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DIAS—a novel technique for measuring in situ shear modulus

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Abstract DIAS (duomorph in situ acquisition system) is an alternate technology requiring a single duomorph probe for measuring shear modulus in situ. The duomorph probe is a bending plate device that is vibrated and the resulting deflections measured using strain gauges. The ratio between the unconstrained bending of the duomorph in air and the constrained bending in sediment is a function of the sediment dynamic modulus from which shear modulus is calculated. This paper describes the theory underlying the DIAS system, the design of the system, the data reduction methods, and results from the initial deployment of the prototype system in Eckernförde Bay.

Introduction

Accurate measurements of sediment elastic moduli are required for better prediction of acoustic scattering and propagation and for many engineering applications. Because sediments cannot be sampled and analyzed in the laboratory without significant disturbance and, hence, changes in sediment properties, in situ measurements are desirable. In situ sediment geoacoustic properties are generally measured using pulse techniques (e.g., Richardson et al. 1990, 1991; Barbegelata et al. 1991; Richardson and Briggs 1996) that require multiple probes and accurate knowledge of probe placement, which is difficult to measure accurately in the marine environment. DIAS, an alternate technology requiring a single duomorph probe for measuring shear modulus, is currently being developed at the Naval Research Laboratory.

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Background

The duomorph technology, used successfully in the laboratory under low effective stresses (Breeding and Lavoie 1988; Lavoie 1990) has now been repackaged as a probe for in situ use that can be deployed from a line or, alternately, by a diver. The duomorph is a bending plate device that is vibrated, and the resulting deflections measured. The device consists of a stainless steel plate sandwiched between a pair of piezoceramic crystals with metallic strain gauges glued to the center of each crystal (Fig. 1). The piezoceramic crystals are low-power, electromechanical transducers capable of converting electrical energy to mechanical energy and vice versa. When stimulated by an alternating current, the duomorph vibrates with a parabolic shape. The ratio between the unconstrained bending of the duomorph in air and the constrained bending in sediment is a function of the sediment dynamic elastic modulus.

Duomorph Theory

The underlying concept of the duomorph is based upon the interaction of a plate subject to deforming stresses and the surrounding medium. The duomorph consists of a thin steel plate sandwiched between two piezoceramic crystals in a symmetric fashion. When an exciting voltage is applied to the piezoceramic crystals, their response stresses the steel plate. The plate deforms with a parabolic motion in response to this applied stress (Fig. 2). Because the stress is applied symmetrically, the neutral axis of the gauge does not shift; as the center of the gauge deflects to the left of the neutral axis, the edge shifts to the right and vice versa. Strain gauges attached at the center of each face allow for the measurement of this deformation. This deflection (magnitude and phase shift relative to the excitation) may be measured in air to determine the unconstrained response of the duomorph.

When the duomorph is subsequently embedded in an

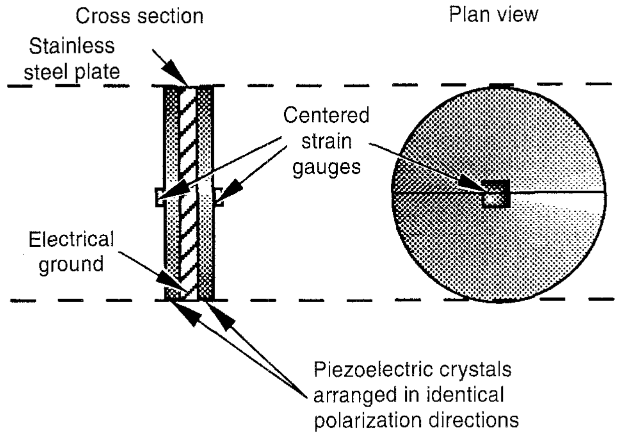

Fig. 1 Schematic diagram of the duomorph sandwich. The piezoceramic crystals are arranged with the polarities in the same direction. Strain gauges are centered on each crystal. The sandwich is excited with an alternating current that results in the parabolic vibration of the duomorph sandwich. The amplitude of the deflection is measured using the strain gauges

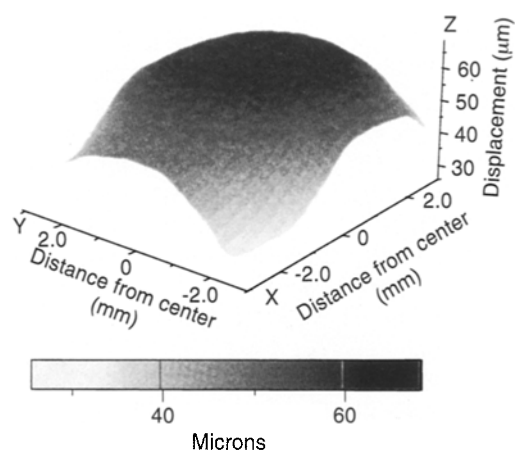

Fig. 2 The motion of the duomorph sandwich is measured using optical techniques. The tab to which the electrical wires are attached (right' side) affects the sandwich such that the motion is slightly aparabolic during excitation

elastic or viscoelastic medium, the characteristics of the medium will alter the response of the duomorph. Because the unconstrained response of the duomorph is known, the constrained response of the embedded duomorph, a result of the interaction between the duomorph and the medium, can be used to determine the characteristics of the medium.

Much of the following analysis of the duomorph and its interaction with the surrounding medium is based on the work of Briar et al. (1976). This analysis is structured in several parts. First, classical thin plate theory (after Timoshenko and Goodier 1970) is used to analyze the unconstrained motion of the duomorph in air. Next, continuum mechanics is used to model the effect of a stress imposed on an infinite elastic medium from an internal point. Finally, the coupling between the duomorph and the embedding medium, which relates the flexure of the duomorph when embedded in the medium to the mechanical properties of the medium, is considered. This analysis of the duomorph is subject to the following assumptions: (1) classical thin plate theory accurately models the behavior of the duomorph; (2) the sediment is elastic and infinite, and (3) inertial effects are negligible at the frequencies used (below 500 Hz). The analysis also indicates that sediment stresses and deformations are significant only within a cube having an edge length equal to twice the duomorph disk diameter.

The duomorph is symmetric about the center plane at $x = 0$ (Fig. 1; this analysis uses a cylindrical coordinate system and presupposes cylindrical symmetry). Excitation of the piezoelectric drivers causes strains in the duomorph sandwich equivalent to a concentrated edge moment being applied to the circumference of the disk; this moment is denoted by Mo. The applied moment causes the disk to deflect about the center plane of the sandwich; the neutral axis itself does not shift. This deflection assumes a parabolic shape; thus, during excitation the duomorph disk is a parabola of revolution alternately concave left and concave right. When the center of the disk is left of the $x = 0$ plane, the edge is to the right of the plane. (Actually a slight distortion in the parabolic shape occurs due to the presence of small tabs for the necessary electrical attachments. We envision that the next generation of duomorphs will have thin metal foil connections in an attempt to minimize deviations from a parabolic shape.)

Because a strain gauge is cemented to the center of the duomorph disk, strain at the center can be measured directly. The relationship between the moment applied to the edge of the disk and the strain at the center of the disk is given by the equation:

$$\varepsilon_C = \frac{h}{2(1+v)D} Mc + \varepsilon_0 \tag{1}$$

where ε_C is the strain at the center of the disk, h is the thickness of the duomorph sandwich (7.62×10^{-4} m), v is Poisson's ratio for the sandwich (0.33, estimated); ε_0 is the strain at the edge of the disk (since this version of the duomorph is symmetric, $\varepsilon_0 = 0$), and D is the flexural rigidity of the disk and may be computed from the mechanical parameters of the sandwich.

In air, the moment at the edge is equal to the moment at the center, and therefore $Mca = Moa = Mo$.

In addition, the plate deflection in air as a response to the applied edge moment Mo is given by:

$$W_m(R) = \frac{Moa^2}{2D(1+v)}\left(1 - \frac{R^2}{a^2}\right) \tag{2}$$

where $W_m(R)$ is plate deflection in the x direction at a radial distance R from the disk center due to the moment Mo, R is the distance from the center at which deflection is measured, and a is the radius of the disk.

To accomplish the second part of the analysis, a stress is applied to an interior point of a bulk elastic material normal to the $x = 0$ plane at the plane and the response calculated using the methods of continuum mechanics. If the stress is applied at a radial distance R from the origin and the response is measured at a point at a radial distance R' from the origin with ϕ the angle between these radii, the axial deflection (i.e., movement in the x direction) $w(R')$ is given by:

$$w(R') = \frac{3R'}{4\pi\hat{E}}[l_1 + l_2] \tag{3}$$

where $\hat{E} = \dfrac{(1-\nu)E}{(1+\nu)(1-\frac{4}{3}\nu)}$, E is Young's modulus, and ν is Poisson's ratio. Further,

$$l_1 = \int_0^1 P(R'x_1^{1/2})k(x_1)dx_1, \quad \text{and}$$

$$l_2 = \int_{(R'/a)^2}^1 x_2^{-3/2}P(R'x_2^{-1/2})k(x_2)dx_2$$

where P is the applied pressure at R, x_1 is R^2/R'^2, x_2 is R'^2/R^2, and $K(x)$ is the complete elliptic integral, defined as $K(x) = \int_0^{\pi/2}(1 - x\sin^2\phi)^{-1/2}d\phi$.

This analysis is further complicated by the fact that the pressure distribution P is not known a priori when the duomorph disk is the source of the pressure. Accordingly, a piecewise constant pressure distribution scheme is used. This method divides the disk into a central area and a series of concentric rings; the width of the rings decreases as the edge of the disk is approached. By superposition, the total result is the sum of the deflections from each of these sources.

Finally, the interaction between the duomorph disk and the medium is considered. Again by superposition, the deflection of the gauge is the sum of the deflections due to the applied moment (the excitation) and to the force on the disk due to the attempted displacement of the bulk medium (the medium response). Again, this is calculated by dividing the system into a central area and a series of concentric rings. This leads to a system of equations in matrix form given by:

$$[W]\{q\} = \{l\} \tag{4}$$

where the dimension of the system is the number of rings subdividing the disk. This system is solved for the vector of nondimensional pressures $\{q\}$, from which the ratio of the moment at the center to the moment at the edge (Mc/Mo) can be calculated.

Because strains at the center of the disk are measured directly using the attached strain gauges, Eq. (1) can be used to find the moment at the center of the disk in either air or the medium. Moreover, since in air the moment is uniform and $Mo = Mc$, this yields the moment at the edge in air. Furthermore, the moment at the edge in air and the moment at the edge in the medium are the same. Therefore, the ratio of the moment at the center in the medium to the moment at the edge in the medium is equal to the ratio of the strain at the center as measured by the strain gauges in the medium to the strain measured in air:

$$e_c/e_{ca} = Mc/Mo \tag{5}$$

In theory, Eqs. (2–4) can be used to determine Young's modulus E (or equivalently, its real and imaginary components E' and E'') by reversing the course of the analysis. In practice, this is not possible. The calculation is done by first assuming we know the characteristics of the surrounding medium and then computing numerically the effect of this medium on the gauge response using the methodology outlined above. From a series of such computations, a nomograph may be constructed that relates the gauge response and the material characteristics. Two computer programs written in FORTRAN are used for the numerical computation of the interaction and to automate the use of the nomograph.

Duomorph design

Duomorphs were built with varying thicknesses (0.0031, 0.002, and 0.0012 cm) of stainless steel plates in order to determine the best configuration for the sediment being analyzed. The piezoceramic crystals were obtained in two separate lots from Piezo Electric Products, Inc., Metuchen, New Jersey, 08840, USA. The piezoceramic crystals used were a G-1278 type, fired silver, with a thickness of 0.279 mm and a diameter of 2.54 cm. On each piezoceramic crystal, a 350-ohm resistance metallic strain gauge (obtained from MicroMeasurements Group, P.O. Box 27777, Raleigh, North Carolina, 27611, USA, was fixed. These gauges have a 0.152-cm gauge length, a 0.254-cm grid width, an overall length of 0.381 cm, and an overall width of 0.254 cm. They are an EA type, which measure up to 5% strain.

The stainless steel plate was sandwiched between the two crystals with the polarity of the two crystals in the same direction. Strain gauges were then fixed with adhesive to the crystals. Thin wires of equal length were carefully soldered to the crystals, the steel plate (ground), and the tabs on the strain gauge.

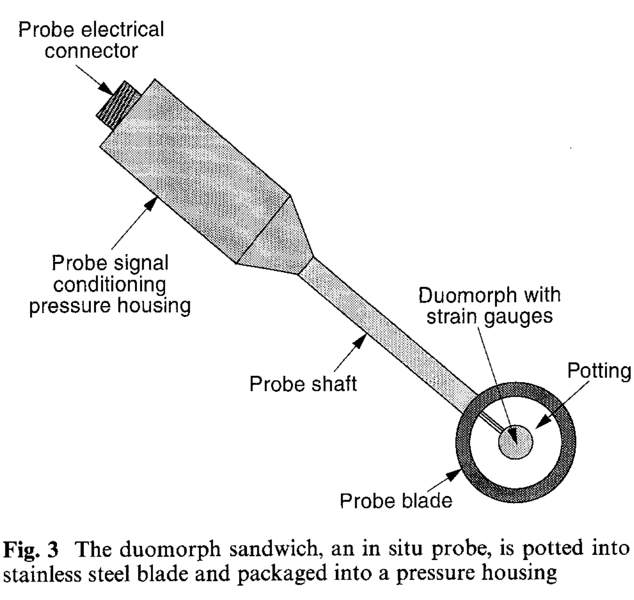

Fig. 3 The duomorph sandwich, an in situ probe, is potted into a stainless steel blade and packaged into a pressure housing

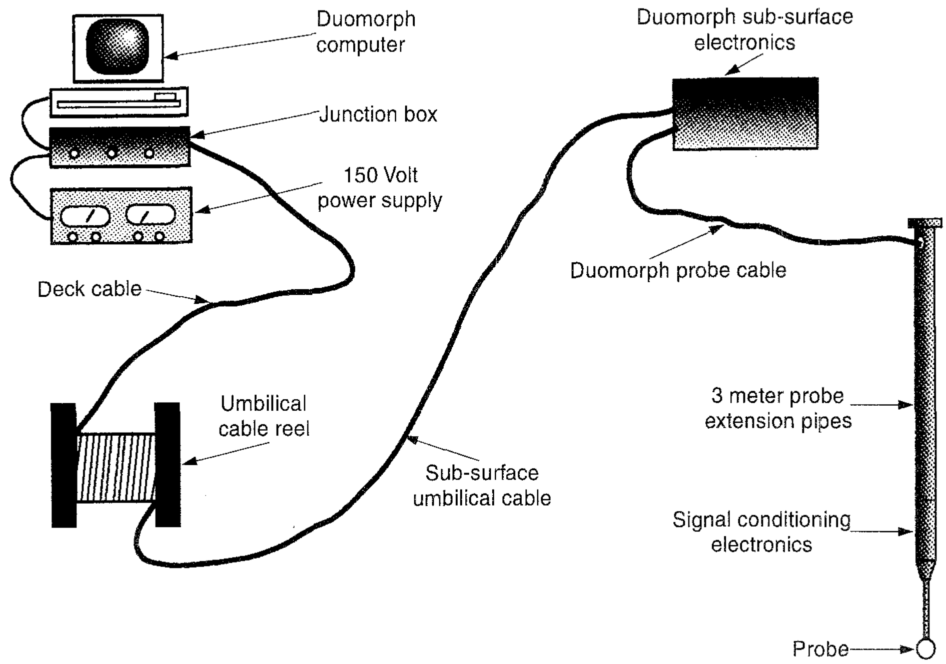

Fig. 4 The duomorph probe is connected to the subbottom electronics and controlled by a shipboard computer with custom software

This entire duomorph sandwich was potted into a circular, stainless steel probe blade using a low derometer multipurpose elastomer, TC 960 A/B (Fig. 3). The blade provides protection for the delicate ceramic sandwich during probe insertion. The blade is attached to a pressure housing with a hollow shaft. Three twisted shielded pairs (TSP) run through the shaft into the pressure canister where the signal conditioning electronics are located.

The data acquisition system consists of topside electronics, bottom-side electronics, and probe electronics. The topside electronics, a personal computer running custom-designed software, provides data storage, signal display, system control and data analysis functions. Communications to the bottom-side electronics is provided by an RS-422 serial interface. Power (150 V DC) is provided by a commercial switching DC power supply. A junction box interfaces the computer and power supply to the 100-m umbilical cable (Fig. 4).

Bottom-side electronics (Fig. 5) are housed in a 25-cm-diameter, 70-cm-long pressure canister. An IBM-compatible single board computer receives control information over the RS-422 bus and performs the requested operations. Signal digitization is performed by a four-channel, 1M sample/second, 12 bit A/D board. The sample rate of the A/D board is user selectable. A programmable function generator is used to produce the desired driving function and a custom built amplifier increases the signal power. Generally, the probe is driven by a 40-V peak-to-peak 250-Hz sine wave. The frequency is chosen to stay below probe resonance, and the amplitude is chosen as a tradeoff between overdriving the ceramic, which causes decoupling with the sediment, and signal digitization resolution.

Signal conditioning is provided by the probe electronics. These electronics provide bridge completion resistors for the strain gauges as well as a regulated supply voltage for the Wheatstone bridge. The strain gauge signals are

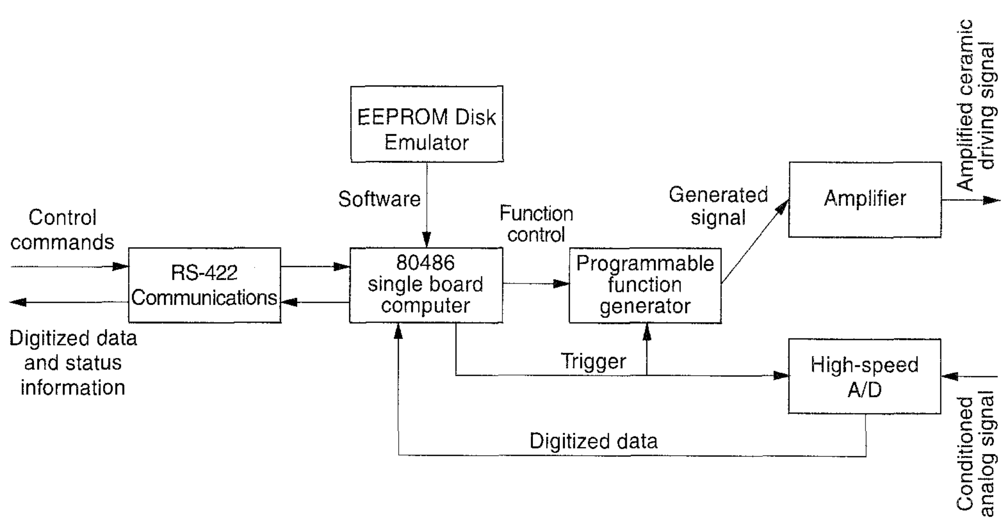

Fig. 5 Schematic illustration of the subbottom components of the DIAS system

amplified by a pair of two-stage preamplifiers that provide 72 dB of gain. The first stage of the amplifiers provides a 32-dB gain and low-pass filters the signal (4-kHz cutoff frequency). The second stage high-pass filters (10-Hz cutoff frequency) the signal and provides the remaining 40 dB of gain. The high-pass filter is important primarily to block any DC offset caused by static bending of the probe ceramic. This can be caused by shells or rock against the probe or insertion of the probe at an angle. With such high-gain amplification, a small DC offset can push the preamplifiers' output to the rail, inhibiting the dynamic measurements.

Data reduction

The methods used to reduce the sampled data are outlined below:

1. Phase and amplitude of the input and output voltages are measured by exciting the potted duomorph in air.
2. The amplitude of the in situ wave forms are directly proportional to the voltage; the displayed wave form on the computer represents the amount of dynamic strain detected by the strain gauges. The ratio of the voltage in air and in the sediment is used in the following equation to determine the modified moment ratio:

$$\left|\frac{Mc}{Mo}\right| = \frac{(es/ea) - k}{1 - k} \tag{6}$$

where es is the voltage (strain) in sediment under a load, ea is the voltage (strain) in air, and k is the electromechanical coupling coefficient, a measure of the piezoelectric effect. This is a constant dependent on disk design (for the duomorph with a 0.008-cm steel plate, $k = -0.664$) (Briar et al. 1976).

$$\frac{1}{k} = 1 - \frac{3\beta\, hz(hz + t)(2 + Est/Ez\, hz)}{h^2[1 + (Es/Ez - 1)(t/h)^3]} \tag{7}$$

where β is 0.5 $(1 + hm/hz) = 0.86364$, hz is the thickness of the piezoceramic crystal, t is the height of the duomorph overall, Es is Young's modulus of steel plate, and Ez is Young's modulus of the piezoceramic crystal.

The modified moment ratio, $\left|\frac{Mc}{Mo}\right|$ is a complex value having both magnitude and phase. A nomograph has been constructed that is essentially two curves sharing a common independent axis M' for each value of the independent variable, $\tan\phi$ (Fig. 6). From this nomograph, values can quickly be found of M' and $\tan\phi$ used in the calculation of the sediment elastic modulus, E':

$$E' = \frac{M'D}{a^3} \tag{8}$$

where a is the radius of the duomorph and D is the disk flexural rigidity.

Shear modulus, G, and shear wave velocity, Vs, are determined as follows:

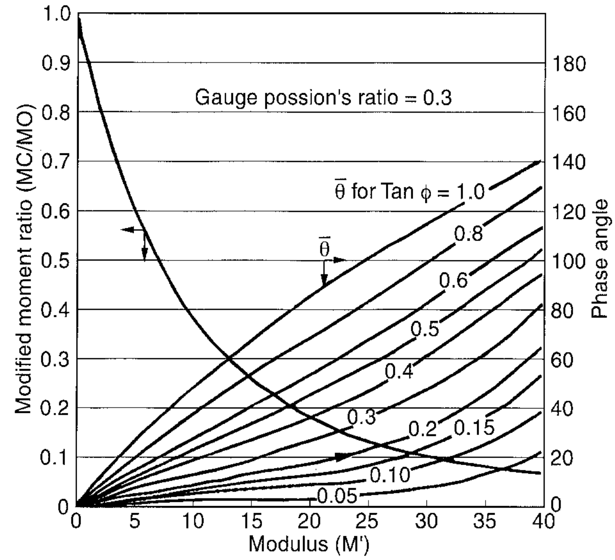

Fig. 6 Nomograph constructed to simplify the data analysis. The modified moment ratio is a complex value from which the magnitude and phase are determined; both are required for the solution of the sediment elastic modulus

$$E'' = E' \tan\phi \tag{9}$$

$$|E^*| = \sqrt{E'^2 + E''^2} \tag{10}$$

$$G = \frac{|E^*|}{2(1 + v)} \quad \text{(from Hamilton 1971)} \tag{11}$$

v is Poisson's ratio.

$$Vs = \sqrt{\frac{G}{\rho}} \tag{12}$$

where ρ is the measured density.

Eckernförde Bay results

The DIAS system was deployed for the first time in Eckernförde Bay in an area of soft muddy sediments within the Baltic Sea. Initial shear modulus measurements were made on deck under controlled conditions in box cores 168 and 175. The initial probe insertion in box core 168 clearly caused the pore pressure around the probe to increase in both box cores. The amplitude of the early received signals was significantly higher than for subsequent waves (Fig. 7a), which resulted in calculated values of shear modulus increasing rapidly during the first 20 min and then stabilizing to a near-constant value (Fig. 7b). A timed test run in box core 175 gave similar results (Fig. 8a and b), although the initial increase in shear modulus was slightly lower, possibly due to a difference in sediment, which was apparent to the eye, or because of a 1-min delay in the initial reading. The measured values became stable after approximately 100 min; thus time is a consideration when evaluating the duomorph data. The actual value of the

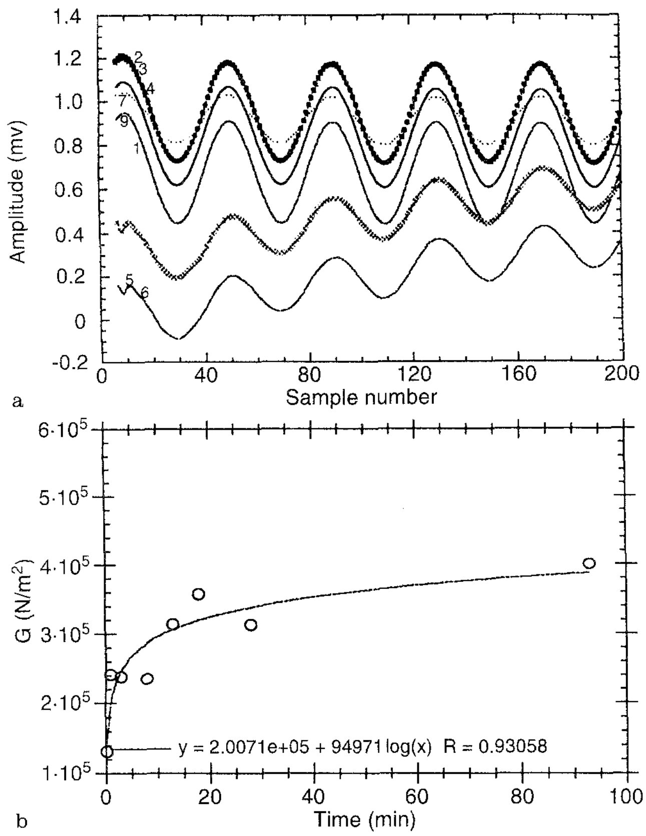

Fig. 7 **a** The amplitude of the received signal measured in soft muddy sediment in box core 168 decreases with time as the pore pressure equilibrates after probe insertion. The signal with the highest amplitude was recorded after 1 min; the lowest amplitude signal recorded after 93 mins. **b** The resulting shear modulus is the value asymptoptically approached with increasing time, in this case after 30 min

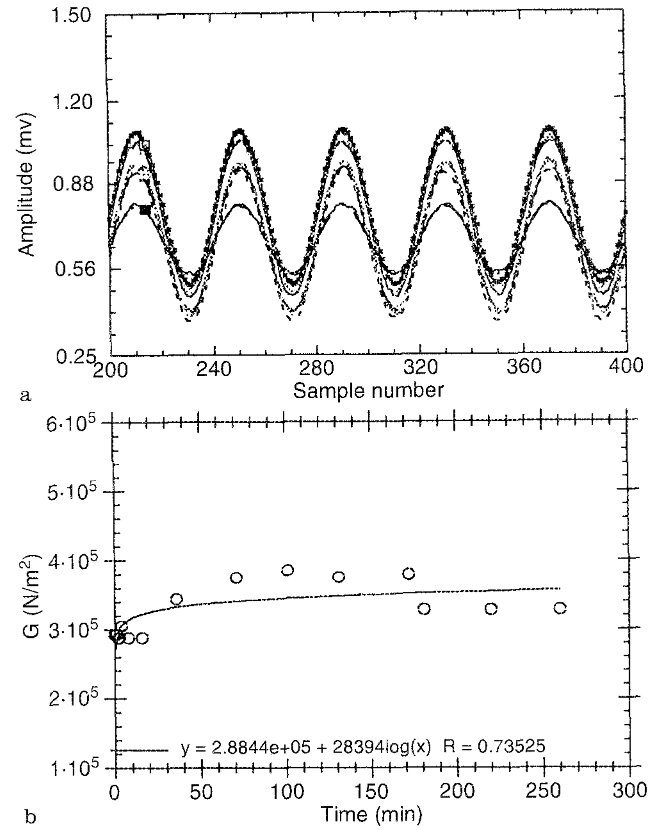

Fig. 8 Time tests run in box core 175 show decreasing amplitude of the received signals with time **a** and a gradual increase in measured shear modulus **b**

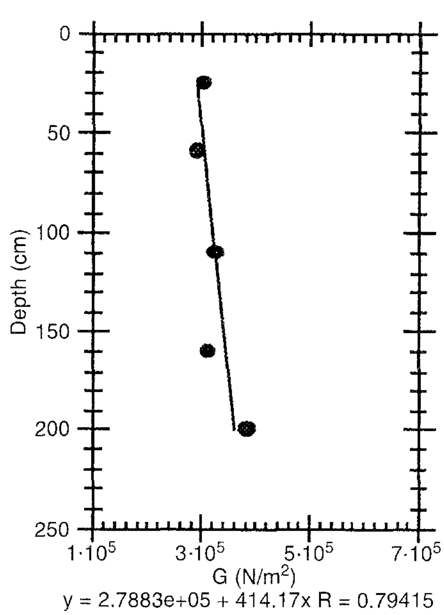

Fig. 9 DIAS measured in situ values of shear modulus for Eckernförde Bay muds measured during the 1993 CBBL experiment

modulus, undisturbed by probe insertion, is the value asymptoptically approached with increasing time.

For the *in situ* measurements, the DIAS system was deployed from a wireline and initially inserted to a depth of 20 cm by divers. The probe was allowed to equilibrate over 100 mins until it was determined that all excess pore pressure had dissipated (determined from piezometer data measured during the same experiment) (Bennett et al. 1996). The probes were inserted to five premeasured depth intervals by divers until a complete series of measurements versus depth was achieved. The results have been combined into one in situ profile of shear modulus versus depth (Fig. 9) at the Planet site in Eckernförde Bay.

Summary and discussion

The DIAS system was developed to measure shear modulus in situ in real time and to provide an estimate of in situ shear wave velocity. The prototype system was designed to be convenient and reliable. The measured results appear to be consistent and repeatable.

Several considerations, including calibration and design, need to be addressed for the next generation of DIAS systems. The probes were deployed and the measured results compared favorably to shear wave velocity results obtained in situ using an existing set of shear wave probes (Richardson et al. 1991; Richardson and Briggs 1996). A more controlled set of calibration experiments are underway at NRL using Shell 200 wax, a substance with known properties and one that transmits shear waves.

Secondly, the slightly aparabolic motion of the probe needs to be reduced. This can be achieved by reducing the size and width of the tab holding the wiring. A wire mesh tab is currently being tested for this purpose. At the present time, the effects of the slightly aparabolic motion are being compensated by our calibration procedures.

To obtain valid measurements, the probes must remain in place until the pore pressure in the sediment being measured has equilibrated. The time required depends on the rate of pore pressure decay after probe insertion and can be estimated by monitoring the amplitude of the received DIAS signals until such time as no additional decrease is noted.

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