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Acoustic Backscatter Measurements of Estuarine Suspended Cohesive Sediment Concentration Profiles

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ABSTRACT

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Methods of monitoring suspended sediment concentration profiles have largely relied on *in situ* point sampling by water bottles, coupled with optical instrumentation. These intrusive methods can affect the measurements, and optical instrumentation must usually be raised and lowered through the water column at rates too slow to obtain near-instantaneous profiles. At the extremely high suspended sediment concentrations sustained by cohesive sediments in estuarial waters optical attenuation is severe, and optics cannot provide data on concentrations or gradients without very short path lengths, or use of multi-sensors. Remote sensing acoustic backscatter techniques overcome these difficulties, and provide high resolution spatial (~ 1–10 cm) and temporal (~ 0.1–1 s) concentration profiles. Despite their use for over a decade, acoustic backscatter measurements in the field have been confined almost wholly to non-cohesive sediments. Measurements of suspended cohesive sediment concentration profiles in Changjiang Estuary demonstrate the capability of acoustic instrumentation to obtain high resolution profiles at dynamic scales in a difficult environment with high gradients and concentrations.

ADDITIONAL INDEX WORDS: *Acoustic, suspended, sediment, monitor, estuarine, cohesive, sediment concentration.*

INTRODUCTION

Aims

This paper aims to provide an introduction to use of acoustic backscatter techniques in monitoring suspended sediment concentration profiles, particularly for the difficult regime of cohesive suspensions. Acoustic and optical means of estimating suspended sediment concentration (SSC) profiles are briefly compared to put the acoustic methods into context. Examples of cohesive suspended sediment concentration profiles measured by acoustic backscatter for the Changjiang Estuary and Hangzhou Bay, East China Sea are used to illustrate the capabilities of the acoustic techniques. High concentration and high gradient profiles with high variability have been successfully measured. These measurements have been reported elsewhere (SHI *et al.*, 1996, 1997); but use by others of acoustic backscatter to measure SSC profiles has apparently been confined to non-cohesive suspensions (*e.g.* OSBORNE *et al.*, 1994), or to laboratory measurements (*e.g.* THORNE *et al.*, 1991). We seek to introduce the utility and versatility of acoustic backscatter techniques for monitoring cohesive suspensions to a wider audience.

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Why Measure SSC?

Particulate matter in suspension is defined as the material that is retained on a 0.4~0.5 micron pore size filter (EISMA, 1993). Smaller material is considered to be dissolved. Measurements of SSC are used for engineering and scientific purposes. Knowledge of SSC profiles allows estimates of: sediment transport rates; erosion and deposition rates; underwater visibility or water clarity (turbidity); acoustic 'visibility' i.e. whether sonar echo sounders or acoustic imaging instrumentation operating at particular frequencies can function; and knowledge of the dynamics causing or affecting turbidity *e.g.* wave processes.

What is a Cohesive Sediment?

Cohesive suspensions contain a significant amount of fine sediments, particularly clay size i.e. less than 2 microns, and/or a proportion of silt size (4 to 62 microns). According to Eisma (1993) bottom sediments require less than 5% fine material to be cohesive. Ions carried by the small particles overcome repulsion forces, causing particle aggregation, and producing a sticky sediment.

Why Emphasize Cohesive Suspensions?

Cohesive suspensions are intrinsically interesting, and impact on man's engineering, mariculture, and recreational activities. They have distinctive and unusual properties caused by the combination of physical and electro-chemical processes. Unlike sand suspensions cohesive suspensions have rheological behaviour; which can change with density. This is caused by adsorption of ions causing inter particle attraction and repulsion forces. Thick, soupy suspensions can be maintained for long periods through a balance of upward diffusion and settling processes, whereas sand suspensions are strongly dependent on wave activity to maintain high concentrations. Lutoclines (high gradients in SSC) are ubiquitous in cohesive suspensions, supporting internal wave processes, a possible source of re-entrainment and resuspension events. Particle sizes can change rapidly in cohesive suspensions from micron diameter clays to 100 microns because of aggregation (flocculation) processes, and breakup of flocs can reverse this behaviour. At concentrations $\sim$ 1gL $^{-1}$, cohesive suspensions often occur in conjunction with fluid muds *e.g.* EISMA (1993), which can be easily entrained, and which can move *en masse* along the seabed. Cohesive suspensions occur in conjunction with riverine discharges. Consequently many world areas of unique scientific, economic, or environmental interest experience cohesive suspensions *e.g.* the Amazon river delta, the Changjiang (Yangtze) Estuary, and the Great Barrier Reef lagoon of Australia.

TECHNIQUES OF MEASURING SSC PROFILES: OVERVIEW

There are four principal methods of estimating SSC profiles in estuaries: (A) water point-sampling; (B) optical methods; (C) acoustical methods and (D) nuclear methods (not discussed - see Eisma 1993 for brief details).

Water Point-Sampling

The most direct and accurate way of obtaining SSC profiles is by use of water samplers made from inert materials *e.g.* Niskin bottles, followed by filtering and weighing. This also allows identification of the materials in suspension, including chemical composition, particle size distribution, particle shape, and other physical and chemical properties such as grain density. However the method disturbs the environment being investigated, and provides rather poor vertical and temporal resolution.

Optical Methods

Optical instruments such as nephelometers and transmissometers have been widely used to infer SSC, through optical back-scatter (OBS) and light attenuation measurements respectively (*e.g.*, Tyler and Preisendorfer, 1962). Rapid developments in laser technology and optical instrumentation allowed the construction of relatively small, low power devices which allowed SSC profiles to be inferred at resolutions vastly superior to point sampling by water bottles.

Simple Theory for Transmission of Light in Water

Attenuation of light in a medium can be expressed as

$$I(r) = I(0) \times \exp(-\xi\, r) \qquad (1)$$

where I(0) is source intensity, I(r) is intensity measured at distance r from the source, and ξ = attenuation coefficient.

$$\xi = \alpha + \beta \qquad (2)$$

where α = absorption coefficient due to dissolved materials and the medium, and β = backscatter coefficient due to suspended material. Units are m $^{-1}$. Transmissometers measure the loss of intensity of a collimated beam of light over some fixed path length, from which ξ can be calculated (beam attenuation coefficient for a collimated light beam). A nephelometer measures scattering of radiation in the infra-red range for some particular scattering angle. Scattering is a strong function of number of particles and particle size. Infrared radiation is used because it is strongly absorbed by water, reducing the effects of ambient light contamination. By assuming β and ξ are directly related to SSC, both β and ξ can be used to estimate SSC, following instrument calibration against a reference suspension (usually formazin) or preferably against *in situ* water samples.

Limitations of Optical Methods

The formazin 'standard' may have no relation to the actual field values of SSC, ξ is also affected by dissolved substances through absorption α, and it is the experience of one of us (HAMILTON, 1994), that nephelometer values may have no obvious relation to SSC determined from water samples. Optical measurements are affected greatly by bubbles (*e.g.* OSBORNE *et al.*, 1994), particle size, shape, composition, and refractive index, so that measurements made in one area are usually unrelated to measurements in another area, so far as SSC estimates are concerned. Sensors are subject to biological and other fouling, and can be sensitive to the ambient light field. The optical instruments are often large compared to SSC spatial variability (gradients), so the measurements are highly intrusive. Continuous SSC profiles are obtained by raising and lowering the instrument through the water column. This does not provide temporal resolution of profiles at the dynamic scales of resuspension ($\sim$ seconds). It also introduces a further problem: undulations introduced to suspended profiling instruments by vessel motions (roll) can both degrade vertical resolution and cause artifacts in profiles. Multi-sensors can be used, but the measurement is intrusive. MAA *et al.* (1992) found that an OBS sensor responded differently with salinity (perhaps because of flocculation effects); and with clay mineralogy of kaolinite, illite, and montmorillonite; and that operational range for clays at about 0–1 gL $^{-1}$ was much lower than for sands of about 0–20 gL $^{-1}$, perhaps because of flocs giving stronger reflections than sand sizes.

Some Advantages of Optical Sensors

Despite the above limitations the instruments are accurate and reliable (if sensors are not fouled), and simple to use, and cost is low enough to make them an effective method of obtaining indirect measures of SSC for low resolution profiles, or for high resolution (but intrusive) measurements at a fixed point.

Ranges of Optical Measurements of SSC

Extremely high SSC values have been inferred using optical instruments, although not at dynamic scales, and usually with low accuracy. NITTROUER *et al.* (1986) used 5 cm path length transmissometers to infer SSC as high as 544 mgL^{-1}, based on laboratory calibrations using Amazon muds. 'Good' resolutions (<25% differences from bottle samples) were obtained up to 100 mgL^{-1}, after which the instruments were relatively insensitive. KINEKE and STERNBERG (1992) used a miniature nephelometer (or optical backscatter sensor OBS), to measure concentrations of 0–320 gL^{-1} in fluid muds on the Amazon shelf. Response was approximately linear for SSC < 10 gL^{-1}, and decreased in an exponential fashion for SSC > 36 gL^{-1}. The OBS response increased for the low range and decreased for the high range. Some results differed greatly from calibration data, perhaps because the sensor face became fouled by fluid mud. The nonlinearity and fouling cause ambiguities which can only be resolved by obtaining *in situ* calibration points for each profile.

Acoustic Methods

Acoustic backscatter (ABS) methods provide a non-intrusive, high resolution spatial and temporal method of remotely inferring SSC profiles without the need for profiling of the actual instrument (depending on the depth and the range of the device). Use of acoustic techniques to monitor sediments was perhaps first proposed by JANSEN (1978), the application being to detect the onset of grain or pebble movement by measuring the noise produced by colliding grains. This passive method provided limited quantitative information on concentrations, but could be used to examine thresholds of sediment movement, and to trigger other instrumentation *e.g.* photography. Active techniques of ensonifying the water column now allow quantitative inferences of SSC profiles from backscatter measurements.

Transmission of Sound in Water

Sound speed is highly dependent on temperature, and much less dependent on pressure and salinity. When sound is used to detect underwater objects *e.g.* the bottom in the case of depth finding sonars, the sound transmission is described by the Sonar Equation (*e.g.* URIK, 1975):

$$R = I - 2TL - TS \tag{3}$$

where I is source intensity, R is intensity of the received signal or echo, TL is transmission loss (with factor 2 for a two-way path), and TS is target strength. TL = absorption + spreading + scattering. The limit of detection is often imposed by the scattering, which leads to volume reverberation (reception of backscatter or echoes from scatter at different ranges), since power output (gain) of the source can be increased to overcome the other losses. For depth finding sonar the reverberation is a handicap, lowering the signal to noise ratio. ABS devices process the backscatter to obtain information about the concentration of suspended sediment. For high suspended sediment concentrations, backscatter devices also lose sensitivity with range.

Acoustic Backscatter Instrumentation

For SSC measurements very short (10 micro-second) pulses of high frequency (MHz) are output, and material in suspension scatters some sound back to a receiver. After allowance for transmission losses, the received backscattered signal is a function of concentration and size of suspended sediment. Time gating and/or pulse encoding techniques allows calculation of range down to about 1 cm, and profiles may be obtained in about 0.1 s for ranges of metres (*e.g.* THORNE *et al.*, 1991). In practice averaging is needed to reduce noise and variability, so that 10 cm and 1 s are perhaps more appropriate.

Limitations of ABS

With respect to calibration, ABS instruments suffer from many of the same problems as optical instruments. A calibration should be obtained at each site against water samples; backscatter is a function of particle properties and shape; and bubbles can severely affect measurements. The backscatter function at a particular site for each set of calibration data is assumed to be invariant in time and space, a necessary but weak link in the calibration (LIBICKI *et al.*, 1989). Optical calibration is direct in the sense that a sample can be taken in close proximity to the sensor and compared directly to the instrument reading, but ABS calibration is indirect and involves several assumptions. THORNE *et al.* (1991) concluded that the degree of accuracy and reliability obtainable for ABS instrumentation is reasonable, particularly when compared to other methods.

Other factors to be considered are different near and far field beam patterns (and spreading losses) for the acoustic transducer, absorption due to water and the sediment itself (which causes a non-linear response at high concentrations), and variations of sound-speed (and absorption) with temperature and salinity. See LIBICKI *et al.* (1989) and THORNE *et al.* (1991) for more detailed considerations. Good SSC calibration is dependent on coincident monitoring of environmental parameters. Attenuation due to absorption is severe at high frequencies, leading to short transmission ranges (*e.g.* 2 m for 1.5 MHz and 10 m for 0.5 MHz), still an order of magnitude better than optical transmissions. To overcome this in deeper waters, a vertical array of acoustic suspended sediment monitors (ASSMs) could be used (spaced to have overlapping coverage), or a single ASSM could be profiled in depth stages, at the expense of a more intrusive measurement and loss of an instantaneous total profile respectively.

In contrast to OBS sensors, OSBORNE *et al.* (1994) described ABS as being sensitive to larger, not finer, sediments. ABS are also sensitive to changes in acoustic impedance, making them susceptible to bubbles (and organic material). OSBORNE *et al.* (1994) assumed organic material to be neutrally buoyant, and therefore likely to be well distributed through the water column. Bubbles are much more efficient at scattering than equivalent sized sediment (LIBICKI *et al.*, 1989), particularly at bubble resonance, but have extremely short lifetimes. A depth of 3 m below the surface was estimated as sufficient to negate wind generated bubble effects for a 3 MHz sensor.

Acoustic measurements are subject to noise. "To be statistically significant, backscattered pressures at any level must be averaged, since they are Rayleigh distributed; uncertainty in the measured pressure level decreases as the square of the number of samples" (OSBORNE *et al.*, 1994; also see LIBICKI *et al.*, 1989). Approximately 100 samples are needed for a 10% accuracy in concentration. For this reason nothing is lost by discarding the raw data and retaining only averages (LIBICKI *et al.*, 1989). Exploitation of this in real-time allows considerable saving in data storage, since high resolution necessitates high sampling and data transmission rates, and increased processing and storage requirements. Intensive data processing is required for high resolution measurements, so calibrated profiles may not be available in real-time, only raw backscatter values, depending on processor speed.

Some Advantages of ABS

ABS has several major advantages compared to other types of measurements: (1) Near instantaneous high resolution SSC concentration profiles can be obtained. (2) The ABS measurements can be made at time scales approaching that of point measurements of water speed. (3) ABS allows "location of the bottom" (*e.g.* OSBORNE *et al.*, 1994), an important consideration for suspended profiling instruments, particularly those deployed from vessels in conditions of wave or swell and *e.g.* for those suspended a fixed depth below the surface over a tidal cycle where water depth can change by several metres. (4) It may not always be practicable to place instrument frames on the seabed or to use profiling instruments in certain key areas of interest *e.g.* busy waterways and harbour entrances. In these situations an ASSM could provide fast SSC profile measurements.

ASSM INSTRUMENTATION

We will use the particular acoustic suspended sediment monitor (ASSM) developed chiefly by S.Y. Zhang (ZHANG, 1996) at Shanghai Acoustics Laboratory to outline how technical and scientific difficulties associated with backscatter measurements mentioned earlier are overcome, and to demonstrate the application of a 0.5MHz ASSM to the Changjiang Estuary. Other acoustic backscatter instruments are discussed elsewhere (*e.g.* ORR and GRANT, 1982; YOUNG *et al.*, 1982; HESS and BEDFORD, 1985; HANES *et al.*, 1988; and LIBICKI *et al.*, 1989). As mentioned earlier these latter instruments were used for non-cohesive suspensions or in the laboratory.

The ASSM System

The entire system (Figure 1) is under PC-computer control for the synchronization of sampling and preliminary data reduction and storage. The ASSM has a frequency of 0.5MHz, beam width of 1.5 degrees, and a pulse length of about 40 μs. It measures the vertical profile of sound scattered from suspended sediments in range bins with a vertical resolution of 10 cm and temporal resolution of 1.5 s, depending on noise and range which is about 10 m maximum. In a typical use the data are sampled at a rate of approximately 75 KHz for a 12 minute burst each hour. Each burst then consists of 450 profiles of backscattered acoustic energy from the suspended sediments. Usually profiles are averaged to reduce noise. The instrument can be suspended below the surface, or placed in a frame on the bottom. Measurement range is 0.1 to 5–10 kgm^{-3}. Much higher concentrations can be measured which show suspension processes, but absolute values and gradients are subject to uncertainty until further calibration work.

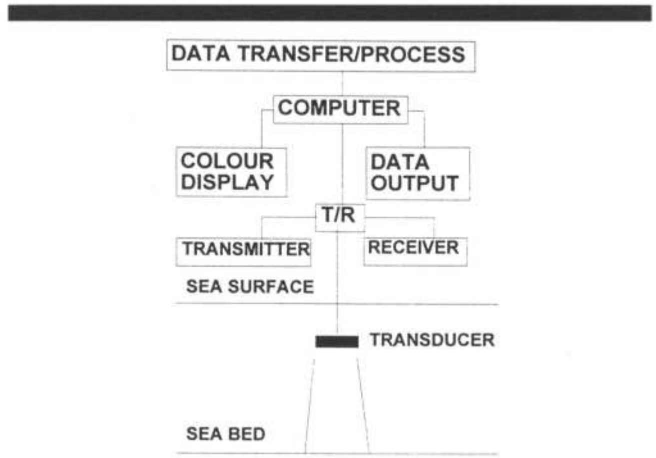

Figure 1. Schematic of the ASSM system.

Real-time Measurement and Processing

To allow for near surface wave generated bubbles, the ASSM is suspended 2 m or deeper below the surface. For a typical setup, a 10 pulse burst is transmitted at 1.5–2 second intervals, with the burst itself taking 0.1–0.2 s. The time between bursts is used for processing the returns. Each pulse is processed and results for the 10 pulses are averaged in real-time. This is the first step in reducing uncertainty in the Rayleigh distributed backscatters. Time between bursts may be altered *e.g.* lengthened for longer ranges. Uncalibrated intensities of each profile are displayed in real-time as a vertical bar on a PC screen (Figure 2), where the ordinate is depth, and the abscissa is time. For the particular example given, the width of the bar is plotted as 2 seconds. About ten minutes of data is displayed. Fifteen colours are used to express the intensity of the raw backscatter, with a 3db increase in level per colour band. Beyond a certain range at high concentrations the uncalibrated display could show decreasing instead of increasing concentrations with depth, so should be interpreted with care when high concentrations are indicated.

Post Processing and Calibration Theory

For the ASSM, low multiple scattering and Rayleigh type scattering (acoustic wavelength much less than the flocs di-

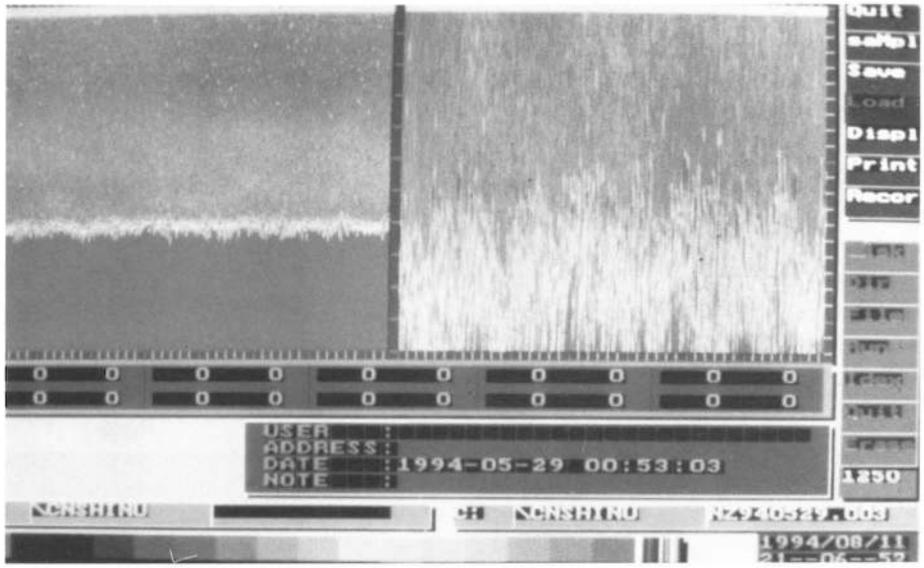

Figure 2. Example of the ASSM display.

ameter) are assumed. Outside of the Rayleigh region, where particle diameter is of the same order as acoustic wavelength, other criteria should be used (*e.g.* LIBICKI *et al.*, 1989). Under these two conditions it is assumed the ASSM response is a linear function of concentration, and quantitative estimates of SSC can then be obtained. This approach is supported by the work of GREEN and BOON (1993). They assumed that signals from scatterers could be added linearly, assuming that constituents of non-homogenous suspensions were not seen by backscatter sensors as interacting through grain shielding or multiple scattering. Their assumptions were supported by laboratory measurements on silt and sand mixtures for concentrations up to 900 mgL^{-1} for their particular infrared sensor. Although a linear response to concentration is assumed, the received backscattered power is a nonlinear function of range due to absorption and spreading losses.

Compensation is applied to the raw intensities in post-processing to allow for variations in column sound-speed and attenuation; and for near and far field beam patterns and spreading losses; using a form of the following equation (after LIBICKI *et al.*, 1989; THORNE *et al.*, 1991; OSBORNE *et al.*, 1994):

$$M(r) = kV^2(r)r^2\psi^2(r)\frac{1}{\tau \cdot c(r)}\exp\left[4\int_0^r \alpha_w(r')\,dr' + 4\int_0^r \alpha_s M(r')\,dr'\right] \quad (4)$$

where k = a scaling factor which is a function of system response and of acoustic backscatter strength of the suspended sediment (the latter is assumed constant at a particular site to simplify the problem)

r = one way range from transducer to scatterer (m)
$c(r)$ = sound-speed at range r
$M(r)$ = particle mass concentration per unit volume at range r
$V(r)$ = transducer response to measured backscatter pressure (volts) from range r.
α_s = attenuation due to the sediment for unit concentration ($kg^{-1}m^{-1}$)
α_w = attenuation due to water (m^{-1})
τ = pulse length (s)
$\psi(r)$ = a factor to account for different beam patterns in the near, transition, and far fields ($\psi = 1$ in far-field) (THORNE *et al.*, 1991)

The expression has the same form in the near and far-fields if a cylindrical beam is assumed in the near-field and a directional beam (of constant beam angle) is assumed in the far-field. The transition region is not necessarily well defined by the expression. The integrals express the fact that α_s and α_w may vary through the water column. Both α_s and α_w may be calculated by formulae *e.g.* THORNE *et al.* (1991). Attenuation due to the sediment is assumed to be a linear function of sediment concentration. α_w is a strong function of temperature, and α_s may be calculated from the equivalent sphere radius for the sediment particles (THORNE *et al.* 1991), determined from water sampling.

Below a certain concentration and detection range the backscatter is a linear function of concentration, and instruments can be optimized for these limits. In principle under such conditions only one calibration point is needed at a site to calibrate all profiles, assuming statistical stationary for the suspension (THORNE *et al.*, 1991). In practice this is a dangerous assumption in the field because of variability; and non-linearity at higher concentrations. "At high concentrations the exponential term dominates the range dependence and the backscattered amplitude reduces, beyond a particular range, for further increases in concentration" (THORNE *et al.*, 1991).

Field Data and Compensation Curve

In a typical application, bursts of data are taken *e.g.* for 12 minutes on the hour. Six calibration points for the water column are taken coincidentally using water samplers, or the samples can be taken at different times. Statistical stationary is assumed, and a calibration profile is formed. The form of equation (4) used for calibration is $M(r) = K\,V^2(r) r^{n(r)} \exp(4\,\alpha\,r)$. α here represents average column absorption from transducer to range r. The exponent n is 1 in the near-field and 2 in the farfield to account for cylindrical and spherical spreading respectively, and varies between these limits in the transition range in an unknown manner. In the near and farfields K is the only unknown, and a determination of K is made from calibration points in these regions. Exponent n (and α) are then altered by trial and error to obtain a smooth compensation curve in the transition region. This is a practical approach to the unknown form of ψ (r) in the transition region. Nine segments are used for the full curve to obtain a piecewise continuous compensation curve. A compensation curve f(r) with depth is then formed to convert $V^2(r)$ to M(r), where $M(r) = f(r) \cdot V^2(r)$ and $f(r) = K\, r^{n(r)} \exp(4\,\alpha\, r)$. The compensation curve is applied to all profiles in a burst. Since absorption due to sediment is not recalculated for each profile, the compensation curve provides considerable saving in post processing, at the expense of some accuracy. Ideally absorption should be recalculated for each profile, and this is recommended when high SSC values occur. By assuming statistical stationarity, ensemble averaging can then be used to improve the signal to noise ratio, with the facility provided for user selectable time-depth windowing. It has been estimated that the procedure produces concentrations with about ±20% accuracy. Apparent motion of the bottom caused by sensor movements is small under usual conditions, and is not allowed for.

APPLICATION OF ASSM TO CHANGJIANG ESTUARY AND HANGZHOU BAY

Experimental Details

Our field experiments were carried out at spring tide (28–29 May 1994) in the Changjiang Estuary and neap tide in the Hangzhou Bay (Figure 3). A full tidal cycle (28 hours) was monitored. Sampling work was completed aboard the Dong Diao 221. Vertical profiles of SSC were measured by the acoustic suspended sediment monitor (ASSM) described in a previous section. The ASSM transducer (pointing downward) was placed at 2.0 m below the water surface, to avoid any surface generated bubbles. At the same site, current velocity and direction were measured using a current meter (for details see SHI *et al.*, 1996). The vertical structure of cohesive suspension concentration in the Changjiang Estaury is maintained by horizontal advection ($\bar{u}_H \cdot \vec{\nabla}_H C$), downward settling ($\omega_s\, \partial C/\partial z$), and upward turbulent diffusion ($\partial/\partial z(K_s\, \partial C/\partial z)$). In general, current- and wave-induced forcing are generating mechanisms responsible for re-entrainment and resuspension of cohesive sediment. In the present study area, surface wave-forced resuspension is less important than tidal resuspension because of relatively deep water depth.

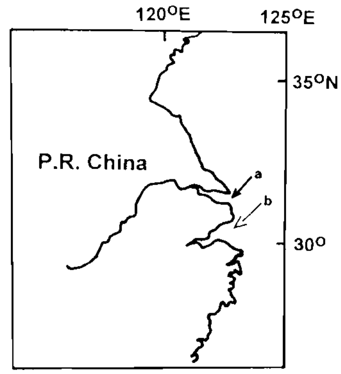

Figure 3. Locations of Changjiang Estuary (a) and Hangzhou Bay (b), P.R. China.

RESULTS

Continuous and High Resolution Cohesive Suspension Profile

This section shows the overall structures of suspensions observed by using the ASSM, to demonstrate the capability of the ASSM to obtain continuous and high resolution cohesive suspension profiles. Figure 4A–D are the grey-scale plots of *ca.* 15 min burst each hour (the usual form of the display is in colour). Four patterns of vertical suspension profiles were identified at flood and ebb tides. Type I is L-shaped at flood tide (seven Blocks in Figure 5A). Most of SSC are less than 1 gL^{-1}, relatively low concentration suspensions. Type II is jet-like at max flood tide (Figure 5B). Vertical gradients in SSC are large. Type III is characterized by an exponential increase in SSC from surface to bottom at ebb tide (Figure 5C). Type IV is jet-like in the mid-water at max ebb tide (Figure 5D). SSC near the bed reaches or exceeds 10 gL^{-1}. Vertical gradients in SSC are large. Figure 5A–D assembles the graphical image of resuspension in progress at flood, max flood, ebb and max ebb tides, respectively.

Acoustic Imaging of Cohesive Sediment Resuspension and Re-Entrainment

Our acoustic observations have also revealed the difference between re-entrainment and resuspension, as suggested by others (MEHTA *et al.*, 1989; SCARLATOS and MEHTA, 1990; MEHTA and SRINIVAS, 1993). Re-entrainment of the mobile fluid mud layer is controlled by turbulent shear flow interfacial instability, while resuspension of the cohesive mud bed is characterized by dislodgement and entrainment of surface flocs due to applied stress. Thus, resuspension is controlled by both the scale of near-bed turbulence and the structures of velocity and density profiles (SCARLATOS and MEHTA, 1990).

Two types of near-bed high concentration suspensions

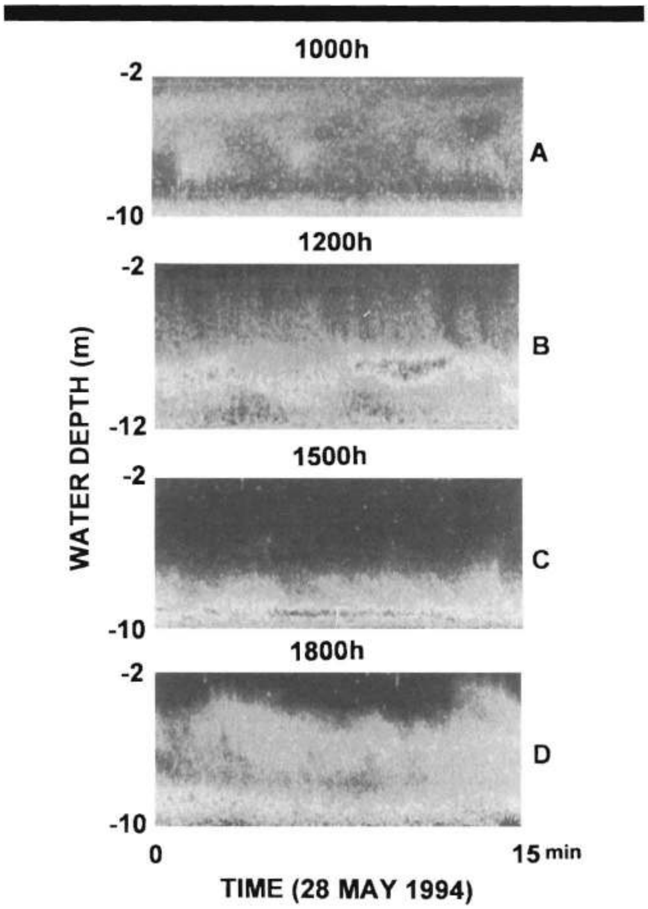

Figure 4. Grey scale plots (adapted from Shi *et al.*, 1996).

(>1gL^{-1}) were indicated by our acoustic images in the Changjiang Estuary: upper high concentration layer and lower high concentration suspension (mobile fluid mud layer) (Figure 6). Upper high concentration suspension layer is indicated by pink color (1300 h, 28 May 1994) while lower high concentration suspension is indicated by yellow color (1400 h, 28 May 1994). The upper high concentrations occurred in two different configurations. At 1600 h (28 May 1994) cloudy upper high concentration suspensions overlaid the lower mobile fluid mud layer. At 1700 h (28 May 1994), the upper high concentration suspension is floating in mid-water and overlying the lower high concentration suspension (Figure 6). Lower high concentration suspensions are confined to the lower 2 m of the water column. It was observed that high concentration suspensions corresponded to conditions of high salinity but low velocity.

Two lutoclines (*i.e.* regions of sharp concentration gradient) are also revealed by the acoustic images (Figure 6). Upper and lower lutoclines are separated by natural breakpoints at 0.5 and 2.0 gL^{-1}, respectively. Such structures had not previously been recognized in the Changjiang Estuary, due to low resolution of point-sampling methods. Similar features have been found elsewhere (NICHOLS, 1984; KIRBY, 1992). These high concentration suspensions most likely correspond to low-density hyperpycnal plumes and high-density hyperpycnal plumes respectively, similar to those observed over the Yellow River delta front (WRIGHT *et al.*, 1986, 1990). However, the lutocline is attributed to the formation of kinematic waves in the suspended sediment distribution initiated by perturbations in the vertical suspended solids distribution and maintained by buoyancy induced turbulent dissipation (SMITH and KIRBY, 1989).

Figures 6A, B, C and D show the acoustic images of vertical suspension concentration for a 12 min burst each hour. Figures 6a, b, c and d show the enlarged acoustic images of the bottom part shown in Figures 6A, B, C and D. Each graph in Figures 6a, b, c and d indicates episodic resuspension events, occurring with at least two different frequencies. High frequency events of a few seconds duration are superimposed on low frequency events of a few minutes duration. For example, at 1700 h, there are three cycles of low frequency events, superimposed by high frequency events of a few seconds (sharp upward and downward fluctuations). These high frequency events shown in Figures 6a, b, c and d are indicative of "turbulence scale" resuspension processes on the cohesive mud bed. Resuspension is a significant process responsible for the formation of a near-bed high concentration suspension (mobile fluid mud layer). When the resuspension flux exceeds lower layer re-entrainment into the upper water column, a mobile fluid mud layer can form (ROSS and MEHTA, 1989).

Figure 7 shows the vertical profiles of current velocity and salinity. The upper part of vertical velocity profiles has a high velocity with a low gradient, corresponding to low concentration suspension (<1gL^{-1}) in Figure 6. The lower part of velocity profiles has low velocity with a high gradient, corresponding to near-bed high concentration suspension in Figure 6. High gradients of velocity are indicative of high bed shear stress, which cause resuspension of the cohesive mud bed. A classical boundary layer is shown at 1700h in Figure 7. Salinity measurements often indicate stratified surface water overlying relatively well-mixed bottom water (Figure 7). This density structure can support strong internal wave activity.

Acoustic Observations of Interfacial Waves within the Near-Bed High SSC Suspensions

WRIGHT *et al.* (1986) provided acoustic images of large-scale internal waves over the Huanghe delta front. It should be pointed out that they only observed a single scattering layer at any one time. ADAMS *et al.* (1990) interpreted optical measurements of turbidity as showing internal waves propagating on a lutocline in an intertidal mudflat tidal channel, Korea. However, they only showed turbidity fluctuations at one height above the bottom between the 25 cm path length of a transmissometer. These studies have therefore only detected internal waves at one level, and have not obtained the full vertical profile of SSC.

In our recent study of Hangzhou Bay, internal waves were able to be observed within the complete vertical profiles of SSC through the water column. The following layered structures were found within the near-bed high concentration suspensions: the upper high concentration suspension, the lower high concentration suspension, and the fluid mud layer. Our

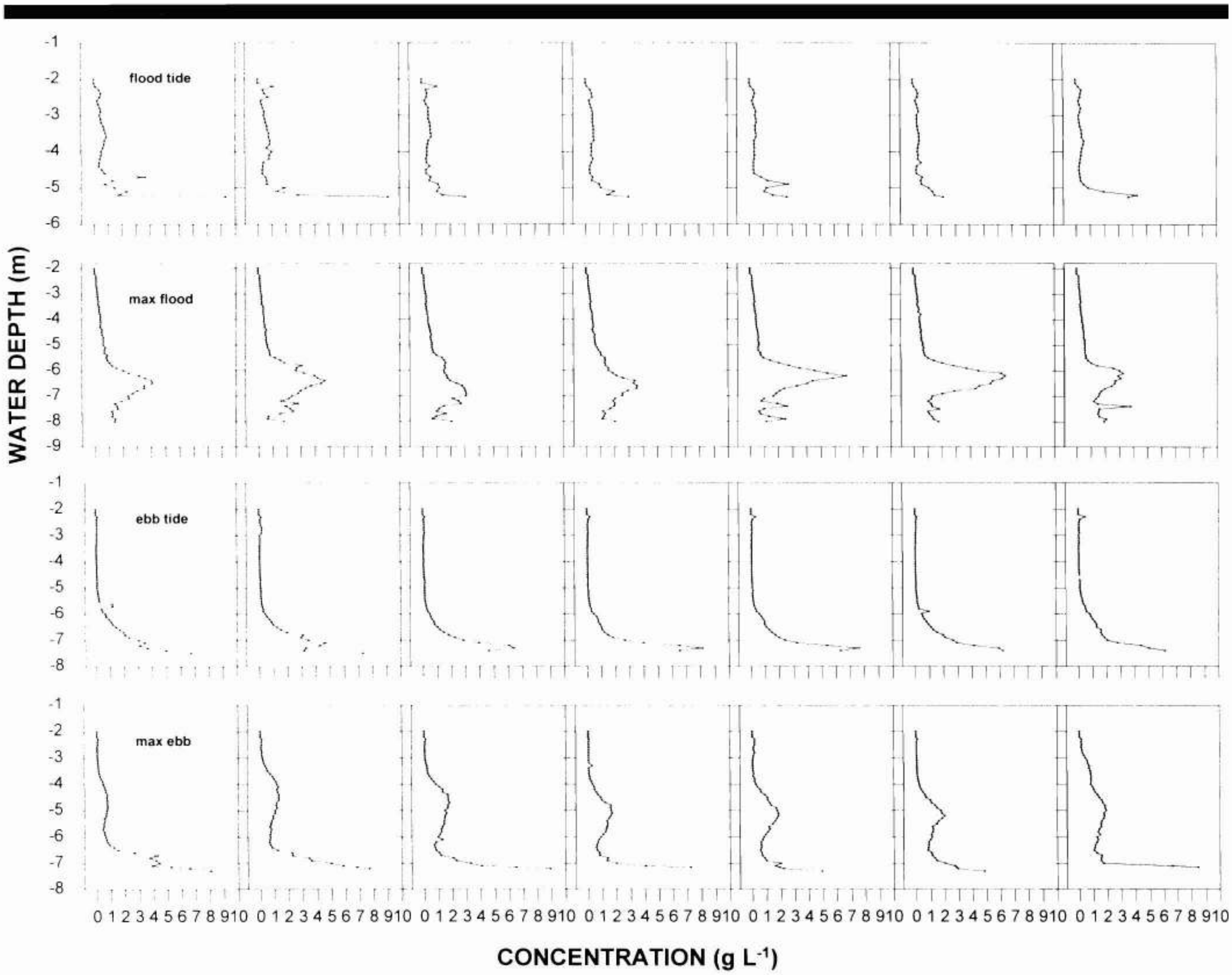

Figure 5. Four patterns of vertical suspension profiles in the Changjiang Estuary, corresponding to each plot of Figure 4, respectively (modified after Shi *et al.*, 1996).

acoustic observations reveal three types of internal waves: (1) low frequency interfacial waves, which occurred between the upper high concentration suspension and the fluid mud; (2) low frequency internal waves between the fluid mud layer and the cohesive mud bed, on which are superimposed (3) high frequency internal waves (Figure 8). A variety of mechanisms are contributing to the internal waves observed which will not be discussed here *e.g.* instability in the currents, wave activity, and possibly atmospheric forcing.

DISCUSSION

How Important Is the ASSM to Estuarine Cohesive Sediment Transport Studies?

We consider the ASSM to be highly useful in sediment transport studies. It is able to remotely estimate near-instantaneous SSC profiles at temporal and spatial resolutions far superior to optical instrumentation and point sampling, without disturbing the environment. Measurements in the Changjiang (Yangtze) Estuary demonstrate the capability of acoustic techniques to measure high concentration, high gradient, and high variability profiles at dynamic scales of processes which produce them. The time seems ripe for a wider use of acoustic backscatter techniques to routinely monitor suspended sediments.

Limitations of ASSM and Future Improvement to ASSM

Clearly, the results above suggest that the ASSM is a powerful technique for measuring cohesive sediment concentration in the high turbidity waters. However, future work is still required. Beyond a certain concentration level, absorption due to suspended sediment is too severe, and the instrument can not function at all. Calibration must rely on field measurements and simplifying assumptions with regard to

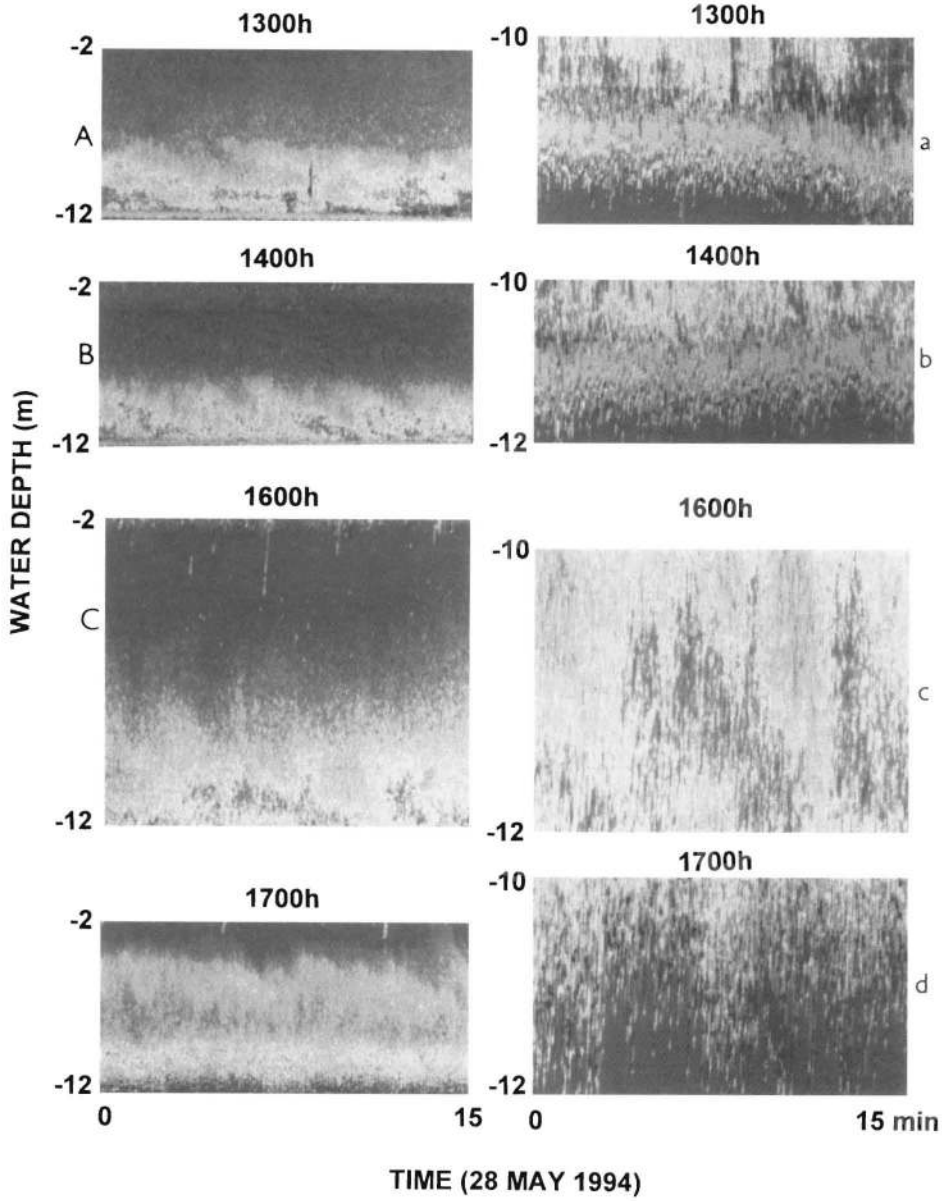

Figure 6. (Left) Upper/lower high concentration suspensions in the Changjiang Estuary. (Right) Enlarged (5×) bottom 2 m of Figures 6A, B, C and D (modified after Shi *et al.*, 1997).

particle properties. Much post processing is required compared to optical measurements. Several researchers, *e.g.* GREEN and BOON (1993) have suggested the pairing of acoustic and optical sensors. The principal aim is to obtain independent measures of SSC which can be verified against each other. There are several possible problems to overcome *e.g.* the instruments look at different sized volumes of water, response times of ABS and optical sensors to dynamic events may be different, non co-location of sensors, different responses or sensitivities to non-homogeneous suspensions, different sampling rates, disturbances introduced by *in situ* optical sensors, and so on. Settling characteristics such as whether disc shapes fall or tumble could also lead to different measurements for the same particles when they are examined by horizontal (optical) and vertical looking ABS sensors (OSBORNE *et al.*, 1994). Pairing of ABS with optics does offer one interesting possibility: if the optics are calibrated even roughly against SSC in the laboratory, an approximate field calibration of the ABS could be made using the optically inferred SSC values. Fouling of optical sensors, particularly in cohesive suspensions, has been barely addressed in the literature, but is certainly a major problem. James Cook University of North Queensland Australia have installed 'windscreen wipers' on nephelometers used on tidal mud flats to

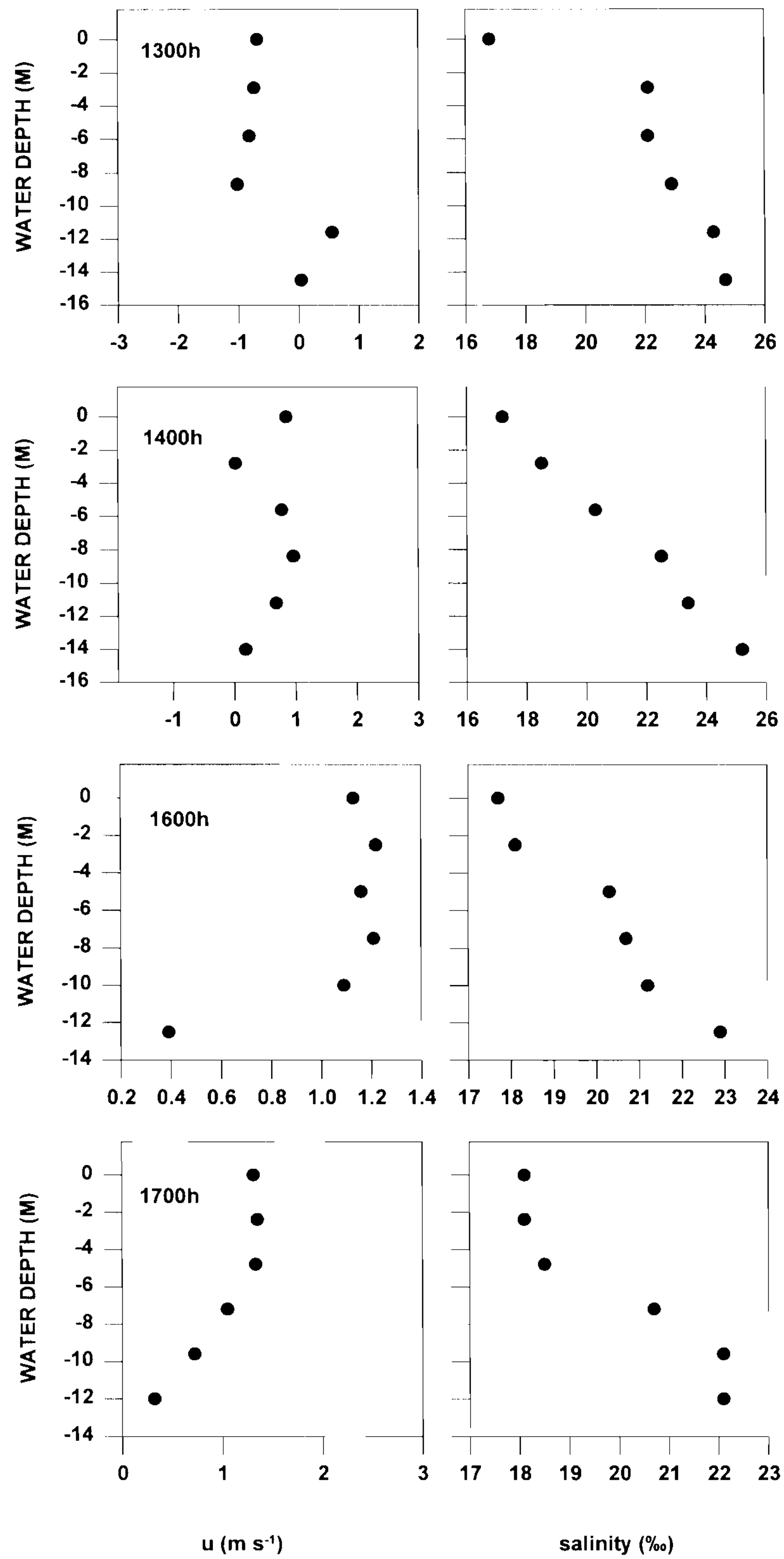

Figure 7. Tidal current and salinity profiles corresponding to Figure 6.

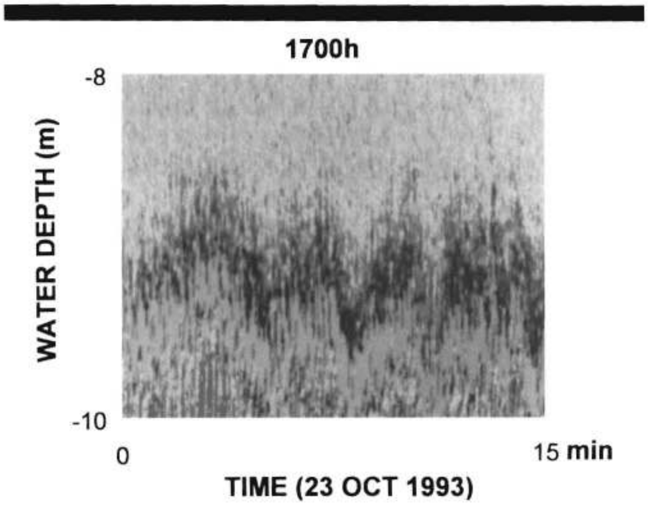

Figure 8. Interfacial waves within the near-bed high concentration suspensions in the Hangzhou Bay.

remove biological fouling (Larcombe, personal communication). However for high resolution measurements this is a further disturbance of the environment. Use of multi-frequency acoustic backscatter devices may help define the size distribution of the suspended sediment (THORNE *et al.,* 1991).

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