and since this investigation is not directly concerned with instrumentation, only a few special characteristics need be discussed.

With the standard transducer resonant at about 12kHz, the sound pulse length is about 0.25 ms., as shown in Figure 3. This feature, resulting from capacitor discharge circuitry, permits resolution of reflecting interfaces separated by only 0.2 meters when the speed of sound is taken to be 1500 meters/second.
Figure 2
Distribution of Sections Surveyed, 1965
At the highest recorder drum speed, which gives an eighty-seven foot (twenty-seven meter) distance scale across the five-inch record, the pulse rate is twenty-nine per second. With such a great rate of information, visual correlation of signals on the record is quite high.

Figure 3
Output Sound Pulse

[Diagram showing a sound pulse with an echo from water surface]
Field Procedure

The Continuous Seismic Profiling Apparatus

Great care was taken to suspend the transducer so that the main lobe of the sound field pointed vertically downward. Although the beam width to the half-power points is about 30°, the directivity of the total system is greater because the projector also serves as the receiver. Experience with this apparatus has shown that a five degree error in transducer pointing is certainly apparent on the resulting record. To aid in keeping the transducer pointed correctly and to keep the transducer depth constant, permanent supporting lines were prepared.

This recorder is not equipped with either a scale-line generator or a precisely controlled time base; therefore calibration is necessary. The recorder drum speed may be measured with a stroboscope. From the resulting determination of time per sweep, a distance scale may be based upon the known sound velocity in sea water. A more direct procedure for use in the field is to suspend a reflecting target at known distances beneath the operating transducer and record its echo. A three-inch diameter brass sphere is easily detected to depths greater than twenty feet. By suspending the target at several depths below sea level, not only is the distance scale calibrated, but also the transducer depth may be determined.

During the entire period of this survey, the distance calibration was found to be constant at full sweep=87 feet.
Since one of the aims of the research was to determine locations for coring operations, it was found desirable to operate with no more than 0.25 joule of energy storage and to damp the output pulse resistively to obtain high resolution of the layering and to follow reflecting surfaces almost to the water interface. Deeper penetration into the sediments could have been obtained by using higher energies, but resolution would have been reduced and upper layers would have been obscured by bottom reverberation.

**Navigational Control**

Survey lines were run between marker buoys placed about 1000 feet apart. Buoy positions were determined by taking sextant angles between pairs of prominent landmarks from each buoy. This procedure, which may be easily followed in work from small boats, is discussed in detail in Appendix I. An error analysis shows that, for typical distances to landmarks encountered during the investigation, buoy positions can be determined to an accuracy of tan feet. The overall positional error is less than five percent of the buoy separation. Comparison of records obtained in the same area on different days confirms the achievement of high positional precision.
Data Reduction

Each survey line is indicated on the raw continuous seismic profile record by marks made at the beginning and end of the section. The buoy positions for a given day's work are all plotted with a three-way protractor on a plotting sheet made from a 2X enlargement of the USC & GS Chart 246 (Boston Harbor). The length of each section is determined from measurements of the plotted buoy separation.

The raw CSP record is then subdivided into 100 foot intervals for further analysis. An aid for this operation is a surface upon which is drawn a family of uniformly spaced diverging lines. The record is moved over this set of lines until it is divided into the correct number of hundred foot intervals.

A transparent plastic overlay scale is used to show 10 foot depth intervals on the record. The record for each section is then replotted with a vertical exaggeration of 20:1 to aid in correlating all the information. These cartoon drawings of each section show the bottom profile, some prominent sub-bottom layers, and any bedrock or till surfaces.

Tidal Corrections

In order to be able to compare data obtained at different times, a datum of Mean Low Water (MLW), which corresponds to the Boston City Base, was adopted. Mean Low Water at Boston
is 4.9 feet below mean sea level. A tidal correction to this datum is readily made. From the predicted times and heights of high and low tide at Boston Harbor, a graphical presentation of tide heights as a function of time is made assuming a sinusoidal rise and fall. For Boston, where the tide is strongly semi-diurnal, this assumption is valid. Moreover, since work in the Harbor was done only on fair, calm days, meteorological effects, which might cause the real tide to differ from the predicted tide, may be ignored. From the height of the water surface above MLW, the transducer depth of two feet is subtracted to give the position of MLW with respect to the zero line of the record. The position of MLW is plotted on the 20:1 section drawings as a red line.
Results

Characteristic Features of the CSP Records

Blue Clay

The most prominent feature of the CSP records is a sequence of closely spaced, parallel echoes which may total over one hundred feet thick. This sequence has been identified as the Boston Blue Clay from the character of the echoes, their vertical and horizontal extent in the harbor, surficial cores, and correlation with boring data in and around the harbor.

The origin of the blue clay, and in particular the problem of whether it is a marine or fresh water deposit, is a disputed subject. Phipps (1964, pp. 17 and 18) summarizes the arguments and describes the blue clays:

They have a blue-grey to slightly greenish-grey color when unoxidized; oxidized they become yellow-brown. The fresh clays are tough and plastic but contain extremely fine quartz. Layers of sand and/or silt, varying in thickness from less than one inch to more than one foot, occur in the clays and appear to be rhythmically deposited, but on too coarse a scale to be classified as varves.

The silty or sandy layers probably are responsible for the apparent layering seen in the records. As yet, no attempts have yielded clay cores of sufficient length to permit correlation with CSP records to identify reflecting interfaces.
Rock or Till Surface

The blue clay appears to be deposited on an uneven surface of either glacial till or bedrock. It is not now possible from the CSP records alone to differentiate till from either bedrock or bedrock overlain with a thin deposit of till. In the President Roads area, this surface probably represents till, but this conclusion is based upon indirect evidence. In his thesis, Phipps (1964) attempts to differentiate between rock and till surfaces by the quality of the reflection on the CSP records, a till interface being less distinct. While such a correlation may indeed be accurate for Boston Harbor, a smooth till surface might give a more distinct echo than a rough rock surface.

On June 10, 1965, Mr. Vincent J. Murphy of Weston Geophysical Engineers, Inc. cooperated with us in conducting a seismic refraction study over a peak in this bedrock or till surface. The results so far have not yielded a definite determination of the nature of the interface. However, results of the CSP studies may possibly be used to refine the refraction data to greater accuracy.

Black Mud

The Boston blue clay is covered by a relatively thin layer of black mud over much of the harbor. These areas are such good reflectors of sound that no penetration takes place. Most probably, anaerobic decomposition in the mud produces
gaseous products (principally methane, with some hydrogen sulfide). Very small volume percentages of a gas phase in a liquid can cause a tremendous acoustic impedance mismatch with the pure liquid (Spitzer, 1943; Foldy, 1944; and Grouse and Brown, 1963).

Quality of Acoustic Penetration

One of the major reasons for working in the President Roads area is the excellent acoustic penetration possible over much of the region. Yet, over some immediately adjacent areas, seismic penetration does not occur.

Figure 4 indicates the quality of penetration experienced on the survey lines profiled during 1965. Lines or parts of lines in black indicate where no sub-bottom echoes were obtained. Solid red lines indicate good penetration, and dashed red lines show where poor quality, but useful records resulted.

Those parts of the President Roads where a channel has been dredged generally have very good acoustic penetrability. Strong tidal currents and frequent passage of large ships may keep other parts of the harbor free of sound-reflecting surficial deposits.

To the north of the area surveyed in 1965 is an extensive mud flat, where gas-producing black mud makes the harbor bottom highly reflective and no penetration takes place. Other surface deposits such as gravel, boulders, or shell beds may also limit acoustic penetration of the bottom. Regions
Figure 4
Quality of Acoustic Penetration

KEY:
Good Penetration solid red
Poor Penetration dashed red
No Penetration black

Spectacle Island

Long I.
of no seismic penetration just north of Spectacle Island probably result from deposits of gravel and boulders as products of erosion of Spectacle Island Head. Surface samples from this part of President Roads are sandy and contain cobbles. Often rocks prevent the VanVeen sampler from closing.¹

Figure 4 suggests where it might be worthwhile to enlarge the area studied during 1965. At the west end of President Roads, work could be done short distances north of Sections 49, 58, and 63. The region just north of Section 23 might also prove fruitful. Probably another row of sections could be surveyed north of sections 119, 125, 129, and 167. Extension of the survey further south is less likely to yield good records than the northward extensions indicated. However, much usable information will probably be obtained.

Presentation of Data

Perhaps the best two-dimensional method of presenting the CSP survey data is by means of a fence diagram (orthographic projection). Unlike contouring, which uses only a small fraction of the available information and appears to be based on a continuous distribution of data, a fence diagram is an almost direct presentation of the information actually obtained.

Figure 5 is a 4:1 vertically exaggerated fence diagram of the survey work done in the President Roads in 1965. This scale was chosen after some experimentation. A greater vertical exaggeration would help to make slope information

¹ Boston Harbor Study Group Field Notes: Samples 165-170.
more apparent, but it would also superimpose more of the information and thus make the whole presentation more difficult to understand. Less vertical exaggeration tends to obscure slope information. Many sections are omitted from the diagram either because they would obscure more information than they would add or because the section was run in a direction nearly coincident with the direction of projection (N-S).

Figure 6 shows serial north-south sections across the Presidents Roads area. Their locations are indicated on the overlay to Figure 2. It must be stressed that a presentation in serial sections is interpretive; the original data is degraded in the process of projection onto north-south lines. Nevertheless, the serial sections show very clearly the trends of the layering.

**Storage of Original Records**

Due to the great quantity of original data and to facilitate future work, all of the CSP records studied during this investigation have been placed with the Boston Harbor Study Group in the M.I.T. Department of Geology and Geophysics. Field notes, plotting charts and the 20:1 analysis drawings are similarly preserved.
Discussion of Results

Layering in the Blue Clay

Perhaps the most impressive fact revealed by Figures 5 and 6 is the extremely rapid scale of variation in this part of the harbor. A surface defined by an interface in the clay is very complex. This result indicates the need for conducting closely-spaced surveys when studying layering.

Large scale trends of layering in the blue clay appear to be controlled by the topography of the underlying bedrock or till surface. Phipps (1964) suggests that this phenomenon results from differential compaction in the clays. No evidence of slumping or faulting was found.

The upper surface of the clay does not follow the layering in general. Erosion of at least twenty feet of the clay must have occurred.

Bedrock or Till Surface

The bedrock or till surface is certainly one of the most striking features of the CSP records. Study of this interface was not an object of this investigation; yet, even with 12kHz sound of low energy, it is apparent on almost half the sections run. It is not possible to determine from the CSP records alone whether this surface represents glacial till or bedrock; indeed, in some areas it may be till and in others, rock. Indirect evidence such as experience on land, probable pre-Pleistocene drainage patterns, and nearby depths to bed-
rock suggests that in the President Roads, this surface represents glacial till.

To the northeast of the end of Spectacle Island, this surface appears to form a ridge trending east-northeast. This feature is quite prominent in Figure 5, but it may also be seen in Figure 6. If the interface does represent glacial till, we may ask why it should form a ridge trending to the northeast. This direction is approximately both parallel to the axis of folding of the Boston Bay Group rocks and perpendicular to the local direction of glacial movement (LaForge, 1932). One explanation is that underlying bedrock topography may govern the location of the till. This mechanism is thought to account for the placement of the drumlins forming Long Island, just south of President Roads. However, the possibility that this east-northeast ridge is some morainic feature cannot be ruled out.

Coring Locations

A major objective of this study was to choose areas for optimum coring. Figure 5 indicates areas in the President Roads where a considerable thickness of clay is horizontally layered. Ideal locations for obtaining deep cores are near the junctions of sections 49, 50, and 54 or sections 10, 11, and 42. Not only are thick, horizontally-layered clay sequences found in these areas, but also excellent acoustic penetration would permit the data obtained from cores to be correlated
with CSP records. If possible, deep cores ought also to be obtained on the southern side of the rock or till ridge shown in Figures 5 and 6 so that CSP records from both areas may be correlated. Possible sites for such coring are near the intersections of sections 88, 89, and 94 or 151 and 152. Were it possible to obtain inexpensively eight to ten foot cores, then it would be worthwhile to core in areas where the bedding slopes to intersect the harbor bottom. Many such areas are shown in Figure 5.

Certainly the most direct way to determine the nature of the bedrock or till surface would be to obtain a sample. Locations of peaks in this surface are shown in Figure 5, and these would of course be ideal locations for drilling.

For all these major sampling activities, it would be desirable to take CSP records from a second boat during the operation. In this way, core locations may be exactly correlated with CSP studies. During 1965, this procedure was tried for Boston Harbor Study Group cores 136 and 137; however, the cores obtained were too short for comparison with CSP data.

**Velocity of Sound in Boston Blue Clay**

In all our work, the assumption was made that the velocity of sound in Boston Blue Clay does not differ greatly from the sound velocity in sea water. This is an assumption frequently made in CSP surveys over compacted clays; in Bos-
ton Harbor, seismic refraction studies for engineering purposes confirm the validity of this assumption (Vincent J. Murphy, personal communication).

On surveys which cross the edge of the channel dredged into the harbor bottom this sound velocity assumption can be checked. Were the sound velocity in the clays greater than that in sea water, the discontinuity in the bottom topography would be seen in the sub-bottom reflecting interfaces on the CSP record. Were the clay sound velocity less than the sea water sound velocity, the bottom discontinuity would appear in the sub-bottom echoes in the negative sense. No consistent effect could be demonstrated in Boston Harbor; therefore the sound velocity in the blue clay may justly be assumed to be equal to that of sea water.
Suggestions for Continued CSP Research

The overall success of the closely-spaced CSP survey program of 1965 is most encouraging. The general pattern of layering in the blue clay is now known for most of the President Roads area. Techniques for conducting such a survey were worked out, and, equally important, a system of processing the CSP records and presenting results was established. The use of the CSP studies to aid in selection of locations for various types of sampling should result in substantial savings of time and money.

Continuation of this work should involve much more than simple extension of the survey to cover those remaining areas of President Roads where acoustic penetration occurs. It should be possible, using lower frequency transducers or high-energy sources, to explore more fully the bedrock or till ridge northeast of Spectacle Island. In particular, it would be of interest to learn whether the ridge runs beneath Spectacle Island, and how far it goes in the opposite direction toward Deer Island. Another question to be answered is whether other peaks in the bedrock or till surface are parts of a ridge-like structure.

Surely, the next area which should be examined with a closely-spaced survey is the region south of Rainsford Island. Here, bedrock which outcrops as the Quarantine Rocks, can be traced beneath the sediments for considerable distance. Also, there is some boring data with which to correlate the
CSP results.

With the availability of a large boat, procedures can be greatly simplified. Rather than running survey lines between buoys, the CSP apparatus can be run continuously while a crew of two men and a recorder take sextant angles about once a minute. The area that can then be surveyed in a day would approach a square nautical mile. Also, different sound sources might be used simultaneously to obtain high near-surface resolution and deep penetration. Certainly with a larger boat broad reconnaissance exploration of the entire harbor ought to be an immediate goal.

Recent dredging operations in the Inner Harbor and Chelsea Creek have probably made possible excellent CSP work in these areas. A reconnaissance survey of these parts of the Harbor would be useful. It will probably prove fruitful to extend the President Roads survey further west to include some of the recently dredged areas.

To facilitate future work, all of the CSP records studied during this investigation have been placed with the Boston Harbor Study Group in the M.I.T. Department of Geology and Geophysics. Field notes, plotting charts and the 20:1 analysis drawings are similarly preserved.
Navigational Control

From a small boat with limited crew it is not possible to keep a continuous record of position. One possibility for making an accurate survey from a small boat involves shore-based observation: stations to take sights on the craft, but this operation involves a great deal of preparation and manpower. A second solution is to set up range markers on shore and use them to determine a straight course. However, it is difficult to maintain a constant speed along a long straight course, and each survey line requires new range markers. The third approach involves establishing secondary references on the water, determining their positions, and piloting with respect to them. This third method was adopted for the President Roads survey work.

Five-gallon plastic bottles, painted orange-red for visibility, served as buoys. They were anchored with limited scope by fifteen-pound iron weights. The buoy positions were determined by taking sextant angles between pairs of landmarks on shore from each buoy. Buoys were generally spaced about 1000 feet apart.

Continuous seismic profiles were made along all possible lines joining the buoys. A certain amount of skill is required to move in a straight line despite wind and currents. However, if a profile is not accurately made, it takes very little time to try a second time; the end points remain
The accuracy of positioning may be examined most easily by a graphical analysis. Figure 7 shows the President Roads area with circles of constant angular separation shown for three navigational landmarks, the smokestacks on Deer Island, Long Island, and Spectacle Island. The curves in each family are shown at $10^\circ$ intervals. Succeeding curves in a family are separated from each other by greater and greater distances as one moves away from the reference landmarks. The shapes of the areas enclosed by pairs of curves from each of two families vary from almost square to very flattened diamond shapes. For positions where the observer and all three objects lie on the circumference of the same circle, the two families of curves do not intersect at all, and position is indeterminate (the degenerate "rotator case"). Therefore, the landmark references to be used in a given area should be close to that area and should give nearly orthogonal intersections.

A chart similar to that shown in Figure 7 was constructed for several pairs of prominent landmarks to aid in choosing which of them to use. For the region of interest, the greatest distance separating $10^\circ$ curves is about 1500 feet for the typical case shown in Figure 7. Sextant angles were always measured to the nearest minute of arc, $1/600$ of $10^\circ$. Therefore, allowing for small errors in setting and reading the sextant, the buoy positions can be determined to an accuracy of about 10 feet. For a survey grid spacing of about
Figure 7
Sextant Angle Curves
1000 feet, this is a high order of accuracy, indeed; much higher in fact than is required or usable. It should be noted that our sextant could be read to the nearest 10 seconds of arc, so readings to the nearest minute were quickly and easily made. The index error was checked several times and found to be 20" and therefore negligible. To decrease the chances for error in recording readings, the sextants were always read twice, often independently by two people. Because survey work was done only during good weather and often at slack tide, I believe that the error between ship's position and the assumed straight-line, constant-speed path is less than 5% of the buoy separation.
REFERENCES


LaForge, Lawrence, (1932), Geology of the Boston Area, Massachusetts, U.S. Geological Survey Bulletin 893.


Figure 5
President Roads Fence Diagram

Key:
- water surface (MLW)
- bottom
- sub-bottom clay layers
- bedrock or till surface.

Scale:
- horizontal 400' /"'
- vertical 100' /"'

Spectacle Island
Figure 6

President Roads Serial Sections

Scale:

Horizontal 1" = 400'
Vertical 1" = 100'

Datum: Mean Low Water

Locations of sections are indicated on Figure 2 overlay.