THE USE OF LOVE WAVES TO DETERMINE THE GEOACOUSTIC PROPERTIES OF MARINE SEDIMENTS

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ABSTRACT

The importance of the geoacoustic properties of marine sediments for low-frequency shallow water propagation is well established. Reliable compressional properties can be obtained from laboratory analysis of collected samples. The shear properties, however, are highly affected by the deterioration of the chemical and mechanical bindings caused by de-pressurization and change of temperature in the core sampling process. These properties therefore have to be determined in situ. Isolated shear waves are not easily generated due to partial coupling into compressional waves at all interfaces. In the case of stratified, isotropic media, however, coupling can be avoided if the polarization of the shear waves is parallel to the interfaces. Here an experimental technique is described for generation and detection of horizontally polarized shear waves - or Love waves - in a horizontally stratified sea-bed. Shear velocity profiles are determined indirectly by numerical modelling of the experimental data. Results are presented for different types of marine sediments.

INTRODUCTION

The importance of the geoacoustic properties of marine sediments for low-frequency acoustic propagation is well established [1]. Geoacoustic properties also provide a major source of information for the determination of the static and dynamic characteristics of the sea-bed.

When seismic waves propagate through the marine sediments, the dynamic properties of the sediments determine the speed and the attenuation. An investigation of the seismic propagation characteristics can therefore provide accurate information on the geotechnical characteristics of the sea-bed.

Assuming that the sea-floor sediments behave like elastic media, the seismic propagation is controlled by the bulk modulus K, the shear modulus

G, and the density ρ. These parameters are related to the compressional wave velocity, C_p, and the shear wave velocity, C_s, by

$$C_p = [(K + 4G/3)/\rho]^{1/2} \quad \text{and}$$

$$C_s = (G/\rho)^{1/2}$$

If the compressional wave velocity (C_p) and the shear wave velocity (C_s) of an idealized marine sediment can be measured concurrently with a measurement of bulk density, the elastic parameters of the sediments can be completely characterized (see Tables 1 and 2).

Table 1.

BASIC WAVE TYPES AND VELOCITIES
a) BODY WAVES
–COMPRESSIONAL (longitudinal) $C_P=[(K+4G/3)/\rho]^{1/2}$
–SHEAR (transverse) $C_S=(G/\rho)^{1/2}$
b) DUCTED WAVES
– LOVE $C_L=(G_l/\rho)^{1/2}$
c) SURFACE WAVES
– SCHOLTE $C_{SCH} \sim (G/\rho)^{1/2}$

Table 2.

ELASTIC PARAMETERS IN TERMS OF WAVE VELOCITIES AND BULK DENSITY (ρ)
K: BULK MODULUS (incompressibility)
$K=\rho(C_P^2-4C_S^2/3)$
E: YOUNG's MODULUS
$E= 2C_S^2\rho(1+\sigma)$ or
$E=\rho C_P^2(1+\sigma)(1-2\sigma)/(1-\sigma)$
σ:POISSON's RATIO (transv./long. strain)
$\sigma = 1/2(C_P^2-2C_S^2)/(C_P^2-C_S^2)$
G:SHEAR MODULUS (rigidity)
$G=\rho C_S^2$
λ=LAME's CONSTANT
$\lambda=\rho(C_P^2-2C_S^2)$

Several laboratory and field methods are available to measure density and wave velocities in bottom sediment cores. However, the reliability of such measurements is degraded by sample disturbance and temperature and pressure changes. In particular, the shear properties are highly effected by the deterioration of the chemical and mechanical bindings caused by the differences in temperature and pressure between the sampling and the laboratory measurements. Also, in the laboratory, the small size of the sample does not allow direct information to be obtained about the response of these materials to low-frequency seismic/acoustic waves. Therefore the most reliable geoacoustic measurement techniques for ocean-bottom sediments are therefore in situ techniques.

The choice of an actual experimental technique is strongly influenced by the structure of the sea bed. If the bottom was homogeneous to a significant depth, the wave speeds and attenuation could be measured directly because different seismic wave types could be separated. In reality, however, recent sediments consist of a relatively thin top layer of unconsolidated clay or silty clay overlying semi-consolidated silts and sands [2,3]. This structure results from the lowering of sea levels during the glaciation of the Pleistocene epoch in which sand was deposited over wide areas of the continental shelves. The shelves were subsequently covered by unconsolidated sediments during sea level rising during the post-glacial times. Sedimentary processes such as sorting, compaction and consolidation, also have contributed to the highly stratified structure of the sea bed.

In such a layered sea bed the compressional and shear waves couple, yielding an often complex wave field. The geoacoustic properties therefore must be determined indirectly (inversely) from the propagation characteristics. The most important attenuation mechanism of low frequency propagation in shallow water is the conversion of acoustic energy in the water column into shear waves in the bottom [1]. Because of this importance this mechanism has received special attention during the past decade. Because the propagation of seismic interface waves (also known as Scholte waves) is almost entirely controlled by their shear properties, significant effort has been applied to the analysis of these properties [4,5]. However, the inversion involves significant numerical effort not easily automated.

Here it will be demonstrated that horizontally polarized shear waves (SH), also called Love waves, can be generated by simple means in the low-velocity duct formed by the upper sediments. Because the shear waves do not couple into compressional waves in a horizontal stratification of isotropic layers, their propagation characteristics directly reflect the shear properties. The Love waves therefore form an alternative to the seismic interface waves as the basis of the shear property inversion. Further, the scalar nature of the wave equation for Love waves significantly decreases the calculations involved in the inversion compared to the requirements for the interface waves.

EXPERIMENTAL PROGRAMME

The Love wave experiments were caried out as part of a multinational research programme to measure the velocity and attenuation of seismic waves and supporting geotechnical parameters in marine sediments. The programme was initiated by SACLANT to bring together experts in geophysics, geology and acoustics to compare various measurement and analysis techniques for data gathered under identical environmental conditions.

For this program four institutes played a leading role in the specific problems related to sampling, analysis and interpretation of ocean bottom sediments. The institutes and their tasks were:

- Institute of Marine Geology (IGM-CNR), Bologna, Italy; sampling the sea-bed using different techniques, geotechnical analysis and interpretation, and geological description;

- Centro de Fisica Applicada (CENFA), Madrid, Spain; measuring reflection loss under controlled conditions in a layered sea-bed with variable sensitivity gradients, and testing a model developed by the CENFA scientists;

- US Naval Ocean Research and Development Activity (NORDA), Bay St. Louis, MS, USA; sediment sampling, laboratory analysis of the samples for compressional and shear wave velocities, sediment mass property analysis, measurements with the ELAC Sea-Bed Classifier to define high-resolution layering, and sediments classification;

- SACLANT ASW Research Centre (SACLANTCEN), La Spezia, Italy; programme coordination, measurement of seismic wave velocities and attenuation using ocean-bottom seismometers, sampling and geoacoustic analysis of sediments and site surveying (using side-scan sonar and seismic profilers); SACLANTCEN theoretical propagation models were used with seismic data to determine the sea-bed properties.

MEASUREMENT TECHNIQUES

The techniques developed by the different institutions were applied to four different sedimentary areas in the vicinity of La Spezia, Italy (Fig. 1).

Shear-wave velocity measurements

A directional energy source was developed to excite both interface and ducted Love waves. Figure 2 illustrates the techniques used by SACLANTCEN. Five ocean bottom seismometers (OBS), each with tri-axial geophones and a hydrophone, were deployed along the measurement range in each area. For the short ranges applied (<25 m), a high energy source level was not needed. The signals were generated by shooting a spear from a hydraulic gun mounted on a frame into a mass resting on the sea-bed (Fig. 3). This type of source generates a signal below the elastic limits of the sediments, thus avoiding changes in sediment properties. The direction of the gun-mount could be changed as appropriate to generate different wave types. The experiment was conducted by diving scientists [6].

Figure 4 shows examples of the signals received at a distance of 25 m from the source. For example, in Fig. 4a, the geophone received maximum energy from a transverse (shear) pulse traveling in the x-direction. The alignment of the corresponding particle-motion diagram (hodograph) also

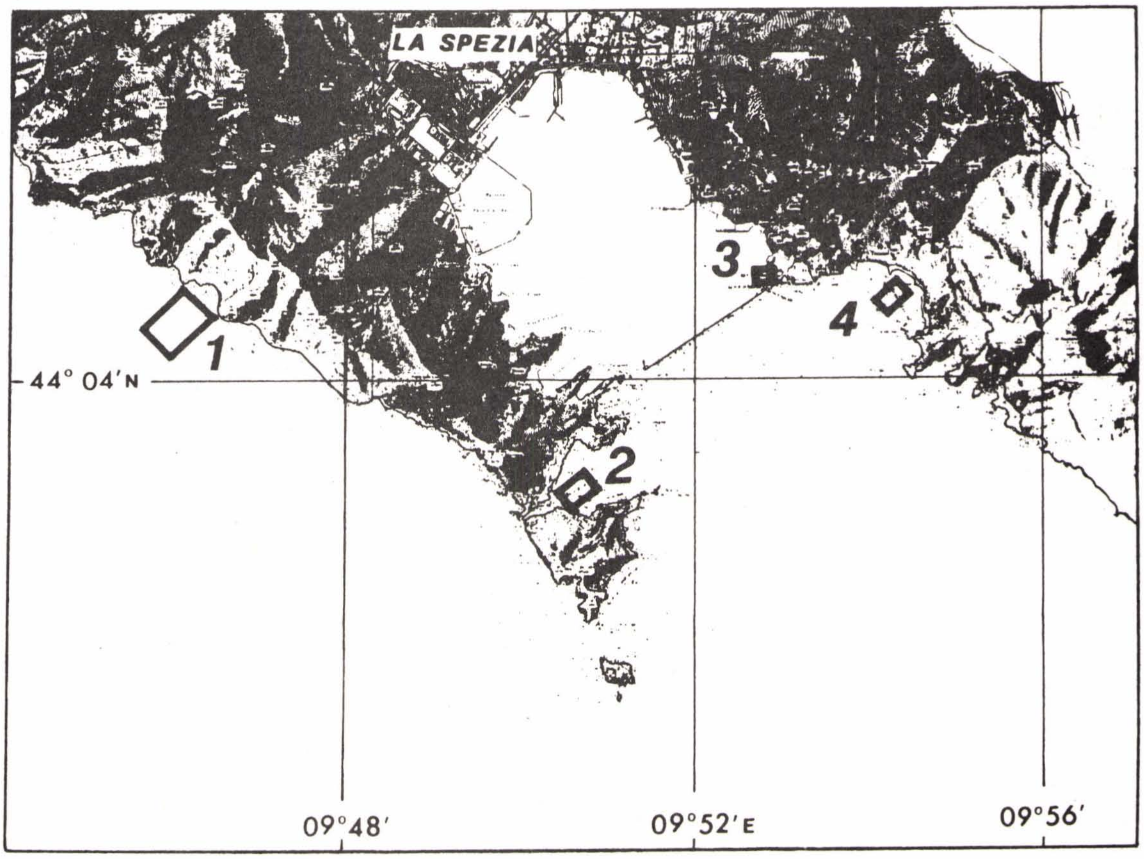

Fig. 1 Experiment areas, La Spezia, Italy.

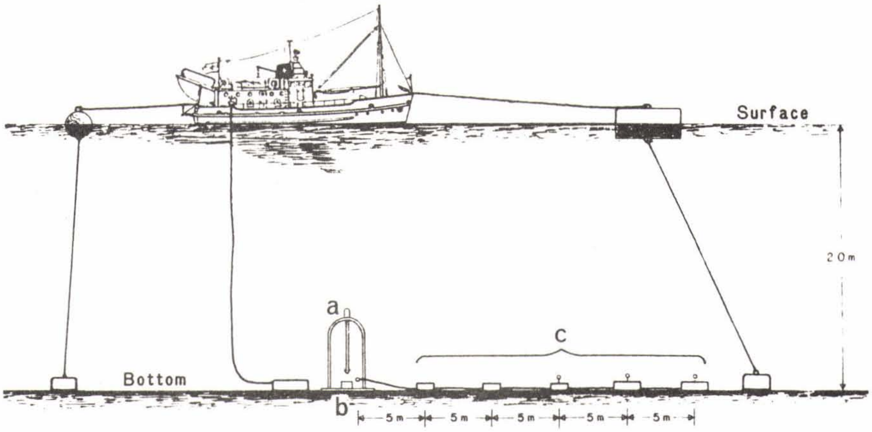

Fig. 2 Techniques used to measure Love wave velocity

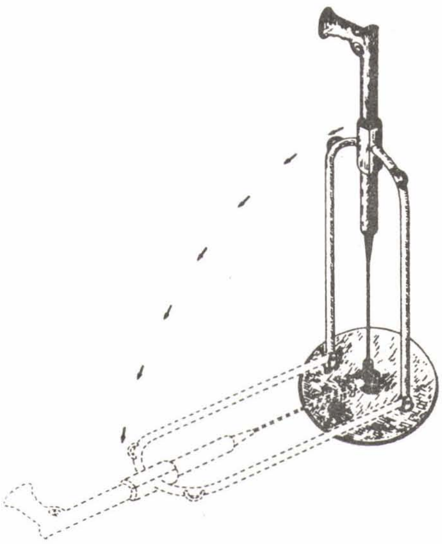

Fig. 3
SACLANTCEN technique to generate seismic signals; a gun shoots a spear against a mass coupled to the sea-bed with a heavy metal plate.

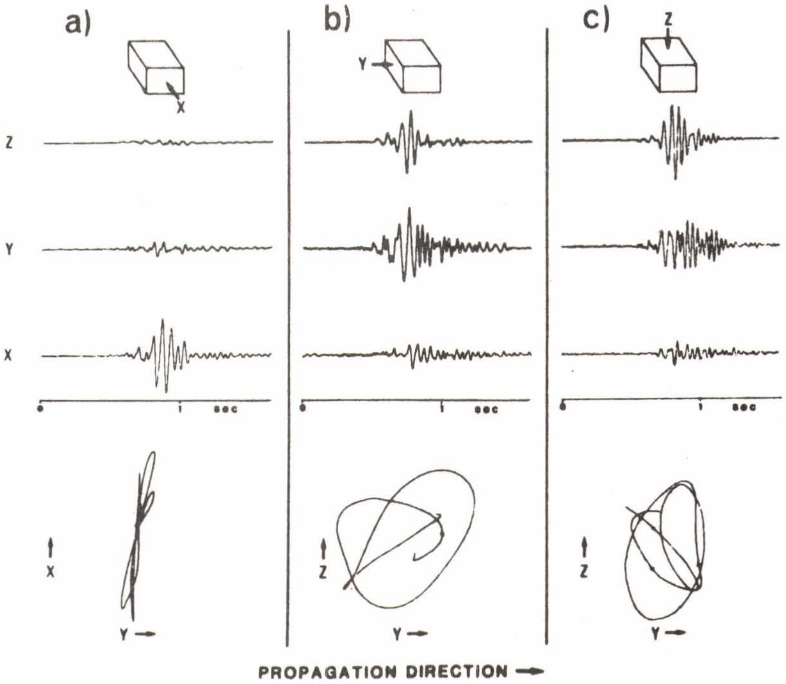

Fig. 4 Acoustic signals received at a distance of 25 m from the source, and corresponding particle motion diagrams (hodographs).

confirms that the signal is confined to the horizontal plane (x-axis). This dispersed form of the transverse signal indicates that this is not a pure body wave but a Love wave propagating within the upper sedimentary layer. This assumption was confirmed by synthetic seismograms produced by the numerical model SAFARI [7]. The radial (Fig. 4b) and vertical (Fig. 4c) signals were much more complex; the particle motions were confined to either the radial or vertical plane with very small transverse deflections, a characteristic behaviour of interface waves [4].

Bottom reflectivity measurements

Figure 5 illustrates the system used by NORDA and CENFA to measure the acoustic reflection characteristics of the bottom. NORDA's ELAC Sea-Bed Classifier (30 kHz) was used both to obtain high resolution sub-bottom layering information and high-resolution bottom reflection loss measurements. SACLANTCEN also used an EG&G UNIBOOM seismic source for bottom reflection measurements.

Sediment sampling

Figure 6 shows the techniques used to sample sea bed sediments. Samples were collected by the diver-scientists who used a grab sampler, a box corer, a gravity corer, and IGM's newly developed compressional air-powered corer.

Side-scan sonar

The site surveys, using side-scan sonar (EG&G MARK1B) provided knowledge of both the surface sediment distribution and the sea bed topography.

Continuous seismic profiling

An EG&G UNIBOOM source/receiver and a streamer were towed behind the survey ship. Resolution was poor in water depths less than 10 m.

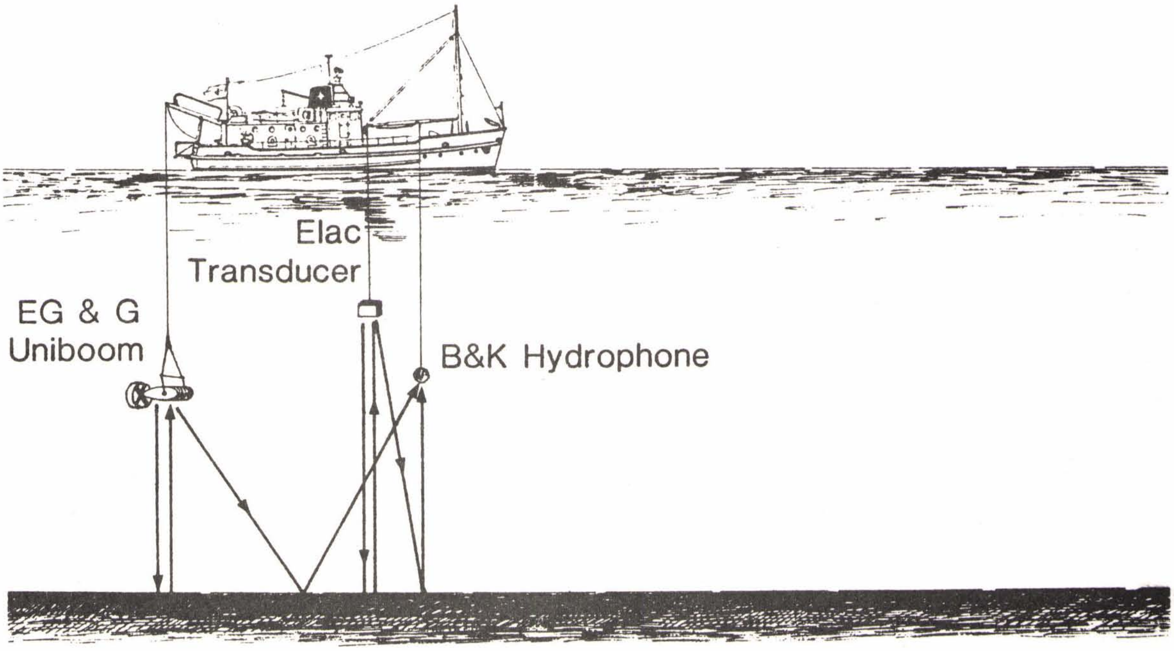

Fig. 5 NORDA and CENFA systems to measure the acoustic reflection characteristics of the bottom.

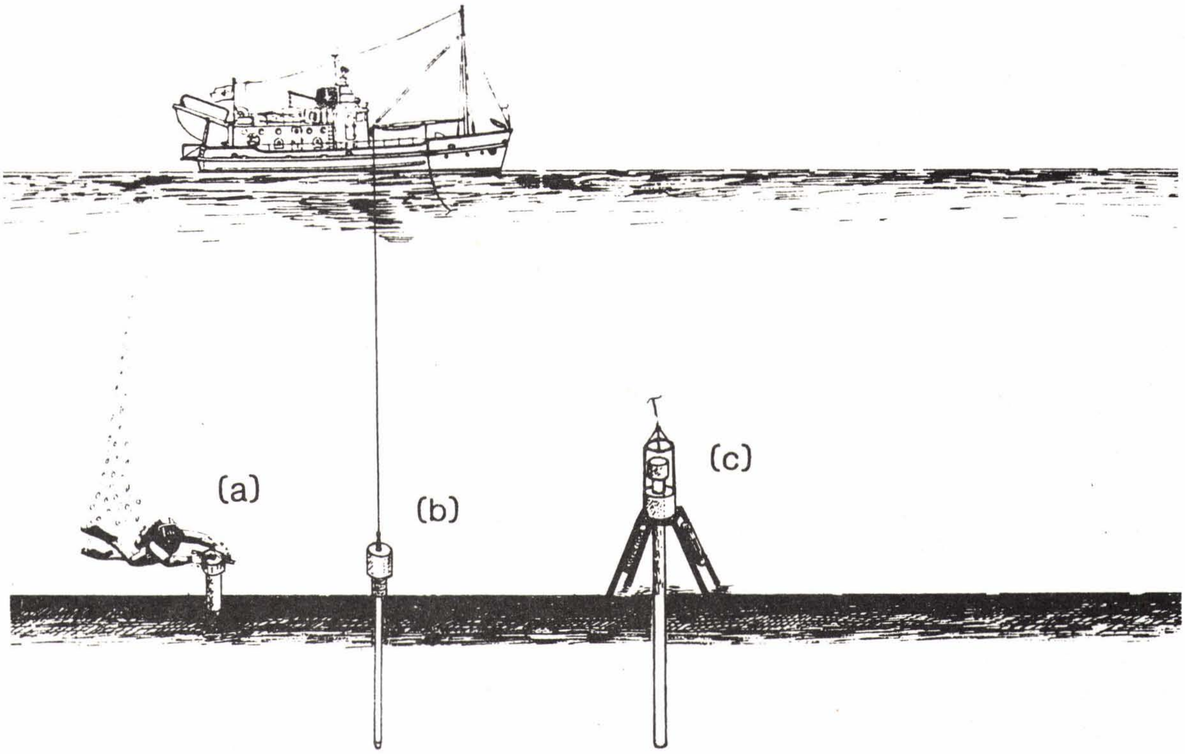

Fig. 6 Techniques used to sample sea-bed sediments
a) hand corer
b) gravity corer
c) IGM's compressional air-powered corer

Laboratory analysis

The cores were analyzed every 2 cm along their length for the following properties and characteristics:

- compressional wave velocity
- shear wave velocity
- porosity
- water content
- wet density
- dry density
- torvane and shear strength
- Attenberg limits
- grain size
- mineralogic composition

EXPERIMENTAL RESULTS

Data from two areas, 1 and 2, with different bottom conditions are presented here (see Fig. 1).

Area A is situated along the Cinque Terre coast of the Ligurian Sea; Area B is situated at the eastern entrance to the Portovenere channel of the Gulf of La Spezia.

Area 1

This study area had a water depth of 15 m. The sea-bed consisted of coarse sand and fine gravel. Side-scan sonar and observations by diving scientists indicated that the area was covered with ripples (approximately λ = 2 m) created by wave action. To avoid distorting the propagation path the axis of the measurement range was laid out parallel to the axes of the ripples. Seismic profiles (Fig. 7) show a sub-bottom reflector approximately 2 ms from the bottom. The bottom sediments apparently were derived from land slides and the reworking of sediments along the steep coastline.

Figure 8 summarizes the measured parameters along a core sample taken in this area. The high percentage of gravel in the sea bed limits the core penetration to less than 20 cm. This gravel consists mainly of limestone, slate, and sandstone, apparently derived from the adjacent mountains which have a similar lithology.

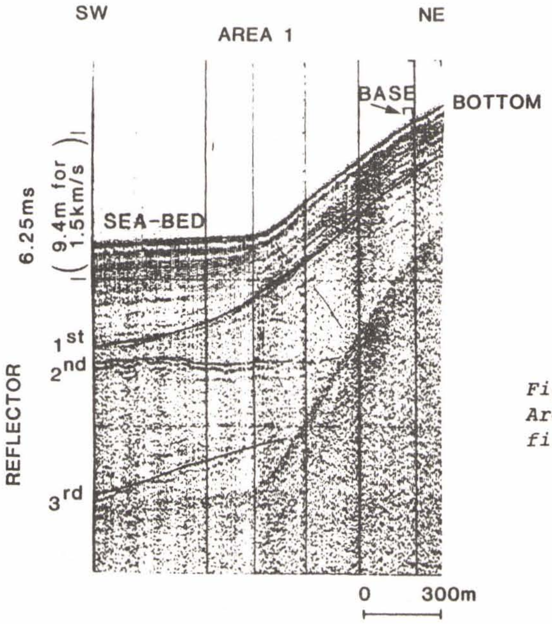

Fig. 7
Area 1. Continuous seismic profiling record and interpretation.

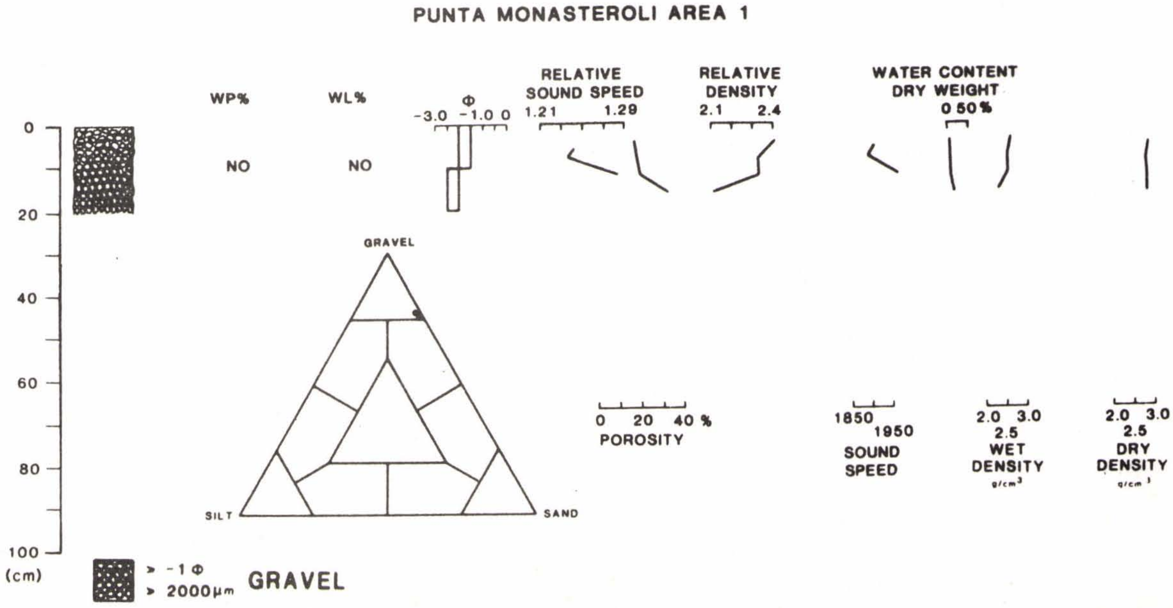

Fig. 8 Area 1. Measured parameters along a core sample.

Figure 9 is a time vs distance plot of the output of the transverse (shear) wave sensitive geophone. Distinct wavelets can be observed traveling with speeds up to 90 m/s. The inversion was performed by means of the SAFARI model [7], using trial and error. The very simple shear velocity profile shown in Fig. 10a yielded the synthetic seismograms shown in Fig. 10b, which agree well with Fig. 9.

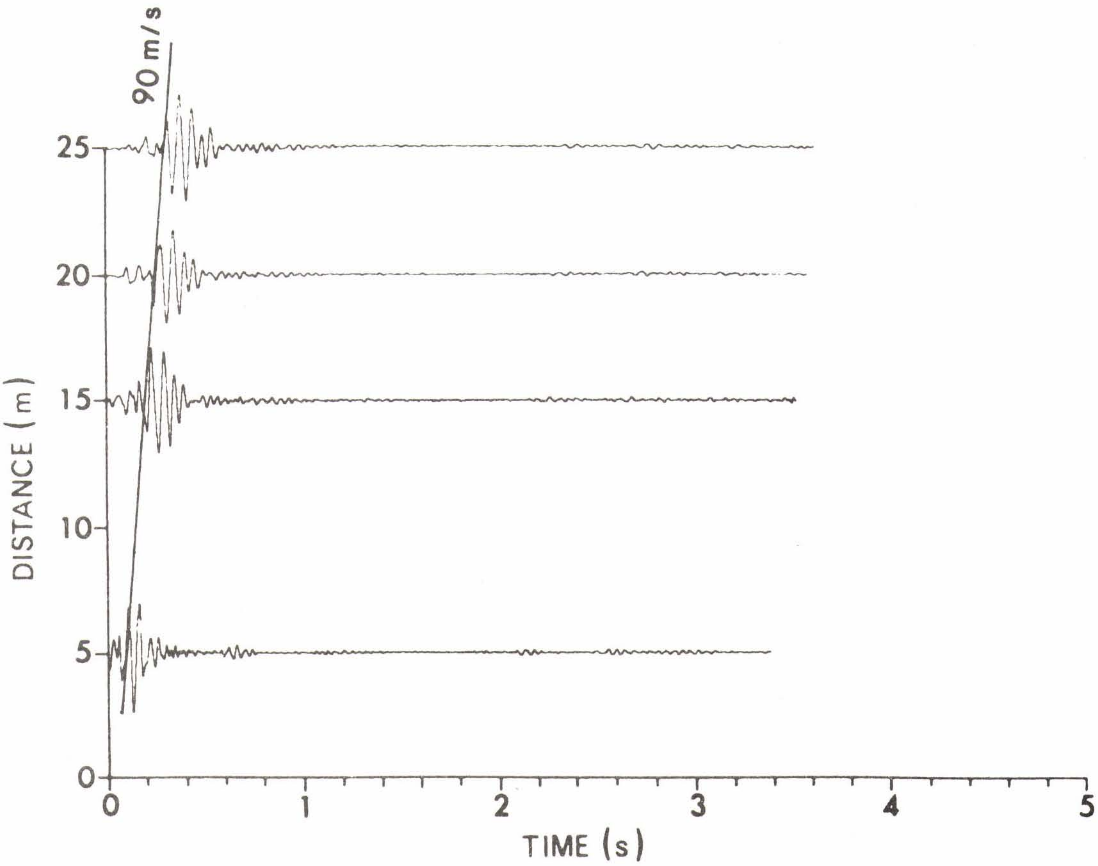

Fig. 9 Area 1. Time vs distance plot of the shear wave sensitive geophone.

Area 2

Side-scan sonar records of the eastern entrance fo the Portovenere Channel indicate a flat bottom. Sub-bottom profiles taken along the measurement base indicate four distinct reflectors (Fig. 11).

Figure 12 illustrates the physical parameters measured along one of the cores taken in Area 2. The material consists of silty clays and clayey silts with very small variations. The mineralogy of these sediments consists mostly of quartz and calcite with some magnesium. Of the clay minerals, 60% is illite, 10% chlorite and 30% smectite and kaolinite. The percentage of illite increases towards the bottom of the core sample with the depth in the core (and hence the sea bottom). Attenberg limits measured were 51 to 55% for the liquid limit (W_L) and about 25% for the plastic limit (Wp). The liquid limit tends to increase with depth, verifying that the sediments become finer towards the bottom of the core. Figure 13 shows the shear waves detected by transverse wave sensitive geophones. A distinct wavelet, traveling at 30 m/s, indicates Love wave speeds in the upper sedimentary layers about 1/3 of that in Area 1.

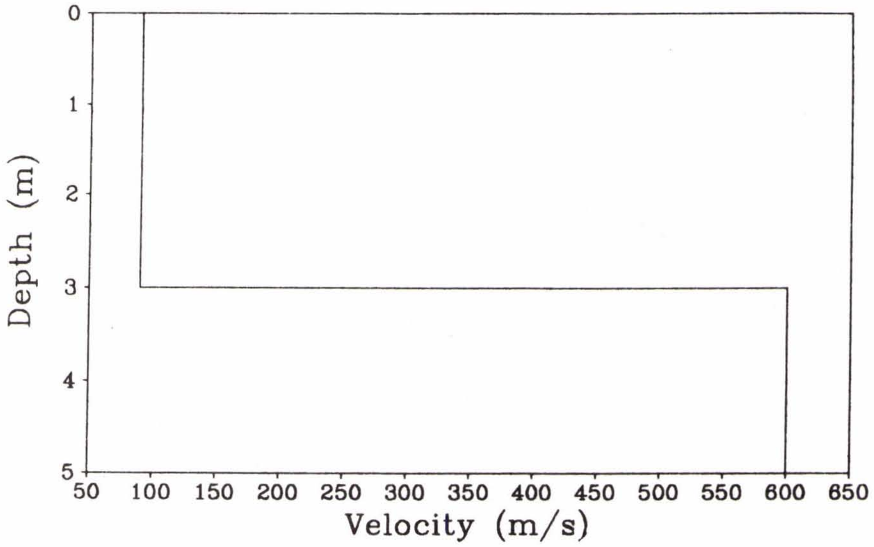

Fig. 10a Shear velocity profile.

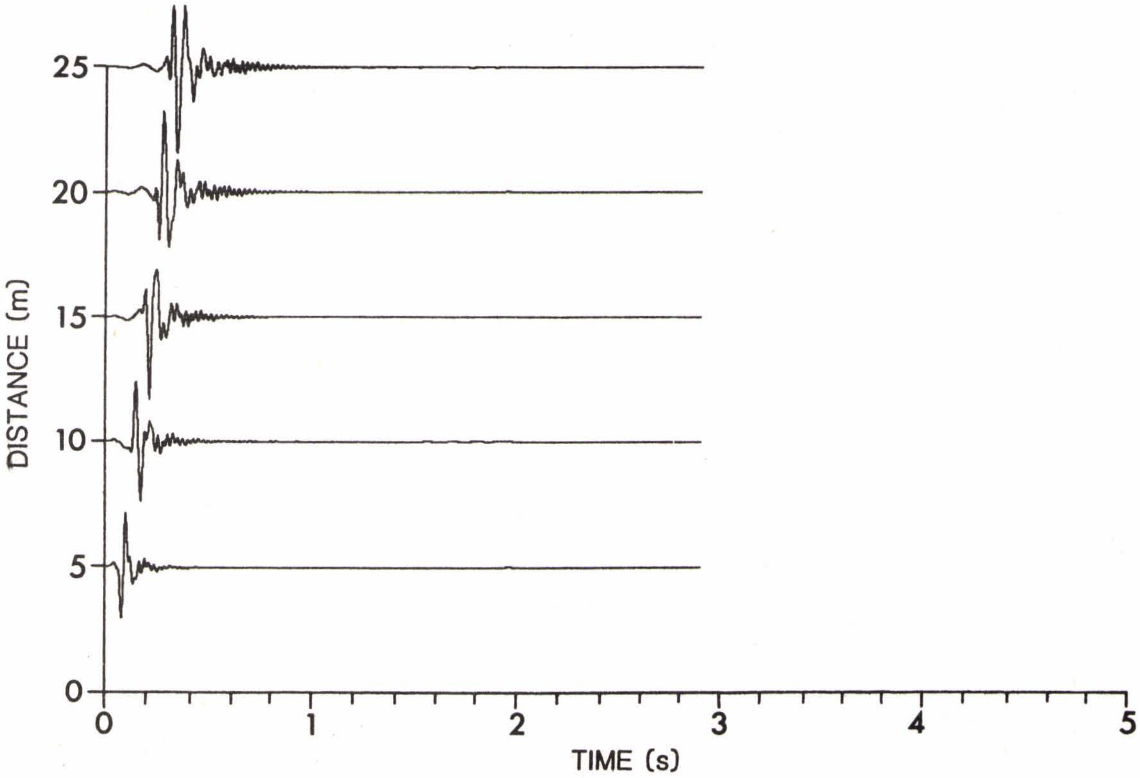

Fig. 10b Synthetic seismograms.

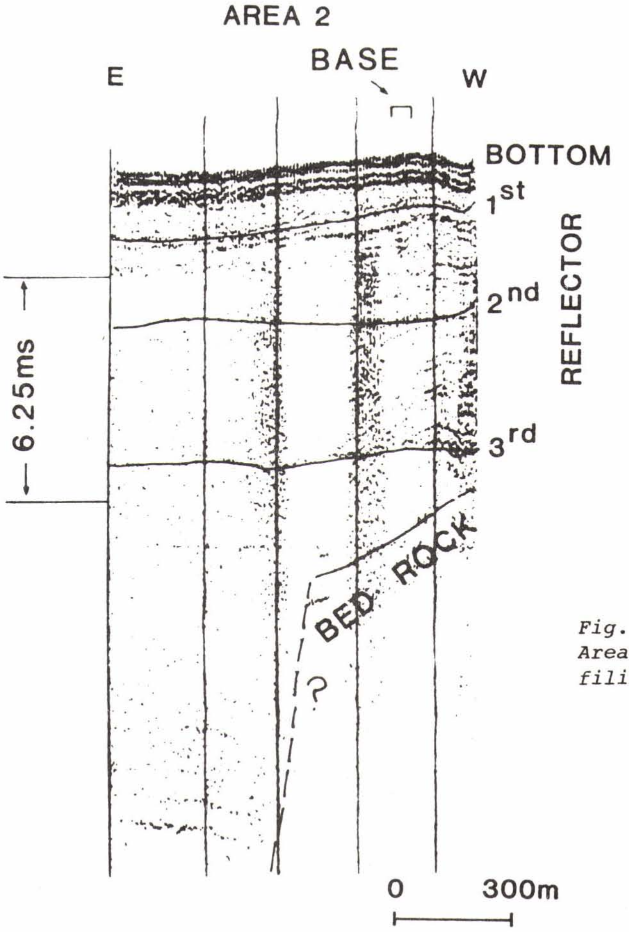

Fig. 11
Area 2. Continuous seismic profiling record and interpretation.

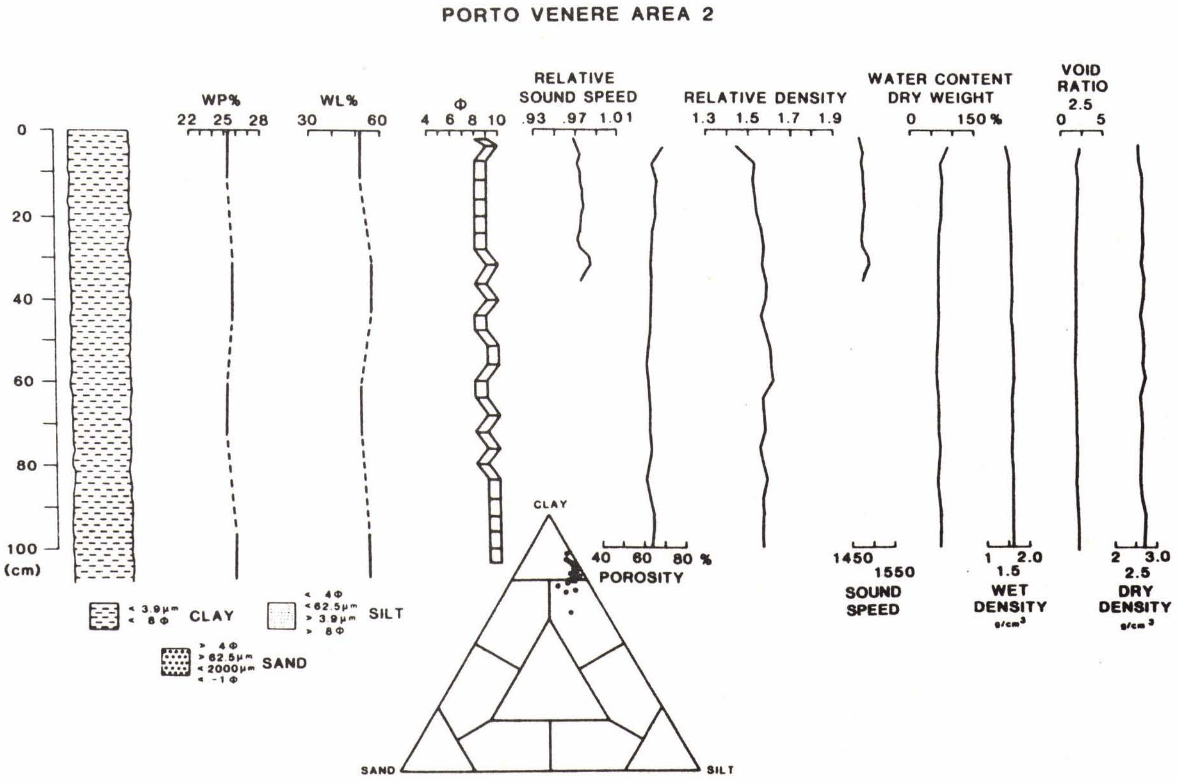

Fig. 12 Area 2. Measured parameters along a core sample taken off Porto Venere.

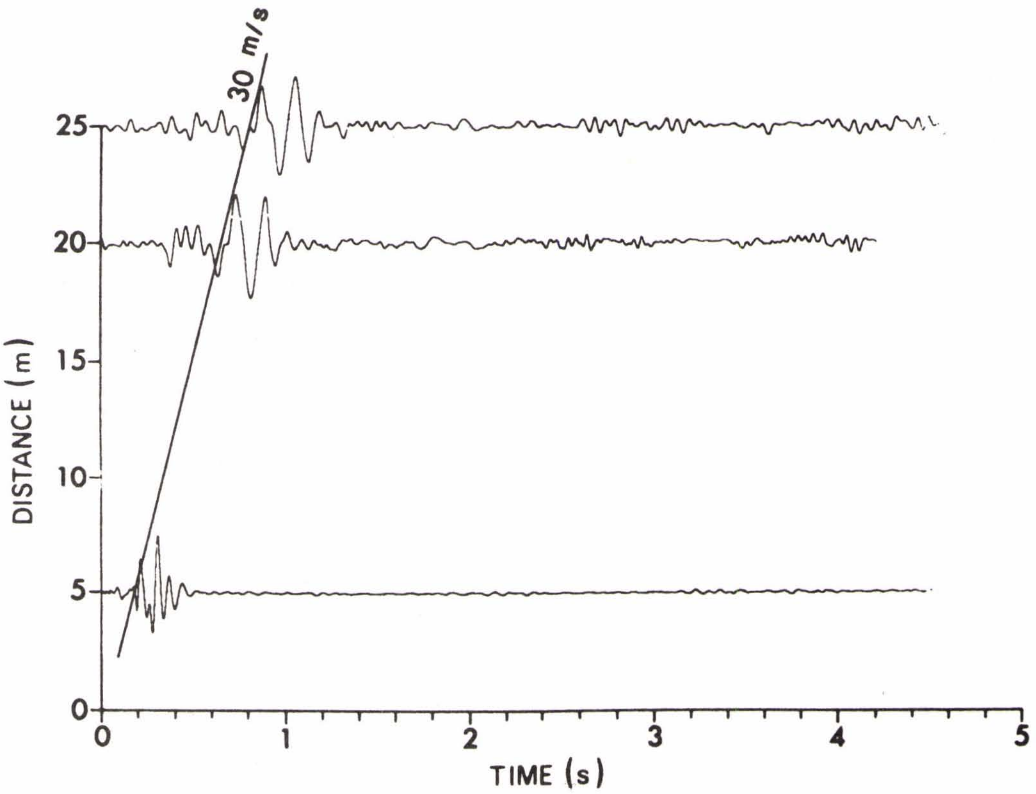

Fig. 13 Area 2. Time vs distance plots of the shear wave sensitive geophones, and shear-wave speed.

CONCLUSIONS

These simple experiments have demonstrated that Love waves can be generated in the low velocity duct formed by the uppermost unconsolidated sediment layers. The Love waves are horizontally polarized shear waves; in horizontally stratified environments they do not convert into other wave types. This property greatly simplifies theoretical modelling of their behaviour. Love waves may therefore form an alternative basis for determination of the sediment shear properties which in recent years has been based on the properties of the more complex seismic interface waves. The experiment demonstrated that two wave types (Scholte and Love) can in fact be generated and detected in a single experimental setup. The combination therefore is a realistic possibility which, if applied, can improve the prediction accuracy of deduced shear speed profiles. Further, the combination can elucidate the degree of anisotropy in the upper sedimentary layers.

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