Laboratory Evaluation of Instrumentation used in Field Studies of Wave-Sediment Interactions

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Abstract

Restrictions imposed by the physical size of testing facilities has limited the range of trials undertaken on field instruments and little is known about interactions between the observed processes and large frames used to deploy equipment in the sea. Further, limited information on the physical processes from the field leads to ambiguity in interpretation of field data. This paper describes tests of the autonomous multi-sensor instrument STABLE, and process studies conducted in the Deltaflume (230 m long, 5 m wide and 7 m deep) of the Delft Hydraulics Laboratory. Regular and random waves with a specified time history and height up to 1.5 m, were used to test instrument performance and to examine sediment processes under waves on beds of medium (D_{50} = 0.329 mm) and fine sand (D_{50} = 0.162 mm). Selected results from studies of hydrodynamics, bedforms and suspended sediments are presented.

Introduction

Instruments used to measure near-bed hydrodynamic conditions and sediment dynamics in field situations are usually tested and calibrated in relatively 'small-scale' laboratory facilities where it is not always possible to simulate natural processes accurately. In many instances the physical size of these calibration facilities has restricted the range of trials undertaken and frequently little is known about the interactions between the observed processes, the instruments, and the bulky frames used to deploy instrumentation in the sea. Further, instrumentation frequently provides only limited information on the processes under investigation leading to ambiguity in some aspects of field data interpretation. Whilst some of these deficiencies can be addressed through recourse to numerical modelling, recent field experiments have highlighted an urgent requirement to examine critically the performance of

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state-of-the-art field instrumentation in a range of controlled experimental conditions at full-scale.

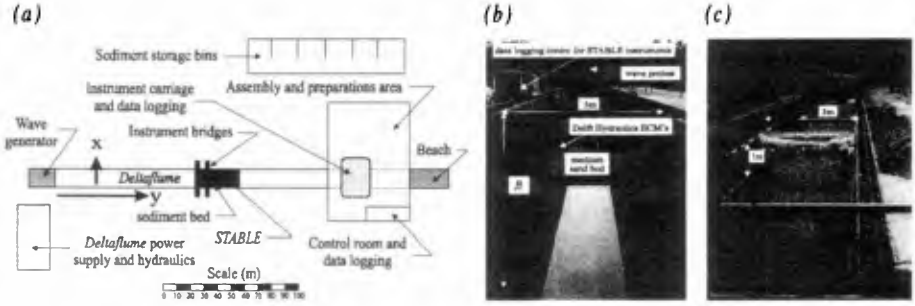

Figure 1 *(a)* Schematic plan of the *Deltaflume* research facility; *(b) Deltaflume* before filling showing the medium sand bed *in situ*; *(c)* 1 m regular waves in the *Deltaflume*, *test A4b*.

This paper describes research undertaken in the large *Deltaflume* facility, *Figure 1*, of Delft Hydraulics during a six-week period in July and August 1997. The work aimed to evaluate the performance of the autonomous multi-sensor frame *STABLE* (Sediment Transport And Boundary Layer Equipment, *Humphery & Moores, 1994*), *Figure 2*, and to measure in detail, bed sediment response to forcing by waves.

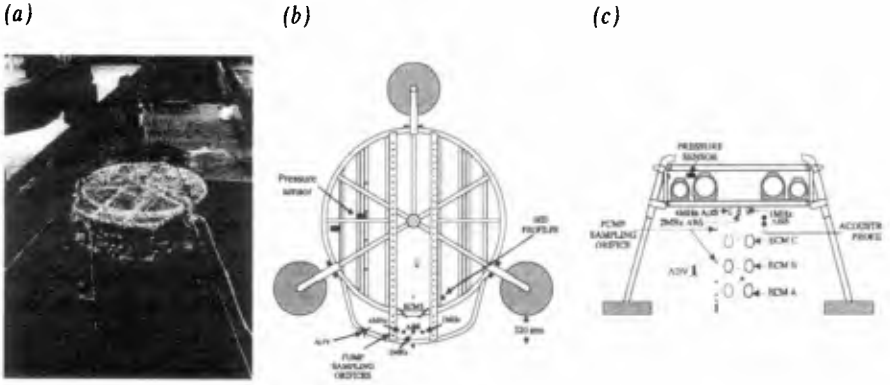

Figure 2 *STABLE*: *(a)* deployment in the *Deltaflume*; *(b)* plan view; and *(c)* side view

During tests, *in situ* measurements of wave characteristics, flow turbulence, bedforms and vertical suspended sediment concentration profiles were obtained in regular and irregular waves conforming to the JONSWAP spectrum. Hydrodynamic conditions below, approximating to and exceeding the threshold for resuspension of the bed material were examined. Independent measurements of wave-induced flow and vertical suspended sediment concentration profiles were obtained from locations adjacent to the side-wall of the *Deltaflume*.

Equipment and Methods

The *Deltaflume*

The Delft Hydraulics Laboratory *Deltaflume* is 230 m long, 5 m wide and 7 m deep, *Figure 1*. Regular and irregular waves with a height up to 2 m can be generated according to a required time history. During the present tests, 10 cm discus-shaped electromagnetic current meters were fitted to the side-wall of the flume at heights z = 25 cm, 50 cm, 100 cm, 150 cm and 250 cm above the bed at a distance y = 120.9 m from the wave generator. Two resistive wave measurement probes positioned at y = 117.9 m and at 120.9 m (*Figure 1a*) were used to measure wave height, H. Data from these instruments were logged at 25 Hz. Delft software was used to calculate a number of wave parameters including wave period, T, and in the case of random waves, significant wave height, H_s and peak wave period, T_p.

Samples of suspended sediment were obtained at 10 heights above the sand bed using a pump-sampling device deployed using vertical guide rails at y = 121.5 m. The sampling device consisted of 10 intake nozzles (diameter 4 mm) orientated at 90° to the wave orbital motion. Each nozzle in the array was connected to a plastic pipe through which a mixture of water and sediment was drawn to the surface by means of a peristaltic pump. The resulting water/sand mixture from each sampling position in a given array was collected in 10 litre buckets.

Sediment beds

Two sandy test beds were studied: *(a)* medium sand (median grain diameter, D_{50} = 0.329 mm); and *(b)* fine sand (D_{50} = 0.162 mm). The sandy beds were approximately 30 m long, 5 m wide and 0.5 m deep, and were placed at y = 105 m in the *Deltaflume*, (*Figure 1*). Both ends of the test beds were tapered to reduce erosion. To minimise bed disturbance, drainage was laid beneath the sediment bed to allow the free passage of water during filling of the *Deltaflume*. The sandy beds were compacted by mechanical vibration. After filling and prior to taking any acoustic measurements, large waves were generated for approximately 4 hours to force remaining air out of the bed and to develop equilibrium bedforms.

STABLE

Instrumentation on *STABLE* measured waves, flow turbulence and suspended sediment concentrations. A *Digiquartz* pressure sensor with integral pressure housing was used to measure the water-depth at wave frequencies at z ≈ 170 cm. Near-bed fluid motion induced by waves was measured using *Valeport Series 800* electromagnetic current meters (*ECM*'s) with a diameter of 10 cm and a resolution of ±0.1 cm/s. *ECM* sensors were arranged in pairs set at 90° to each other at $z \approx 30$ cm, 60 cm, and 91 cm. Horizontal separation between each *ECM* sensor was 20 cm. Measurements of flow turbulence were also obtained at $z \approx 30$ cm using a SonTec acoustic Doppler velocimeter, *ADV*, Ocean Probe operating at approximately 5.0 MHz. Measurements of horizontal and vertical wave induced fluid motion were measured using *POL* coherent Doppler sensors.

Bedforms beneath *STABLE* were measured using an acoustic ripple profiler (*ABP*) and a sector scanning sonar (*SSS*) device (*Bell & Thorne, 1997*). Acoustic backscatter, *ABS*, instruments (*Thorne & Hardcastle, 1997*) operating at 1.0 MHz, 2.0 MHz, and 4.0 MHz, were located 15 cm in front of the *ECM* sensors at $z \approx 128$ cm. These instruments measured the vertical suspended sediment concentration profiles, $\overline{C}$ *profiles*, from the bed to $z \approx 120$ cm at intervals of 1 cm. A vertical array of pump sampling nozzles was also fixed to the *STABLE* frame. A calibrated volume meter was then used to determine approximately, the suspended sediment concentration at each sampling height, (*Bosman et al., 1987; Havinga, 1992*). Subsequent analysis of samples in the laboratory gave dry weight sediment concentration values and the suspended sediment grain size at each sampling height. *ECM* and *PS1* data were sampled at 8.0 Hz and *ABS1, ABS2* and *ABS3* data were sampled at 4.0 Hz over a period of approximately 19 minutes. *ADV* data were sampled at 25.76 Hz during the same period. A schematic illustration of the experimental set-up is given in *Figure 3* and a summary of all hydrodynamic and morphodynamic variables measured during *Deltaflume* tests is given in *Table 1.* Further details of *STABLE* and the *Deltaflume* are given by *Williams et al., (1998a).*

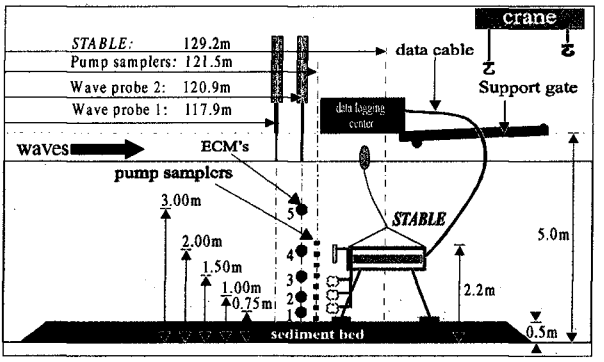

Figure 3 Schematic of experiment layout showing *Deltaflume* and *STABLE*

Variables	Instrumentation	Accuracy	Sampling frequency
Water temperature	Thermistor	± 0.05°C	0.016Hz
Water (dynamic) pressure	Pressure sensors	± 0.15%	8Hz
Water velocity	*ECM*'s	± 0.2cm/s	8Hz
Turbulence	*ECM*'s	± 0.2cm/s	8Hz
Turbulence	SonTec *ADV*	± 0.1cm/s	25Hz
Vertical flow component	Coherent Doppler	± 0.1cm/s	8Hz
Horizontal flow cross-correlation	Coherent Doppler	± 0.1cm/s	8Hz
Horizontal flow component	Coherent Doppler	± 0.1cm/s	8Hz
Free surface elevation	Surface following gauge	± 2.5cm	10Hz
Free surface elevation	Resistance type gauge	± 1cm	10Hz
Suspended sediment	*ABS* (1.0; 2.0; 4.0MHz)	0.001g/l	4Hz
Suspended sediment	Pump sampling	± 20%	-
Bed morphology	*DH* ripple profiler	± 2mm	1cm grid
Bed morphology	Sector scanning sonar	± 2mm	0.016Hz
Bed morphology	Acoustic ripple profiler	± 2mm	0.032Hz
Orientation of *STABLE*	Compass & inclinometers	± 1°	0.016Hz

Table 1 Hydrodynamic and morphodynamic variables measured during *Deltaflume* tests

Measurements programme

The sequence of experimental conditions was chosen to run from low to high wave conditions so that erosion of the bed was minimised. Surveys showed that the depth of sediment either side of the *STABLE* deployment site remained approximately constant throughout the tests. Six separate synchronised data logging systems were needed to handle the diverse and extensive data from the various sensors deployed on *STABLE* and in the *Deltaflume*. All data sets were time and date stamped to allow easy cross-referencing. *Table 2* summarises the range of wave conditions in the *Deltaflume* during tests on the medium and fine sand beds.

	regular waves		irregular waves	
Wave height (m)	**medium sand**	**fine sand**	**medium**	**fine sand**
0.50	$\tau_c < \tau_t$	*f03a*	$\tau_c < \tau_t$	*f04a*
0.75	*A08a*	*f11a*	*A09a*	*f07a*
1.00	*A05b*	*f08a*	*A10a*	*f10a*
1.25	*A11a*	*Not tested*	*A12a*	*f12a*

Table 2 Approximate wave conditions for tests on the medium (*A*) and fine (*f*) sand beds (wave period ≈ 5 seconds in all cases)

Results and discussion

In this section only selected results from the experiments in the *Deltaflume* are presented in order to illustrate the breadth and detail of the present study. The range of data acquired during the experiments was very extensive and it is possible here only to present a fraction of the results currently obtained. Since the main thrust of the work has been to assess the performance of sensors on the *STABLE* frame at approximately field-scale, attention here is

focussed primarily upon results that aid in this assessment exercise. Work examining $\overline{C}$ *profiles* is currently in review (*Williams et al., 1998b*).

Hydrodynamics

In order to assess instrument performance, comparisons have been made between the *STABLE ECM*'s and the *ADV*. *ECM* data were calibrated and despiked and corrected for misalignment using a modified form of the method described by *Soulsby et al. (1991)*. Values for the zero-mean orthogonal flow components u, v and w were calculated using the method described by *Williams et al. (1997)*. In the case of the *ADV*, values for u, v and w were also corrected for misalignment using the rotation angles determined for the *ECM*'s and knowledge of the position of the instrument on the *STABLE* frame.

Figure 4 shows power spectra on log-log axes derived using a fast Fourier transform for u and w components measured above the fine sediment bed by the *ECM*'s and by the *ADV* during: (*i*) test *f08a* (regular waves, H = 1.0 m, T = 5.0 s); and (*ii*) test *f10a* (irregular waves, H_s = 1.0 m, T_p = 5.3 s). In the case of regular waves, u spectra show peaks at approximately wave, half wave and quarter wave frequencies. A broad peak in u spectra spanning the frequency range 0.1 Hz to 0.3 Hz is measured for the irregular waves. In contrast, spectra for the w component are much flatter. However, there are peaks in energy corresponding to those in the u spectra. These are attributed to wave asymmetry.

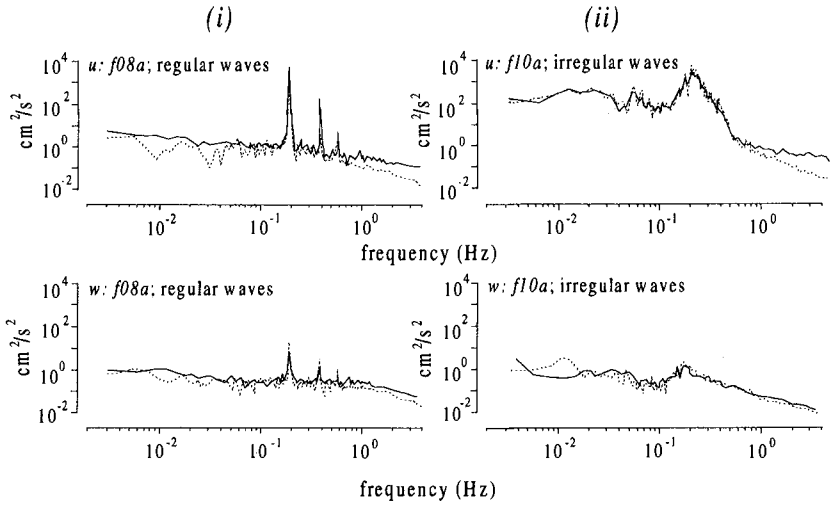

Figure 4 Typical u and w power spectra for 1.0 m regular and irregular waves: —— *ECM* spectra; ····· *ADV* spectra.

In all cases the spectra derived from *ECM* and *ADV* time-series are broadly similar over the frequency, *f*, range 0 001 Hz to 0 3 Hz At frequency values greater than 0 7 Hz, *ECM* and *ADV* spectra diverge significantly, demonstrating the high frequency cut-off attributable to the larger sampling volume and lower sampling frequency of the *STABLE ECM* system These results demonstrate that broadly speaking, the *ADV* and the *ECM*'s give comparable results across a wide frequency band

If one considers the implication of these results in the context of current-only or wave-current situations, then failure of the *ECM*'s to measure all the high frequency energy has consequences when *ECM* data are used to derived estimates of the bed shear stress, τ using the eddy correlation, *EC*, turbulent kinetic energy, *TKE*, or inertial dissipation, *ID*, approaches Specifically, the present *ECM*'s system will always underestimate τ However, since the total amount of energy missing from the *ECM* spectra is estimated to be less than 3% of the total, estimates of τ are unlikely to be seriously in error The relative importance of these errors in the context of sediment transport in the marine environment is almost insignificant when one considers the imprecision with which entrainment threshold, settling velocity and bedform dimensions are known

Bedforms

Figure 5 shows long-crested vortex ripples on the medium sand bed measured using the *SSS* The side-walls of the *Deltaflume* and imprints left in the sand by *STABLE* feet are clearly visible Of particular relevance to the present study is the proof provided by *Figure 5* and other images, that ripple geometry is unaffected by the presence of the rig This result confirms unequivocally that *STABLE* has no detectable influence upon the process of ripple formation in wave-only conditions

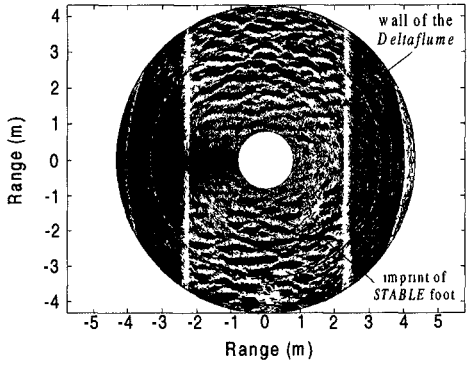

Figure 5 SSS image of long-crested vortex ripples on the medium sand bed

Temporal changes in ripples on the medium sand bed measured during test *A13a* and *A14a* using the *ARP*, (H = 1.0 m, T = 5 0 s), are illustrated in *Figure 6* This figure shows vortex ripples migrating up the flume towards the wave generator a distance of approximately 1 0 m in 80 minutes

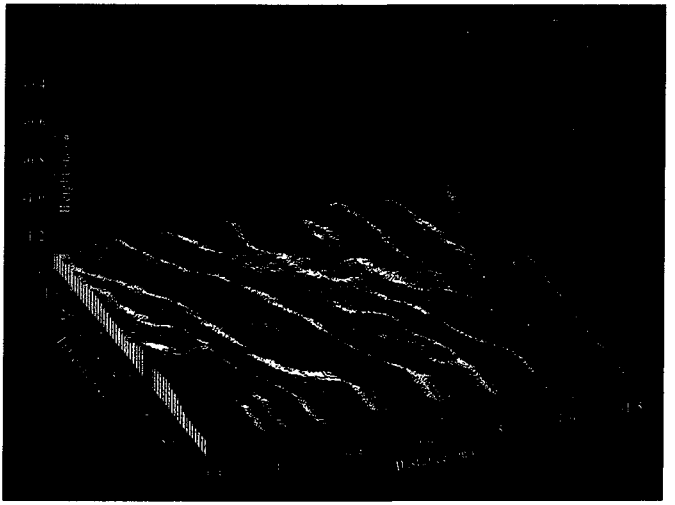

Figure 6 Temporal and spatial variation in h_r and λ_r measured by the *ARP*

Values for ripple height, h_r, and wavelength, λ_r, measured using the *ARP* are found to be in good agreement with predicted vortex ripple dimensions in regular wave conditions (*Nielsen, 1992*) Whilst some of the temporal variability in ripple geometry may be attributed to random wave conditions during the tests, the migration of ripples shown in *Figure 6* probably results from a compensating current near the bed and from wave asymmetry The ability to monitor continuously the bed geometry directly beneath *STABLE* is clearly demonstrated by *Figure 6* It is considered that in future field deployments of *STABLE*, measurements from the *ARP* and the *SSS* will prove to be invaluable in characterising the local micro-morphology of the sea bed

Suspended sediments

Typical $\overline{C}$ *profiles* measured from *STABLE* and from the *Deltaflume* using the pump-sampling equipment on are shown using log-log axes in *Figure 7a* for. *(a)* regular waves above the medium and fine sand beds [*tests A11a* and *f11a*], and *(b)* for irregular waves above the medium and fine sand beds [*tests A10a* and *f07a*] For the $\overline{C}$ *profiles* considered here, time - averaged suspended sediment concentration, $\overline{C}$, values measured at the sampling

position closest to the bed span a range from approximately 0.01 g/l to 10.0 g/l. In most cases, $\overline{C}$ values measured during the experiments by the volume method and in the laboratory differ by less than 50%. However, at a given height above the bed, differences between $\overline{C}$ values measured from *STABLE* and from the *Deltaflume* frequently exceed 100%. These differences are thought to arise owing to the combined effect of different sampling locations relative to bedforms, side-wall effects, zero datum errors and flow turbulence generated by *STABLE*.

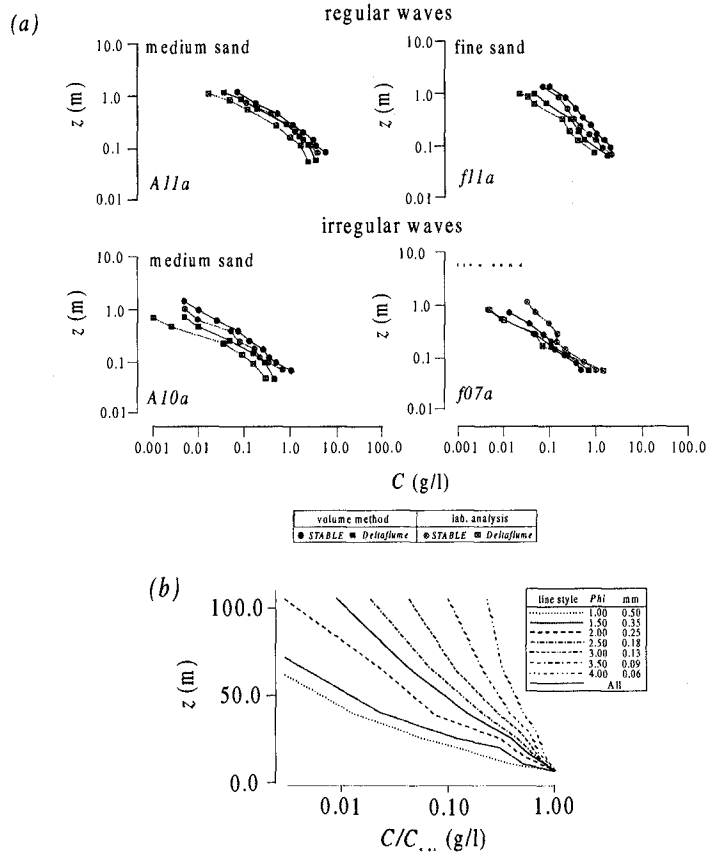

Figure 7 *(a)* $\overline{C}$ *profiles* measured above bed of medium and fine sand in regular and irregular wave conditions; and *(b)* $\overline{C}$ *profiles* for separate grain size fractions, *test A11a.*

Figure 7b shows normalised $\overline{C}$ *profiles* for separate grain size fractions measured during *test A11a* on the medium sand bed In common with other published data, $\overline{C}$ values at any given height increase with decreasing grain size and demonstrate that suspended sediments are composed principally of the fine fraction of sediments comprising the bed Detailed study and modelling of $\overline{C}$ *profiles* has been undertaken by *Williams et al , (1998b)*

An example of data from the 2 0 MHz *ABS* instrument is shown in *Figure 8* This figure shows the response of the medium sand bed to a group of 8 waves during random wave conditions and is typical of other results Modulation at approximately the wave frequency is evident as is a general increase in the average suspended sediment concentration It is also seen that by the passage of the fifth wave appreciable quantities of suspended sediment are present at $z = 0\,6$ m Also evident is a parcel of suspended sediment in the region $0\,4\text{ m} < z < 1\,0$ m under wave 7 in the group This suspended sediment is surrounded by fluid containing little in suspension and may be the manifestation of vortex detachment from ripples on the bed A similar but much smaller volume of suspended sediment is also evident under wave 8 It is considered that both suspension structures are related where the structure beneath wave 7 is the remnant of the first structure These data provide a fascinating insight into the intricacies of inter-wave period sediment resuspension processes and a major study to quantify these mechanisms is currently underway

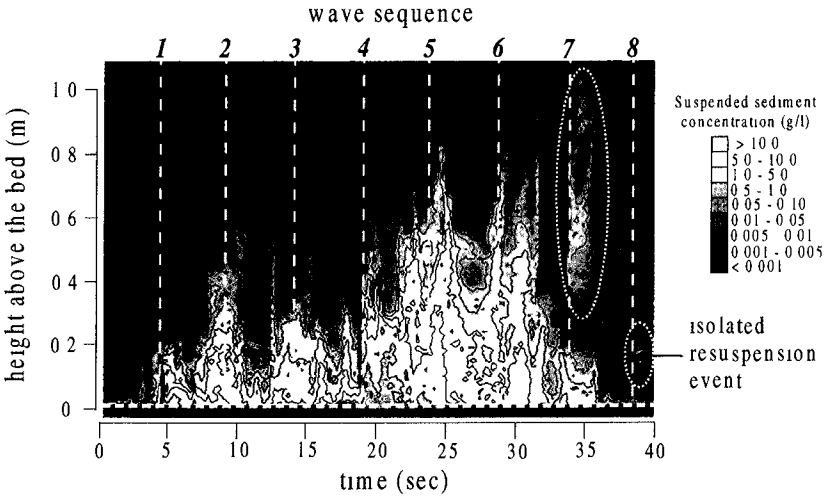

Figure 8 Example of data from the 2 0 MHz *ABS* instrument showing resuspension by a wave group

Summary

This paper describes experiments conducted in the *Deltaflume* of Delft Hydraulics to evaluate the performance of field instrumentation used to measure near bed hydrodynamic conditions and sediment dynamics from the large tripod frame *STABLE*. Tests were conducted on beds of medium (D_{50} = 0.329mm) and fine (D_{50} = 0.162mm) sand under regular and irregular waves of sufficient size to re-suspend the bed material. Measurements of waves, turbulence, vertical suspended sediment concentration profiles and bed morphology were obtained using a comprehensive suite of state-of-the-art acoustic and electromagnetic sensors and *in situ* samples of sediment in suspension were obtained by pump sampling.

In order to illustrate the nature and quality of the measurements, selected results from the experiments pertaining to bedforms (vortex ripples), to hydrodynamic conditions close to the bed and to suspended sediments have been presented. These data will make possible critical evaluation of the performance of field instruments and will aid interpretation of existing data sets from past deployments in the field. Furthermore, the data will aid the study of the detailed processes leading to the mobilisation and resuspension of sandy sediments in wave conditions and provide a rigorous test case for existing and future numerical models of sediment entrainment and suspension. Exploitation of the *Deltaflume* data set is already underway through the European MAST 3 project *INDIA* and the UK EPSRC Programme COSMOD. In the future it is also planned to make these data available to researchers through the publication of a CD-ROM .

Acknowledgements

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