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MEMORANDUM

Sediment shear waves: A comparison of in situ and laboratory measurements

M.D. Richardson, E. Muzi, L. Troiano
and B. Miaschi

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Sediment shear waves:
A comparison of in situ and laboratory measurements

M.D. Richardson, E. Muzi, L. Troiano and
B. Miaschi

Executive Summary: The conversion of compressional wave energy to shear wave energy at the sediment-water interface is an important loss mechanism for acoustic transmission in the ocean. Surficial sediment shear wave velocity and attenuation are the required input parameters used by most propagation models to predicted this loss. The lack of in situ measurements makes the prediction of near-surface shear wave velocity both difficult and tenuous.

We are developing new techniques for the in situ measurement of important sediment geoacoustic properties, such as shear and compressional wave velocity and attenuation. In this status report we present data on shear wave velocity measured both in situ and from sediment cores in the laboratory. Easily measured sediment mass properties such as porosity, water content and sediment density are also reported.

In situ shear wave velocity ranged from 16 m/s in flocculent clays to 90 m/s in hard packed fine sands. We have developed an empirical relationships to derive in situ shear wave velocities from laboratory values of shear wave velocity and/or easily measured sediment mass properties. These results are an important contribution to prediction of in situ sediment shear wave velocity as well as to understanding of the propagation of acoustic energy through marine sediments.

Future reports will extend these results to cover all sediment types of NATO ASW interests. In situ of compressional wave velocity and attenuation as well as shear wave velocity will be reported. Near-surface gradients of sediment geoacoustic properties will also be investigated.

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Sediment shear waves:
A comparison of in situ and laboratory measurements

M.D. Richardson, E. Muzi, L. Troiano and B. Miaschi

Abstract: Surficial sediment shear wave velocity measurements were made at eight sites (water depths 7–22 m) in the vicinity of La Spezia, Italy. Values of shear wave velocity measured in situ ranged from 16 m/s in flocculent clays to 90 m/s in hard-packed sands. Values of laboratory measured shear wave velocity were 6–22 m/s lower from the same sites. Low variability of measured shear wave velocities allowed laboratory measurements to be corrected to in situ conditions using the following empirical relationship:

$$V_s\,(\text{in situ}) = 10.46 + 1.17\,V_s(\text{lab}).$$

The most likely causes for the lower laboratory shear wave velocities were sediment disturbance during collection, transportation, storage and measurement both by mechanical manipulations and by changes in confining pressure. Sediment porosity, void ratio or wet density can be used to predict in situ shear wave velocity. Further studies are required to refine and extend these empirical relationships, and to accurately define the high gradients in shear wave velocity predicted for the upper few meters of sediment.

Keywords: in situ sediment properties ∘ marine sediments ∘ sediment physical properties ∘ shear modulus ∘ shear waves ∘ shear wave velocity

Contents

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1 Introduction

In recent years, scientists from such diverse fields as geophysics, seafloor engineering, sedimentology, soil mechanics and underwater acoustics have devoted considerable attention to the measurement of sediment shear wave velocity and/or sediment dynamic modulus. These fundamental sediment properties are important to predicting the stability of sediment slopes, the consolidation behavior of sediments, the strength of marine foundations, and the conversion of waterborne energy to sediment shear wave energy at the seabottom, to give just a few examples.

Sediment shear wave velocity has been measured in situ using probes deployed by scuba divers, submersibles (Hamilton et al., 1970), and remotely from surface ships (Bennell et al., 1982). Shear wave velocity has also been measured in and between boreholes using explosive and various vibratory techniques (Warrick, 1974). Scholte waves and Love waves have been used to estimate shear wave velocities in surficial sediments by numerous investigators (Rauch, 1986; Akal et al., 1986; Snoek, to be published).

Hamilton (1976,1980,1987), in recent reviews of in situ measurements of shear wave velocity, found that the relatively few good measurements had such a wide range of values as to make the prediction of shear wave velocity in surficial sediments difficult and tenuous. Hamilton reported typical velocities of 50–150 m/s in the upper meter of clays increasing to 100–200 m/s at 10 m depth. Sands had similar values for the upper meter of the sediment increasing to 200–300 m/s at 10 m.

Numerous attempts have been made to measure shear wave velocity of natural and artificial sediments in the laboratory. Many of these measurements have been based on the ceramic bender transducer technology pioneered by Shirley (1978). Shear wave velocities have been measured on freshly cut cores (Richardson, 1983; Richardson et al., 1987; Schultheiss, 1985; Lavoie, to be published). Shear wave velocities have also been measured on artificial sediments at atmospheric pressure (Horn, 1980; Brunson and Johnson, 1980) and under confining pressures meant to represent consolidation under several meters of sediment (Schultheiss, 1981). Lovell and Ogden (1984) measured shear wave velocity gradients on both surficial and naturally consolidated sediments under confining pressures representing 0–400 m overburden pressure. Laboratory measurements of shear wave velocity have also been made using the resonant column test (see Hardin and Richart, 1963 for a review of these techniques). Shear wave velocities as low as 2 m/s have been reported for artificial sediments created from settled kaolinite (Shirley and Hampton, 1978), and typical velocities of 20 m/s (silts and clays) and 50 m/s (sands) have been reported for surficial sediments collected with cores (Richardson et al., 1987).

Seismic refraction techniques (Danbom and Domenico, 1987) have also been used to determine shear wave velocities in marine sediments but these techniques integrate shear wave velocities over profiles kilometres long and hundreds of meters thick. More short-range seismic experiments, such as those reported by Stoll et al. (1988) are required to determine sediment geoacoustic properties in the upper few meters of sediments. Recent advances in deep-towed seismic sources and receivers will also increase the vertical resolution of these techniques (Fagot, 1986).

Shear wave velocity can be estimated using the empirical relationships of Hamilton (1971,1976,1987), Bryan and Stoll (1988) or calculated from physical models such as the Biot/Stoll Model (Ogushwitz, 1985; Biot, 1962; Stoll, 1980). Both models (given appropriate depth-dependent input parameters), as well as empirical relationships, can be used to estimate shear wave velocity with depth in the sediment. The relatively few shear wave measurements, differences in measurement techniques and a controversy about the actual physical mechanisms that control this type of low-strain acoustic propagation have lead to a rather confused picture as to the actual velocities of shear waves in surficial marine sediments.

It is the purpose of this report to compare values of shear wave velocity obtained both in situ and in the laboratory using similar measurement techniques. The existence of an empirical relationship between in situ and laboratory shear wave velocity is explored. Empirical relationships between in situ shear wave velocity and easily measured sediment physical properties are examined. Hamilton (1987) laments the lack of in situ measurements in modern marine sediments. The data we present and measurement techniques we develop will help fill this void and lead to an improved fundamental understanding of the propagation of acoustic waves through marine sediments.

2
Materials and methods

2.1. GENERAL

Eight sites were chosen to represent a wide selection of sediment types within diving depths (Fig. 1). Several of the sites have been the locations for saclantcen acoustic and geoacoustic experiments conducted over the last six years (Akal et al., 1984,1986; Richardson, 1986; Rauch, 1980,1986; Schmalfeldt, 1986; Snoek et al., 1986; Snoek and Rauch, 1987; Snoek, to be published).

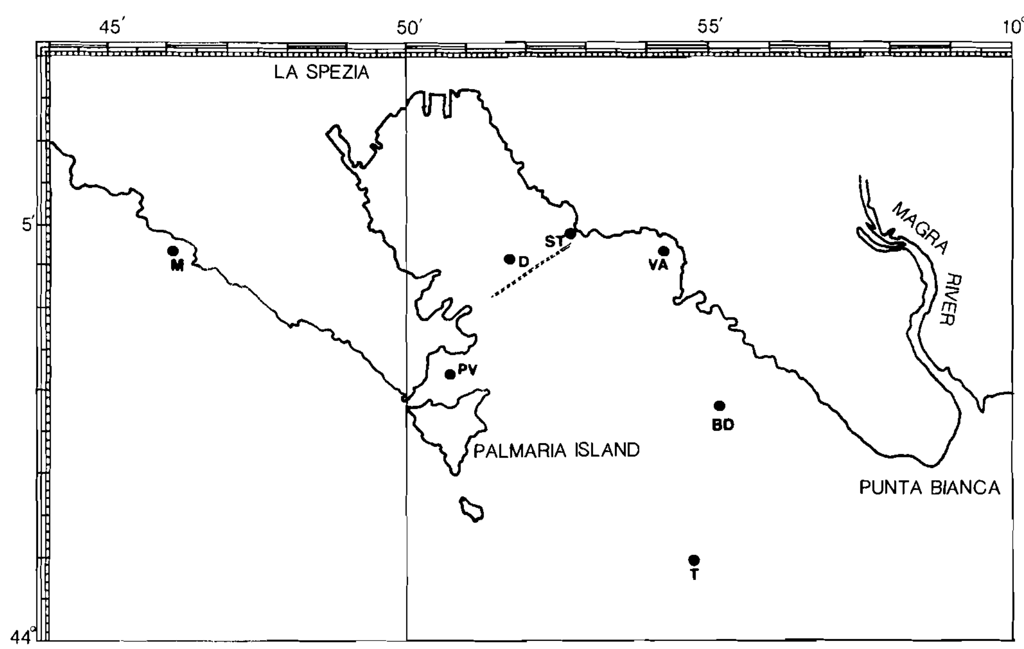

Fig. 1. Location of sampling sites: Diga (D), Venere Azzura (VA), Santa Teresa (ST), Portovenere (PV), Turf (T), Boa Dragaggio (BD) and Monasteroli (M). Viareggio site (43°48.62′N, 10°07.16′E) was 33 km southeast of Palmaria Island.

Sediments were collected using a 12.0 cm inside diameter PVC hand-operated corer.

At least three cores were collected at each site. Nearbottom temperature and salinity were measured by scuba divers using hand-held probes. In situ shear wave velocity measurements were made with the probes described in the next section. At least three deployments were made at each station. Sediment cores were carefully transported to the laboratory and kept under refrigeration at 4 °C until laboratory shear wave velocity measurements were made. After the acoustic measurements, sediment samples were collected from each core for mass property determination.

A summary of environmental conditions for each station occupancy is given in Table 1. During our study measured salinities ranged from 37.5 to 38 ppt and are not reported for each deployment.

Table 1
Summary of environmental conditions for the eight sampling sites (some sites sampled more than once)

Site	Depth (m)	Date	Temperature (°C)	Sediment type	Porosity (%)	Density (g/cm^3)
Diga	7	6–7 October '87	26.0	silty-clay	69.2	1.54
Diga	7	14 March '88	12.4	silty-clay	68.9	1.54
Venere Azzura	7	15 March '88	12.5	sand	47.1	1.88
Santa Teresa	10	17 March '88	12.5	silty-clay	67.5	1.54
Portovenere	12	18 March '88	12.5	silty-clay	63.4	1.63
Turf	18	27 April '88	14.5	silty-sand	50.8	1.83
Diga	7	28 April '88	14.5	silty-clay	–	–
Boa Dragaggio	14	30 April '88	14.5	sand/silty-clay	57.9	1.71
Venere Azzura	7	25 July '88	24.1	sand	–	–
Monasteroli	16	26 July '88	19.5	sand	43.7	1.91
Turf	18	28 July '88	18.8	sand/silty-clay	52.6	1.77
Viareggio	22	29 July '88	19.5	silty-clay	61.9	1.60

2.2. *IN SITU MEASUREMENTS*

Sediment shear wave velocity was measured using a pulse technique. Transmitters and receivers were identical 1.25 in (31.75 mm) square × 0.019 in (0.48 mm) thick bimorph ceramic benders (Fig. 2). The ceramics were potted in a stainless steel ring with silicone rubber (Shore A = 35) to allow relatively unrestricted bender movement. A thin covering of much harder polyurethane resin (Shore A = 80) holds the ceramics in place and provides a tough coating to protect the ceramics during insertion into the sediment. The received signals were amplified using a 40 dB gain amplifier located in the head of the receiver probes. A block diagram of the shear wave measurement system is presented in Fig. 3. Shear waves are generated as a 6-cycle sine wave pulsed every 10 ms. Driving frequency (135–1120 Hz) and driving voltage (150–230 V p-p) varied depending on coupling characteristics, sediment shear wave velocity and attenuation and the pathlength between receiver and transmitter. Transmitted and received signals were recorded with a digital waveform recording oscilloscope.

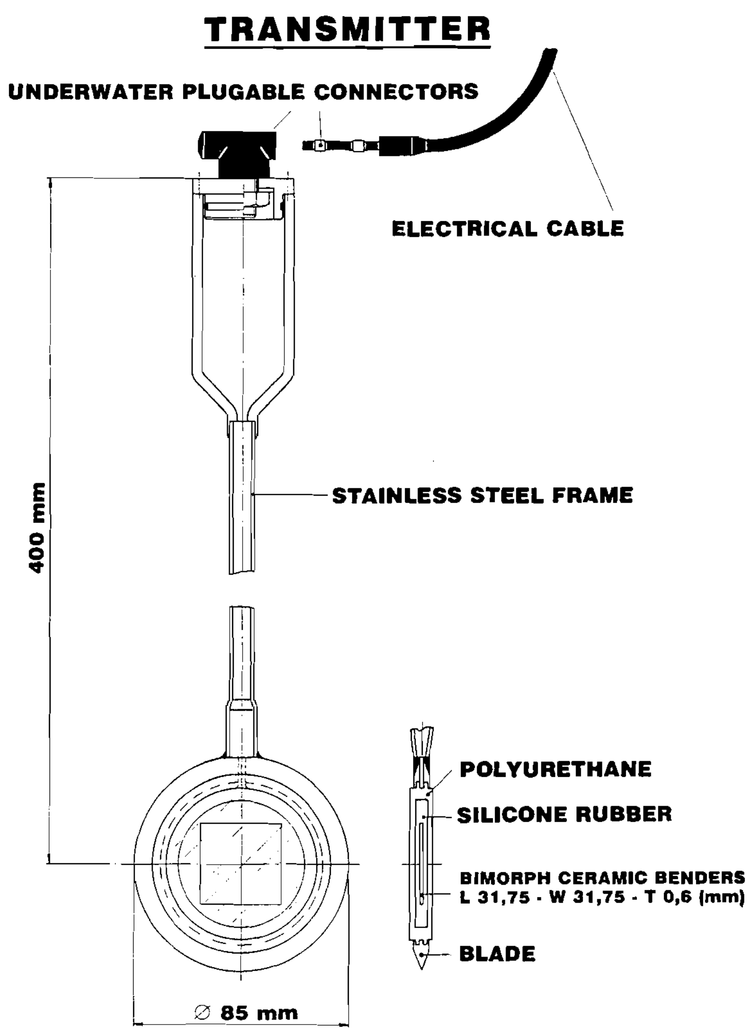

Fig. 2. In situ shear wave transmitter.

In October 1987 three isolated probes were used to test the system at the DIGA site. The transmitter was placed by hand at 30 cm depth in the sediment, and two receivers were inserted to 30 cm depth 200 cm on either side of the transmitter. The probes were inserted by hand to eliminate any electrical or mechanical connection between probes. After time-delay measurements were made, the receivers were moved successively in 25 cm intervals closer to the receiver. The resulting 17 distance *vs* time delay were plotted (Fig. 4) to determine the shear wave velocity (25.4 m/s) and offset at 0 distance (0.013 cm). Receivers were then rotated 180° to demonstrate phase reversal of the received signal, a characteristic of shear and not compressional wave received signals.

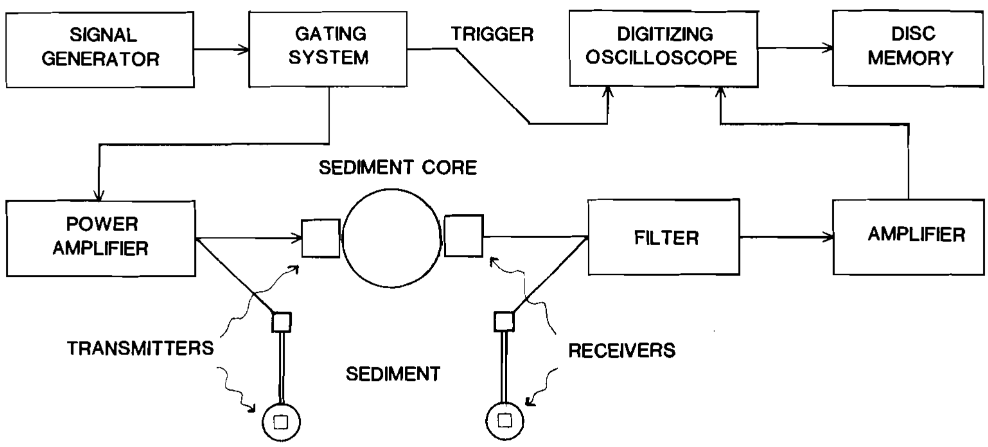

Fig. 3. Block diagram of in situ and laboratory shear wave measurement system electronics. Preamplifiers (40 dB gain) located in the receivers are not shown.

The beam pattern of the combined transmitter/receiver system was investigated by rotating the receivers in a semicircle (50 cm radius) around the transmitter. The resultant 1.0 and 12.0 dB loss of signal at 45° and 90° suggests a wide beam pattern in the horizontal axis. A wide beam pattern in the vertical axis was demonstrated in a similar manner. These October trials proved the shear wave probes could be used to accurately measure shear wave velocity up to distances of 200 cm and because of the relatively wide beam pattern were insensitive to small changes in relative orientation.

In the March trials, the shear wave probes were rigidly attached to a 200 cm long stainless steel frame. The receivers were placed at 30 and 70 cm distance from the transmitter. A small amount of energy passed through the frame complicating the time-delay measurements. We were able to visually separate the frame and sediment born signals by making time-delay measurements over a wide range of frequency (100–5000 Hz). In April the shear wave transmitter was potted in a 70 mm × 190 mm

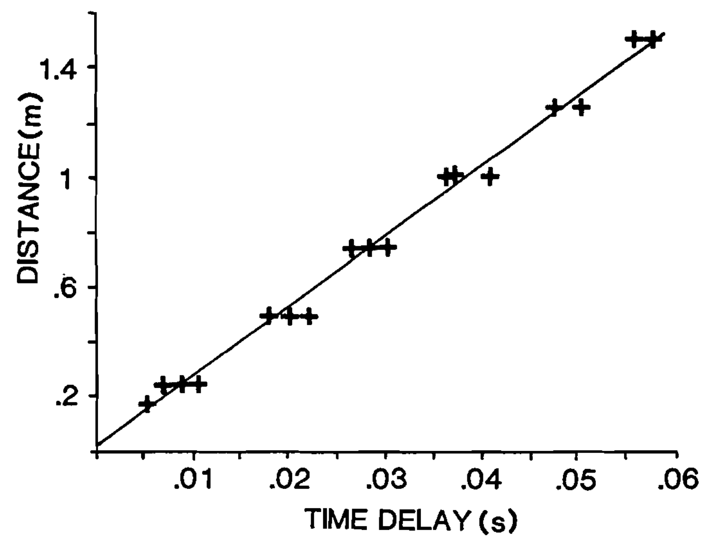

Fig. 4. Shear wave velocity (25.4 m/s) calculated from repetitive distance and time delay measurements.

cylinder of silicone rubber which eliminated most the energy transmission through the frame. For added isolation the receivers were similarly potted for the July trials. The frame used for the April and July measurements was triangular (100 cm on a side) and held four compressional wave probes in addition to the shear wave probes (Fig. 5). Examples of received signals are presented in Fig. 6.

The current frame requires divers to deploy in order to avoid damage to the delicate probes. The next generation frame has been designed to operate independent of divers and will contain probes to measure sediment temperature and electrical resistivity in addition to sediment shear and compressional wave velocity and attenuation. In this report we restrict ourselves to the presentation of in situ shear wave velocity.

2.3. LABORATORY MEASUREMENTS

Laboratory shear wave velocity measurements were made using the pulse technique described by Richardson et al. (1987). Shear waves were generated and received by bimorph ceramic bender elements which were cantilever mounted to a brass mass (Fig. 7). Transducers were electrically and mechanically isolated from each other with a generous amount of rubber foam (Fig. 7), and the sediment was grounded to the electronics to eliminate electromagnetic feedover. The transmitter was driven by a 150–200 V p-p pulsed sine wave. Driving frequencies ranged from 150–1500 Hz depending on sediment type. The same electronic instruments were used to generate

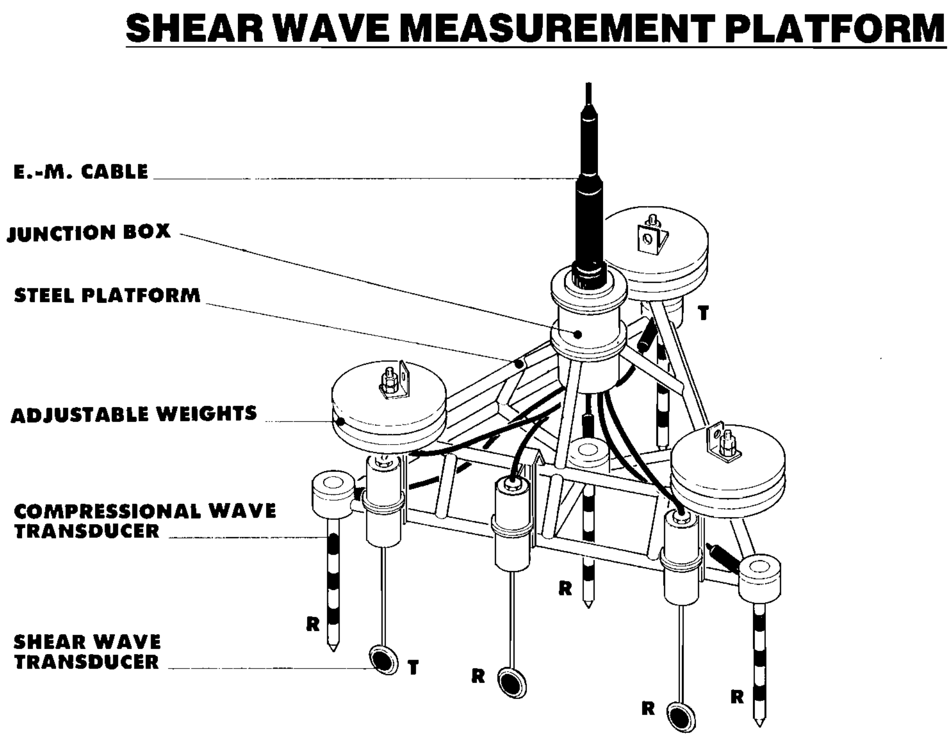

Fig. 5. Acoustic measurement system as deployed in April and July 1988.

and record signals for in situ and laboratory shear wave measurements (Fig. 3). Examples of transmitted and received signals are presented in Fig. 8.

Most time-delay measurements were made on sediments which remained in the 12 cm PVC cores. We drilled 3 cm diameter holes in opposite sides of the core liner, snugged the transducers to the sediment, and recorded both time delay and distance between transmitter and receiver. Received signals were observed over a wide frequency range in order to separate shear wave signals transmitted through the sediment from those signals propagating along the core-sediment interface. Signals propagating along the core-sediment interface had lower amplitudes, much narrower band widths and shorter time delays than shear wave signals transmitted through the sediment. Values of shear wave velocity measured on sediments removed from the cores were not significantly different from sediments remaining in cores, suggesting we successfully separated these signals. A time delay was subtracted from each measurement to account for the transit time of the signal through the electrical and mechanical system. This correction factor, measured with transducers touching, ranged from 2–14% of the sediment time-delay measurements (Fig. 8).

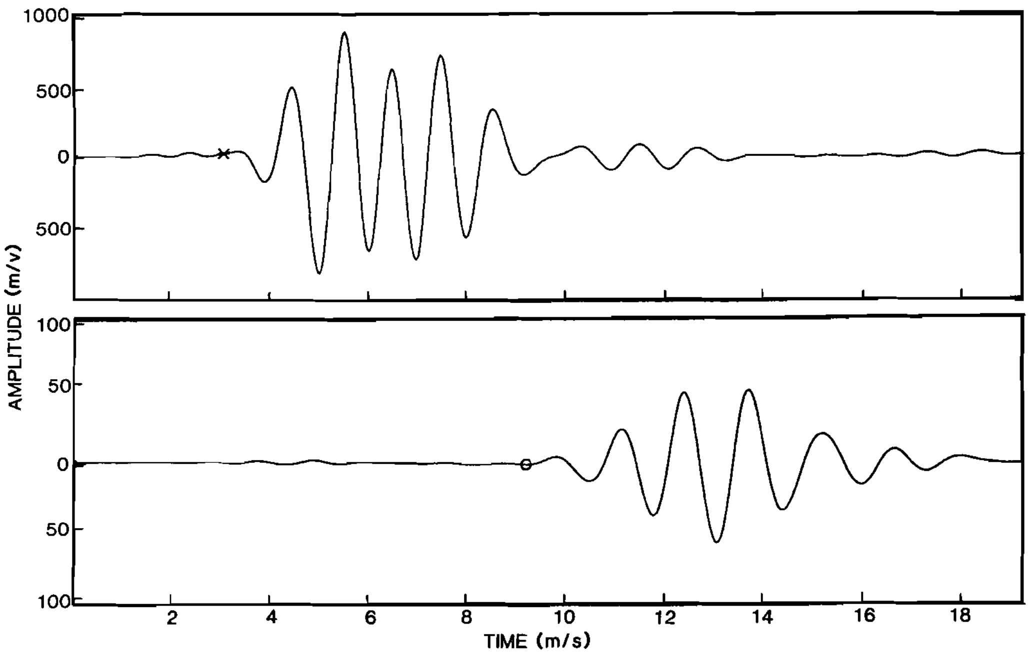

Fig. 6. Examples of signals recorded from two shear wave receivers at the Venere Azzura site. Calculated shear wave velocities were 88.2 m/s at 33 cm (top) and 82.4 m/s at 71 cm (bottom) distance between probes.

Sediment subsamples were collected from the cores after laboratory shear wave measurements were completed. Dry-sediment density was determined with a helium pycnometer. Sediment porosity, void ratio and wet density were calculated from weight loss of the sediment dried in a oven at 105 °C for 48 h and the measured dry density (Kermabon et al., 1969).

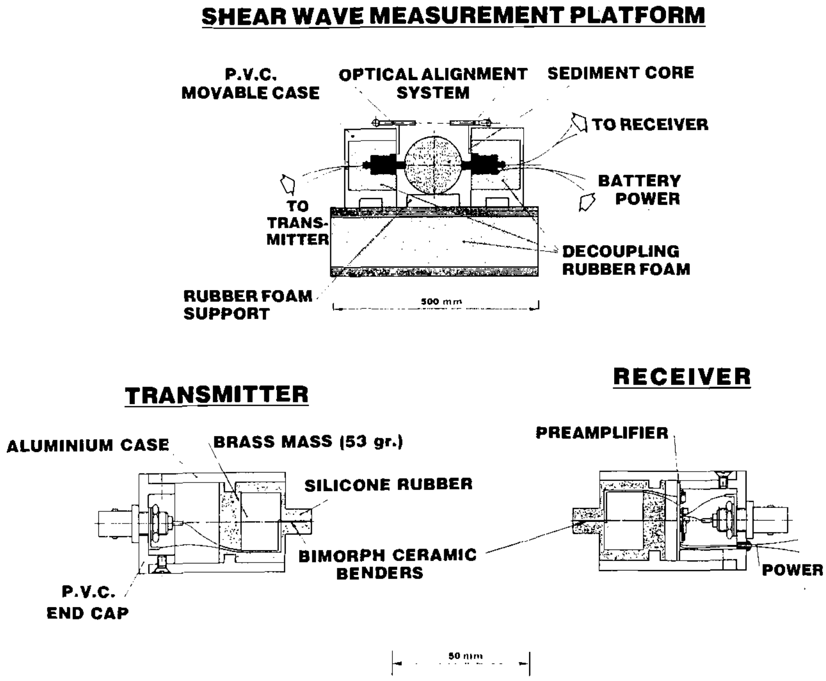

Fig. 7. Laboratory shear wave measurement system.

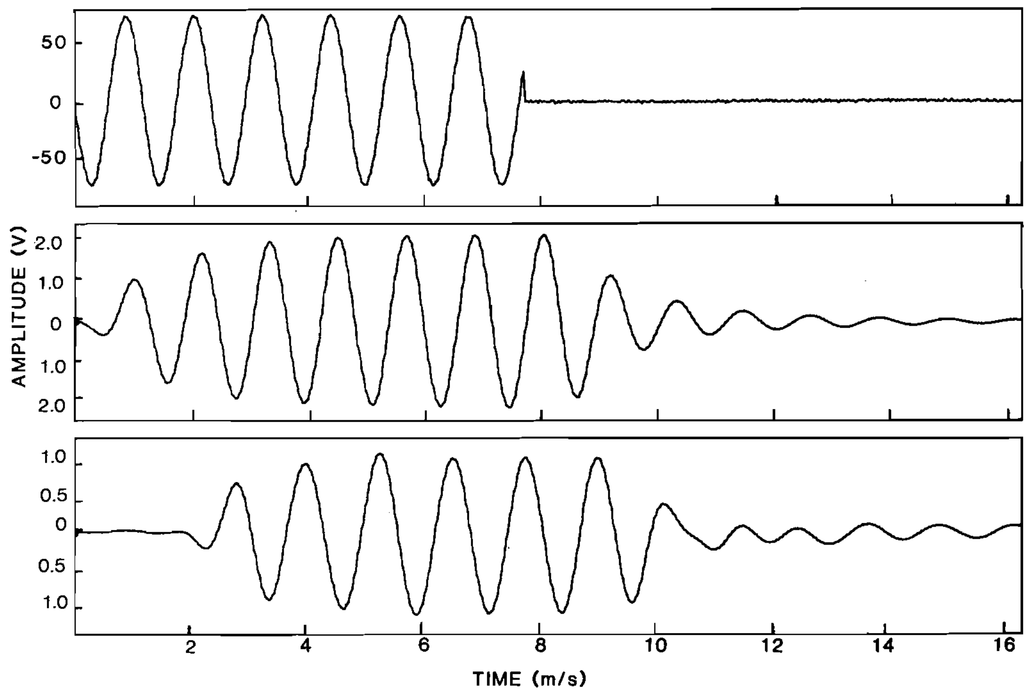

Fig. 8. Examples of transmitted (a) and received signals for cored sediments collected at the Monasteroli site. The time delay with transducer and receiver touching (0.14 ms in b) was subtracted from time delay measured across 11.5 cm of sediment (1.86 ms in c) to calculate a shear wave velocity of 66.9 m/s for this sandy sediment.

3

Results

Values of in situ sediment shear wave velocity ranged from 16.4 m/s in the silty-clay sediments of Santa Teresa to 90.5 m/s in the hard-packed fine sands at Monasteroli (Table 2). Mean values of shear wave velocity measured on core sediments collected from the same locations were 6.5–22.1 m/s less than mean in situ values. Shear wave velocity (in situ and laboratory) was negatively correlated with porosity and void ratio and positively correlated with sediment wet density (Table 3).

Table 2
Summary of values of shear wave velocity measured in situ and from core samples in the laboratory

Site	Date	V_s (in situ) (m/s)		V_s (lab) (m/s)	
		mean	range	mean	range
Diga	6–7 October '87	25.4	22.0–27.0	15.6	13.7–18.1
Diga	14 March '88	27.0	25.8–28.2	16.2	11.9–19.8
Venere Azzura	15 March '88	78.8	65.7–89.9	61.4	60.5–62.9
Santa Teresa	17 March '88	19.7	16.4–23.3	13.2	10.2–15.4
Portovenere	18 March '88	29.3	24.8–37.4	14.3	10.5–16.8
Turf	27 April '88	41.7	33.7–57.9	24.4	22.6–25.6
Diga	28 April '88	23.6	19.5–28.1	–	–
Boa Dragaggio	30 April '88	40.2	37.0–45.3	22.4	19.2–29.1
Venere Azzura	25 July '88	77.4	69.7–88.6	–	–
Monasteroli	26 July '88	83.4	75.7–90.5	61.3	55.6–70.8
Turf (sand)	28 July '88	74.0	72.1–75.7	53.7	46.6–61.1
Turf (silty-clay)	28 July '88	41.6	34.6–46.8	21.1	16.8–25.1
Viareggio	29 July '88	27.1	24.1–33.0	14.9	12.9–17.9

Table 3
Pearson product-moment correlation coefficients (r) calculated between values of in situ and laboratory shear wave velocities (m/s) and sediment physical properties

	Porosity (%)	Void ratio (%)	Wet density (g/cm^3)
V_s (lab)	−0.85	−0.82	0.85
V_s (in situ)	−0.91	−0.87	0.92

4

Discussion

The graphic relationship presented in Fig. 9 suggests that laboratory values of shear wave velocity can be corrected to in situ conditions using the following formula:

$$V_s\,(\text{in situ}) = 10.43 + 1.17V_s\,(\text{lab}).$$

In spite of the high correlation between these two measurements (R-square = 0.975), this formula should be applied with caution to other data sets. The relationship applies only to surficial sediments and should not be extrapolated outside of the limited range of sediment types presented in this paper.

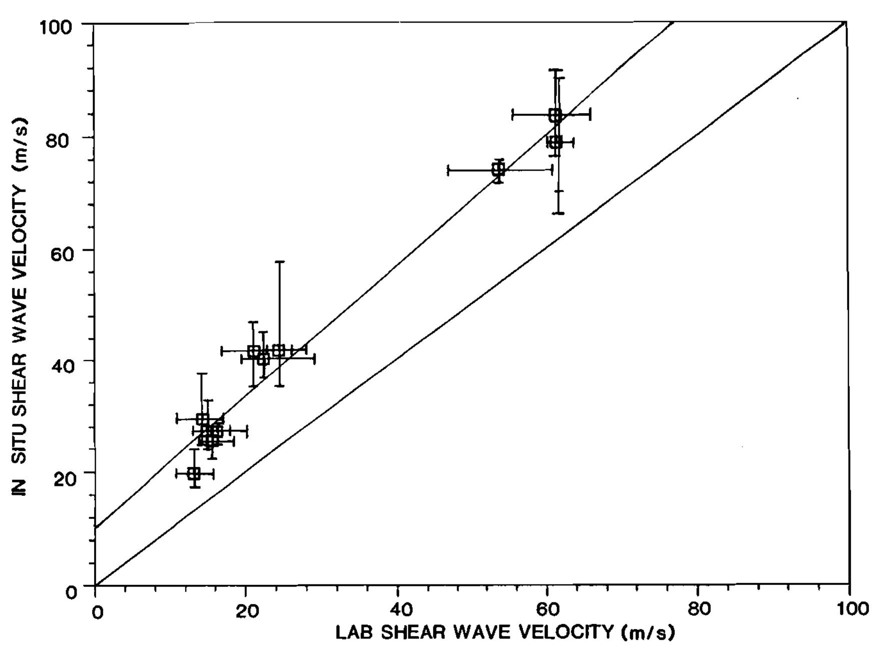

Fig. 9. Comparision of laboratory and in situ shear wave velocities.

Richardson et al. (1987) listed several factors which might contribute to the differences in laboratory and in situ measured values of shear wave velocity. These included: (1) disturbance of sediments during collection, handling and measurement; (2) changes in pore pressure and/or physical characteristics which result from the release of confining pressure when sediments are removed from the bottom; (3) differences in frequencies used for measurements; (4) differences in techniques used to measure shear wave velocities or shear modulus; (5) poor measurement techniques and (6) natural variability of shear wave velocity in sediments. We can add (7) changes in sediment temperature, (8) differences in strain values used for measurements and (9) predicted strong vertical gradients in near surface shear wave velocity.

We can dismiss six of these factors for the current comparisons. In situ and laboratory shear wave velocity measurements were made with the same type of transducers at approximately the same frequencies and strain levels. Both laboratory and in situ transmitters were driven with a 150–230 V p-p pulsed sine wave. The resultant behaviour of the sediments under these low strains ($< 0.00001\%$) is considered purely elastic, yielding the maximum values of dynamic shear modulus and shear wave velocity (Davis and Bennell, 1986). The resonant frequency of the pulsed sine wave, for both in situ and laboratory probes, ranged from 135–1500 Hz, depending on the mechanical impedance of the sediment. This frequency was generally lower for muds (135–430 Hz) and higher for sands (300–750 Hz). The time-delay measurements for single sediment specimens varied less than 5% over a wide frequency band (100–3000 Hz). The range of natural variability of values of shear wave velocity is presented in Fig. 9 and preserves the basic relationships as reported. Values of shear wave velocity measured at sites sampled more than once were not significantly different in spite of differences in sediment temperature. Although great care was used to develop accurate measuring techniques, we can not rule out systemic errors caused by poor techniques. The most likely causes for the lower laboratory shear wave velocities are sediment disturbance during collection, transportation, storage and measurement both by mechanical manipulations and by a reduction in sediment confining pressures.

Numerous comparisons between values in situ and laboratory shear wave velocity have been made for terrestial sediments using cross-hole and/or down-hole seismic techniques and laboratory resonant column tests (Anderson et al., 1978; Arango et al., 1978; Anderson and Woods, 1975; Cunny and Frey, 1973; Stokoe and Richart, 1973). Care must be taken in comparing these results to ours because strain amplitude, effective stress, time and frequency of vibration must be accounted for (Davis and Bennell, 1986). Laboratory resonant column tests were run on sediments that had been subjected to effective confining pressures of up to 100 m, brought to the surface then compressed to in situ pressures. This can result in permanent changes in sediment microstructure. Our samples had no such stress history and no attempt was made to return sediments to in situ surficial conditions. In spite of these major differences our results are in general agreement with these comparisons for terrestial sediments. Stoll et al. (1988) reported values of in situ dynamic shear modulus to be 1.3–2.5 times the laboratory values. This is in general agreement with a comparison of in situ and laboratory dynamic shear moduli (mean 2.77; range 1.68–4.5) calculated from values of shear wave velocity for this study (Table 4).

Table 4
Comparison of calculated and measured values of sediment dynamic modulus[1]

Site	Date	Void ratio	Dynamic shear modulus (atm)		
			calculated	lab	in situ
Diga	6–7 October '87	2.23	2.7	3.7	9.8
Diga	14 March '88	2.23	2.7	4.0	11.1
Venere Azzura	15 March '88	0.90	23.6	70.0	115.2
Santa Teresa	17 March '88	2.08	3.3	2.6	5.9
Portovenere	18 March '88	1.75	5.8	3.3	13.8
Turf	27 April '88	1.04	18.0	10.8	31.4
Boa Dragaggio	30 April '88	1.41	10.4	8.5	27.3
Monasteroli	26 July '88	0.78	29.0	70.9	131.1
Turf (sand)	28 July '88	0.75	30.3	54.1	102.7
Turf (silty-clay)	28 July '88	1.13	15.7	7.8	30.3
Viareggio	29 July '88	1.63	6.8	3.5	11.6

[1] Dynamic shear modulus was calculated from the empiricial relationship between void ratio, confining pressure (effective stress) and shear modulus given by Bryan and Stoll (1988).

Akal et al. (1984, 1986) reported velocities of ducted Love waves from four of the sites occupied during this study. Measurements were made at short ranges (< 25 m) using stacked received signals from up to five ocean-bottom seismometers in series. Values of Love wave velocity (considered by Akal equivalent to values of shear wave velocity) at the Santa Teresa (16 m/s), Portovenere (30 m/s), Venere Azzura (65 m/s) and Monasteroli (90 m/s) sites were similar to in situ shear wave velocity values reported here. Akal's measurements at the Monasteroli site were for sandy-gravel sediments in contrast to sandy sediments we collected. The depth of propagation of Love waves in the sediment was estimated to be between 0–3 m, complicating comparisons between techniques.

Bryan and Stoll (1988) summarised the effects of overburden pressure p' and void ratio e on sediment dynamic modulus μ with the following relationship:

$$\mu = \mu(p'/p)^n e^{te},$$

where $\mu = 2526$ atm, $n = 0.50$ and $t = -1.5$. The formula was based on 494 concurrent laboratory measurements of dynamic shear modulus, confining pressure and void ratio compiled from the literature. Using an average depth of 30 cm, we calculate the sediment dynamic modulus for each of our sample sites from the values of void ratio and wet density (Table 4). Sediment dynamic modulus μ was also calculated from mean values of sediment shear wave velocity V_s and wet density ρ using the following:

$$\mu = V_s^2 \rho.$$

Values of calculated sediment dynamic modulus were more similar to laboratory measured values than in situ values, as expected. The rapid increase in predicted dynamic rigidity in the upper meter of sediment makes more exact comparison difficult.

Sediments held in the laboratory at 0 atm confining pressure support shear waves and therefore have a measurable dynamic shear modulus (Tables 2 and 4). We suggest that this laboratory modulus is less than or equal to the minimum in situ measurable surficial sediment dynamic modulus (i.e. at 0 atm confining pressure) for that sediment. In the marine environment biological, chemical and physical processes alter surficial sediment (upper 1 m) properties (Richardson and Young, 1980; Richardson et al., 1983; Richardson, 1983). Most of these processes increase sediment dynamic rigidity by compacting the sediment or chemically increasing sediment rigidity. Most surficial marine sediments are, therefore, overconsolidated compared to laboratory compressed sediments (see Richards, 1984 for an essay on the apparent overconsolidation of marine sediments). Modification of the formulations of Hamilton (1987) and Bryan and Stoll (1988) may be needed to predict sediment shear wave velocity gradients in the upper meter of sediment.

The empirical relationships between in situ sediment shear wave velocity and easily measured sediment physical properties (Fig. 10) provide reasonable estimates of surficial shear wave velocities for most marine sediments. Additional concurrent measurements are required to refine and extend this relationships to other sedimentary provinces. Hamilton (1971) suggests shear wave velocities should be highest in very fine sands with porosities of 45–55%. Sediments coarser and finer should have lower values of shear wave velocity because of a reduction in dynamic rigidity. The empirical relationship presented by Bryan and Stoll (1988) predicts an increase in sediment dynamic rigidity with increasing void ratio values over the range of 0.35–1.5%. Additional measurements of shear wave velocities are required to extend our empirical relationships to coarse sand and gravel sediments.

The rapid increase in shear wave velocity predicted for the upper few meters of sediment in reviews by Bryan and Stoll (1988) and Hamilton (1976,1980,1987) complicates comparison and predictions of sediment shear wave velocity. These empirical predictions were based on laboratory measurements of artificial, terrestial and marine sediments and extrapolation of in situ seismic measurements to the upper few meters. Very little data are available on the gradients of in situ shear wave velocity in the upper few meters of marine sediments. An extensive measurement program

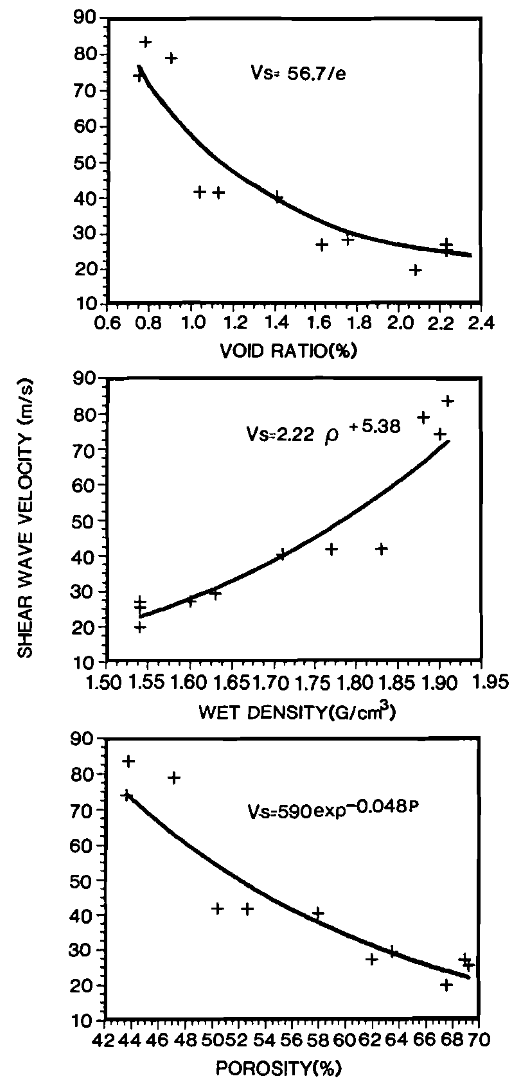

Fig. 10. Empirical relationships between in situ shear wave velocity and sediment physical properties.

is, therefore, required to define the variability and vertical gradients of shear wave velocity in marine sediments.

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