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Seabed shear modulus profiles using a gravity wave inversion

Les profils de module de cisaillement du fond de l'océan à partir de l'inversion de la gravité des vagues

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SYNOPSIS A previously developed theory (Yamamoto and Torii 1986) enables seabed shear modulus profiles to be extracted by inverting measurements of seabed motion and water wave-induced pressures at one location near the seafloor. Based on this theory, a new instrumentation system, known as a Bottom Shear Modulus Profiler (BSMP), has been developed and tested. Comparisons between BSMP inversion results, in situ sediment strength tests, and laboratory analysis of core samples show that this method can predict accurately the magnitude and depth structure of the sediment shear modulus. The most recent BSMP units reported in this paper are capable of measuring the shear modulus profile of the seabed with maximum penetration of 200 m and a maximum depth resolution of 1 m. BSMPs have been successfully deployed in water depths ranging from 2.0 m to 135 m.

INTRODUCTION

As ocean waves propagate over continental shelves, they induce motions of the seabed sediments through variations in pressure on the seafloor. According to a model developed by Yamamoto and others (1978), the layered seabed sediments under usual circumstances can be seen to behave in a massless, incompressible, elastic manner in response to water wave-induced pressures. Under these circumstances, it is possible to realistically predict the seabed response to passing water waves if the sediment shear modulus at every depth is known. Conversely, through the use of geophysical inverse methods, it is possible to extract the shear modulus with depth profile from measurements of seabed motion and water wave-induced pressure.

A complete statement of the theory behind this new shear modulus inversion method is given in a recent paper by Yamamoto and Torii (1986). Recently, we developed an instrument and tested this method in a real marine environment (Trevorrow et al, 1988). We call this new system the Bottom Shear Modulus Profiler (BSMP).

Another important application of the instrument is the detection of seismic signals and noise fields propagating through the ocean floor. For this purpose, an array of up to seven high-resolution BSMPs were built and deployed at the New Jersey shelf in the summer of 1987. In this paper, we present the highlights of the sea experiments.

HR-BSMP INSTRUMENTATION AND SEA EXPERIMENTS

An electronic block diagram of the HR-BSMP system is shown in Figure 1.

The seismometer package consists of three orthogonally mounted seismometers (Teledyne-Geotech Model S-750) and two tiltmeters (Sperry Model 02383-01). The frequency response of the S-750s is flat between 0.01 and 100 Hz. A new differential pressure sensor was specifically designed for the measurements of small amplitude, low-frequency pressure fluctuations (1 mm water column, periods of 1 to 125 seconds) up to 200 m water depth. The InterOcean model WS200 incorporates an advanced piezoresistive semiconductor differential pressure sensor combined with a unique hydraulic filter and depth compensating arrangement. The seismometer package is connected to the InterOcean pressure sensor by a 2 m, 12 conductor umbilical cable. A 32 conductor, electro-mechanical cable connects the InterOcean pressure sensor to an accompanying ship.

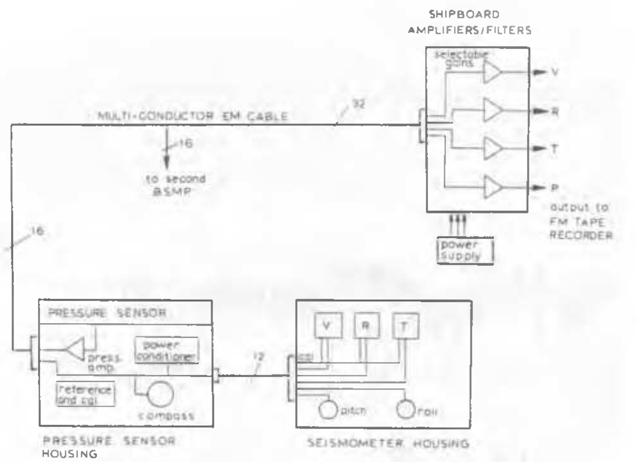

Fig. 1 Electronic Block Diagram of the HR-BSMP System.

The shipboard data recording system consisted of 28 band pass filter amplifiers followed by 3 multichannel instrumentation recorders. The three data recorders were each 14-channel units. Of these, 12 were dedicated to data and 2 reserved for ID# and tape servo. The tape speed was 1.2 cm/sec. (16 hours continuous per reel). To synchronize all recordings, a once per minute pulse was generated and applied in parallel to one channel of each recorder.

A newly designed BSMP burial system is to bury the seismometer package up to 0.75 m below the seafloor. This was done to improve the seabed-to-BSMP coupling. The hydraulic jet BSMP burial system is practical for water depths up to 200 m. After burial, the hydraulic jets and dome are removed so as not to influence seabed and water motions. A total of five HR-BSMP arrays were deployed at five sites on the New Jersey Shelf in water depths ranging from 12 to 135 m, using the R/V Atlantic Twin in August 1987. A series of airgun shots were made around the ship, and the time of arrival of the acoustic signal at the vertical seismometers in the array was used to precisely locate the BSMPs. Also, in some cases, acoustic transponders were deployed to determine the locations of the instruments.

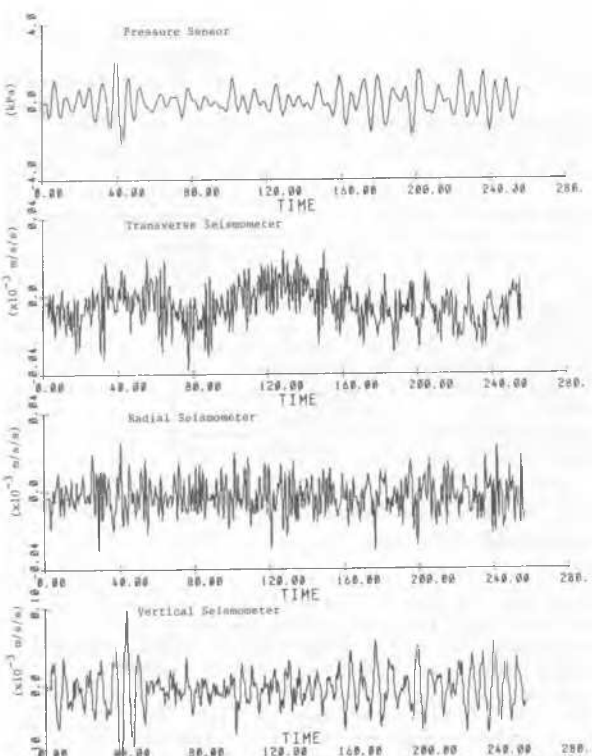

Fig. 2 Examples of Raw Time Series data from a BSMP at AGS site.

DATA ANALYSIS AND RESULTS

A BSMP raw data set consists of an analog recording of the 3 seismometer acceleration and pressure transducer signals as shown in Figure 2. Typically, several (as many as seven) instruments were deployed and recorded simultaneously, for durations as long as 15 hours (usually 8 hrs). The basic goal of the data processing algorithms is spectral averaging. This reduces the acceleration and pressure time-series into a form useful to the shear modulus inversion algorithm, and drastically reduces the effects of ambient, random noise. The pressure and three-component acceleration time-series are digitized at 4 Hz and divided into 1024 s (17 min) segments. Each segment is converted into power spectra, cross-spectra, and horizontal and vertical admittance spectra. The power, cross, and admittance spectra from each time segment are averaged over all the segments in the entire data set.

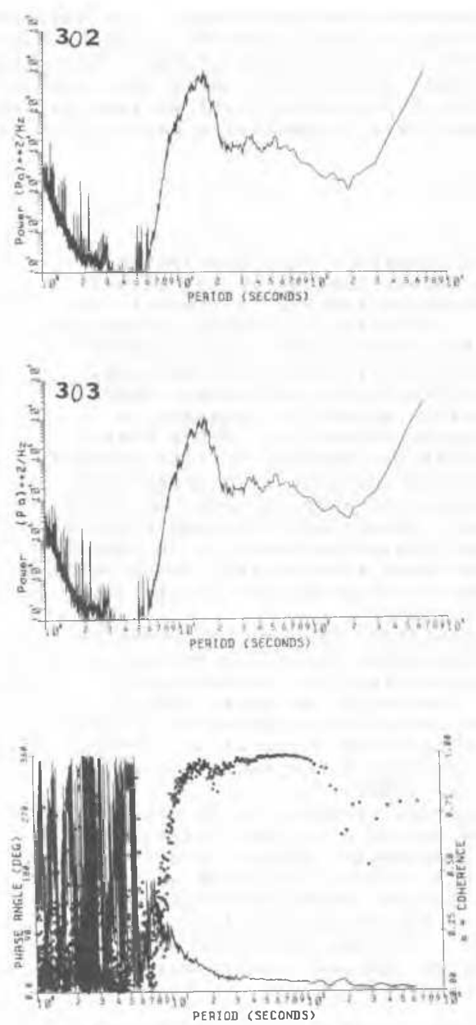

Fig. 3 Power Spectra, Coherence and Phase Lag of Two Pressure Signals from BSMPs 302 and 303 at AMCOR 6010 Site.

AMCOR 6010 Site (N 39°03', W 73°07')

At the AMCOR 6010 site (water depth, 70 m), one BSMP (303) was buried and another (302) was deployed on a plate. The separation between the two BSMP was approximately 30 m and the array axis is oriented N220°. Waves were traveling roughly from NE. The power spectra, coherence, and the phase lag between the pressure signals from the two BSMPs are shown in Figure 3. Notice that the two power spectra are almost identical. For a wide band of wave periods between 8 s to at least 200 s, the coherence between the two pressure signals is very high. For the same wave period band, the phase varies continuously from 90° to 10°. Note that the wavelength of a surface gravity water wave with period of 8 s is 100 m. The phase lag of 90° corresponds to a quarter of a wavelength, which is about 25 m. As the incident ocean swell propagated nearly parallel to the BSMP array axis, this confirms that the pressure signals are due to the gravity water waves. It is most significant to note that the low frequency pressure signals as low as 5 mHz are due to travelling gravity waves. The power spectra of the vertical acceleration, the coherence and the phase lag between the vertical acceleration and the pressure and the admittance spectra from BSMP 303 are shown in Figure 4. The coherence is high in the microseismic band (period less than 3 s) and the surface wave band periods between (8 s to 20 s). For the long wave bandwidth (with periods between 20 s to 200 s), although there is some coherence between the vertical acceleration and pressure, the coherence is not as high as that for the two pressure signals because of limited sensitivity of seismometers at this frequency band. Although not shown here, coherence is lost significantly for the plate-mounted BSMP. This indicates that the BSMP-seabed coupling is important at this water depth, and is significantly improved by burial.

Twenty discrete values of vertical admittance from Figure 4 are used in the shear modulus profile inversion. Figure 5 shows the inverted shear modulus profile with error band within the top 200 m of seabed. The error band is ± one standard deviation, and comes from the combination of admittance data uncertainty and the use of the truncated eigenvalue expansion. Admittance data used in the inversion are compared with the computed admittance in the inset of Figure 5.

The inverted shear modulus profile is compared with the porosity profiles and other geotechnical properties of sediment cores measured during the AMCOR coring project

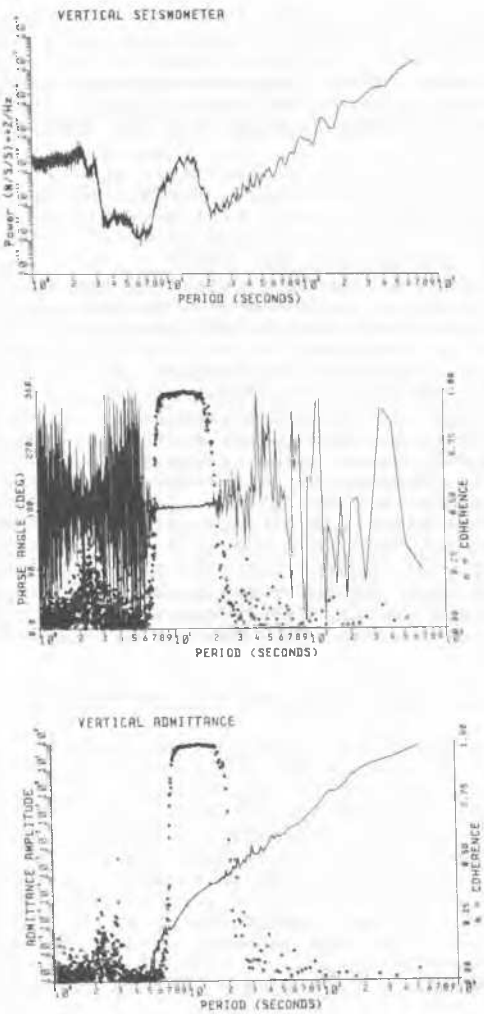

Fig. 4 Power Spectra of Vertical Association Signal, Coherence and Phase Spectra between Pressure Signal and Vertical Acceleration Signal and Admittance Spectra from BSMP 303 at AMCOR 6010 site.

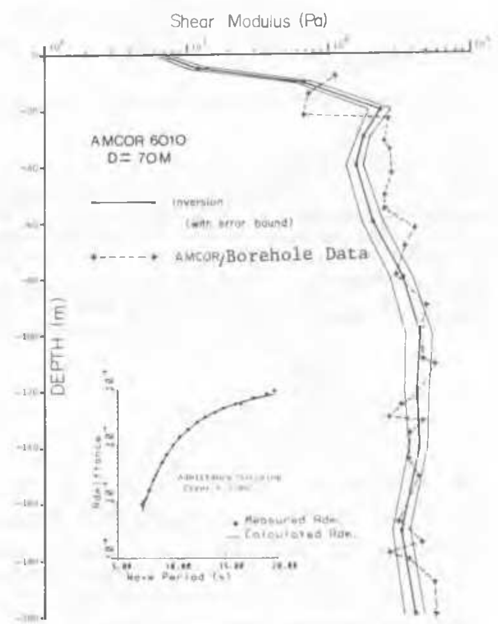

Fig. 5 Comparison between Inverted Shear Modulus Profile and Borehole Data for AMCOR 6010 Site, BSMP 303.

(Hathaway et al, 1976). The conversion to elastic shear modulus is accomplished through the use of a well known empirical relation.

$$G = F(e)\,\sigma_0^{0.5}$$

Here, G is elastic shear modulus, F(e) is an amplitude function of void ratio e, and σ_0 is the confining effective stress. The value of σ_0 at a given depth is calculated from the porosity profile, the average value of the measured internal friction angle of the sediment (30°), and an averaged value of the measured density of grain (2.65 g/cm^3). Agreement between the BSMP remote sensing and the borehole data is remarkable.

<u>Atlantic Generating Station Site (N 39°28', W 74°15')</u>

At AGS site (water depth 12.5 m), seven BSMPs were deployed to measure the directional spectra of seismic/pressure fields. Preliminary analyses indicate that in the short period microseismic band, 1-4 seconds, motion of the seafloor is primarily a result of Scholte interface waves travelling at 200 to 300 m/s. At longer periods, 4 to 200 seconds, gravity wave coupling of the seafloor dominates the motion of the seabed. Using the gravity wave excitation of the seafloor motion, we measured the shear modulus profiles of the seabed.

In Figure 6, an inverted shear modulus profile, an SPT (Dames and Moore, 1974) at bore hole 824, and laboratory analysis data are compared. The SPT blow count results are converted to elastic shear moduli using an empirical relation of Ohsaki and Iwasaki (1973). The laboratory result is based on a torsional resonant column test on a short core sample taken from the experimental site.

In general, the SPT borehole profiles reveal highly structured sediments. It can be seen from Figure 6 that there is good agreement between the inverted and reference profiles.

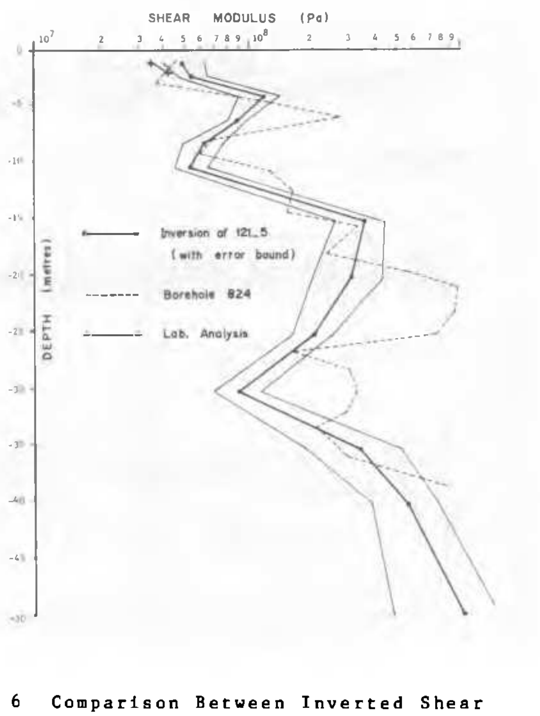

Fig. 6 Comparison Between Inverted Shear Modulus Profile and Borehole 824 Data for AGS Site.

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