Hydraulics Research
Wallingford

ESTUARINE SEDIMENTS - NEAR BED PROCESSES
Field measurement systems

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CONTRACT

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ABSTRACT

The ability to predict the movement of cohesive sediment within coastal, estuarine or inland waters has a significant economical and ecological importance in the development of new engineering works and the maintenance of existing installations. Schemes such as the reclamation of intertidal flats, or the construction of new berths, or the enlargement and extension of dredged channels require a sound engineering appraisal of the likely changes in the patterns of sediment movement which will result after the scheme is built. Furthermore, the capability to predict the movement of cohesive sediment is crucial in the understanding of the distribution of certain pollutants, in particular heavy metals which are adsorbed on to clay and silt particles.

The processes of deposition, consolidation and erosion of cohesive sediment are controlled by a complex array of physical and chemical factors which are only partly understood. Any attempt to predict the movement of cohesive sediment must first investigate the nature of the hydrodynamics of the water and then relate the movement of water to the movement of cohesive sediment.

The aim of the development of a field measurement system was to enable measurement of the rate of cohesive sediment erosion, transport and deposition and the controlling hydrodynamic parameters. This principally required measurement of the hydrodynamics of the near-bed flow, the near-bed suspended sediment concentration and the velocity and suspended sediment concentration profile in the water column. It has been recognised in previous work that high resolution measurement of flow velocity and suspended sediment concentrations are required in the region up to 1m above the bed. Two systems have been employed: a simple system which gives data throughout the water column and a more complex near bed system.

The simple field measurement system measured through depth profiles of suspended sediment concentrations and flow velocity. The measured flow velocities were used to find bed roughness, friction velocity and the shear stress on the bed. The suspended sediment concentration vertical profiles were integrated up to find the total mass in suspension. From the variation of total mass with time the rate of erosion and deposition can be calculated. From the flow velocity and suspended sediment concentrations together a sediment transport vector can be calculated.

The near bed and more complex system enabled measurement of bed level and high frequency (5.0Hz) measurement of velocity (in x, y and z directions at 0.1 and 0.5m above the bed), water pressure variations (at 0.8m above the bed) and suspended solids concentration at 0.1m and 0.5m and 1.0m above the bed. The bed level measurements in conjunction with bed density measurements will enable erosion and deposition rates to be calculated. The high frequency measurements of the flow velocities enable calculation of shear stress from peak bottom orbital velocity and total kinetic energy as well as from velocity profiles. The water pressure variations enable the characterisation of the wave conditions.

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1 INTRODUCTION

1.1 Background

The ability to predict the movement of cohesive sediment within tidal waters has a significant economical and ecological importance in the development of new engineering works and the maintenance of existing installations. Schemes such as the reclamation of intertidal flats, the construction of new berths, or the enlargement and extension of dredged channels require a sound engineering appraisal of the likely changes in the patterns of sediment movement which will result after the scheme is built. Moreover, prediction of the movement of cohesive sediment is crucial in the understanding of the distribution of certain pollutants, in particular heavy metals which are adsorbed on to clay and silt particles.

The processes of transport, deposition, consolidation and erosion of cohesive sediment are controlled by a complex array of physical and chemical factors which are only partly understood. Any attempt to predict the movement of cohesive sediment must first investigate the nature of the hydrodynamics of the water and then relate the movement of water to the movement of cohesive sediment. As yet, it is not possible to predict the behaviour of a cohesive sediment from its physical and chemical properties alone and the principal thrust of research has been to determine in the laboratory or in the field, for a given set of flow conditions, the behaviour of a cohesive sediment.

1.2 Objective

The objective of the research is to increase understanding of near bed processes and their influence on cohesive sediment transport processes. The knowledge acquired will enable an improvement in accuracy and precision of predictive models of cohesive sediment movement.

The accuracy of the prediction of the movement of cohesive sediment is at present limited by the degree of understanding of the near bed hydrodynamics and the influence of the hydrodynamics on sediment transport processes.

It has been recognised in previous work that high resolution measurement of flow velocity and suspended sediment concentrations are required in the region up to 1m above the bed (Ref 1,2). The flow measurements should not only be of tidal flow but also of wave induced flow. The sampling frequency of the flow should be sufficiently high to measure the turbulent fluctuations. These flow measurements will enable the hydrodynamics to be sufficiently characterised to enable the bed roughness factor and vector of the tide and wave induced shear stresses on the bed to be found using methods described by Soulsby (Ref 3).

The aim of the development of a field measurement system was to enable measurement of the rate of cohesive sediment erosion, transport and deposition and the controlling hydrodynamic parameters. This principally required measurement of the hydrodynamics of the nearbed flow, the nearbed suspended sediment concentration and the velocity and suspended sediment concentration profile in the water column. Two systems have been deployed: a simple system which gives data throughout the water column and a more complex near bed system.

The simple system which measured mean tidal flow and suspended sediment concentrations through the water column enabled calculation of tide induced bed shear stress and erosion and a suspended transport rate for each set of measurements throughout the tidal cycle. This comprised use of a lightweight sandflux meter (Ref 4) for near bed measurements and a Severn current meter (Ref 5) in conjunction with either a Partech turbidity monitor and pump sampler or a rapid drop profiler (RDP) (Ref 7) for upper water column profiling.

The more complex near bed system involved the high frequency measurement of: flow in x, y and z directions at 0.1m and 0.5m above the bed, water pressure variations at 0.8m above the bed, suspended sediment concentrations at 0.1m, 0.5m and 1.0m above the bed and bed level measurements. A frame developed previously by HR and deployed initially on tidal mud flats (Ref 6) was used for the near bed measurements.

2 THROUGH DEPTH MEASUREMENT SYSTEM

2.1 Upper column profiler

Measurements of uni-directional flow (speed and direction) and turbidity were made using a HR Severn current meter in conjunction with a Partech turbidity monitor and water pump sampling tube for calibration samples. Alternatively a rapid drop profiler is used in place of the Partech turbidity monitor.

The Severn current meter was specifically designed by HR to operate from a small boat in high tidal flows (Ref 4). It consists of a Braystoke impeller meter, a purpose built fluxgate compass and a Druck solid state pressure transducer for depth measurement.

The RDP, also developed by HR, enables detailed profiling of mud concentration and salinity. It comprises an underwater unit equipped with an inductive conductivity (salinity) sensor, an infra red turbidity sensor, and a pressure sensor. The electrical leads and lifting cable are incorporated into a purpose built electro-mechanical cable to reduce drag in high flows.

The apparatus was operated over the side of the boat, with the height of the instrument being controlled manually. A fixed weighted line from the boat to the bed was used as a guide to further limit the effects of current drag. Profiles were taken at 30 minute intervals with readings taken at 1m, 2m, 3m, 4m, 6m, 8m, and 12m above the bed. Water samples were taken over a range of concentrations to enable confirmation of the calibration of the turbidity sensor.

2.2 Bed frame

The frame used for the near bed measurements was an HR lightweight Sand fluxmeter (Ref 4). This consists of an alloy frame which rests on the bed. A central column with a large base is free to slide vertically in the frame so that the plate rests on the bed irrespective of the level of the tubular skids. A swinging arm carrying a current meter, turbidity meter and sampling intake is pivoted from the central column, its vertical movement can be controlled from the attendant launch by means of a push pull cable. The height can be adjusted from 0m to 1.5m above the bed.

The frame is deployed at slack water and is aligned with the impending tidal flow direction. Measurements are taken at heights of 0.05m, 0.15m, 0.3m and 0.6m above the bed at 30 minute intervals in conjunction with the upper water column measurements.

3 NEAR BED MEASUREMENT SYSTEM

3.1 Design of complex frame

The field bed frame was designed so that it could be deployed either on inter-tidal mudflats or from a boat. It had previously been deployed with success on intertidal mud flats (Ref 6). The frame was lightweight, incorporating brackets for equipment, sufficiently small so that it would present little obstruction to water flow and strong enough so that it would not vibrate in flowing water and not be damaged in boat deployment. The bed frame design is shown in Plate 1.

The frame is triangular in plan with three vertical extendable legs with a diameter of 0.05m. The legs are adjusted in length to suit the depth and softness of the bed.

The frame was initially designed to support the following instruments:

- two electro-magnetic current meters (EMCM)
- two Partech turbidity sensors
- three ultrasonic flaw detector probes
- a water pressure sensor
- a Braystoke current meter
- a compass (not needed on inter-tidal deployment)
- a pitch and roll sensor (not needed on inter-tidal deployment)

The two EMCMs were mounted to measure two horizontal components of velocity (parallel to the main tidal flows, x, and perpendicular to the main tidal flow, y) at 0.1m and 0.5m above the bed. For convenience they were mounted from the same horizontal bar with one pointing upwards and one pointing downwards.

The Partech turbidity sensors were mounted at 0.1m and 0.5m above the bed in a position that would not interfere with the flow around the two EMCMs. The three ultrasonic flaw detector probes were mounted on the short horizontal bars extending from each leg approximately 0.3m above the bed. The pressure sensor was mounted on a diagonal bar opposite the two EMCMs. The pitch and role sensor and the compass were mounted on plates at the top of the frame.

The frame was modified to accommodate two additional EMCMs mounted to measure flow in the x and z directions, at 0.1m and 0.5m above the bed. Two more Braystoke current meters were also added to enable measurement of tidal flow at 0.1, 0.5 and 1.0m above the bed. Each of the three Braystokes were mounted on a swivel to enable orientation with the flow direction.

3.2 Logging equipment

A portable IBM compatible computer with a 286 microprocessor and a 40MB hard disk was used for data logging. The data acquisition was via a DT2801 input/output board. Single ended inputs were used for the voltage inputs. Plate 2 shows the logging equipment set up on board the boat.

The output voltage from the EMCMs control unit was approx 0.3VDC per ms^{-1}. Each of the output signals (x and y directions from both current meters) was sent to the microcomputer via an electronic Chebyshev filter which removed very high frequency voltage fluctuations.

The output voltage of the Partech turbidity sensors was 0 to 1VDC The concentration corresponding to 1V output was dependent upon the instrument settings. The output was sent directly to the portable computer.

The water pressure sensor output was 0.1VDC per metre head. The output was sent to the computer via a signal isolator to prevent interference with the ultrasonic probe traces.

The output from an ultrasonic probe is a trace on the oscilloscope of the control unit. The position of a peak on this trace can be interpreted as the distance between the probe and the water/mud interface at the bed. The instrument was set to give a DC voltage output proportional to the distance of the peak from zero on the x axis. Hence, the voltage output was proportional to the distance to the bed from the ultrasonic transducer. Changes in bed level before and after the logging period could be checked manually after the tide had receded by measuring at the ultrasonic probes.
The Braystoke current meter readings were logged manually.

3.3 Calibration and Deployment

The four EMCMs have 50mm diameter heads of the bi-directional type and were calibrated using a circular current meter calibration tank at HR. These were used to measure flow at a sampling frequency of 5Hz for ten minute periods.

The Braystoke current meters were used to give mean tidal flows and a field calibration of the EMCMs. They have 30mm impellers and were calibrated at HR.

The Partech turbidity monitors were calibrated using samples taken during each deployment.

The pressure transducer, manufactured by Druck, had a maximum head capacity of 10m. The calibration was set by the manufacturer and checked at HR before use. It was mounted in a protective cylinder 200mm long and 110mm diameter. The pressure was also sampled at 5Hz.

The ultrasonic flaw detector probes were manufactured by Sonatest and operated on a frequency of 5-7MHz. These were mounted at 0.3m above the bed and used to detect changes in bed level. These were calibrated using water from the survey area.

The frame was deployed at the beginning of the monitoring period (at slack water) and remained in place until the following slack water. It was placed on the bed with the aid of divers who guided its orientation and depth of penetration of its legs into the bed. Data was logged directly onto the computer over periods of 10, 30 or 60 minutes.

At the start of the data logging period the signal from each of the three ultrasonic probes was examined visually. The clearest signal was logged directly onto the computer over the duration of the logging period.

The reading from each instrument except the Braystoke current meters was input to the computer as a DC voltage. This voltage was sampled at 0.2 second intervals and the reading stored as a real number. The voltage readings were then converted into real actual the calibrations and the 30 minute and 60 minute acquisition files were split into files containing ten minutes of data.

4 ANALYSIS ROUTINES

4.1 Analysis of through depth measurements

The suspended sediment concentration profiles above 1m were calculated from the turbidity and water pressure readings taken using the upper column profiler at each 30min interval. Suspended sediment concentrations between 0.05m and 1.0m from the bed frame readings were added to these to give concentration profiles of the water column with high detail in the near-bed region.

In the same way the Severn current meter readings were used to give the velocity profile in the water column from 1m above the bed to the water surface at 1m, 2m, 3m, 4m, 6m, 8m and 12m. These measurements together with the flow readings obtained from the bed frame measurements gave comprehensive tidal flow profiles. The flow direction was taken from the compass readings of the upper profiler. When using the near bed measurement system the flow directions at 0.1m and 0.3m above the bed could also be found from the EMCM readings (see section 4.2)

4.2 Analysis of water pressure data

Analysis of the water pressure data to give significant wave height (H_s), mean wave period (T_z) and mean water depth involved several stages. First, each ten minute record was filtered to remove the change in baseline water pressure caused by tidal level change. The average of each successive block of 256 values was calculated and a simple linear fit applied to the variation of mean water level from block 1 to block 2, from block 2 to block 3 etc. Each value was then set to the difference between the original value and the 'mean' depth at that instant. Error checking was limited to an automatic alert if the difference between successive pressure values exceeded a given value.

The pressure fluctuations could not as such be used to calculate wave heights directly because of differences in pressure attenuation between low and high frequencies. A standard correction factor dependent upon the water depth and frequency had to be applied the data.

At the high frequency end of the spectrum there tends to be a small proportion of spurious energy. This tail part of the spectrum assumed much greater proportion when converted to a surface elevation spectrum. Accordingly, an upper frequency cut off was set at 0.75Hz to exclude this energy from the spectrum.

The significant wave height (H_s) and mean wave period (T_z) could then be calculated for each ten minute record using the following equations:

$$H_s = 4\, m_o^{0.5}$$
$$T_z = (m_o/m_2)^{0.5}$$

where

$$m_n = \int_{f_l}^{f_u} E(f)\, f^n df$$

$E(f)$ = wave spectrum

f_u and f_l = upper and lower frequency limits

4.3 Analysis of EMCM velocity data

Each velocity record consisted of a tidal induced component and a wave induced component. The mean tidal induced component was considered to vary slowly. Hence, the running average over a 2-3 minute period will give the mean tidal velocity. This tidal velocity can be subtracted from the original velocity record to give the oscillating wave and turbulent components of the velocity.

The mean tidal velocity over each ten minute period is calculate for the x and y horizontal directions. From these the magnitude and direction of the tidal flow at 0.1m and 0.5m above the bed is computed.

The direction of the waves was calculate from inspection of a probability distribution analysis of the directions of the tide reduced velocity data. The x and y components of this velocity data are first resolved to give speed and direction.

A spectral analysis of the x and y horizontal velocities of the tide reduced EMCM data was then carried out. The frequencies analysed corresponded to those used for the pressure sensor analysis and the spectral distribution of energy was broadly similar. The spectral analysis was expressed as a plot of log energy versus log frequency. This can be interpreted as comprising turbulence from the tidal current with wave induced fluctuations showing as peaks superimposed on top. Each spectrum can be split to separate the turbulent from the wave energy (Ref 3).

The RMS orbital velocity corresponds to the square root of the sum of areas of spectrum, on a linear plot, attributed to the waves of the x and y components. This can be used to confirm the RMS velocity found from water pressure analysis using wave theory. The direction of propagation of the waves can also be found from the ratio of the areas of the x and y components.

The kinetic energy density corresponds to half the sum of square roots of the areas of the spectrum attributed to the turbulence of the x, y and z components. This was also calculated for 0.1m and 0.5m above the bed.

4.4 Calculation of erosion and deposition rates

The total mass in suspension at any particular sampling time was found by summing the concentration profiles. The change in mass in suspension from one instant in time to the next will correspond to the mass eroded from or deposited on the bed assuming uniform conditions over a large area.

The rate of erosion or deposition at a point can also be calculated from the ultrasonic bed level measurements on the complex near bed frame. The mass of erosion is proportional to the bed level change times the density of the bed. The density can be measured using a gamma ray probe or by taking samples for laboratory analysis.

4.5 Calculation of bed shear stress vector

The friction velocity and apparent bed roughness was calculated from the best fit logarithmic line through the lower water column velocity measurements. This friction factor calculated in this way, however, will only represent the real bed friction factor in records which have insignificant wave activity. The direction of this stress was the same as that of the measured flow direction.

To find the peak bed shear stress due to waves the maximum bottom orbital velocity must first be found.

The maximum bottom orbital velocity was calculated from the significant wave height, mean wave period and the water depth using first order linear wave theory. The peak bed shear stress can then be found by assuming a friction factor (Ref 8) or using the friction factor found from the tidal flows as above. The direction of this stress was orientated in the direction of wave propagation.

The wave and tide induced shear stress parameters can be combined to give overall shear stress characteristics.

The high frequency velocity measurements enable the bed shear stress to be calculated from the Reynolds stress and from total kinetic energy (Ref 3). The Reynolds stress was calculated from the spectra of the high frequency velocity data. This in turn can be used to calculate the bed shear stress. The streamwise and transverse components were calculated and combined to give the modulus and direction of the stress.

The shear stress at the bed has been found by other workers to be directly proportional to the turbulent kinetic energy (Ref 3). This has been found to be true of a wide variety of flows including wave plus current flows and enables the shear stress to be estimated.

5 EXAMPLE RESULTS

5.1 Through depth measurements

The results of the measurements taken through the water column are in the form of readings of flow velocity and suspended sediment concentration at twenty minute sampling intervals. An example of a single twenty minute set of data is given in Table 1. The concentration readings are plotted against depth on a linear axis in Figure 1. The suspended sediment concentration decreased with height above the bed. The flow speed is plotted against the natural logarithm of depth (Fig 2). The gradient of the best fit line through the data points is equivalent to $0.4/U_*$ and the intersect on the height at which flow equals zero is the apparent bed roughness. The friction velocity was found to be $0.026 ms^{-1}$, the apparent bed roughness 0.054m and the shear stress on the bed was calculated to be $0.7 Nm^{-2}$.

5.2 Results from the near bed frame

The near bed frame will give information on bed level and high frequency velocity and pressure fluctuations as well as those given by the simple system.

Spectral analysis of the U, V and W high frequency fluctuations of velocity in the x, y and z directions respectively give plots of the type given in Figures 3 to 5. The area under the curve is composed of two parts, the lower area corresponding to turbulent fluctuations, and a peak superimposed on top of the lower area corresponding to the wave energy. The areas under the curves correspond to the turbulent energy and wave energy respectively.

A summary of the results of the analyses of one data set is given in Table 2. This shows that the two methods of calculating bed shear stress from high frequency velocity gave values of $2.7 Nm^{-2}$ and $3.0 Nm^{-2}$. These were of the order of agreement found by Soulsby (Ref 3).

6 CONCLUSIONS

The through depth field measurement system measured profiles of mean suspended sediment concentrations and mean flow velocity. The flow velocity vertical profiles were used to find bed roughness and friction velocity and the bed shear stress. The suspended sediment concentration vertical profiles were integrated to find the total mass in suspension. From the variation of total mass with time the rate of erosion and deposition was calculated. From the flow velocity and suspended sediment concentrations together a sediment transport vector was calculated.

The complex near bed frame measurement system determined the high frequency of velocity (in x y and z directions), water pressure variations and suspended solids concentrations. The high frequency measurements of the flow velocities enabled calculation of shear stress from peak bottom orbital velocity and total kinetic energy as well as from the water column velocity profiles. The bed level measurements in conjunction with bed density measurements enabled the erosion rate to be calculated in addition to the calculation from total mass in suspension.

7 REFERENCES

1. Dyer K R, "Sediment Transport Processes in Estuaries: Future research requirements" Journal of Geophysical Research 19, pp14327-14339 October 1989.

2. Sternberg R W, et al, "An Instrument System for Monitoring and Sampling Suspended Sediment in the Benthic Boundary Layer", Marine Geology 71, pp187-199 1986.

3. Soulsby R L and Humphery J D, "Field observations of wave-current interaction at the sea bed", NATO Advanced research workshop on water wave kinetics 1989.

4. "Sand Fluxmeter (lightweight version for small boats)", Hydraulics Research Limited, Equipment note No 12.

5. "Severn Current Meter", Hydraulics Research Limited, Equipment Note 14.

6. Delo E A, Diserens A P, "Erosion of Mud by Waves: A field measurement system", Hydraulics Research Limited, SR 225, January 1990.

7. "Rapid Drop Profiler", Hydraulics Research Limited, Equipment Note 13 .

8. Delo E A, "Estuarine muds manual", Hydraulics Research Limited, SR 164, February 1988.

TABLES.

TABLE 1 Example of single data set; through-depth measurements

Harwich Haven Authority

Date: 18/09/89 Position: 626216mE Water
234190mN Depth(m): 8.0

Time GMT	Height above bed (m)	Velocity (ms^{-1})	Direction (true)	Sal. (ppt)	Turbidity (mgl^{-1})
09:04	0.05	0.00			701
09:06	0.15	0.05			656
09:08	0.30	0.16			565
09:10	0.60	0.15			520
09:04	1.0	0.17	300	33.5	554
09:06	2.0	0.22	304	33.5	456
09:08	3.0	0.27	298	33.5	406
09:10	4.0	0.31	295	33.5	406
09:12	6.0	0.31	306	33.5	357
09:14	8.0	0.29	303	33.5	333

TABLE 2 Example of results of data processing high frequency velocity fluctuations

Direction	Kinetic Energy Squared		
	Total	Wave	Turbulence
X	0.000155	0.000010	0.000140
Y	0.000637	0.000060	0.000577
Z	0.000210	0.000002	0.000210

Wave rms velocity	7.0ms^{-1}
direction	23 degrees (from x pos)
Kinetic energy (E)	0.00050m^{2}s^{-1}
Bed shear stress	0.10Nm^{-2}

FIGURES.

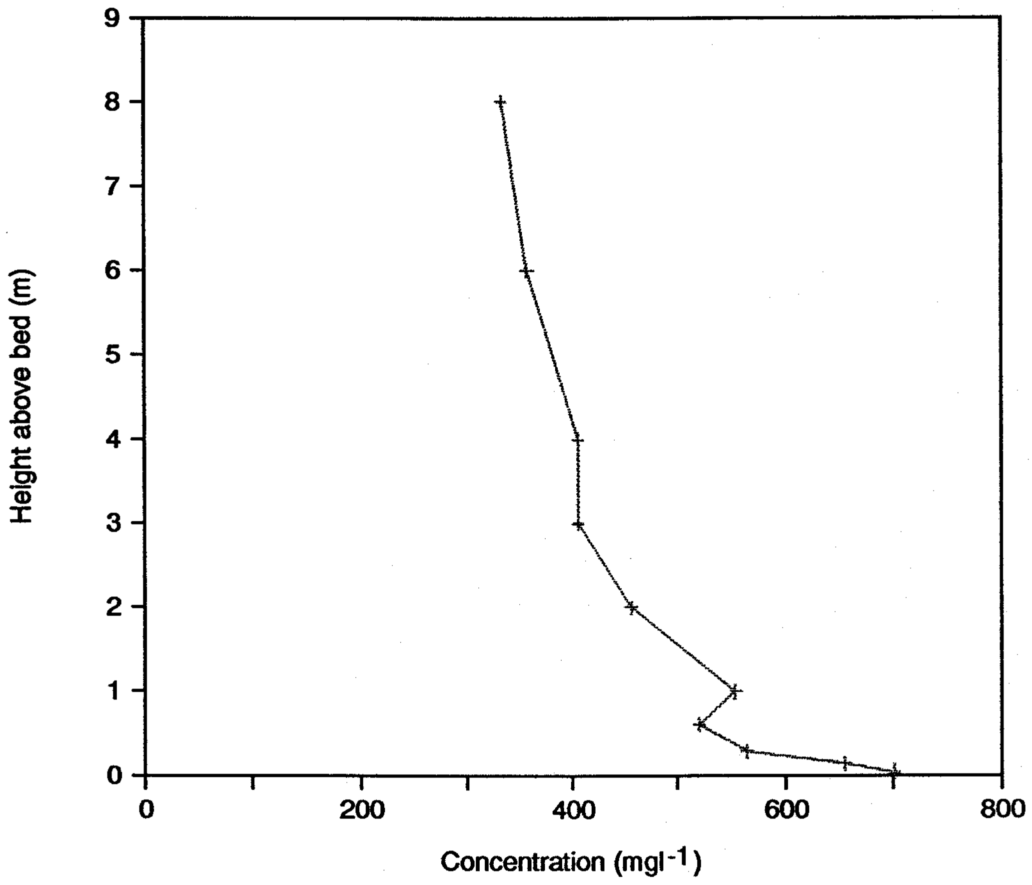

Fig 1 Example of suspended sediment concentration profile

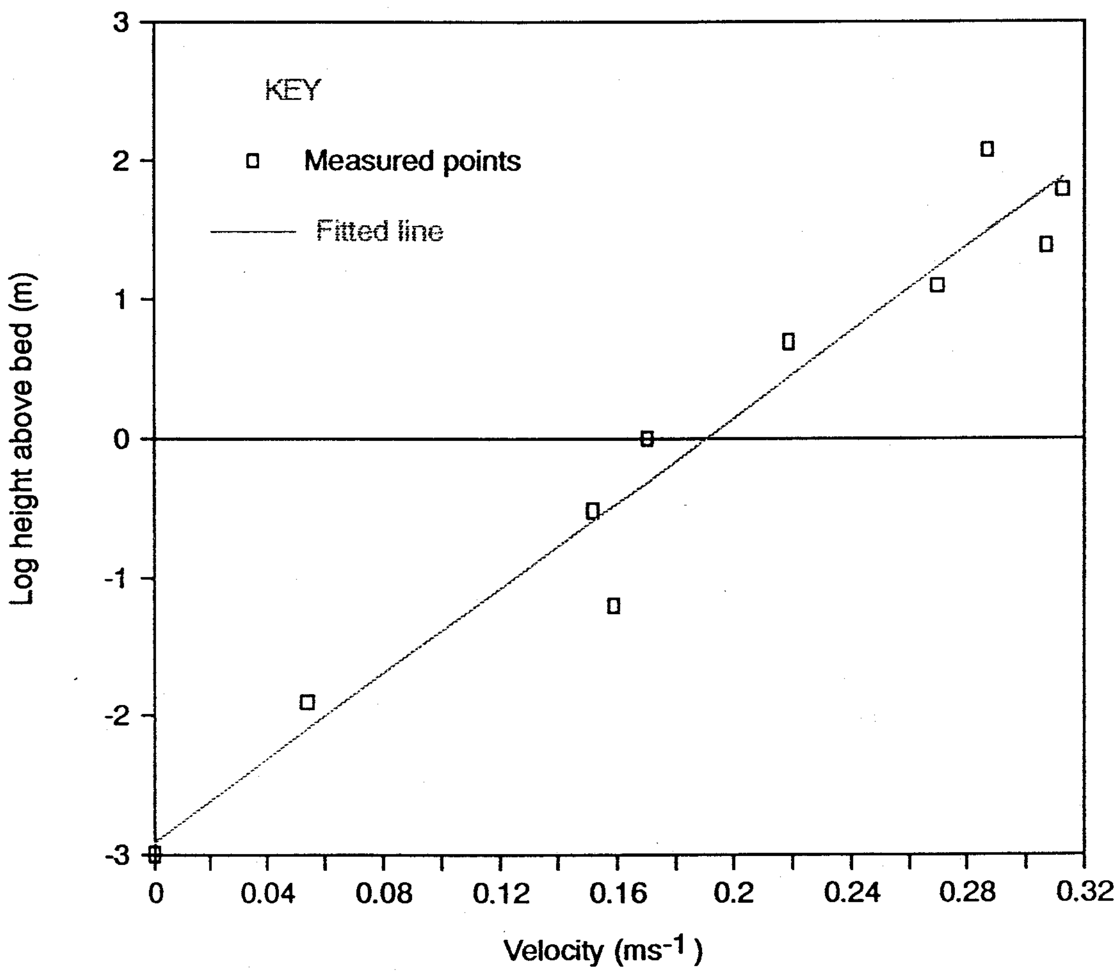

Fig 2 Log plot of velocity profile

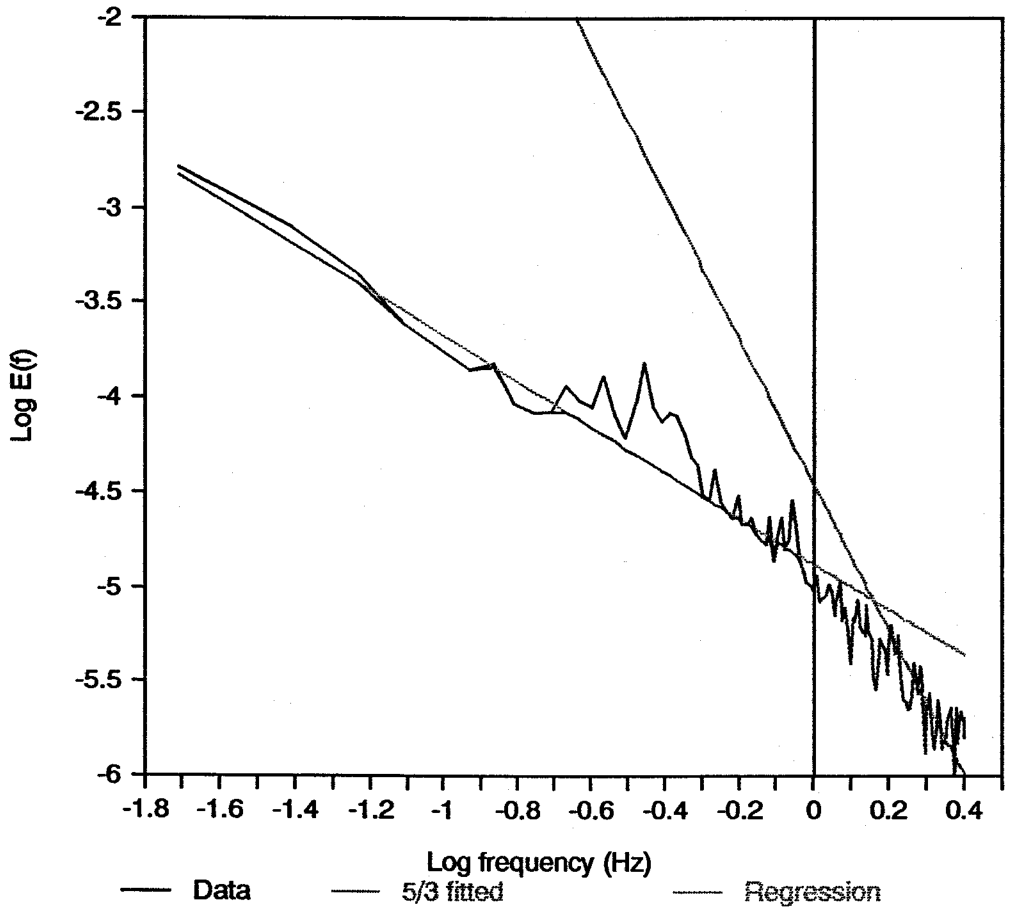

Fig 3 Spectrum of u fluctuations

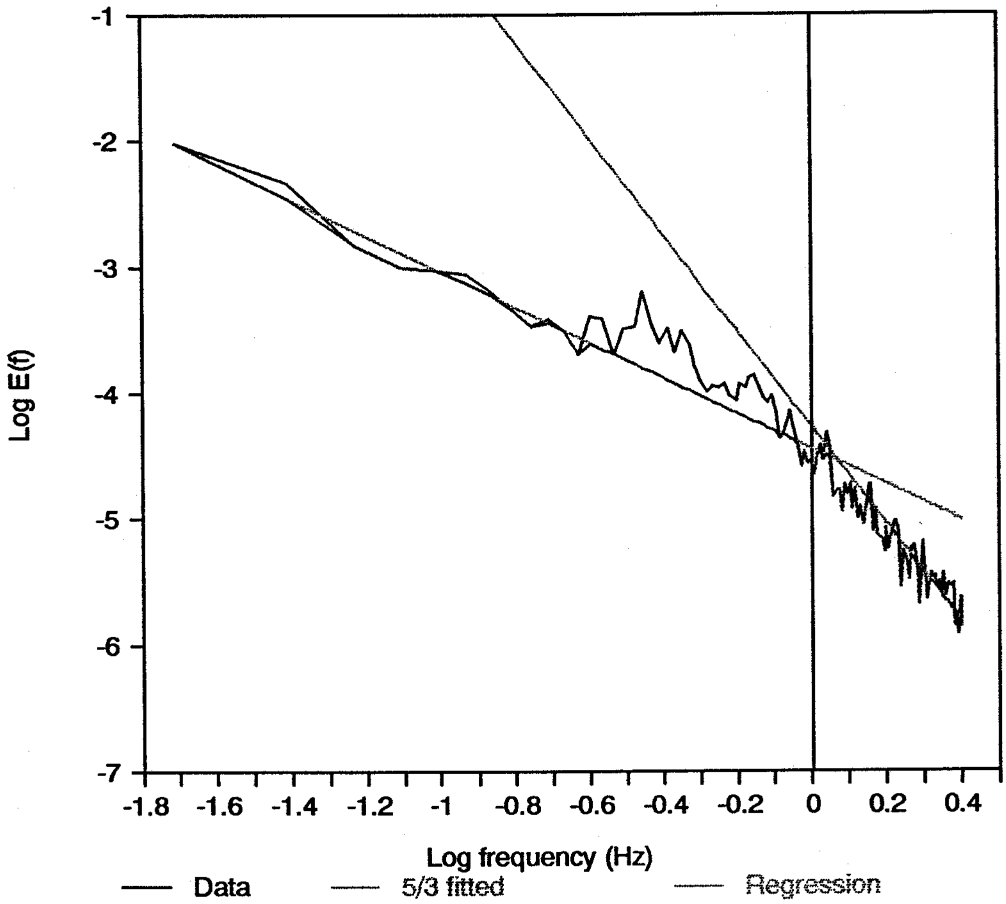

Fig 4 Spectrum of v fluctuations

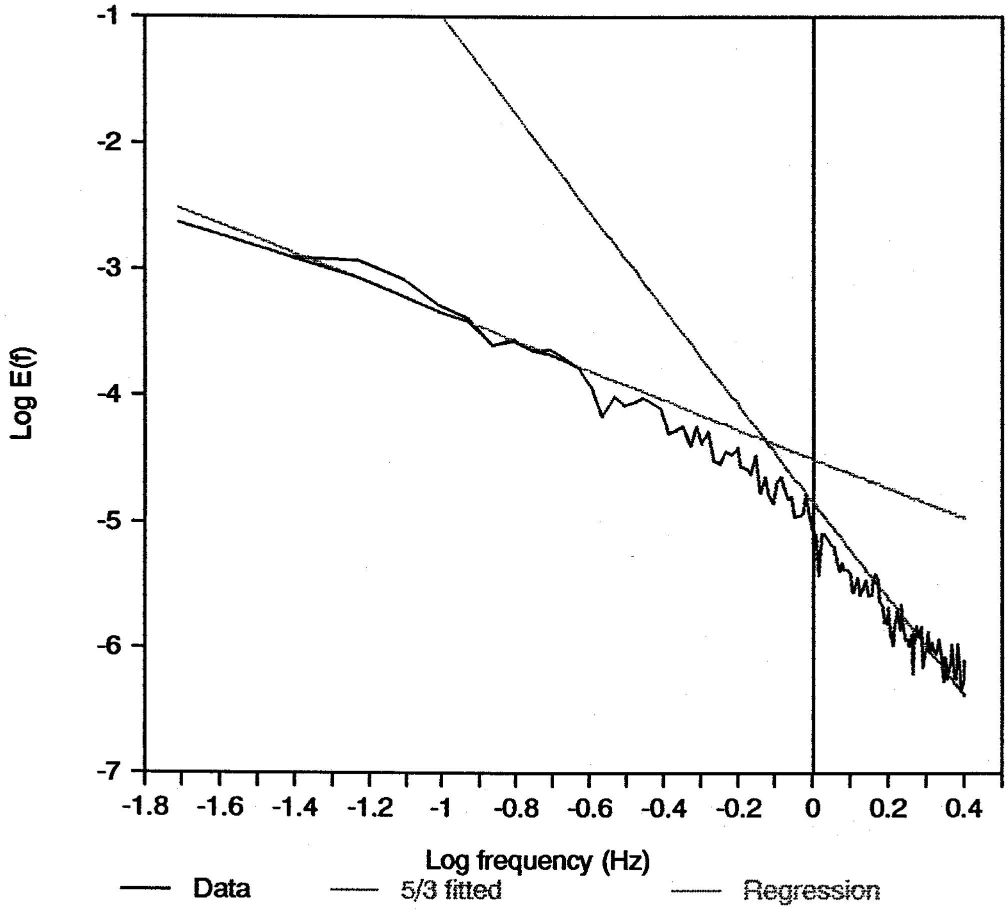

Fig 5 Spectrum of w fluctuations

PLATES.

Plate 1 Bed frame

Plate 2 Logging equipment