PORT AND OCEAN ENGINEERING UNDER ARCTIC CONDITIONS
TECHNICAL UNIVERSITY OF NORWAY

THE APPLICATION OF ACOUSTIC SUBBOTTOM PROFILING TO ENGINEERING PROBLEMS

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Summary

Acoustic reflection profiling represents a means of examining the seafloor and the first 100 m of subbottom sediments for geological information about the nature and distribution of different deposits. Hard bedrock surfaces can be located and under most conditions sand can be differentiated from clay and silt. Highly organic deposits represent a limitation in that they tend to reflect nearly all acoustic energy.

A wide range of sound sources for acoustic profiling is available, such as sparkers, boomers, pingers and air guns. The selection of the proper system must take into consideration the penetration and resolution required. Since these requirements are largely contrary, a compromise must be sought, usually by choosing an optimum frequency range of the sound source.

Acoustic profiling can normally provide a better overall picture of the geotechnical conditions of the subbottom than is economically possible by any other single means of investigation. However, to obtain a complete engineering assessment of an area, the reflection profiles should be supplemented by drilling, coring and possibly seismic refraction work. Such investigations may, however, be reduced to a much smaller cost than that necessary without an acoustic survey.

As a case history the acoustic survey of Narvik Bay in 1970 is described, and the general results are presented with reference to the planned extension of the iron ore loading facilities and the general development of Narvik Harbor.

I. INTRODUCTION

The use of acoustic profiling devices for geophysical investigations of the seafloor can yield useful geologic data which can then be applied to the solution of engineering problems. A large number of these devices are currently available, and it is the task of the investigator to select the system which will provide the greatest amount of pertinent information in the particular area to be surveyed.

Acoustic profiling devices have been in use for a relatively short time. This is primarily a result of the widespread geophysical emphasis on deep penetration into thick sedimentary sequences in the search for oil. A few years ago it was discovered that by simply scaling down a deep seismic exploration system, valuable information could be obtained from the 100 meters (or so) immediately beneath the seafloor.

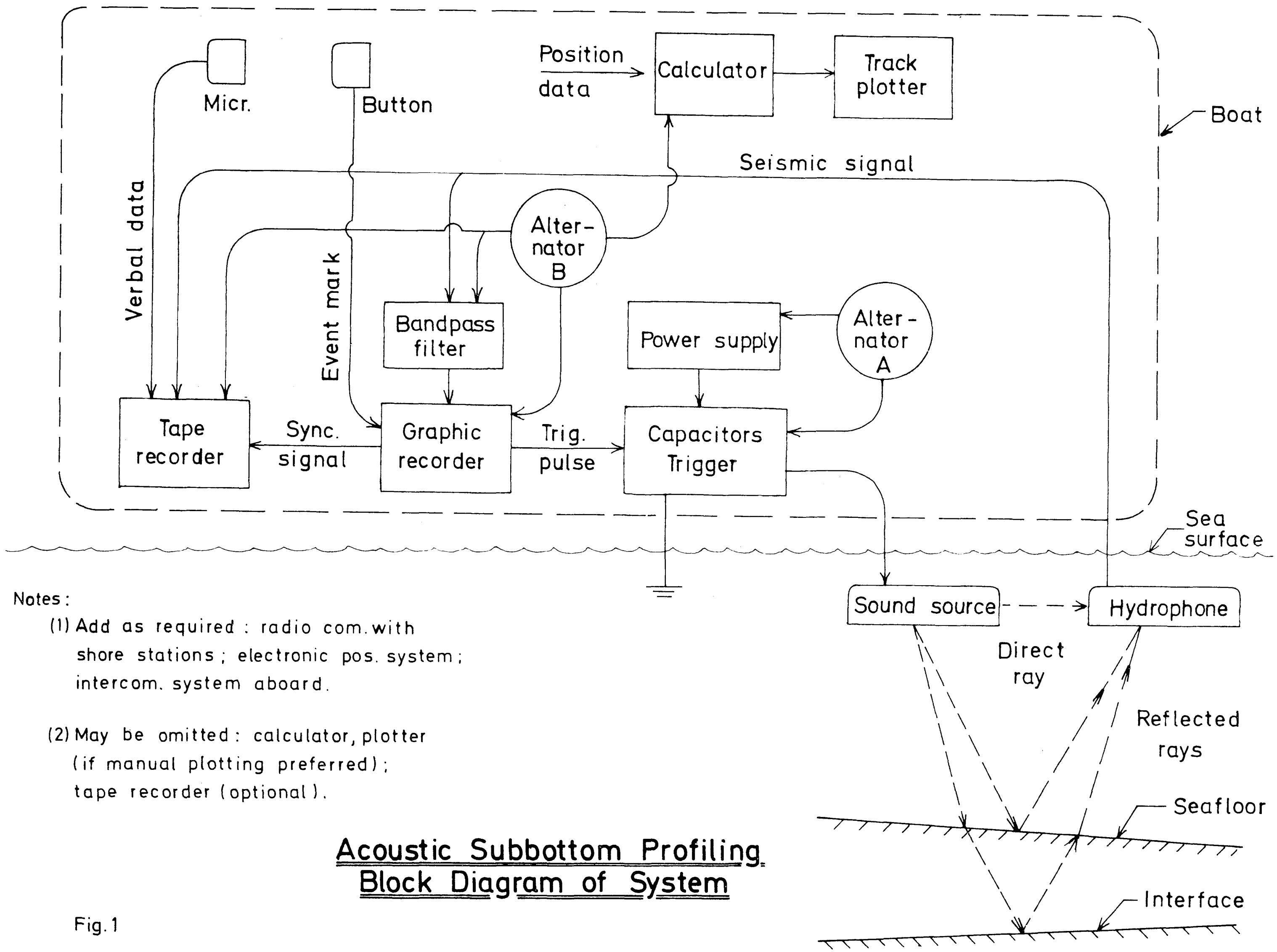
It is the purpose of this paper to discuss the applications of these smaller systems to engineering problems. The term acoustic profiling is used synonymously with continuous seismic reflection profiling (C.S.P.).

II. CHARACTERISTICS OF METHOD

A. Techniques

The general seismic system that is designed for this application consists basically of three parts (Fig. 1): a sound source, of which there are many varieties, a hydrophone pickup which receives the reflected signals, and a graphic recorder, where the data are printed in real-time in the form of a cross-section.

The acoustic energy source, or transducer, is usually towed along the surface of the water a few meters behind the boat and to one side, while the hydrophone array is towed at approximately the same distance behind the boat but on the opposite side. A typical system generally weighs two to three hundred kilos and can thus be mounted on a relatively small vessel (Fig. 10). A 10 to 20 meter fishing boat is usually adequate unless it is known that the sea state will require a larger and more stable vessel. The average speed at which a survey is done is approximately 5 knots, although in special cases it may be anywhere from 2 to 10 knots. Under favorable conditions, it is possible to survey about 30 nautical miles of line per day.



Notes:

(1) Add as required : radio com. with shore stations ; electronic pos. system ; intercom. system aboard.

(2) May be omitted : calculator, plotter (if manual plotting preferred); tape recorder (optional).

Acoustic Subbottom Profiling
Block Diagram of System

Fig. 1

Since any geological information obtained will be meaningless unless one has a precise knowledge of the location from which the data came, the position of the vessel must be kept track of at all times. It is normal operating procedure to take a fix on the vessel's position at 30-second or one minute intervals.

Positioning may be done optically, either by sextants reading horizontal angle on preestablished markers or by surveyors on shore reading intersects on the vessel, or electronically by tellurometers or precise radio navigation systems. The coordinates of the vessel may either be manually plotted or fed into a small shipboard computer coupled to an X-Y plotter. The latter method has the advantage in that the vessel's position is continuously plotted in real-time.

1. Frequency. - The frequency spectrum of the acoustic output signal is extremely important with respect to the kind and quality of data that is going to be received. Generally speaking, the lower the basic frequency, the greater the penetration of the acoustic energy, and, conversely, the higher the frequency, the less the penetration. If the signal frequency is high enough, approximately 40 kHz or higher, it will either be totally reflected by the bottom or by a passing school of fish. Accordingly, these higher frequencies are used in fathometers and fish-finders. At 12 kHz, fish can still be seen, the bottom clearly defined, and, if the bottom is composed of very soft sediments, up to 10 meters of penetration can be achieved. As the frequency becomes lower, the penetration increases, and, at the 60 to 120 Hz range, penetration may range up to thousands of meters, depending upon the power level of the system being used. For engineering geology applications, frequencies lower than 100 Hz or higher than 1500 Hz are rarely used.

2. Signal Character. - The most desired output signal is one with a very short definitive pulse. High frequency devices, by their inherent design, yield shorter, more discrete pulses than do the lower frequency devices. Unfortunately, existing low frequency transducers produce multiple pulses as a result of cavitation and thereby reduce the resolution capabilities of the system.

3. Signal Strength. - The desired signal strength, or power level of the system, is determined by the penetration desired. Although the high powered systems will generally penetrate deeper, they also are accompanied by undesirable side effects such as reverberation of water bottom multiples.

Field experience has shown that there is a point of diminishing returns with respect to power and that only by reaching an appropriate compromise between power and frequency can resolution be optimized. In engineering applications, no more power than is necessary to achieve the desired penetration should be used.

4. Pulse Rate. - The number of times that a system can be fired within a given period is referred to as its pulse rate. The faster the pulse rate, the better the resolution. The pulse rate, however, is dependent upon the power available for the system, and is thus controlled by the power input-output ratio. The higher the power the slower the pulse rate. Commonly used pulse rates are from 4 per second to 15 per minute.

5. Resolution. - The two most important objectives of any marine engineering survey are penetration and resolution. Unfortunately, the two are not compatible, and a compromise is generally required. The higher the frequency and the faster the pulse rate, the better the resolution. Conversely, if one lowers the frequency or decreases the pulse rate, there will be a resulting sacrifice in resolution. It is at this point that the geologist must decide whether he wants to go all out for penetration or sacrifice penetration in return for a clearer and, hence, more meaningful picture.

6. The Effect of Rock Properties. - As the acoustic methods depend on the ability of sound waves to penetrate strata and be reflected at the interfaces, one very important factor to the success of the program is the physical properties of the rocks themselves. Many types of sediments will cause the acoustic energy to both reflect and penetrate whereas some other types passes the energy completely, allowing little or no return, or may be acoustically opaque and absorbing the energy. In general, hard dense rock will be acoustically opaque, whereas soft, unconsolidated sediments (with high water content) will be acoustically transparent. The strength of the reflected signal will depend on the density and velocity ratios of the material on either side of the interface. Peat beds and other organic deposits will completely block acoustic energy, and usually little or no data can be obtained beneath such a bed. Layers of seashells are generally opaque, whereas clay deposits can be penetrated quite easily.

B. Kinds of Acoustic Transducers

1. Piezoelectric. - These transducers are commonly referred to as pingers and come in a great variety of shapes and sizes, power levels and frequency outputs. The same transducer is often used for both transmitting and receiving. Fish-finders and fathometers fall into this group, and, when the pinger is designed to give an output of 12 kHz or lower, it may achieve some degree of penetration in soft, fine-grained seafloor sediments. The pingers will give good bathymetric data, but, except for special cases, they are not recommended for sub-bottom data acquisition.

2. Electromechanical. - These transducers, commonly referred to as boomers, whammers and sometimes thumpers, are activated by a high voltage (3-4 kV) discharges into a coil of heavy gauge copper wire embedded in an epoxy case. One boomer type with vehicle is seen on Figs. 8-9.

The discharge of a large current into the coil sets up an eddy current (in a parallel aluminum plate) which explosively repels the plate. The mutual displacement, which is restrained by either a rubber diaphragm or springs, sets up a pressure wave in the water. This wave represents acoustic energy and travels through the water and into the bottom, from which part of the energy is then reflected back to the hydrophone. The frequency output of these devices is around 800 to 1200 Hz. Experience proves this to be a good level for shallow depth, high-resolution geologic investigations.

3. Gas Bubble Type. - This group of devices is characterized by a discharge of high voltage electricity directly into the water (sparker system) or a discharge of compressed air (air gun systems). The discharge causes a gas bubble to form, which expands very quickly and then collapses. The initial expansion and contraction of this bubble may take place within a few milliseconds. Depending upon the transducer design, expansion and contraction may then occur several times for each bubble and thus reduce the system's effective resolution. These cavitation pulses are an inherent problem in the high power sparker devices and become considerably less troublesome as the power level of the system is lowered. Generally, the frequency output of the sparker system ranges between 80 and 400 Hz. This frequency range makes the sparker a good tool for geologic investigations requiring deeper penetration than the boomer system can provide, or where the water depth exceeds 200 meters. The resolution of the sparker is slightly lower than that of the electromechanical or boomer type systems. Air gun systems are used mainly for very deep penetration.

4. Kind of Data Obtained. - The foregoing family of acoustic profiling devices will produce, with varying degrees, the same types of geologic data. Within the range of detection, buried or exposed bedrock surfaces can be mapped in considerable detail. The thickness and extent of unconsolidated sediments can usually be determined and, in many cases, intraformational interfaces such as unconformities and bedding planes can be seen.
It is also possible to acquire a general knowledge of the sediment types in the area being surveyed. Mud and clay can usually be distinguished from sand and hard rocks and a bedrock surface or a surface of hard, loose rocks, can nearly always be defined. Examples will be given in a subsequent section.

D. Applications

The geological data acquired by this type of survey have many applications. For example, these surveys are often run prior to dredging operations for deepening shipping channels or turning basins. It is very important for the dredger to know whether any hard rock lies at shallow depths below the bottom and also the lithology of the bottom sediments.

Acoustic profiles make it possible to map buried bedrock surfaces, moraines, or unconsolidated sediments for intelligent planning of foundations for docks, piers, loading facilities, drilling platforms, or artificial islands. Acoustic investigations do not replace coring, but enable the correlation of core information to be made with a far greater degree of assurance. In addition, if such a survey is made, it is then possible to place boreholes in locations where they will yield the maximum amount of engineering information. The extrapolation of information (lacking acoustic profiles) from borehole samples and cores can be hazardous. An acoustic survey is also useful in determining the geologic characteristics of the bottom and immediate subbottom prior to the installation of pipelines and telephone cables. It is often possible to determine routes which will enable the proposed installation to take advantage of soft sediments or to avoid draping the pipeline or cables over sharp bedrock outcrops on the seafloor.

This type of geologic investigation has also been used in many parts of the world to determine the most likely location of placer deposits of heavy mineral sands, tin, and diamonds. It is possible to map buried valleys in the bedrock topography and subsequently pinpoint locations for dredging operations which would potentially yield maximum concentrations of ore.

Acoustic Subbottom Profiling

Applications in Engineering Projects

ACOUSTIC SUBBOTTOM PROFILING IS USEFUL IN SITE INVESTIGATIONS FOR :

a) NAVIGATION PROJECTS
Deepening of shipping channels, turning basins
Location of wrecks or other obstacles

b) CONSTRUCTION PROJECTS
Docks, piers, dolphins
Seawalls, bulkheads
Causeways
Bridges
Lighthouses
Artifical islands

c) TRANSPORTATION AND COMMUNICATION PROJECTS
Underwater tunnels
Underwater pipelines
Transmarine cables

d) MINERAL EXPLOITATION PROJECTS
Installation of drilling platforms
Placer mining of seafloor deposits
Underwater mining in bedrock

Fig. 2

III. CASE HISTORY: ACOUSTIC SURVEY OF NARVIK BAY

A. Scope

The port of Narvik (at 68°26' N) is, in terms of annual tonnage handled, the busiest port in Norway. It is ice-free around the year and hence the more important of the two ports exporting Swedish iron ore from the LKAB mines, the other port being Luleå in the Baltic Sea. Narvik Bay (Fig. 7) is also well known as a theatre of sea battles during World War II.

In connection with their plans for extending the ore-loading facilities at Narvik the LKAB company asked for a comprehensive site investigation of the area of Narvik Bay considered for the new ore-loading wharf, which is being planned to receive bulk carriers of up to 350 000 d.w. tons.

Based on our proposal to LKAB and the Narvik Harbor Board a complete acoustic survey of the 5 km^2 large Narvik Bay was undertaken. This included roughly 120 km of subbottom profiling and some 20 km of sonar side-scanning.
In addition, borings and seismic refraction profiling were made in areas of particular interest.

The purpose of the acoustic investigation was firstly to map the thickness and extent of sediments overlying the bedrock in the Narvik Bay and secondly to check the number, positions and sizes of the wartime shipwrecks still present in the bay. This information was considered essential for an intelligent planning of the new wharf foundations, the turning and anchoring areas for ore carriers, and the further general development of Narvik Harbor. The following description concentrates on the method and results of the acoustic subbottom profiling.

B. Method of Survey

1. Boat. - A 45-ft fishing boat (shrimp trawler) was selected for the survey. Acoustically this was a good choice because of the low rotational speed of the boat's one-cylinder semi-diesel engine and cavitation-free propeller at full pitch. The boat had a magnetic compass and an echo-sounder.

2. Acoustic System. - A boomer system as shown in Fig. 1 was used, but without tape recording. The energy rating used was 200 joulesper pulse, and the pulse interval was 0.25 seconds. The boomer float was towed on the starboard side and the hydrophone eel on the port side, either one trailing from a light boom on the aft deck and about 20 m behind the boat.


TEGNFORKLARING
Stasjon for posisjonsbestemmelse
Akustisk profil (boomer) med stasjonsnr. og dybde til fjell (eller hard morene)
Profil se tegn. 8661 - 310 til 316
Alle dybder refererer seg til hydrografisk basis (spring lavvann 1,79m under middelvann)
Kartgrunnlag: Norges Sjökartverk „Narvik Havn", sjökart nr. 461, Stavanger 1960
Narvik Havn
Akustisk profilering. Plan
NORSK TEKNISK BYGGEKONTROLL A/S
JAN FRIIS
Originalkart tegnet i M=1:2500
8661-301 Z
NARVIKBUKTA
ANKENES
Fager-neset
Fagernes

Fig. 3

The graphic recorder (Fig. 11) was placed in the boat's forepeak cabin and the diesel alternator in the hold.

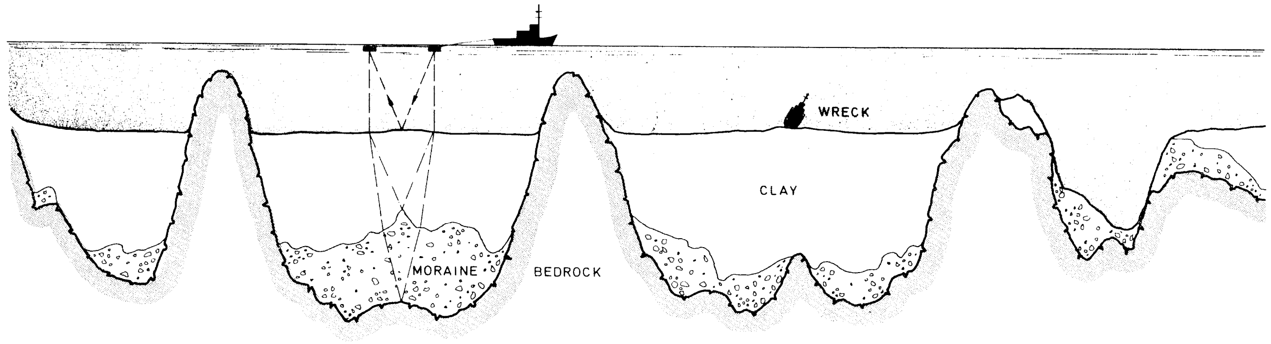
3. Track Plotting System. - A small table was fitted in the pilot house (Fig. 12) for a desk-top computer with a matching XY plotter. We adapted the method of position fixing by intersection of the lines of sight from two shore stations to the boat. On command every 30 seconds (or 1 minute) from one of the shore station surveyors the angles (β and γ) were observed simultaneously on the two theodolites and transmitted by walkie-talkie to the boat. The instants of observation were marked on the acoustic record by a push-button event marker and numbered consecutively. The radio operator on board entered the angles on the desk-top computer, which computed the position coordinates for each fix and made the plotter draw the boat's track on a map. The track plot thus produced continuously during the survey served as (a) an aid to navigation, (b) an instant record of the coverage and (c) a guide to final plotting to a larger scale in the office. For the latter plotting the same computer-plotter was used with similar programs but including a correction for the distance between the boat's mast and the reflection centre point.

The general track plot is shown by Fig. 3, which also shows most of the 9 shore stations used.

C. Interpretation of Acoustic Records

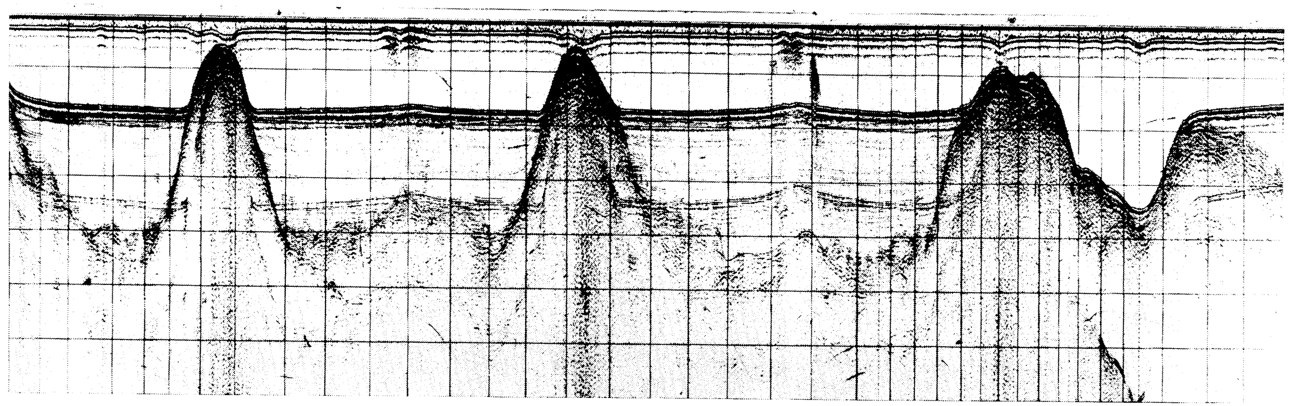
Examples of the echograms produced in the Narvik survey are shown by the lower parts of Figs. 4-5. Although the original records are basically graphs of travel times of sound waves (in milliseconds) versus clock time, they can also be visualized as geological profiles, as illustrated in the upper parts of the figures. These profiles were actually not drawn separately but only traced in color on the record.

This is the first step of the interpretation, which may be easy or difficult depending on the geological composition of the area and the quality of the records. It requires at least a fair geological understanding as well as a good conception of the reflection of sound waves in three dimensions. The extent of the interpretation will depend upon such factors as (a) whether appreciable penetration of the sound waves has been achieved below the seafloor, (b) whether reflecting interfaces are present and representing strata of interest, and (c) how much interpretative work is justified by the problem at hand.



PRIMARY INTERPRETATION OF PROFILE

Reduction of depths (based on sonic speeds and geometry) remains.



PROFILE AS PRODUCED BY RECORDER

Fig. 4

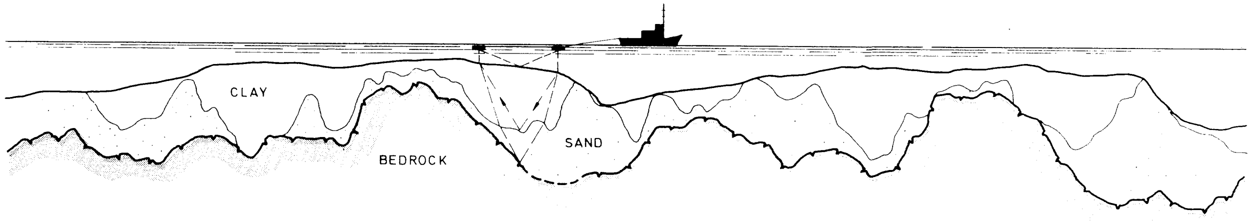
NOTES:

1) The section of record shown has been reduced to approx. 1/6 of its original size which corresponds to approx 4000 m of profiling length.

2) Vertical marker lines represent instants of time at which the boat's position has been determined

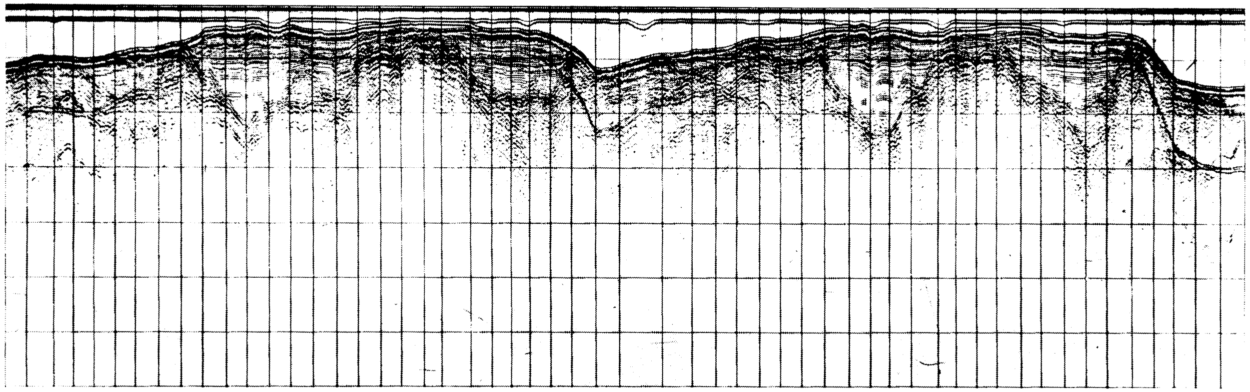
3) Horizontal lines (at 25 millisecond intervals) represent the scale of travel times of acoustic waves.

ACOUSTIC PROFILING Narvik Harbour Boomer Survey, Example 1.	Approx. scales Hor. 1:15 000 Vert. 1:2 000	Date July '71
NORSK TEKNISK BYGGEKONTROLL A/S JAN FRIIS Thv. Meyersgt. 9, Oslo 5	8660-18	



PRIMARY INTERPRETATION OF PROFILE

Reduction of depths (based on sonic speeds and geometry) remains.



PROFILE AS PRODUCED BY RECORDER

Fig. 5

NOTES:

1) The section of record shown has been reduced to approx. 1/6 of its original size which corresponds to approx 4000 m of profiling length.

2) Vertical marker lines represent instants of time at which the boat's position has been determined

3) Horizontal lines (at 25 millisecond intervals) represent the scale of travel times of acoustic waves.

ACOUSTIC PROFILING Narvik Harbour Boomer Survey, Example 2.	Approx. scales Hor. 1:15 000 Vert. 1:2 000	Date July '71
NORSK TEKNISK BYGGEKONTROLL A/S JAN FRIIS Thv. Meyersgt. 9, Oslo 5	8660-19	

1. Primary Interpretation. - Most of the records from Narvik Bay was relatively easily because of acoustically friendly sediments (i.e. little or no organic material) and the existence of sufficient correlation data from borings and seismic refraction profiles. The primary objective was to determine the boundary between the soft or loose sediments, consisting of clay, silt and sand, and the bedrock, being mica schist and gneiss. Where a stratum of ground moraine exists between the soft sediments and the bedrock, such as in Fig. 4, the upper boundary of the moraine was considered, from the dredging and foundation point of view, to be the more important boundary. Fortunately, this boundary was usually more easily determined than the boundary between the moraine and the bedrock, from which reflections were sometimes not well defined.

The prominent peaks in Fig. 4 resulted from the survey boat approaching shore, turning and going out again.

Shipwrecks and several other distinct objects on the seafloor were clearly located and were later studied in more detail by side-scanning sonar to obtain their true dimensions.

2. Data Reduction. - The next step of the interpretation was to assess the sonic speeds of the sediments involved. Based on correlation with borings and refraction work a speed of 1.65 km/s was assumed for clay, silt and sand, and 1.8 km/s for ground moraine. Sea water has a speed of 1.49 km/s at this temperature and salinity. Using these data together with the travel times from the echogram interpretation and the distance between the boomer and the hydrophone, the depths to the relevant interfaces were program-computed and reduced to the hydrographic datum by means of the local tidal record.

3. Final Presentation. - In this way true-scale profiles could be drawn, of which however only a few but representative ones were actually produced (location A-A through K-K in Fig. 6). The bulk of the depth data was compiled into a contour map of the "hard bottom" (Fig. 6), i.e. the upper moraine boundary or, where no moraine is present, the bedrock surface. This 5-meter interval contour map (with heavily shaded areas representing wrecks or dredged bottom) forms, together with the representative profiles the main result of the investigation. This is a good basis for planning the future harbor development, even if borings may be required for specific foundation purposes. A number of objects on the seafloor are shown by circles for later identification by diver.

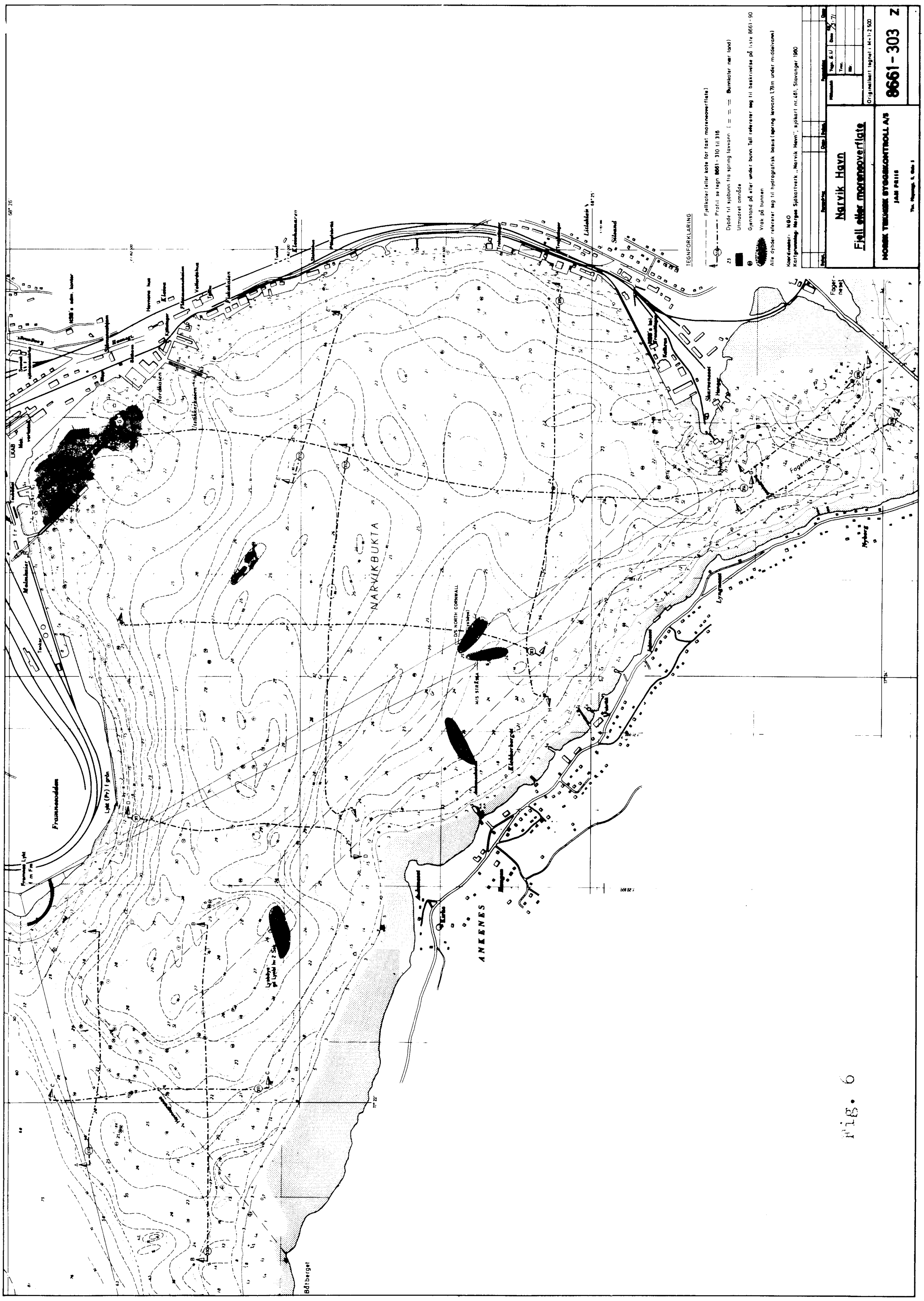

Narvik Havn
Fjell eller morenoverflate
8661-303 Z
TEGNFORKLARING
NARVIKBUKTA
ANKENES
Framnesodden

Fig. 6

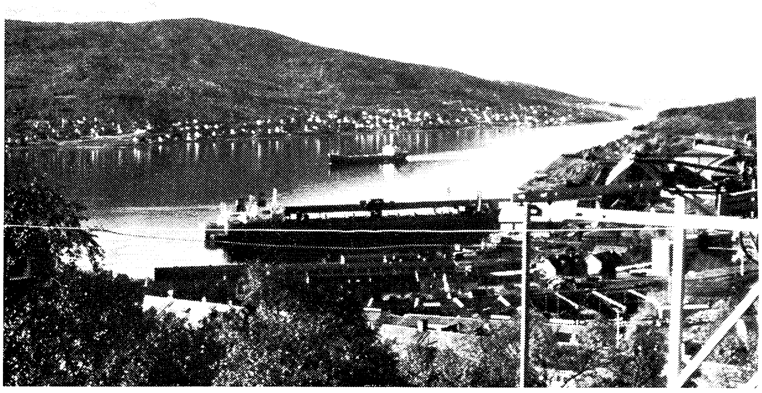


Fig. 7

View of part of
Narvik Bay

Fig. 8

Launching of
boomer

Fig. 9

Towing of boomer

Fig. 10

Inspection boat
adapted for
acoustic survey

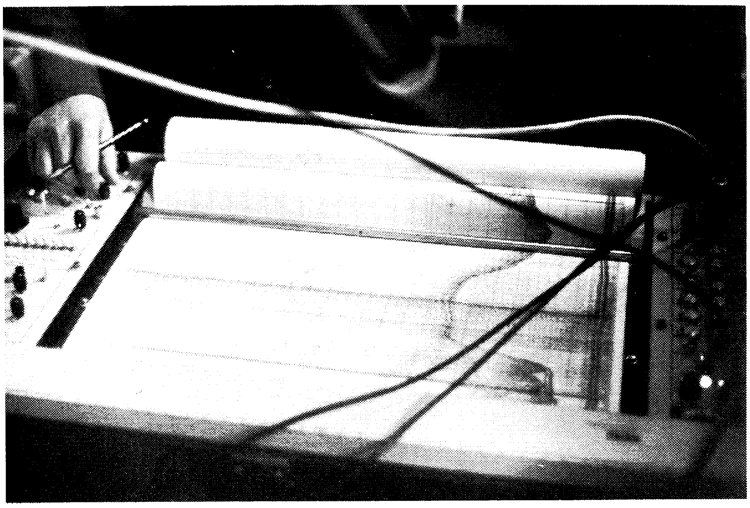


Fig. 11

Graphic recorder
in use

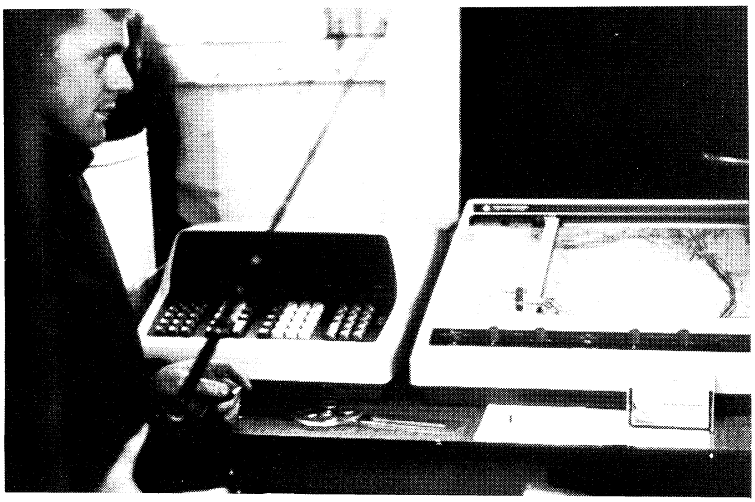


Fig. 12

Radio reception of
position data to be
fed into computer-
plotter

D. Generalized Results of Survey

The overall geological picture of Narvik Bay is one of a saucerlike basin enclosed by an undersea rock and moraine threshold and almost filled by sediments of glacial and postglacial origin. It was not anticipated that the threshold was so pronounced and not easily dredgeable, nor that the sediments were so thick as 75 meters in the central part of the bay.

Most of the sediments are postglacial clay and silt, shown by borings to be partially quick (extra-sensitive). However, in the southern part of the bay, which is more influenced by tidal currents in and out of Beisfjord (outside map to the southeast), there are large sand deposits as illustrated by Fig. 5. A good correlation with borings was obtained in the relatively few points where these exist.

Below the sediments ground moraine partly covers the bedrock, forming ridges which appear to be drumlins. The moraine thickness varies extremely in the bay but tends to be greatest at the exit towards sea. The moraine is considered to require blasting before dredging but should represent a good stratum for foundations where this is of interest.

In concluding it can be said that the acoustic survey has given a geological picture of Narvik Bay which could not have been obtained at a comparable cost by any other known method.