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MEMORANDUM

Instrumentation for crosshole geoacoustic measurements in unconsolidated sediments

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Instrumentation for crosshole geoacoustic measurements in unconsolidated sediments

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Executive Summary: In the shallow waters important to NATO ASW and MCM operations, the sea-floor presents the dominant mechanism for sonar performance. There is considerable involvement of the propagating sonar signal with the bottom, especially under downward-refracting conditions. For high frequency sonars (i.e. mid-audio to ultrasonic band), simple bottom-bounce losses are operative, and the bottom roughness as well as sediment type are important. For lower frequency sonars (i.e. infrasonic to low audio band), both passive and active, there is considerable penetration of the propagating sonar signal into the bottom, and both shear and compressional waves, including interface waves may be excited.

Recently SACLANTCEN has made a commitment to develop several testbed sites where the geoacoustic parameters of the sea-floor could be directly measured and various remote-sensing techniques could be comparatively evaluated, using directly measured 'ground truth data' on the sediment properties. In order to develop the testbed sites, it is necessary to measure the geoacoustic parameters as a function of depth in the sediment. The most important of these parameters are the compressional and shear wave velocities. The attenuation of these wave types is also important.

These requirements obviously necessitate the application of a number of specialized instruments capable of functioning within the sedimentary volume. Previous work at SACLANTCEN has involved acoustic measurements on cores. However, the problem of altering the sediment parameters in the core taking, removal, and storage process is significant. As a result, recent emphasis has been given to *in situ* measurements.

This report presents the tools that enable direct measurements of sediment properties as a function of depth in unconsolidated sediments. The first tool is a hole-making device that sits on the sea floor and utilizes pneumatic and hydraulic forces to remove the sediment from the interior of an encased cylindrical volume, 20 cm in diameter and 6 m deep. This hole can be used to permanently deploy instruments such as seismometers, or it can be lined with a plastic tube as a casing, for subsequent access and the temporary deployment of geoacoustic logging instruments. Two such instruments are described. One is used to measure sound velocity and attenuation for compressional waves while the other measures these parameters for shear waves. The design, development and initial tests of these devices are presented.

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Instrumentation for crosshole geoacoustic measurements in unconsolidated sediments

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Abstract: Research tools are described that enable direct measurements of sediment properties as a function of depth in unconsolidated sediments. The first tool is a hole making device that sits on the sea floor and utilizes pneumatic and hydraulic forces to remove the sediment from the interior of a cylindrical tube, 25 cm in diameter and 6 m deep. This hole can be used to permanently deploy instruments such as seismometers, or it can be lined with a plastic tube as a casing, for subsequent access and the temporary deployment of geoacoustic logging instruments. Two such instruments are described. One is used to measure sound velocity and attenuation for compressional waves while the other measures these parameters for shear waves. The design, development and initial tests of these devices is presented.

Keywords: compressional waves ○ geoacoustic logging ○ sediment properties ○ shear waves ○ sound attenuation ○ sound velocity

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Introduction

In the shallow waters important to NATO naval operations, the sea floor presents the dominant mechanism for sonar propagation loss. There is considerable involvement of the propagating sonar signal with the bottom, especially at long ranges under downward-refracting conditions.

For high-frequency sonars (i.e. mid-audio to ultrasonic band), simple bottom-bounce losses occur and the seafloor parameters of bottom roughness as well as sediment type are important. For lower frequency sonars (i.e. infrasonic to low audio band), both passive and active, there is considerable penetration of the propagating sonar signal into the bottom, and both shear and compressional waves, including interface waves may be excited.

Presently, SACLANTCEN and many individual NATO nations conduct measurements for characterizing bottom loss which are used in turn for sonar performance predictions. Although this is now the most reliable method to describe propagation loss, it has certain limitations. These include a dependence on the prevailing oceanographic conditions at the time of the survey as well as a dependence on the acoustic parameters of the survey instruments. Both necessitate repeat surveys at different times of the year or when different sonar frequencies are used.

Progress in computer modelling of ocean sound propagation now allows new types of survey measurements that eliminate these limitations. By remote sensing the geoacoustic parameters of the bottom, rather than the actual propagation loss for a given sonar signal, it should be possible to compute propagation loss for a wide variety of signal types and frequencies as well as oceanographic conditions.

A number of remote sensing techniques have been researched, but a comprehensive validation is lacking. For this reason, SACLANTCEN in 1988 made a commitment to develop several testbed sites where the geoacoustic parameters of the sea floor could be directly measured and various remote sensing techniques could be comparatively evaluated, against directly measured 'ground truth data' on the sediment properties.

To develop the testbed sites, it is necessary to measure the geoacoustic parameters as a function of depth in the sediment. The most important of these parameters are the compressional and shear-wave velocities along with their attenuations

Ideally, these parameters need to be measured to a depth of a few wavelengths, although this becomes increasingly difficult as the frequency is lowered. Direct measurements as a function of lateral position are also desired to characterize lateral variability.

These requirements obviously necessitate the application of a number of specialized instruments capable of functioning within the sedimentary volume. Previous work at SACLANTCEN has involved acoustic measurements on cores [1]. However, alteration of the sediment parameters due to core taking, removal, and storage process is significant. As a result, recent emphasis has shifted to *in situ* measurements.

The first phase of direct, *in situ* measurements on sediment parameters at SACLANTCEN involved compressional and shear-wave instruments that were inserted into the near-surface sediments at depths measured in tens of centimeters [2].

The next phase, which started later, but ran simultaneously, involved crosshole measurements of sediment geoacoustic parameters at depths measured in meters into the sediment, and is discussed here.

2

Crosshole instruments for meter depth logging

Some of the testbed sites developed by SACLANTCEN are in very shallow water, where SCUBA divers can be used. Notable here are the testbed sites in the Ligurian Sea near Tellaro, at the approaches to the bay of La Spezia. The water depths are about 18 m, and the bottom is composed of a rigid mud, interlaced with sand lenses. In these waters, experimentation can be done with the Centre's 20 m workboat, R/V *Manning*. The sand bottom test sites off the isle of Elba are comparable.

In order to deal with these sites in a timely fashion, and to gain experience with crosshole, *in situ* logging, a diver-operated suite of tools was developed. These instruments would be easier to develop, handle, and modify than would the more sophisticated, remotely operated tools needed for deeper water measurements.

Further it was decided that the approach would be modeled on oil field methods, in that several 'wells' would be permantly 'drilled' in the sediments so that they could be accessed as needed for crosshole measurements. Because the sediments are unconsolidated, it would be necessary to insert 'liners' in the holes, sealed at top and bottom, to prevent their caving in.

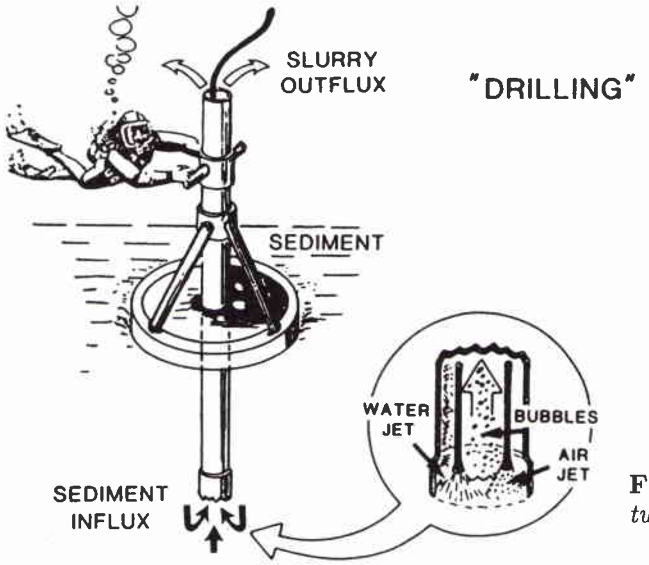


Figure 1 *Hole making apparatus.*

2.1. HOLE-MAKING TOOL

Several techniques are available for minimizing the disturbance of sediment while making holes. The technique chosen at SACLANTCEN involved gradually removing the sediment from the inside of a heavy jetting tube, loosely held in a vertical position by a bushing on a tripod support. As sediment is removed from the inside of this tube, it falls by its own weight into the bottom. A sketch of the apparatus operating in the drilling mode is shown in Fig. 1. This device was designed to make holes 6 m deep with a diameter of 25 cm.

Sediment removal is accomplished by use of compressed air and pressurized water, either one or the other, but preferably both together. The nozzles for both jets are oriented upwards and located within the drill tube at a distance of one half diameter above the lower lip. In this way, only the sediment inside the tube is exposed to the hydrodynamic turbulence, leaving the bottom sediment outside the tube relatively undisturbed.

Compressed air jetting creates turbulence, which breaks up the sediment formation, as well as abundant air bubbles, which provide lift and raises the resulting slurry upward, out of the tube. A compressor producing 8 to 12 bars of air pressure was used. It was found that holes could be made in mud/clay sediments with the use of air alone, although the drilling rate was slow (typically a meter or so per hour). The process slowed down even further when sand lenses were encountered in the sediment formations. When air alone is used, sea water must flow down the drill tube as a supply, as well as up, with the slurry of sediment, air and water.

The addition of even a small amount of low pressure water dramatically increased the drilling rate, possibly due to increasing the efficiency of the water supply to move the slurry up the tube. With the present device, the fire pump on R/V *Manning* was used, which at 18 m depth, delivers 7.2 mc at 2–3 kg/mq. In this combination air/water configuration, 6 m holes were drilled in mud as little as 20 min.

It should be remarked that other laboratories have employed ocean bottom drilling systems that use water jets exclusively, but at much higher pressures and flow rates. The experience at FWG in Germany [3], for example, indicates that water jets can implant anchors to meter depths in times measured in seconds. However, problems can arise with this technique in the control of the direction of tool insertion as well as with restarting the jetting operation, if it is ever stopped, due to an excess suction effect. The use of compressed air jetting with a fixed clearance between the jet and the progressing cavity seems to provide a slower and more controllable operation, that prevents excess suction effects.

Once the hole is jetted to its maximum desired depth, it is necessary to insert a protective liner, prior to removing the heavy jetting tube, to prevent the hole from caving in. For logging work in the mud/clay bottom of the Ligurian Sea, plastic tubes of PVC, measuring 250 mm in diameter and 1 mm in wall thickness were used. These were permanently sealed at the bottom, weighted with metal ballast inside the bottom end, and lowered inside the drill tube to the bottom of the hole. Deployment operations are sketched in Fig. 2. It is also possible to use the hole for some other purpose, such as the deployment of a sub-bottom seismograph, as is shown.

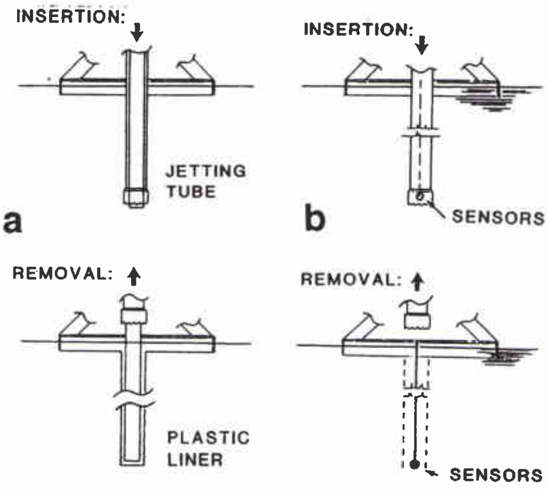


Figure 2 *Deployment operations: liner installation (a); sensor installation (b).*

It was found necessary to plug the hole with the liner as soon as practicable because unconsolidated muds and sands, although seemingly rigid, are actually plastic and will flow up into the hole, given sufficient time. If the drill tube in a mud hole is left unplugged overnight, for example, it may be half full of mud the next morning.

Further, although the liner may be filled with sea water, it is important to cover it at the top with a simple, removable cap. This prevents the easy access of sea life, and nutrients necessary for their survival, into the tube. Shell fish colonies growing on the interior wall can be troublesome when it is desired to mechanically couple instruments to the tube wall. Other species, such as squid, may attach eggs to deployed instruments, and the young hatchlings, of cm sizes, can demonstrate a throbbing movement that introduces noise to geophone measurements. Finally, ordinary swimming fish, either through curiosity or the desire to lay eggs, may enter an unplugged hole at any time, even during the emplacement of sensors. Their entrapment is detrimental to acoustical measurements, and the experiment must be dismantled to permit their release.

The layout of logging holes at a given site is a matter of design and depends on the parameters to be measured, the instruments to be used, etc. For example, for lateral hole to hole measurements of sound velocity and attenuation, it was found convenient to make at least four holes, as shown in Fig. 3. The reference hole, at one end of the field, was intended for the projector, P, while the remaining three holes housed hydrophones, H_n. It was found that using bushings to support the drill tube

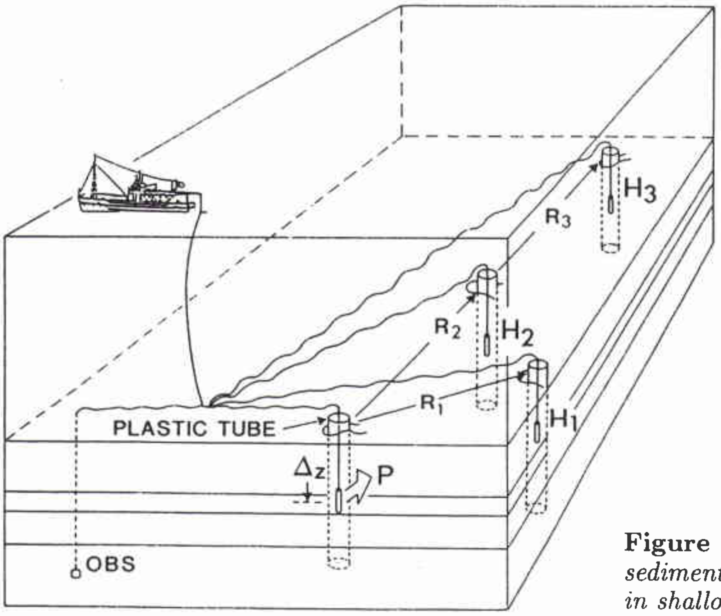


Figure 3 *Measurement of P wave sediment parameters at meter depths in shallow water.*

at the top and bottom of the bottom support tripod enabled the making of holes within a degree or two of the vertical. The first two receiver holes were quite close to the projector hole, at 1.7 m and 2.8 m, while the third was 11.2 m away. This enabled a fair sampling of the sediment structure. Of course, the sampling can never be perfect, since the layering and the integration of the acoustic field are dependent on the geometry.

2.2. COMPRESSIONAL (P WAVE) INSTRUMENTS

The first choice made in designing a sediment acoustic measurement is the frequency band of interest. Here, there are practical as well as physical, engineering, and geological considerations. As a matter of practical interest, one might want to use the band that contains the most important sonar applications. This may not be possible; for example, if the frequency is so low as to render the hole separations small compared to a wavelength, making the required signal resolution physically impossible. The geological effects pertain mostly to the existence of bubbles in the sediments [4] which may cause dispersion and an anomalous attenuation. This is a complicated issue because the frequency band affected depends on the bubble size distribution, which in turn depends on the geochemistry at the site. Most gassy sediments probably become anomalous at frequencies between 10 and 100 kHz, although this may be an oversimplification.

For the application at hand, it was decided to work at the low end of the bubble affected frequency band, so as to span it, having the lowest frequencies probably unaffected, the highest frequencies vulnerable. In this way, the measurement system would be sensitive and indicative if gassy sediments are encountered. As a result,

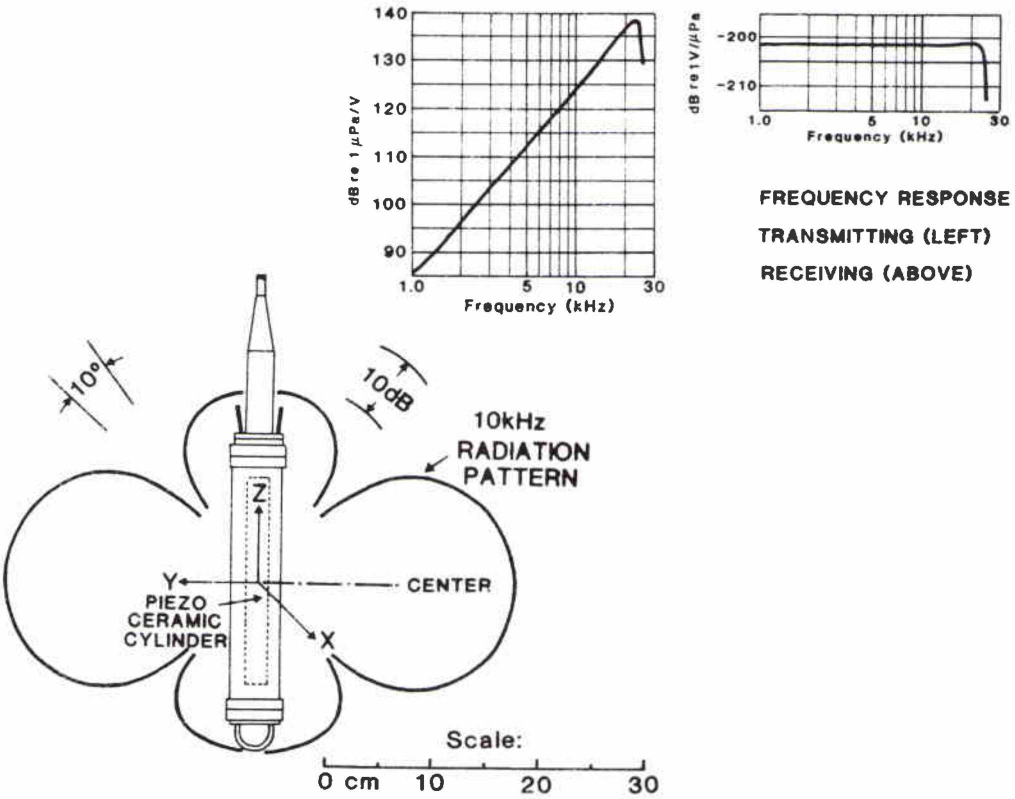


Figure 4 *USRD/NRL Type 36 transducer.*

the 1–20 kHz band was chosen.

It was further decided to use U.S. Navy standard transducers, attractive for their uniformity, their calibration and their availability. In this band, and for this application, the USRD Type F36 transducer was the logical choice for the P wave measurements. This transducer is depicted in Fig. 4. It consists of a cylindrical stack of piezo ceramic cylinders, encapsulated in an oil filled rubber boot, attached to a neoprene covered electrical cable that provides its own suspension. The radiation pattern shows a maximum at broadside, with minor lobes at end fire angles. The projecting sensitivity increases linearly with frequency, up to a resonance near 25 kHz, while the receiving sensitivity is flat over the useful band. These transducers were simply suspended in the holes at equal depths for P wave data acquisition.

The block diagram of the electronics system for driving the transducer and acquiring data is shown in Fig. 5. Emphasis at SACLANTCEN has been placed on multichannel data acquisition systems, so that is what appears here. However, any variable frequency pulse echo system can be used, and these are usually assembled from laboratory equipment.

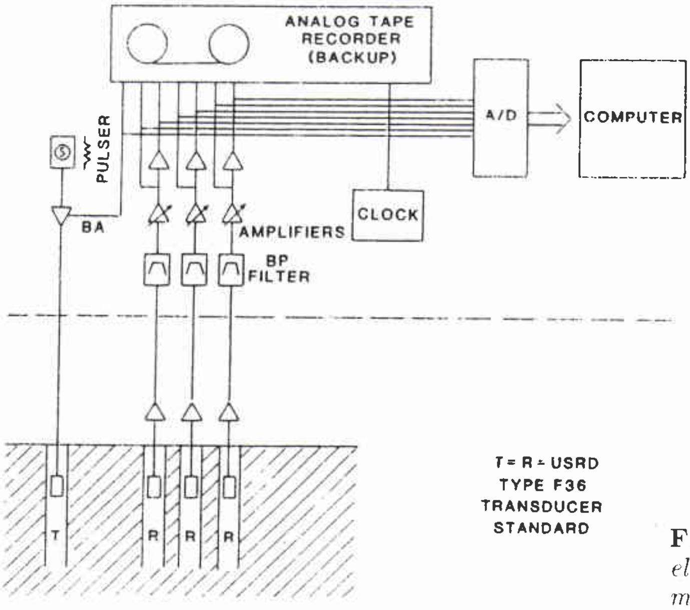


Figure 5 *Block diagram of electronics. P wave measurements.*

2.3. P WAVE DATA

Some examples of time domain data are shown in Fig. 6. Here, a cw pulse at a given centre frequency is transmitted at $t = 0$ and propagates to hydrophones H_1, H_2, and H_3, all located at the same depth, at successively larger distances. Information on the velocities is contained in the arrival time of the propagated signals while the attenuation information is contained in the signal amplitudes, extracted from ratios, taking spherical spreading into account. Repeating the measurement at different centre frequencies builds up a data series from which dispersion curves (velocity vs frequency) can be obtained.

Examples of reduced P wave data are shown in Fig. 7. The top part of the figure shows the velocity and attenuation vs depth in the sediment at a frequency of 6 kHz. There is evidence of alternate layers of soft and hard sediments in the data. The dispersion curve at a depth of 3 m is shown at the bottom. There is a decrease in velocity with increase in frequency, providing evidence of the presence of gas bubbles in the sediment. Extensive sub-bottom profiling with a UNIBOOM system confirms this interpretation as it shows high volume scattering from within the sedimentary volume.

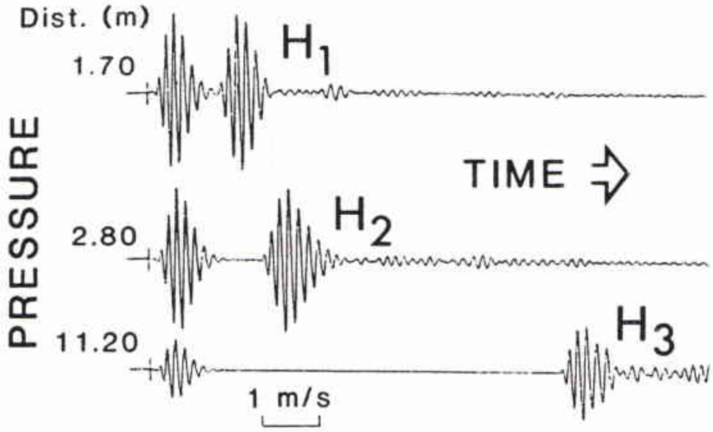


Figure 6 *Raw data, crosshole P wave measurements.*

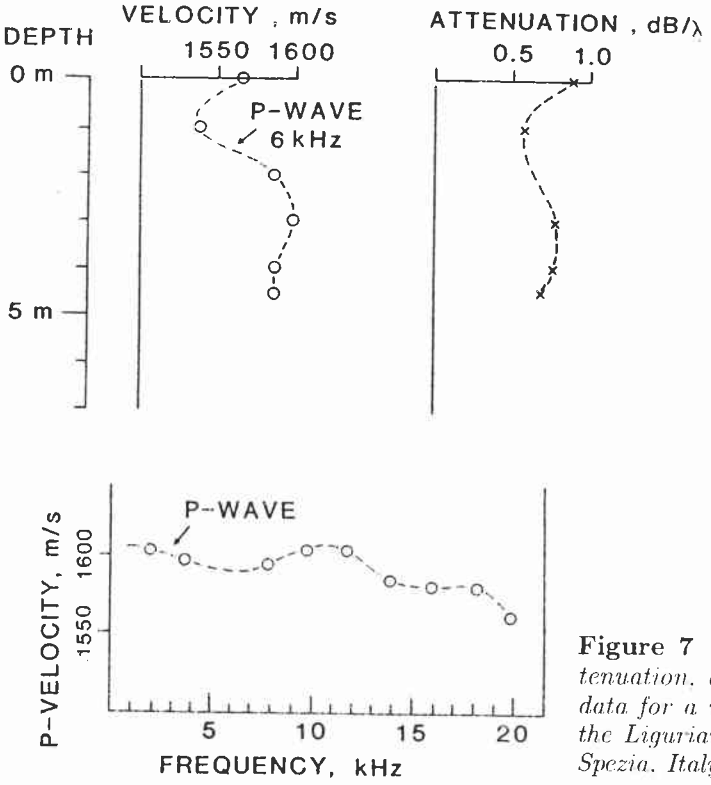


Figure 7 *Velocity, attenuation, and dispersion data for a mud bottom of the Ligurian Sea near La Spezia, Italy.*

2.4. SHEAR (S WAVE) INSTRUMENTS

The fundamental source element for creating shear waves in an elastic medium is a point force, moving along a linear path. The response of the medium is then a shear wave propagating in a dipole field perpendicular to the path of the line force. To generate a shear wave in a cylindrically symmetric tube, an asymmetric excitation must be achieved. (A symmetric excitation generates opposing dipoles that cancel.)

Once created, the shear waves propagate as either bulk waves or interface waves along the sedimentary strata. Tubes immersed in such a medium are set in motion

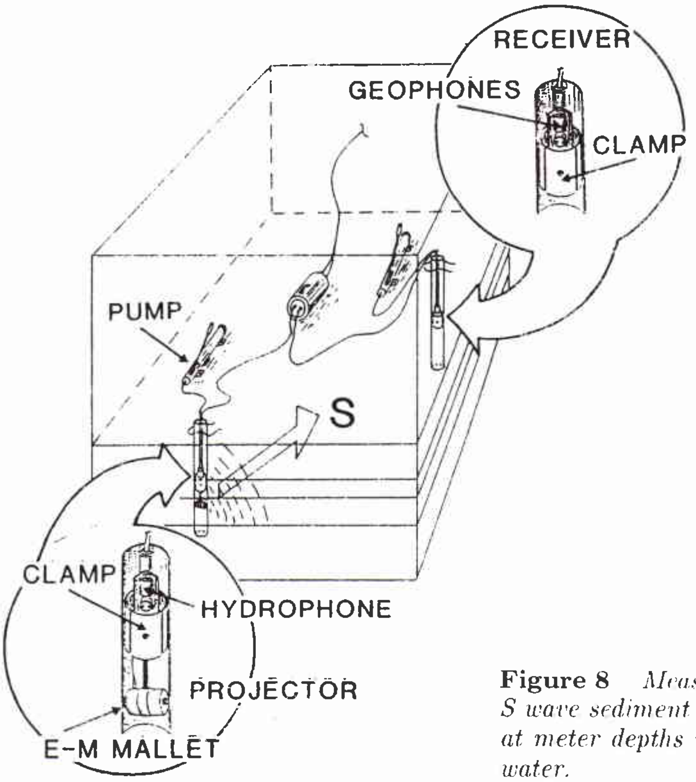


Figure 8 *Measurement of S wave sediment parameters at meter depths in shallow water.*

as the shear wave passes by. Geophones in good contact with the inside tube wall will sense this motion.

A general sketch of the downhole measurement system developed at SACLANTCEN is shown in Fig. 8. The instruments are attached to metal rods and are inserted in the tubes by divers. When the desired depth and orientation is reached, the divers activate a hand pump sending hydraulic fluid down the tube to a three jawed clamp next to the instrument. This clamp rigidly couples the geophone instrument to the tube wall.

The projector, rigidly suspended below one such clamp, consists of an electromagnetic mallet fabricated from a solenoid. The solenoid is actuated when a stepped voltage is applied to its coil, sending a plunger to hit the inside surface of the plastic liner tube. In this way, the point force is realized. A hydrophone is mounted on the hydraulic clamp of the mallet to provide accurate recording of the $t = 0$ onset of shear wave excitation. Engineering details of the apparatus are shown in Figs. 9a–d.

It is important to arrange the swing of the EM mallet to hit the tube wall with adequate force to create a detectable shear wave, without damaging the plastic liner. Although this can be calculated from engineering principles, it is a simple matter to determine by trial and error in a laboratory test. The mallet is driven with a Marelli type 6360082 solenoid, actuated by a boxcar pulse of 12 V at 36 A.

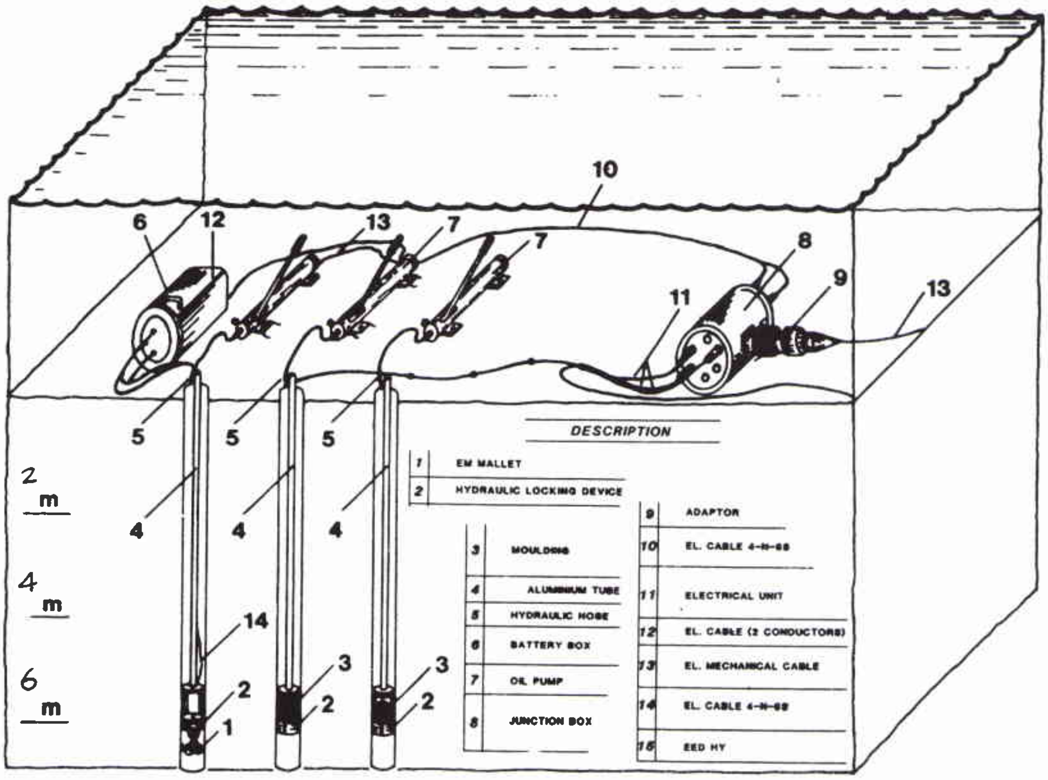


Figure 9a *Electrical and mechanical layout of crosshole S wave measurement system.*

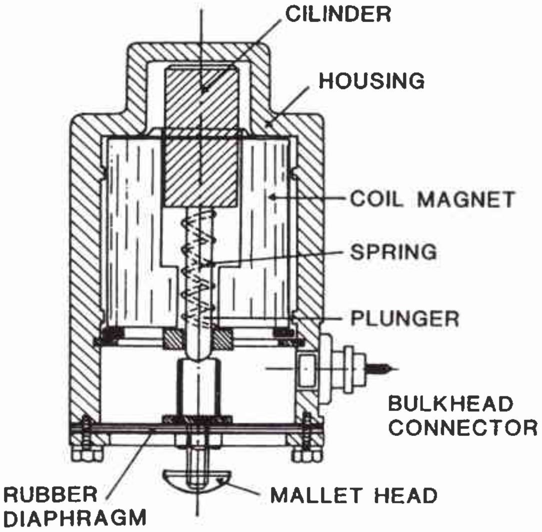


Figure 9b *Cutaway view of electromechanical mallet for crosshole S wave measurements (Marelli type 6360082 solenoid).*

The receivers consist of a pair of vertical and horizontal geophones, potted in a plastic potting compound and rigidly attached to hydraulic clamps that couple them to the liner wall. Geophones made by Mark Products, Ltd. were used; these were the L-15 type, critically damped at a low frequency cutoff of 4.5 Hz, decreasing in sensitivity

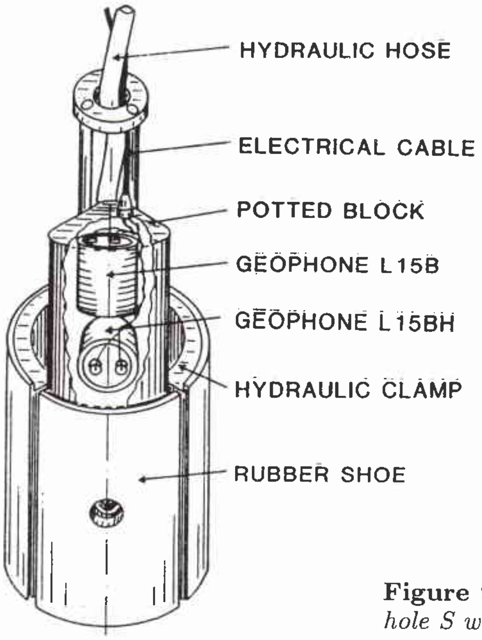


Figure 9c *Seismograph for receiving cross-hole S wave signals.*

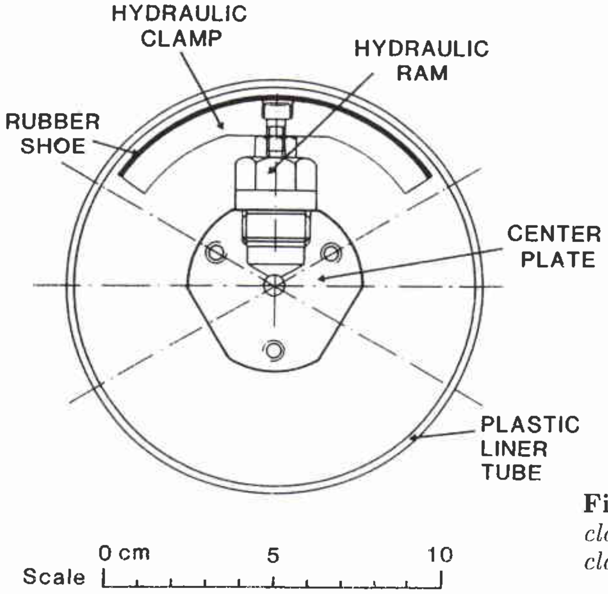


Figure 9d *Top view of hydraulic clamp system, showing one of three clamps.*

below that at a slope of 12 dB per octave. The orientation of the geophone package can be adjusted by the divers to make the horizontal geophone have either a radial or transverse alignment.

In principle, a point force moving transverse to the propagation path in an infinite, homogeneous medium will generate shear waves that will also be detected with geophones oriented transverse to this path. However, in our experiments shear waves were detected with all orientations of the geophones and the EM mallet, including the radial alignment. This could be due to some peculiarity in the structural response of the plastic liner to point force excitation or to layering in the sediment and consequent decomposition of the excitation into multi component interface waves.

2.5. S WAVE DATA

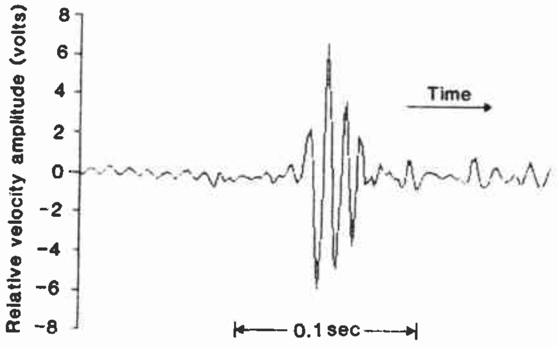
A sample data set resulting from crosshole shear measurements in the mud sediment of the Ligurian shelf near Tellaro (La Spezia) Italy is shown in Fig. 10 for a sensor depth of 4.5 m. Here, the source (EM mallet) and receiver (4.5 Hz geophone) were both oriented in the radial direction at a separation of 2.9 m. Although the EM mallet is a transient force source, the reaction of the dynamic system is to produce a pulsed sinusoid signal containing a few wavelengths with peak frequencies around 100 Hz, and a minor spectral peak around 25 Hz.

A sample of data reduced to obtain the shear wave velocity as a function of depth is shown in Fig. 11. Here, the orientation of the EM mallet and horizontal geophones was transverse, as shown in the figure. The relative arrival times for signal propagation to the receivers were extracted and used with the measured separation distances to compute the shear velocity at depth increments of 0.5 m. It can be seen that there are several possibilities for making hole to hole velocity measurements. For example, data exists for propagation from the source hole to the second hole, from the second to the third, from the source hole to the third hole, etc.

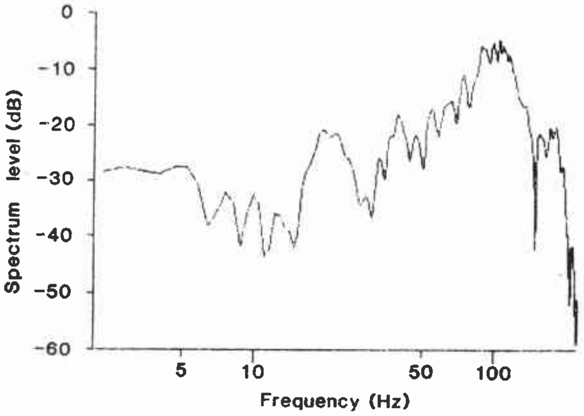
Several samples of the received signals are plotted in Fig. 11 to indicate the scatter in the data, which is quite small, typically only 5%. The curve shows a nonlinear increase of velocity with depth, coupled with a sort of discontinuity at 2.5 m depth that seems to indicate that a harder sediment layer has been encountered.

The attenuation of the propagating shear wave signals was computed by comparing the received spectra as a function of depth, for individual transmissions arriving at various delayed times. The results are shown in Fig 12, in a quasi 3D format showing both the depth and frequency dependence. The data shows that the attenuation, expressed in dB per wavelength, generally decreases with both depth and frequency, although there are depth variations that seem to indicate layering.

The shear wave attenuation vs frequency at a depth of 2 m is shown in Fig 13. The data are well fitted to a curve having a dependence on frequency to the power of 1.5. These are the first *in situ* measurements to show a nonlinear dependence of shear wave attenuation on frequency in unconsolidated sediments. Most seismo acoustic models are presently set up to treat shear wave attenuation with a dependence on the first power of frequency.



a) shear wave pulse arrival ,radial geophone



b) Frequency spectrum of shear wave pulse

Figure 10 *S wave signal, excited and received in radial orientation at 4.5 m depth, 2.9 m range, in a mud bottom of the Ligurian Shelf.*

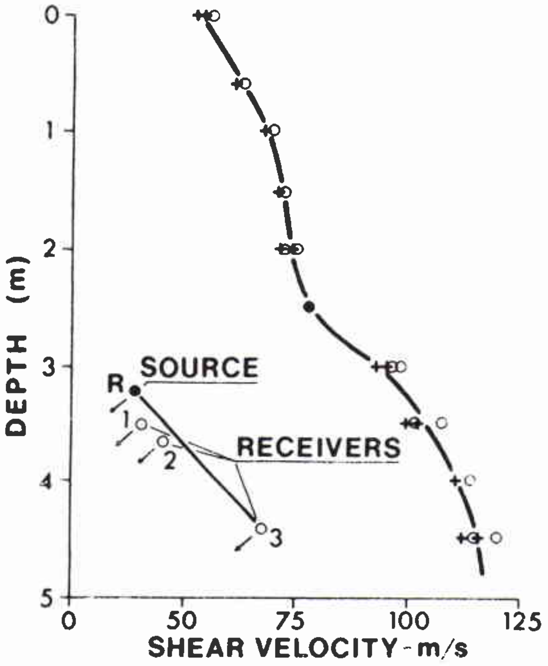


Figure 11 *Sample results from measurement of S wave velocity, with a transverse source/sensor orientation, as shown in the sketch.*

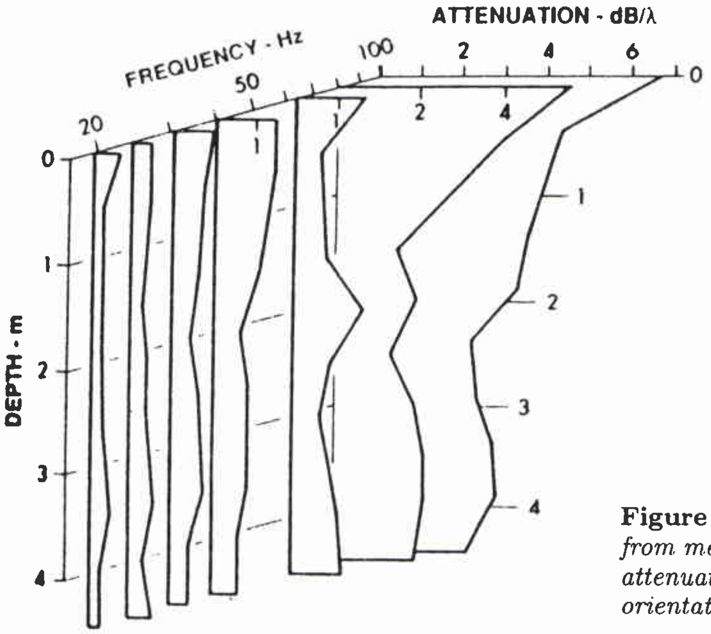


Figure 12 *Sample results from measurement of S wave attenuation, with transverse orientations.*

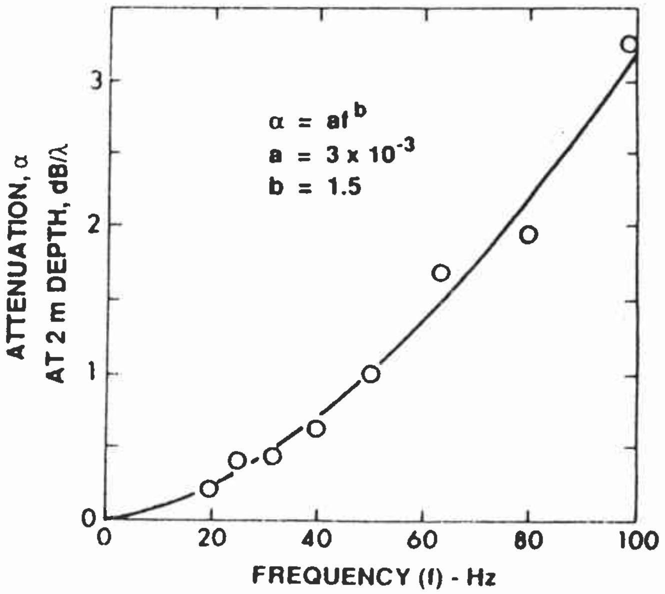


Figure 13 *Conceptual sketch of remotely operated geoacoustic logging tool.*

3

Conclusions

This work was undertaken in support of developing remote sensing techniques for sea floor parameter measurements needed for sonar performance modelling and evaluation in shallow water.

It is difficult to make quantitative measurements on the bottom of the ocean and it is even more difficult to do this within the sedimentary volume. With the advent of remote sensing techniques and the promise of being able to measure sediment geoacoustic parameters without touching the sea floor, it was useful to develop instruments that could be taken to selected areas to directly measure the sediment parameters that may eventually be sensed remotely. In this way, 'ground truth' data can be established to evaluate and compare the remote sensing techniques.

In this report, a research tool enabling crosshole techniques to be applied to unconsolidated sediments was described. Two suites of new instruments were described for measuring the seismo-acoustic velocities and attenuation of compressional and shear waves as a function of depth in the sea floor. These tools and instruments are for sediment depths measured in meters, where diver intensive operations are possible. These devices are inexpensive and can be easily modified from day to day, for various measurements in different areas. They were successfully used to acquire new data on the aforementioned geoacoustic parameters as a function of sediment depth, down to 5 m, at a testbed site in the bottom of the Ligurian Sea near La Spezia, Italy.

A survey paper describing the application of the present results to testbed development and remote sensing has recently been published [5].

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Title

Instrumentation for crosshole geoacoustic measurements in unconsolidated sediments

Abstract

Research tools are described that enable direct measurements of sediment properties as a function of depth in unconsolidated sediments. The first tool is a hole making device that sits on the sea floor and utilizes pneumatic and hydraulic forces to remove the sediment from the interior of a cylindrical tube. 25 cm in diameter and 6 m deep. This hole can be used to permanently deploy instruments such as seismometers, or it can be lined with a plastic tube as a casing, for subsequent access and the temporary deployment of geoacoustic logging instruments. Two such instruments are described. One is used to measure sound velocity and attenuation for compressional waves while the other measures these parameters for shear waves. The design, development and initial tests of these devices is presented.

Keywords

compressional waves, geoacoustic logging, sediment properties, shear waves, sound attenuation, sound velocity

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