Proudman Oceanographic Laboratory

Evaluation of Field Equipment used in Studies of Sediment Dynamics

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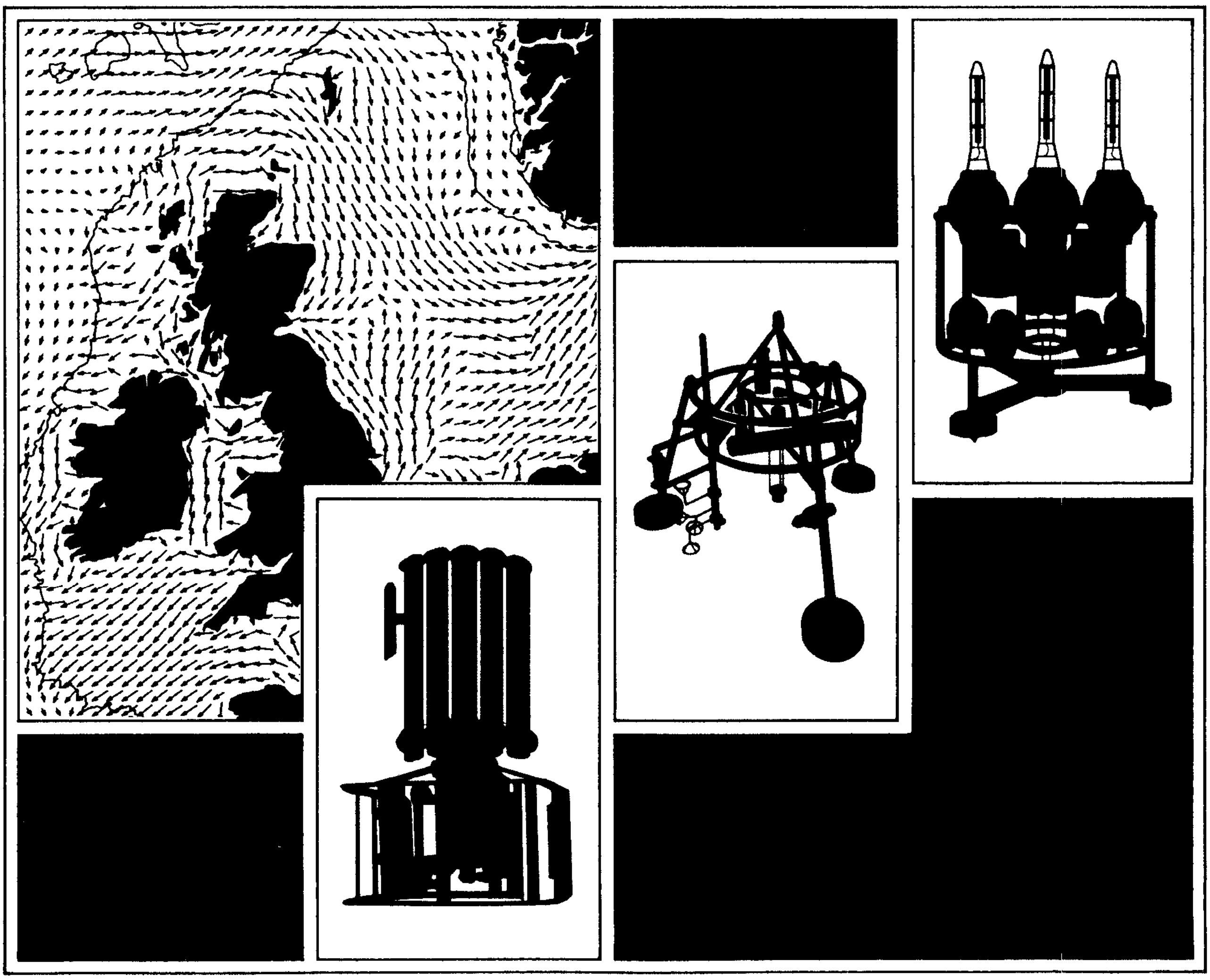
Report No. 53 1998



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February 1998

DOCUMENT DATA SHEET

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TITLE
Evaluation of field equipment used in studies of sediment dynamics.

REFERENCE
Proudman Oceanographic Laboratory, Report No. **53**, 45pp.

ABSTRACT

This report describes research undertaken in the large *Deltaflume* facility (length 230m, width 5m, depth 7m) at Delft Hydraulics, the Netherlands, during July and August 1997. The work was conducted in order to evaluate critically the performance of the *STABLE* (Sediment Transport And Boundary Layer Equipment) field instrument used to measure, in detail, bed sediment response to hydrodynamic forcing in marine conditions. *STABLE* consists of a large (diameter ≈ 3.3m, height ≈ 1.8m), heavy (weight ≈ 2200kg) deployment frame equipped with a comprehensive suite of instruments to measure waves, currents, suspended sediments and bedforms. *STABLE* was deployed in the *Deltaflume* on test beds of medium (D_{50} = 0.329mm) and fine sand (D_{50} = 0.162mm). *In situ* measurements of wave characteristics, flow turbulence, bedforms and vertical suspended sediment concentration profiles were obtained in regular ($H \approx$ 0.5 to 1.3m, $T \approx$ 5s) and irregular ($H_s \approx$ 0.5 to 1.3m, $T_p \approx$ 5s) waves. All data logging was synchronised from a central data centre. Independent measurements of wave-induced flow and vertical suspended sediment concentration profiles were obtained from locations adjacent to the wall of the *Deltaflume*. Valuable data pertaining to the performance of sea-going instrumentation was obtained during the experiments. In addition, the experiment also provided unambiguous information on hydrodynamic processes leading to resuspension of sediment and vertical suspended sediment concentration profiles in wave-only conditions.

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KEYWORDS *Deltaflume* *STABLE* Wave-sediment dynamics	*CONTRACT:* *PROJECT:* **MHT-76-5** *PRICE:*

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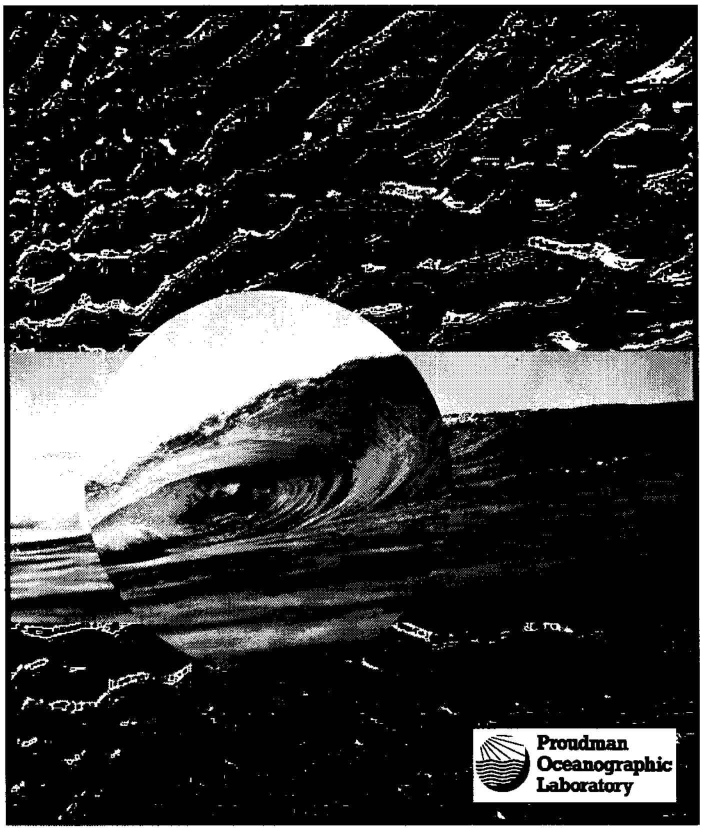

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1.0 Introduction

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. Interpretation of data from these instruments is usually based therefore, upon a limited series of small-scale laboratory observations 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 state-of-the-art field instrumentation in a range of controlled experimental conditions at full-scale.

This report 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 *STABLE* (Sediment Transport And Boundary Layer Equipment, *Humphery & Moores, 1994*), *Figure 2*, and to measure in detail bed sediment response to forcing by waves. *STABLE* consists of a large, heavy deployment frame equipped with a comprehensive suite of instruments and onboard data logging facilities. *STABLE* was deployed in the *Deltaflume* on test beds of medium and fine sand. *In situ* measurements of wave characteristics, flow turbulence, bedforms and vertical suspended sediment concentration profiles were obtained in regular and irregular waves. 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*.

The research team, led by J. J. Williams from the Proudman Oceanographic Laboratory, *POL*, included P. S. Bell, P. J. Hardcastle, J. D. Humphery, S. P. Moores and P. D. Thorne from *POL*, K. Trouw from the University of Leuven, Belgium, L. E. Coates from the University of Birmingham, UK and A. G. Davies from the University College of North Wales, UK. Pump sampling was assisted by students from the University of Leuven. The Delft Hydraulics team was lead by P. Van Vliet and overall TMR project co-ordination was overseen by J. Wouters†.

2.0 Background

The autonomous boundary layer rig *STABLE* has been deployed successfully in a number of UK and EU funded field experiments [e.g. MAST 2 ***CSTAB*** *(Hannay et al., 1994; O'Connor et al. 1994*; *Williams et al., 1996)* MAST 2 ***OMEX*** *(Huthnance, 1994)* and NERC ***LOIS*** RACS(C) *(Prandle, 1994*; *Williams et al., 1996)*]. Whilst in all cases useful data pertaining to wave-current-sediment interaction has been obtained during these deployments, there has always been uncertainty regarding the nature of and changes in the morphology of the sea bed during a given experiment. Further, it has not been possible to obtain samples *in situ* of sediment in suspension. In some cases this has lead to ambiguity in the interpretation of certain experimental results. Whilst instruments similar in function to *STABLE* have been developed by various international research groups (e.g. *Tetrapod*, *BLISS*, *STRESS*), they have never been tested rigorously in laboratory conditions and thus the validity of their data remains uncertain. By providing an opportunity to use field-scale laboratory facilities, the EU TMR Programme "Access to large-scale facilities" allowed critical evaluation of the accuracy of instruments on *STABLE* and the interactions between the deployment frame and the sedimentary processes under scrutiny.

3.0 Aim of research

The fundamental aim of the research described in this report was to evaluate critically the performance of field instruments used to measure hydrodynamic conditions, bedforms and suspended sediment concentration in a region extending approximately 1m above the sea bed. This could only be achieved in a large-scale test facility such as the *Deltaflume*. The experiments also allowed examination of a number of physical processes associated with the mobilisation, and suspension of bed sediments. These included:

- time evolution of bedforms;
- average and instantaneous suspended sediment concentration profiles at various locations relative to the crest of bedforms;
- instantaneous vertical profiles of turbulent flow components;
- acoustic investigation of bed fluidisation processes;
- detailed investigation of the vortex entrainment mechanism; and

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- examination of turbulent bursting phenomenon under wave conditions.

Data resulting from these tests were also to be used to calibrate and test a range of existing state-of-the-art numerical models of sediment resuspension under waves.

4.0 Experimental facilities

4.1 The *Deltaflume*

Located in the De Voorst Laboratory of the Delft Hydraulics Laboratory, and operational since 1980, the *Deltaflume* is a large-scale facility allowing full-scale simulation of waves in controlled laboratory conditions. The *Deltaflume* is 230m long, 5m wide and 7m deep, *Figure 1*. Monochromatic and random waves with a height up to 2m can be generated according to a required time history. A device prevents reflection of waves from the wave board and eliminates low frequency resonant waves. The facility is equipped with a range of instruments to monitor a wide range of hydraulic and geotechnical processes and some 100 data logging channels are available.

Frequently the *Deltaflume* is used for the testing and calibration of field equipment, for the development of remote sensing techniques for the measurement of waves, for assessing the performance of wave energy devices and floating wave energy absorbers, for the testing and training of underwater construction procedures and for the testing of underwater vehicles.

A summary of useful linear wave theory results used to guide design of the test programme reported below is given in *Appendix A1*. Also included in this appendix is a summary of the range of wave conditions that can be generated in the *Deltaflume* facility deduced from knowledge of the water depth and the mechanism of wave generation. During tests these theoretical predictions were modified in the light of actual measurements.

4.2 *STABLE*

Instrumentation on *STABLE* measures waves, flow turbulence and suspended sediment concentrations, *Figure 2*. A *Digiquartz* pressure sensor with integral pressure housing was used to measure the water-depth at wave frequencies at a height above the bed, z, ≈ 170cm. Near-bed fluid motion induced by waves was measured using *Valeport Series 800* electromagnetic current meters (*ECM*'s) with a diameter of 10cm and a resolution of ±0.1cm/s (*Figure 2*). *ECM* sensors were arranged in pairs set at 90° to each other at $z \approx$ 30cm, 60cm and 91cm. Horizontal separation between each *ECM* sensor was 20cm. Measurements of flow turbulence were also obtained at $z \approx$

30cm using a SonTec acoustic Doppler velocimeter, *ADV*, Ocean Probe operating at 5MHz. Measurements of horizontal and vertical wave induced fluid motion were measured using *POL* coherent Doppler sensors. An acoustic cross-correlation technique was also employed to measure current profiles.

Bedforms beneath *STABLE* were measured using an acoustic ripple profiler and a sector scanning sonar device. Acoustic backscatter, *ABS*, instruments (*Thorne et al., 1993; Thorne & Hardcastle, 1997*) operating at 1.0MHz, *ABS1*, 2.0MHz, *ABS2*, and 4.0MHz, *ABS3*, were located 15cm in front of the *ECM* sensors at $z \approx$ 128cm (*Figure 2*). These instruments measured the vertical suspended sediment concentration profiles, $\overline{C}$ *profiles*, from the bed to $z \approx$ 120cm at intervals of 1cm. Tests were performed prior to work in the *Deltaflume* to ensure that the six acoustic instruments mounted onto the frame of *STABLE* did not interfere with each other. A vertical array of pump sampling nozzles was also fixed to the *STABLE* frame (*Figure 2*). *ECM* and *PS1* data were sampled at 8Hz and *ABS1, ABS2* and *ABS3* data were sampled at 4Hz over a period of approximately 19 minutes in '*burst*' mode. Integrated measurements of rig orientation were obtained every minute in '*mean*' mode using inclinometers and a fluxgate compass. The geometry of *STABLE* and associated instruments is illustrated in *Figure 2*. *Table 1* summarises the location of each instrument mounted onto the *STABLE* frame using the x, y and z co-ordinate convention shown in *Figure 2*. A summary of the overall dimensions and weight of *STABLE* is given in *Table 2*.

5.0 Set-up of measurements

5.1 Preparation of the test beds

Before commencing any work, the *Deltaflume* was thoroughly cleaned using a high-pressure washer to remove sediments used in previous test programmes. The sand bed used in the first series of tests (code *A*) was composed of medium sand (median grain size, D_{50} = 0.329mm, *Figure 3*). The bed was approximately 30m long, 5m wide and 0.5m deep, and was placed approximately 105m from the wave generator in the *Deltaflume*. Both ends of the test bed were feathered to reduce erosion and drainage was laid beneath the sediment bed to allow the free passage of water during filling of the *Deltaflume*. The sand bed composed of medium sand just before filling of the *Deltaflume* is shown in *Figure 4*.

Prior to any experimental work, regular waves with a height, H, of 0.75m and period, T, of 5s were generated for a period of approximately 3 hours. These waves were large enough to mobilise the bed sediments and generate regular bedforms. In addition, the waves also forced entrapped air out of the bed. This latter effect was especially significant, as any air bubbles present in the water during tests would seriously compromise the accuracy of the acoustic measurements of suspended sediment concentration. Small quantities of fine material present in the bed sediments were released into the water during this bed preparation phase of the work and resulted in a marked deterioration in visibility in the water. Consequently, tests using an underwater video camera to record entrainment mechanisms were abandoned. Large waves in the *Deltaflume* during test *A12a* are shown in *Figure 5.*

5.2 Installation of Delft Hydraulics instrumentation

Five Delft Hydraulics electromagnetic current meters were fitted to the side wall of the flume at y = 120.9m at distances z above the sand bed of 25cm, 50cm, 100cm, 150cm and 250cm (*Figure 6*). Vertical guide rails were installed at y = 121.5m to allow deployment of the pump sampling equipment (*Figure 6*). The sand was compacted by mechanical vibration. In order to minimise disturbance to the bed the *Deltaflume* was then filled slowly over a period of approximately 24 hours. Following tests over the medium sand bed, the *Deltaflume* was drained and cleaned. The procedure described above was then used to prepare the second test bed consisting of fine sand, (median grain size, D_{50} = 0.162mm, code F, *Figure 3*).

Two wave measurement probes were supplied by Delft Hydraulics (*Figure 6*). These resistive devices were mechanically driven up and down to maintain contact with the water surface. The vertical displacement of each probe monitored waves across a broad range of frequencies. Data from each probe were logged at 25Hz. Subsequent data analysis using Delft Hydraulics software provided a wide range of wave statistics for use in analysis of data from *STABLE* and other instruments. Following guidance from Delft Hydraulics, the positioning and separation between each wave probe were optimised before commencing the experimental programme. The position of *STABLE*, wave probes and Delft Hydraulics *ECM*'s in the *Deltaflume* are illustrated schematically in *Figure 6.*

5.3 Measurements of bed morphology

Following wave action, the morphology of the test beds of sand was measured using a mechanical ripple-profiling device provided by Delft Hydraulics. This consists of a lightweight wheel mounted on the end of a vertical support. When driven forwards, the pressure applied to the wheel was held constant by moving the vertical support up or down in response to changes in bed elevation thereby permitting the measurement of bed morphology. The horizontal position of the instrument was referenced to accurate datum marks installed by Delft Hydraulics. The vertical position of the instrument was calibrated from a zero datum on the beach of the *Deltaflume*. Whilst being rather unreliable during the measurement campaigns, this instrument generally performed well and provided high quality data.

5.4 Measurements of suspended sediment concentration by pump sampling

Samples of suspended sediment were obtained at 10 heights above the sand bed using pump-sampling equipment loaned to the research team by the University of Utrecht. This consisted of two arrays of intake nozzles (diameter 4mm) orientated at 90^o 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. Once full, the sediment was allowed to settle to the bottom of the buckets and excess water was then poured away. The remaining water/sand mixture was then poured carefully into a calibration tube and the volume of sand present was measured. A pre-determined calibration was then applied to convert the volume of sediment into a concentration value with units of kg/m^3. All samples were sealed in plastic bags for subsequent grain size and settling velocity analyses and for accurate measurement of the suspended sediment concentration. The collection of pump samples using the University of Utrecht equipment is illustrated in *Figure 7*.

5.5 Deployment and recovery of *STABLE*

Since the height of *STABLE* exceeded the clearance between the wall of the *Deltaflume* and the maximum lift height of the *Deltaflume* crane, it was not possible to deploy the rig in a straightforward manner. The following deployment and recovery method was devised. A heavy gate normally used to shut off a section of the *Deltaflume* was placed in a horizontal position down-wave of the *STABLE* deployment location approximately 2.5m above the still water surface. This acted as a platform upon which *STABLE* could be placed using an external crane hired by Delft Hydraulics. The first winch on the *Deltaflume* crane could then be used to lift *STABLE* into the flume from the platform by attaching the lifting hook to the three wire supports above the frame. Once in position just below the water surface, a short strop was attached to the lifting point on *STABLE*. This was then used to take the full weight of *STABLE* by connecting it to the second winch on the *Deltaflume* crane and slowly lifting the rig. Once supported from the strop, the first lifting hook could be removed and *STABLE* could then be lowered to the bed on the strop. The strop was then removed from the second lifting hook and tied off to the side wall of the flume. The procedure used to recover *STABLE* followed the steps outlined above in reverse order. Although somewhat laborious, this method of deployment and recovery was found to work well and minimised the risk of damage to the equipment without compromising the safety of personnel on site. The deployment of *STABLE* into the *Deltaflume* is shown in *Figure 8*. A schematic diagram of the experimental layout in the *Deltaflume* is shown in *Figure 6*.

6.0 Measurements programme

The experiments undertaken in the *Deltaflume* were unique simply in terms of the number of sensors and sampling devices deployed in close proximity to one another in order to measure a wide range of physical processes. In total, six separate data logging systems were needed to handle the diverse and extensive data from the various sensors deployed on *STABLE* and in the *Deltaflume*. A pulse from a signal generator was used to synchronise precisely all data loggers at the start of a test. All data sets were time and date stamped to allow easy cross-referencing and to facilitate intercomparison in subsequent analyses of the data. *Table 3* summarises all hydrodynamic, sedimentological and morphodynamic variables measured during the experiment. *Table 3* also states the instruments deployed, their accuracy and the data logging frequency selected for each sensor.

A chronological summary of the measurement programmes conducted using the medium and fine sand beds is given in *Table 4* and *Table 5*, respectively. These Tables show the following information:

- the date;
- the unique experiment number used by Delft Hydraulics;
- the orientation of *STABLE* (0° indicates the *ECM* array support spar, *Figure 2*, is approximately parallel with the side walls of the *Deltaflume*);
- the measured wave height and period (*H* and *T*, regular waves);

- the calculated significant wave height and peak wave period (*Hs* and *Tp*, irregular waves);
- a factor γ associated with the JONSWAP spectrum for irregular waves;
- the code used for pump samples from *STABLE* (*STABLE* PS); and
- the code used for pump samples from the side wall of the *Deltaflume* (Flume PS).

The sequence of experimental conditions shown in *Table 4* and *Table 5* was chosen to run from low to high wave conditions so that erosion of the bed was minimised. Despite this precaution, significant amounts of sediment were moved from the end test bed to towards the beach. However, surveys showed that the depth of sediment approximately 7m either side of the *STABLE* deployment site remained approximately constant throughout the tests.

A summary of all test conditions giving wave height, period and type is given in *Table 6.*

7.0 Data management

To facilitate data logging flexibility, the rapid assessment of data quality, and to allow the preliminary analysis of data from instruments on *STABLE*, data were logged using PC's located alongside the *Deltaflume*. This differs from the normal operational mode of *STABLE* where all data from sensors are recorded by the autonomous logging systems. Once examined, data were backed-up onto CD-ROM for subsequent data analysis.

It has been the policy of the group to follow the European Commissions *Code on data management in MAST projects* for all data obtained during the *Deltaflume* experiments. Through the project leader steps have been taken:

- to quality assure and check all data at all levels of processing;
- to manage preliminary data banking for project use; and
- to manage final data banking and publishing for public use.

At the time of writing this report, data have been banked for the use of project scientists. The *British Oceanographic Data Centre* will produce the final data products approximately 24 months after the end of the project.

8.0 Selected results

8.1 Bedforms

Figure 9 shows a single test bed profile measured along a single line parallel to and 1.5m from the side wall of the *Deltaflume* by the Delft Hydraulics ripple-profiling device. In order to ensure equilibrium conditions were attained, the vortex ripples were developed on the medium sand bed under regular wave conditions over a period spanning approximately 2 hours. Also shown in *Figure 9* is the approximate location of *STABLE* on the sand bed during subsequent experiments.

A composite image of vortex ripples on the medium sand bed computed from a series of 11 ripple profiles obtained using the Delft Hydraulics ripple-profiling device is shown in *Figure 10.* This image was obtained from profiles measured after *STABLE* was removed from the *Deltaflume* and shows clearly the impressions left by the three circular feet (*Figure 2*). At this early stage of data analysis and interpretation, it is encouraging to see that vortex ripples are long-crested and regular and that change in ripple geometry near *STABLE* cannot be detected. Based on the evidence it may be concluded that *STABLE* has no detectable effect upon the hydrodynamic processes giving rise to bedforms.

Figure 11 shows a typical image of vortex ripples on the medium sand bed obtained from the sector scanning sonar device. The image was obtained by lowering the sector scanner into the flume during still water conditions some distance in front of *STABLE.* The side walls of the *Deltaflume* and well developed, long-crested vortex ripples are shown clearly. In common with the previous illustration, *Figure 11* shows the imprints left in the sand by *STABLE* and shows that ripple geometry is largely unaffected by the presence of the rig.

Temporal changes in the geometry of ripples on the medium sand bed during a series of tests in the *Deltaflume* are illustrated in *Figure 12.* These profiles were measured using the acoustic profiler mounted on *STABLE. Figure 12* shows vortex ripples migrating away from *STABLE* a distance of approximately 1.0m in approximately 80 minutes. 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 12* 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 12* and provides a useful *in situ* record of the bed roughness and the position of ripple crests and troughs. This information is required for further detailed studies of the vortex entrainment processes responsible for the entrainment and suspension of sand in the present wave-only conditions and for modelling of suspended sediment concentration profiles.

8.2 Hydrodynamics and suspended sediments

Figure 13 shows in detail, data from the *ADV* ($z \approx$ 30cm), *ECM*'s ($z \approx$ 30cm) and 1MHz *ABS* ($z \approx$ 120cm), *Table 1* & *Figure 2*, obtained under regular waves (H = 1.299m, T = 5s) for a period spanning 10 seconds. *Figure 14* also shows *ADV*, *ECM* and *ABS* data from the same sensors in irregular wave conditions (H_s = 1.223m, T_p = 5.1s) for a period spanning 60 seconds. In both cases data were obtained over the medium sand bed. Relatively short records have been selected in order to illustrate the high temporal resolution nature of the present measurements. Whilst appropriate calibrations have been applied to the *ADV* and the *ECM* data, corrections for sensor misalignment have not been applied. Thus, it is not possible to compare directly the output from the *ADV* and *ECM*. The *ABS* data are simply expressed in terms of the backscatter signal strength and require detailed laboratory calibration before proceeding with further analysis.

Figures 13 and *14* show close agreement between the *ADV* and *ECM* measurements of horizontal (U) and vertical (W) wave induced velocities. The *ADV* signal is less smooth than the *ECM* owing to both the greater sampling frequency (25.8Hz) and to the much smaller measurement volume. However, without further information relating to the still water signal to noise characteristics of this device, it is not possible to comment on the ability of the *ADV* to measure small scale turbulence. Work to resolve this is currently underway. A further comment concerning the *ECM* data relates to the output signal filter characteristics which omit all frequencies above 4Hz. In combination with the relatively large sampling volume of the *ECM*'s it is not surprising therefore that *ECM* measurements do not record small-scale, high frequency turbulent fluid motion. With recourse to numerical modelling and to further detailed work examining the data from the *ECM*'s and the *ADV* it will now be possible to assess quantitatively the performance of these two instruments and to comment critically on their use in past, present and future field studies of wave, current and sediment processes.

Turning attention now to visual correlation between *ABS* signals and the hydrodynamic measurements from the *ADV*/*ECM*, *Figure 13* shows a weak correlation between maximum wave induced velocities and backscatter signal strength measured at z = 4cm and 8cm. *ABS* measurements at z = 2 cm cannot be interpreted without applying an appropriate calibration. Linear wave theory suggests that the conditions at the bed are only just in excess of threshold and thus large sediment resuspension events would not be anticipated. In contrast, stronger visual correlation between *ADV/ECM* and *ABS* measurements is shown in *Figure 14* for irregular waves at z = 4cm and 8cm. In this case, peak wave induced velocities under the largest waves in a group are larger than those shown in *Figure 13* and thus more sediment resuspension is expected. In addition, *Figure 14* demonstrates a lagged response between a measured increase in 'background' *ABS* backscatter signal strength and a group of three large waves at approximately t+30s. This is the manifestation of the well-documented 'wave-pumping' effect observed in marine conditions.

Details of measured sediment resuspension events under regular and irregular waves are shown in *Figure 15*. Here the dark grey shades indicate low concentrations of suspended sediment. This figure illustrates the complex vertical structure associated with resuspension clouds and demonstrates well the ability of the *ABS* instruments to provide innovative measurements in conditions of relatively high-suspended sediment concentration (*circa* 20g/l). It is considered that these data will elucidate physical processes and thereby improve present descriptions of resuspension in numerical models.

Ensemble average measurements (200 waves, H = 1.299m, T = 5s) of vertical wave induced velocities obtained with a coherent Doppler sensor at $z \approx$ 130cm are shown in *Figure 16*. For $0 < t < 2.0$s, the measured vertical velocity structure is relatively regular and shows no significant flow anomalies. For $3.5\text{s} < t < 5.0\text{s}$, vertical velocity structure is rather more disturbed. Since the right hand half of *Figure 16* corresponds to wave induced flow travelling from the rear of *STABLE* to the front (i.e. from left to right, *Figure 2b*), it is considered that the more disturbed vertical velocity structure is attributable to flow turbulence shed from the frame and from the sensors.

Results from pump-sampling of suspended sediments are shown in *Figure 17* for a range of regular and irregular wave conditions. Each graph, labelled (*a*) to (*f*), shows suspended sediment concentration profiles (hereafter referred to as *C* profiles) obtained using pump-sampling arrays on *STABLE* and at the side wall of the *Deltaflume*. Suspended sediment concentration values were derived using the calibration apparatus described above. For regular waves, *Figure 17*(*a*), *17*(*c*) and *17*(*e*) show close agreement between *C* profiles measured from *STABLE* and from the wall of the *Deltaflume*. Whilst comparisons between *C* profiles measured from *STABLE* and from the side wall of the *Deltaflume* in irregular wave conditions show reasonable agreement, there is clearly a larger divergence between the results shown in *Figures 17*(*b*), *17*(*d*) and *17*(*f*). Since any influence of *STABLE* on sediment resuspension processes and on concentration profiles will be present irrespective of the type of wave conditions, these results cannot be explained at present. However, it is noted that zero datum uncertainties associated with the precise measurement heights of pump-sampling nozzles may explain some variability in the data. It is anticipated that the acoustic measurements of bed elevation obtained both on *STABLE* and on the pump sampler located on the side wall of the *Deltaflume* will aid data interpretation in future studies.

9.0 Summary

The report 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. All data from the experiments have been archived and transferred onto CD-ROM for distribution to all project partners. A system of quality assurance has been implemented with checks on all data now being conducted by the originating scientists.

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 MAST 3 *INDIA* project and the EPSRC Programme COSMOD.

Acknowledgements

The work described in this report was funded jointly by: *NERC*; the Commission of the European Communities Directorate General XII through "*Access to Large-Scale Facilities*" in the "*Training and Mobility of Researchers*" (*TMR*) Programme (*EC-Contract ERBFMGECT950045*); and by the Commission of The European Communities Directorate General for Science and Education, Research and Development MAST-3 Project *INDIA* (Inlet Dynamics Initiative: Algarve) under contract number MAS3-CT97-0106. Thanks are extended to Jitse Wouters, Paul van Vliet, Professor Leo van Rijn, Leen Tulp, Dirk Bout, Marsha, Cornelis, Piet and Johan from Delft Hydraulics and the University of Utrecht, The Netherlands. The UK/Belgian research team would also like to express their heartfelt thanks to the staff at the Waterpark Beulaeke Haven for their kind hospitality.

References

HANNAY A., WILLIAMS J. J., WEST J. R. & COATES L. E. (1994). A field study of wave: current interactions over a rippled sandy bed. *EUROMECH 310: Sediment Transport Mechanisms in Coastal Environments and Rivers*, M. Belorgey, R. D. Rajaona & J. A. F. Sleath (editors), World Scientific, 345-359.

HUMPHERY J. D. & MOORES S. P. (1994) STABLE *II* - An improved benthic lander for the study of turbulent wave-current-bed interactions and associated sediment transport. *Electronic Engineering in Oceanography*, IEE Conference Publication No. **394**, 170-174.

HUTHNANCE J.M. (1994) Circulation, exchange and water masses at the ocean margin: the role of physical processes at the shelf edge. pp. B1-B10 in, *Ocean Margin Experiment: OMEX First Annual Report*, np: Université Libre de Bruxelles, (*unpublished manuscript*).

O'CONNOR B. A., KIM H. S. & WILLIAMS J. J. (1994) Hydrodynamics of random wave boundary layers. *Coastal Dynamics '94*, February 21-25, 1994, Universitat Politècnica de Catalunya, Barcelona, Spain, 333-336.

PRANDLE, D., BALLARD, G., BANASZEK, A., BELL, P., FLATT, D., HARDCASTLE, P., HARRISON, A., HUMPHERY, J., HOLDAWAY, G., LANE, A. PLAYER, R., WILLIAMS J.J., WOLF, J (1996) The Holderness coastal experiment '93-'96, *POL Report* **44**, 46pp. (*Unpublished manuscript).*

THORNE P. D., HARDCASTLE P. J. & SOULSBY R. L. (1993) Analysis of acoustic measurements of suspended sediments. *Journal of Geophysical Research*, **98**, 899-910.

THORNE P. D. & HARDCASTLE P. J. (1997) Acoustic measurements of suspended sediments in turbulent currents and comparison with *in-situ* samples. *Journal of the Acoustic Society of America*, **101**(5), 2603-2614.

WILLIAMS J. J., THORNE P. D., O'CONNOR B. A., HUMPHERY J. D., HARDCASTLE P. J., MOORES S. P. & COOKE J. A. (1996) Interactions Between Currents, Waves and Sediments in Calm and Storm Conditions. *Continental Shelf Research* (submitted).

WILLIAMS J. J., MOORES S. P. & CLIPSON D. (1996) Analysis of *STABLE* data from LOIS RACS(C)-I, Holderness UK. *Proudman Oceanographic Laboratory*, Report No. **42**, 98 pp.

Sensor	*x* (mm)	*y* (mm)	*z* (mm)
ECM 'A' port	123	372	302
ECM 'A' starboard	-117	372	302
ECM 'B' port	123	372	606
ECM 'B' starboard	-117	372	606
ECM 'C' port	123	372	910
ECM 'C' starboard	-117	372	910
SonTec *ADV*	-564	149	505
Rotor 1	0	1396	396
Rotor 2	0	1396	576
Rotor 3	0	1396	756
Rotor 4	0	1396	936
Horizontal coherent Doppler	50	894	425
Vertical coherent Doppler	0	-17	1295
Correlation transducer 'A' (front)	607	60	1355
Correlation transducer 'B' (back)	607	238	1355
4MHz acoustic backscatter	-114	145	1240
2MHz acoustic backscatter	0	145	1237
1MHz acoustic backscatter	114	145	1247
Acoustic ripple profiler	334	551	1216
Mean pressure transducer	-970	1340	1702
Burst pressure transducer	-560	1465	1725
PS1	-273	138	53
PS2	-273	138	73
PS3	-273	138	102
PS4	-273	138	131
PS5	-273	138	180
PS6	-273	138	255
PS7	-273	138	400
PS8	-273	138	653
PS9	-273	138	1050
PS10	-273	138	1553

Table 1 Summary of instrument positions on the *STABLE* frame using the *x*, *y* and *z* co-ordinate convention illustrated in *Figure 2*

Overall rig length	3305mm
Diameter of instrument platform	2160mm
Height to top of instrument platform	1845mm
Overall width across front feet	3370mm
Diameter of each foot	610mm
Depth of each foot	160mm
Weight of each foot	500kg
Overall rig weight	2200kg

Table 2 Summary of the overall dimensions and weight of *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 3 Hydrodynamic and morphodynamic variables measured during *Deltaflume* tests

Date	Experiment	θ	d (m)	H (m)	T (sec)	Hs (m)	Tp (sec)	γ	*STABLE* PS	Flume PS
	Medium sand bed completed									
02/07/97	A01a		4.50	0.521	5.00					
02/07/97	A01b		4.50	0.572	5.00					
03/07/97	A02a		4.50	0.745	5.00					
03/07/97	Ripple profiling									
04/07/97	A03a		4.50			0.769	4.94	3.3		
04/07/97	A03b		4.50			0.796	4.78	3.3		
04/07/97	A03c		4.50			0.773	5.08	3.3		
04/07/97	Assembly of *STABLE* completed; Wave probe calibration checks; *STABLE* deployed									
07/07/97	A04a	0	4.50	0.993	5.00					
07/07/97	A04b	0	4.50	1.061	5.00					
08/07/97	A05a	0	4.50	1.074	5.00				A05aS	A05aF
08/07/97	A05b	0	4.50	1.078	5.00				A05bS	A05bF
08/07/97	A06a	0	4.50							A06aF
08/07/97	A06b	0	4.50	0.589	5.00					A06bF
09/07/97	A001 (zero run)									
09/07/97	A07a	0	4.46			0.504	4.98	3.3	A07aS	A07aF
09/07/97	A08a	0	4.50	0.811	5.00				A08aS	A08aF
09/07/97	A09a	0	4.50			0.788	4.92	3.3	A09aS	A09aF
10/07/97	A002 (zero run)									
10/07/97	A10a	0	4.50			1.006	5.1	3.3	A10aS	A10aF
10/07/97	A11a	0	4.50	1.299	5.00				A11aS	A11aF
10/07/97	A12a	0	4.50			1.223	5.1	3.3	A12aS	A12aF
11/07/97	A003 (zero run)									
11/07/97	A13a	0	4.50	0.993	5.00					
11/07/97	*STABLE* recovered:camera fitted									
11/07/97	A14a	45	4.50	1.047	5.00				A14aS	A14aF
11/07/97	*STABLE* turned									
11/07/97	A15a	90	4.50	0.980	5.00				A15aS	
14/07/97	A004 (zero run)									
14/07/97	A16a	90	4.50	1.055	5.00					A16aF
14/07/97	A17a	90	4.50			1.027	4.95	3.3		A17aF
14/07/97	*STABLE* turned									
14/07/97	A18a	0	4.50	0.866	5.00					A18aF
15/07/97	A005 (zero run)									
15/07/97	A19a	0	4.50	1.064	5.00				A19aS	A19aF
15/07/97	A20a	0	4.50	1.027	4.00				A20aS	A20aF
15/07/97	A21a	0	4.50	0.617	6.00				A21aS	A21aF
15/07/97	A22a	0	4.50	0.971	5.00				A22aS	A22aF
16/07/97	A23a	0	4.50	0.810	5.00				A23aS	A23aF
16/07/97	Ripple profiling									

Table 4 Chronological summary of *Deltaflume* tests, medium sand bed (D_{50} = 0.329mm)

Date	Experiment	θ	d (m)	H (m)	T (sec)	Hs (m)	Tp (sec)	γ	*STABLE* PS	Flume PS
23/07/97	Fine sand bed completed									
24/07/97	F01a	0	4.50	0.815	5.00					
24/07/97	Ripple profiling									
25/07/97	Ripple profiling									
28/07/97	Ripple profiling									
29/07/97	F001 (zero run)									
29/07/97	F02a	0	4.50	0.336	5.00				F02aS	F02aF
29/07/97	F02b	0	4.50	0.336	5.00				F02bS	F02bF
29/07/97	F02c	0	4.50	0.346	5.00				F02cS	
30/07/97	F002 (zero run)									
30/07/97	F03a	0	4.50	0.535	5.00				F03aS	F03aF
30/07/97	F04a	0	4.50			0.542	4.963	3.3	F04aS	F04aF
30/07/97	F05a	0	4.50	0.815	5.00				F05aS	F05aF
31/07/97	F003 (zero run)									
31/07/97	F07a	0	4.50			0.784	4.743	3.3	F07aS	F07aF
31/07/97	F08a	0	4.50	1.066	5.00				F08aS	F08aF
31/07/97	F09a	0	4.50	0.470	5.00				F09aS	F09aF
01/08/97	F004 (zero run)									
01/08/97	F10a	0	4.50			1.041	5.255	3.3	F10aS	F10aF
01/08/97	*STABLE* turned									
01/08/97	F005 (zero run)									
01/08/97	F11a	45	4.50	0.762	5.00				F11aS	F11aF
04/08/97	*STABLE* turned									
04/08/97	F006 (zero run)									
04/08/97	F12a	0	4.50			1.373	4.515		F12aS	F12aF
04/08/97	F13a	0	4.50			1.345	4.476			
04/08/97	F14a	0	4.50	0.822	4.00				F14aS	F14aF
04/08/97	F15a	0	4.50	0.739	5.00				F15aS	F15aF
05/08/97	F007 (zero run)									
05/08/97	F16a	0	4.50			1.087	5.225		F16aS	F16aF
05/08/97	F17a	0	4.50	0.792	5.00				F17aS	F17aF
05/08/97	Ripple profiling									
06/08/97	*STABLE* dismantled									

Table 5 Chronological summary of *Deltaflume* tests, fine sand bed (D_{50} = 0.162mm)

D_{50} = 0.329mm

(a)		Wave types		
		Regular	**Irregular (JONSWAP)**	**Asymmetric**
H (m)	**0.50**	*A01a, A01b, A06b,A21a*†	*A07a*	
	0.75	*A02a, A08a, A23a*	*A03a, A03b, A03c, A09a*	*A18a*
	1.00	*A04a, A04b, A05a, A05b, A13a, A14a, A16a, A19a, A20a*‡	*A10a, A17a*	*A15a, A22a*
	1.25	*A11a*	*A12a*	

† T = 6.0s ‡ T = 4.0s

D_{50} = 0.162mm

(b)		Wave types		
		Regular	**Irregular (JONSWAP)**	**Asymmetric**
H (m)	**0.30**	*F02a, F02b, F02c*		
	0.50	*F03a*	*F04a*	*F09a*
	0.75	*F01a, F05a, F11a, F14a*†*, F17a*	*F07a*	*F15a*
	1.00	*F08a*	*F10a, F16a*	
	1.25		*F12a*‡*, F13a*‡	

† T = 6.0s ‡ *Middelkerke Bank wave spectrum*

Table 6 Summary of wave conditions in the *Deltaflume* during tests using: *(a)* a sand bed comprising medium sand (D_{50} = 0.329mm); and *(b)* a sand bed comprising fine sand (D_{50} = 0.162mm).

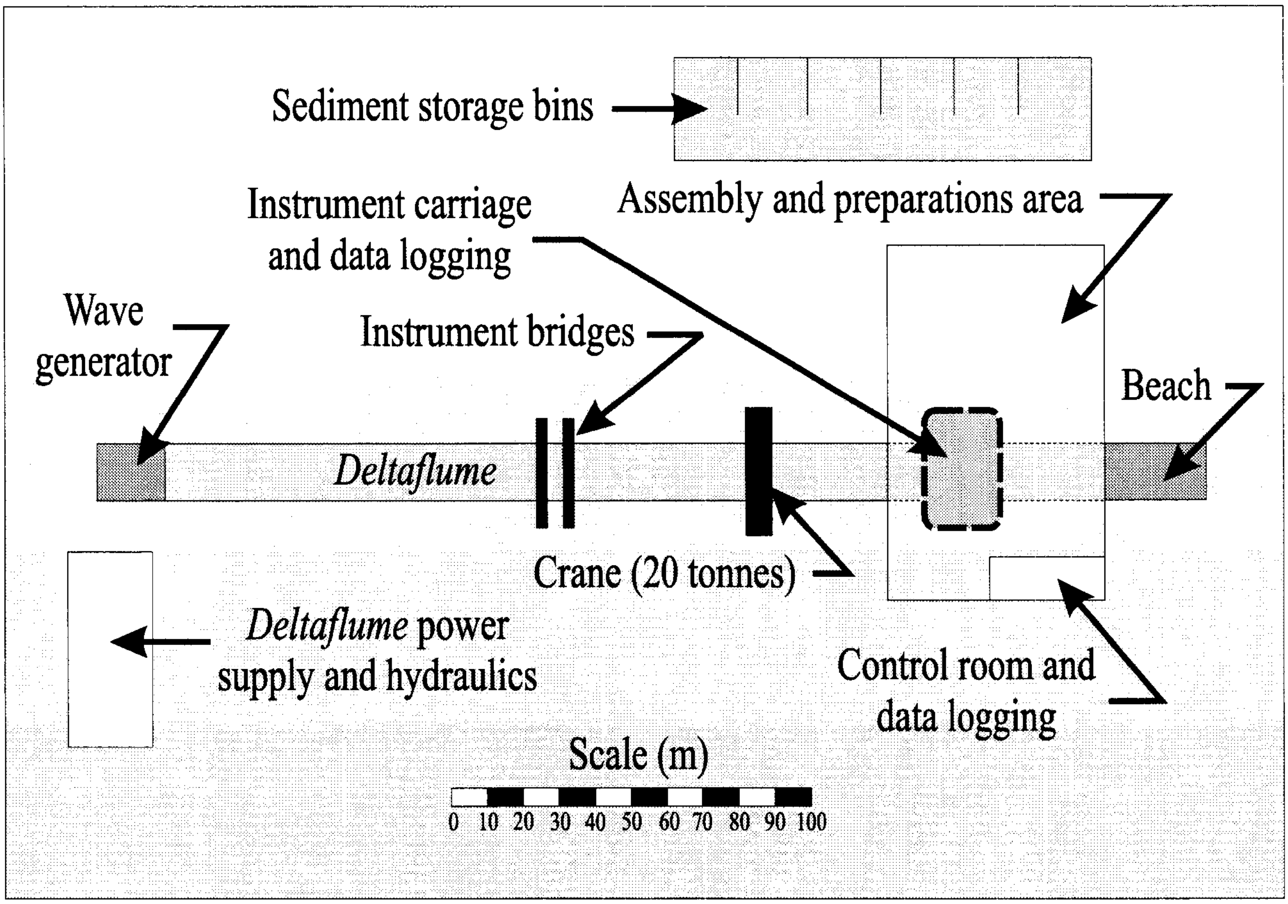

Figure 1 Schematic plan view of the *Deltaflume* research facility

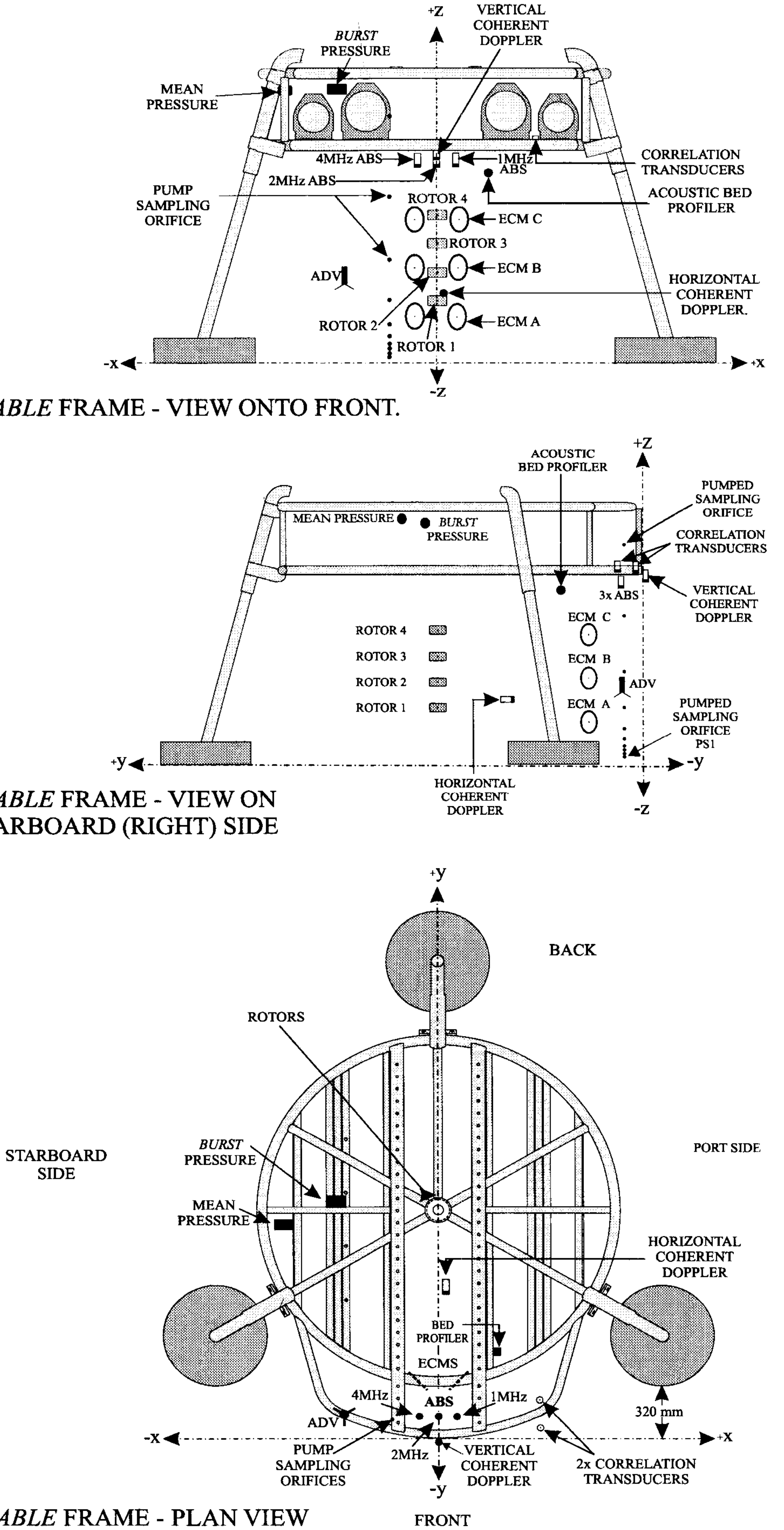

Figure 2 *STABLE*: (a) front elevation; (b) side elevation; and (c) plan. For dimensions and rig statistics see *Tables 1* and *2*.

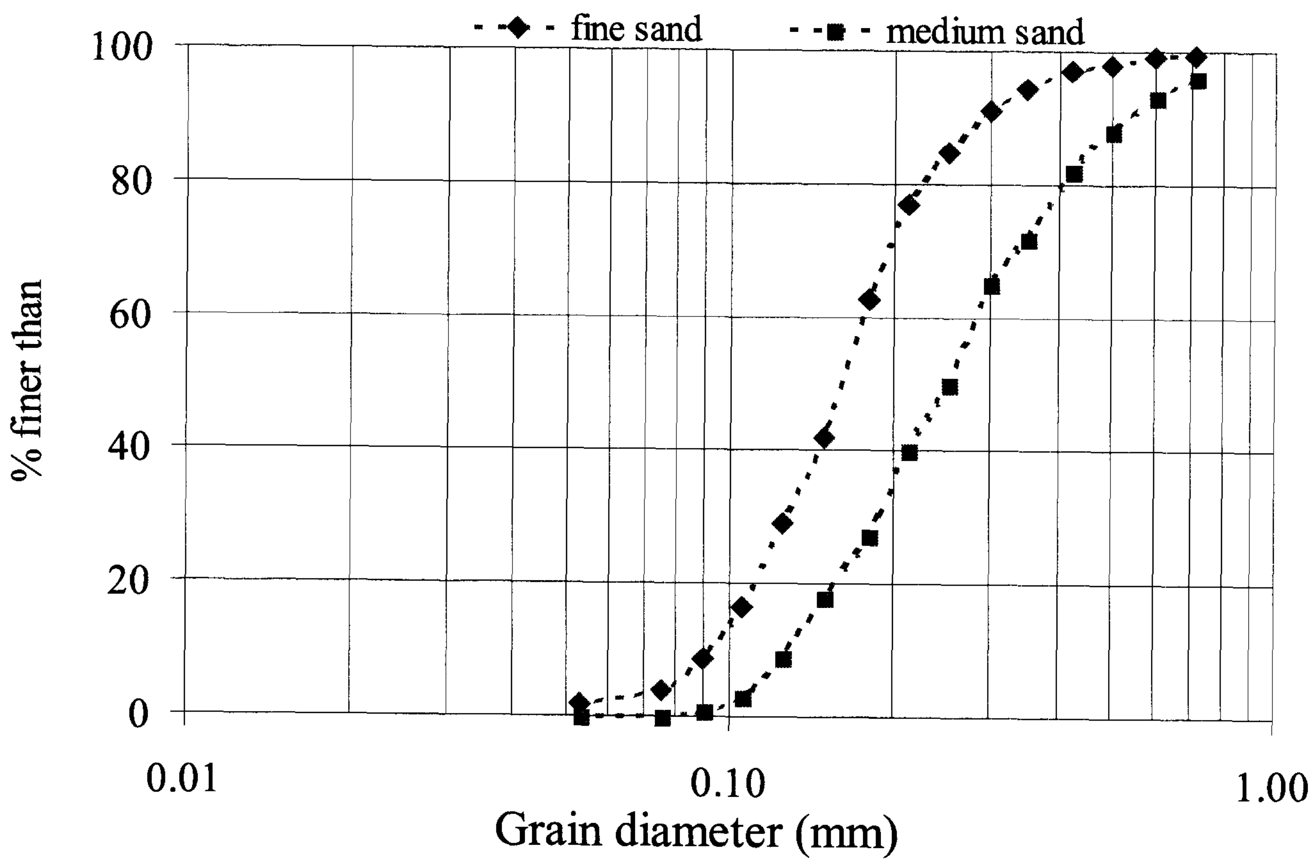

Figure 3 Cumulative grain size distribution for medium and fine sands used in the *Deltaflume* tests

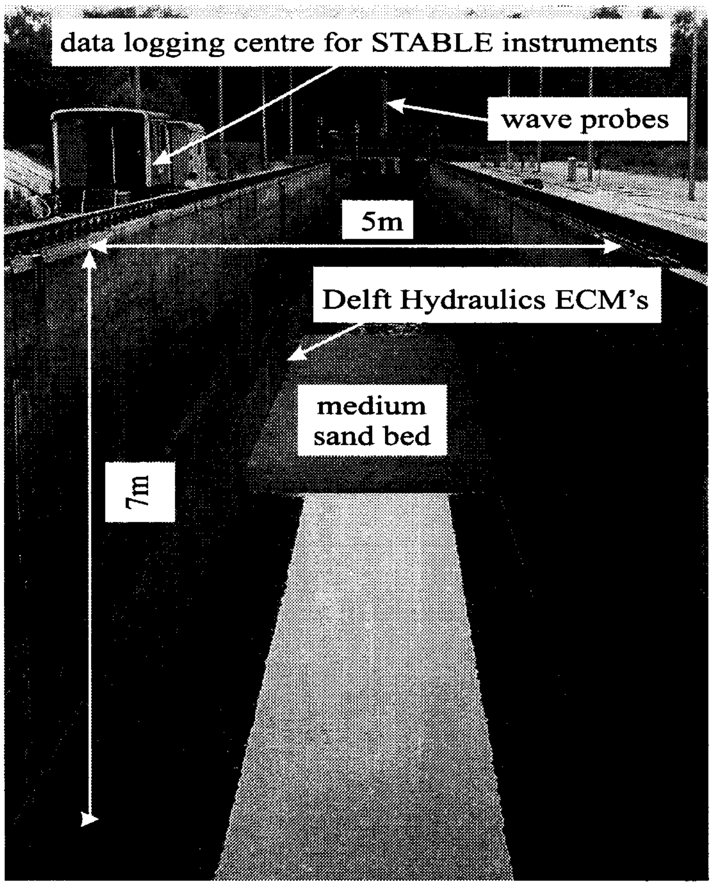

Figure 4 The medium sand bed before filling the *Deltaflume*

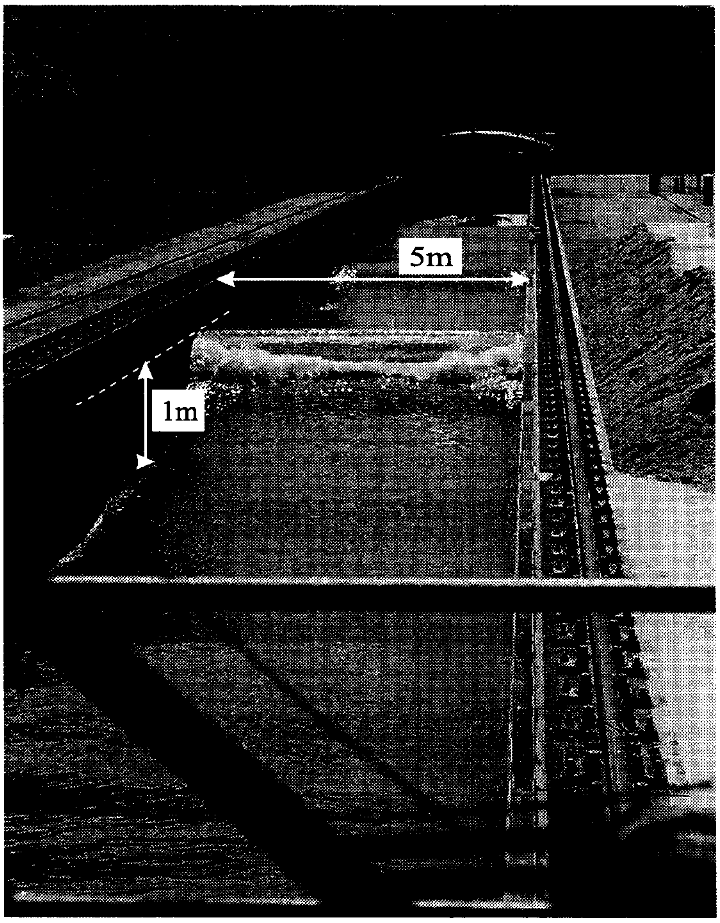

Figure 5 Large waves in the *Deltaflume*

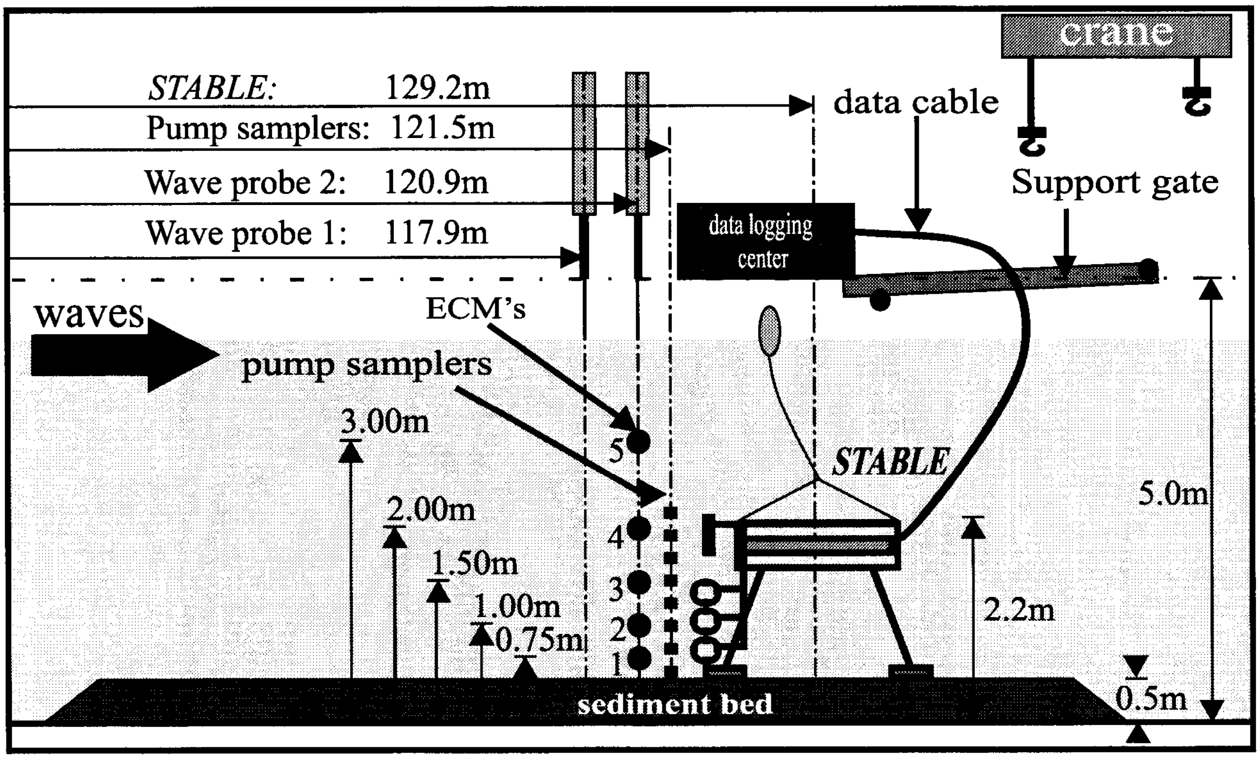

Figure 6 Schematic diagram showing the position of *STABLE,* wave probes and Delft Hydraulics *ECM*'s in the *Deltaflume*

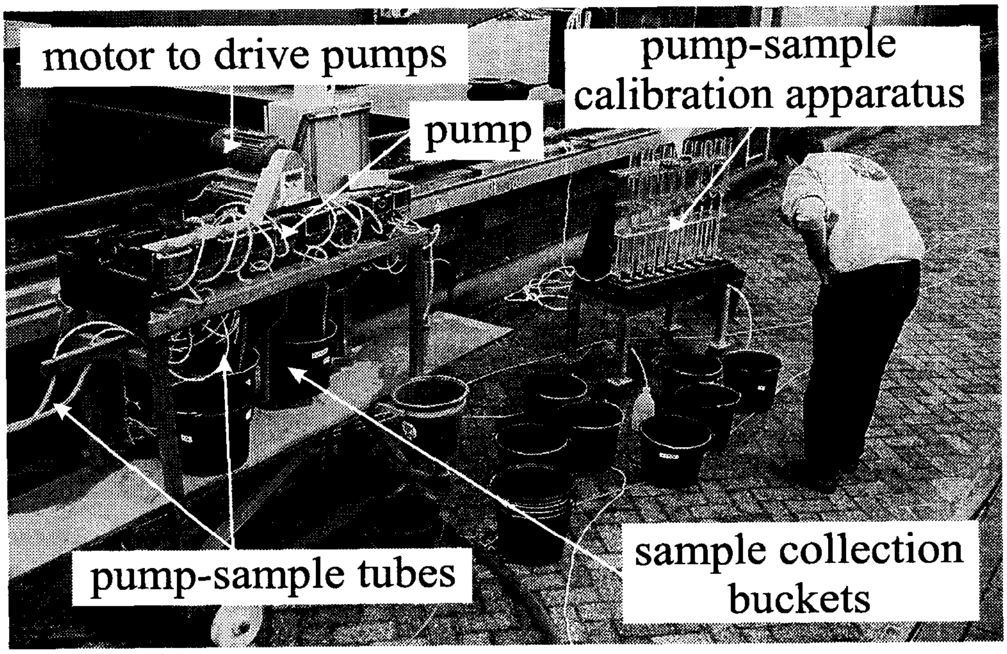

Figure 7 Collection of suspended sediment samples from the *Deltaflume* using pump-sampling equipment

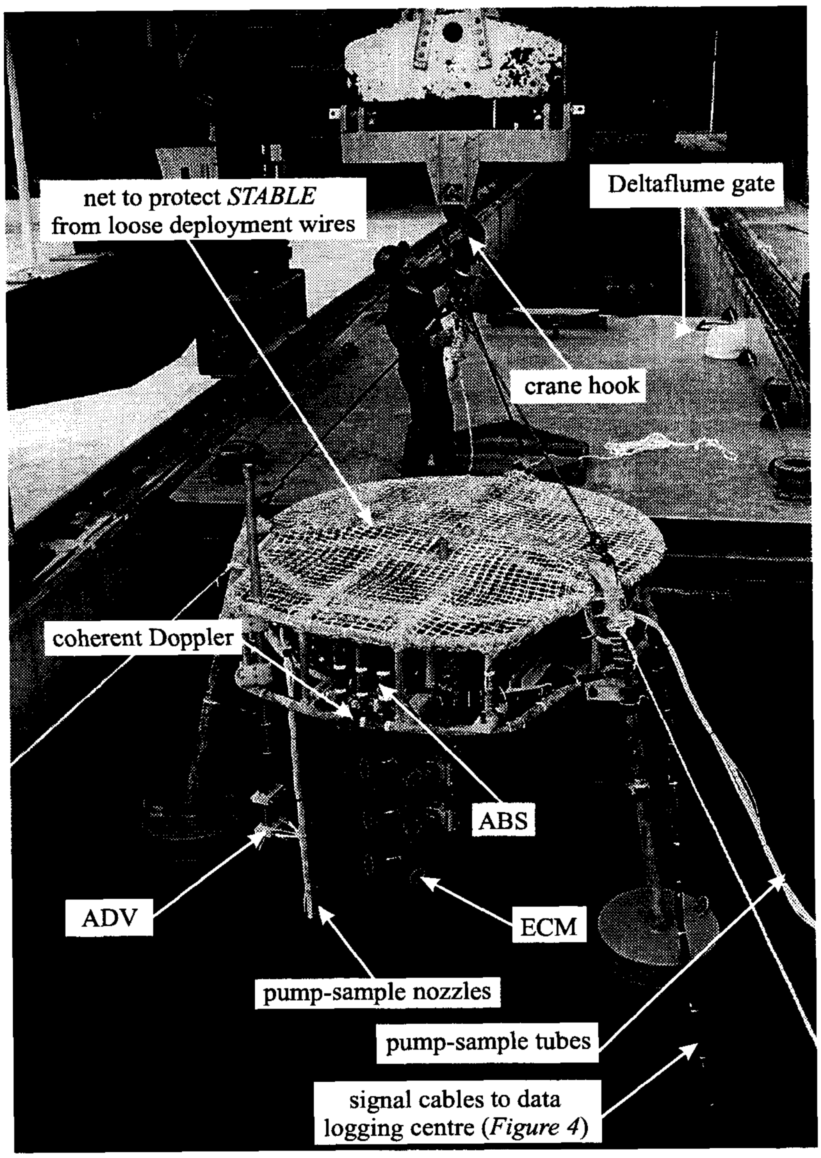

Figure 8 Deployment of *STABLE* in the *Deltaflume*

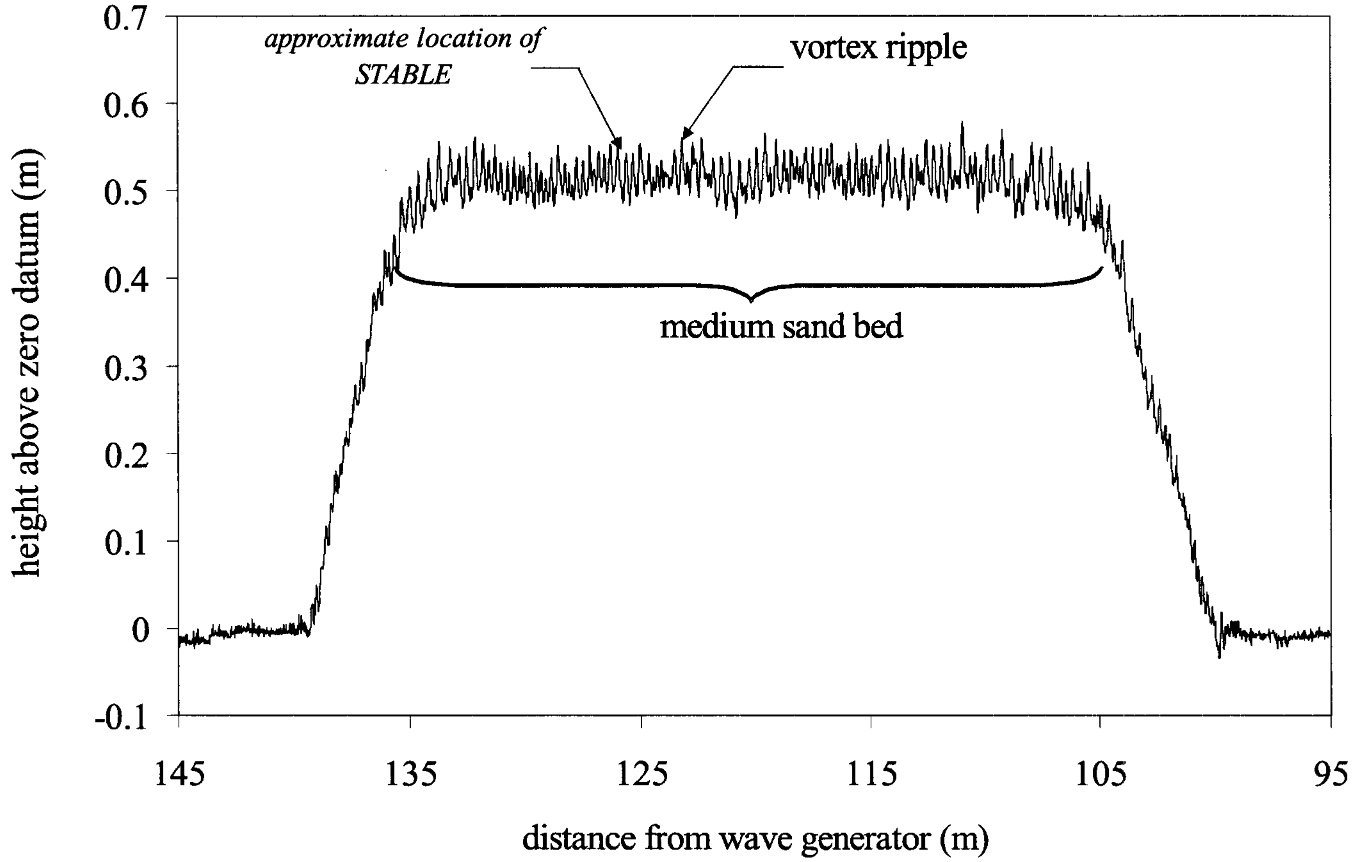

Figure 9 Example of vortex ripples on the medium sand bed measured using the Delft Hydraulics mechanical ripple profiler.

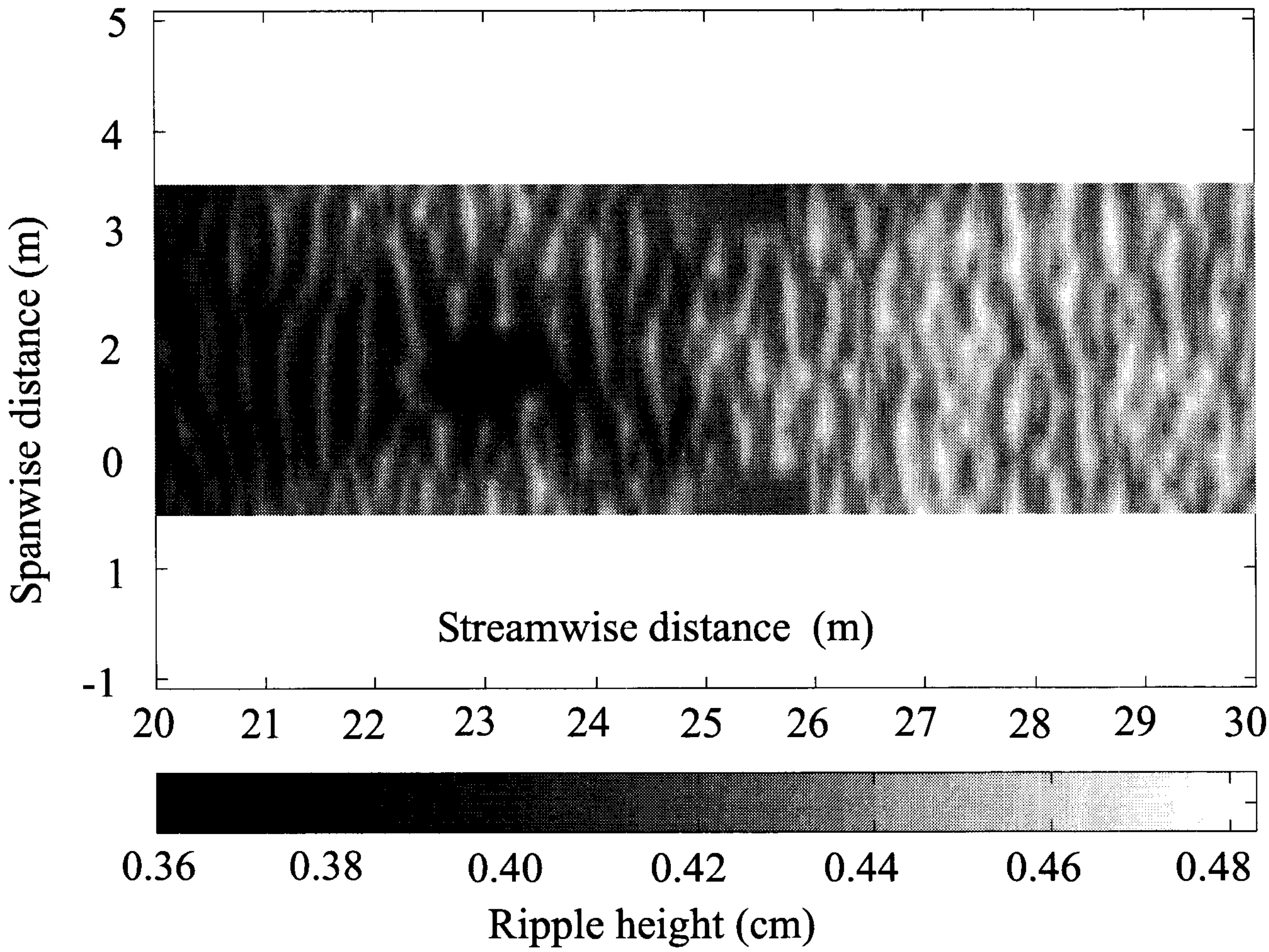

Figure 10 Composite image of vortex ripples on the medium sand bed derived from the mechanical ripple profiler data

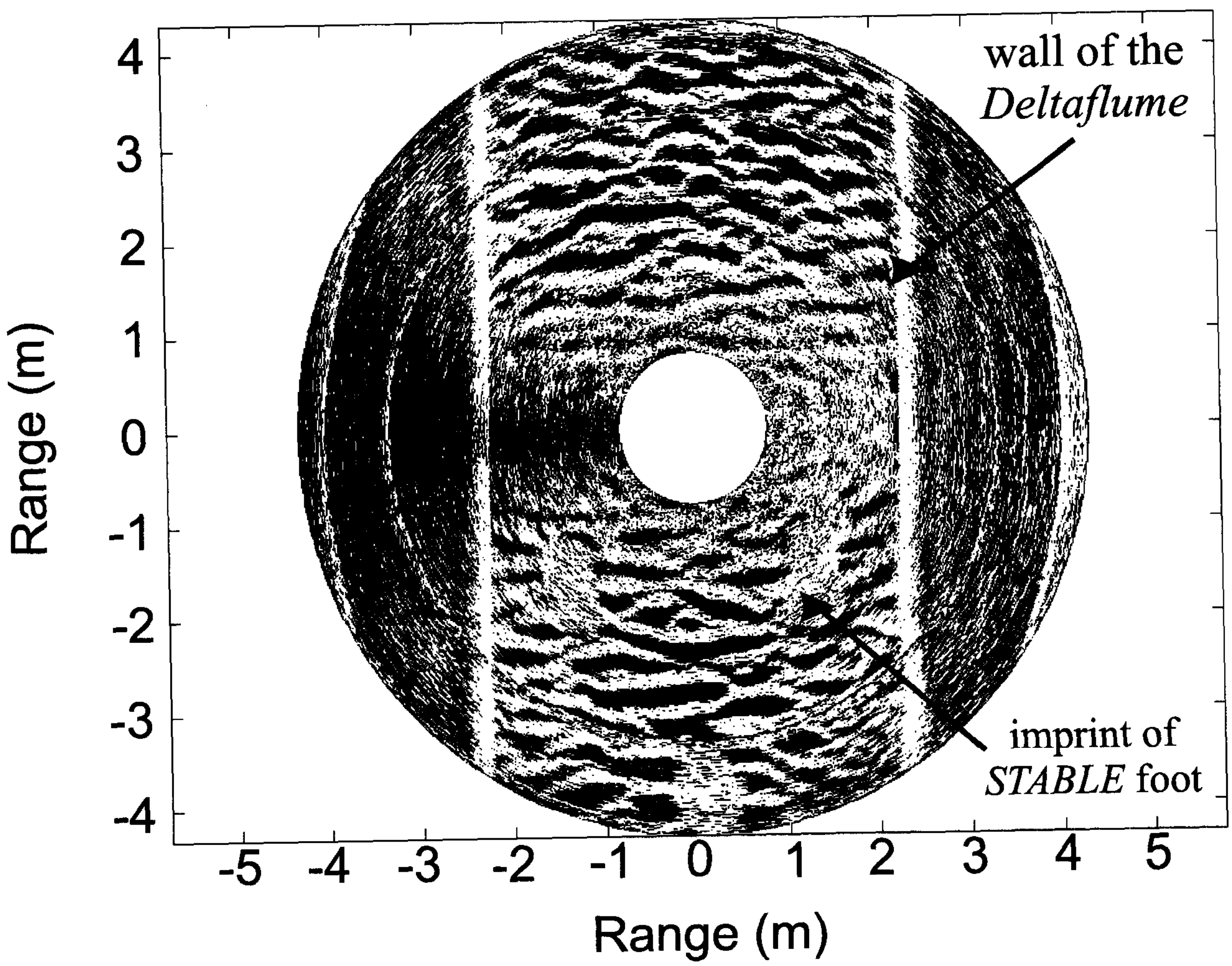

Figure 11 Sector-scanning sonar images of the medium sand bed showing walls of the *Deltaflume* and imprints left by *STABLE* feet.

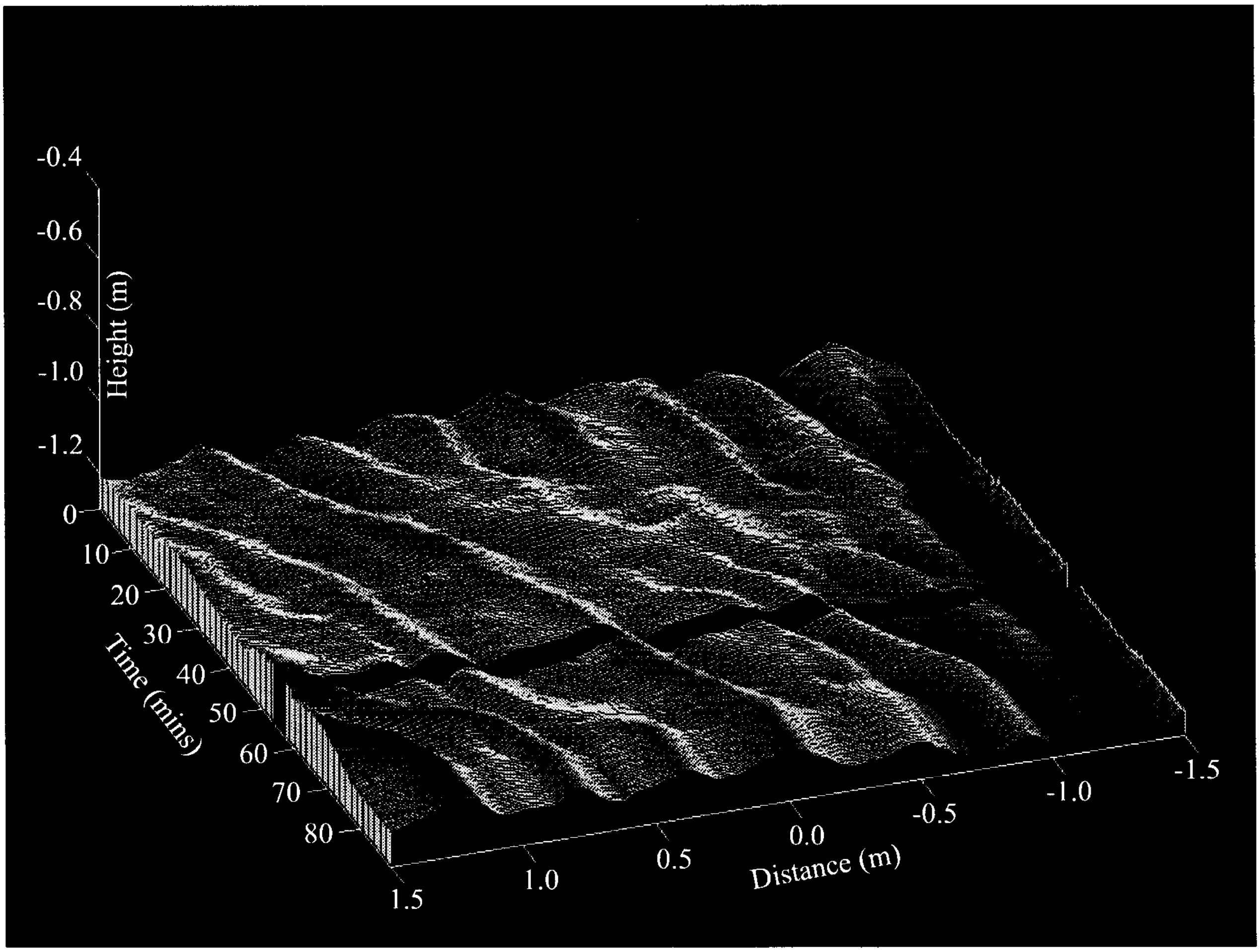

Figure 12 Temporal and spatial variation in ripple height and wavelength measured by the acoustic ripple profiler on *STABLE*

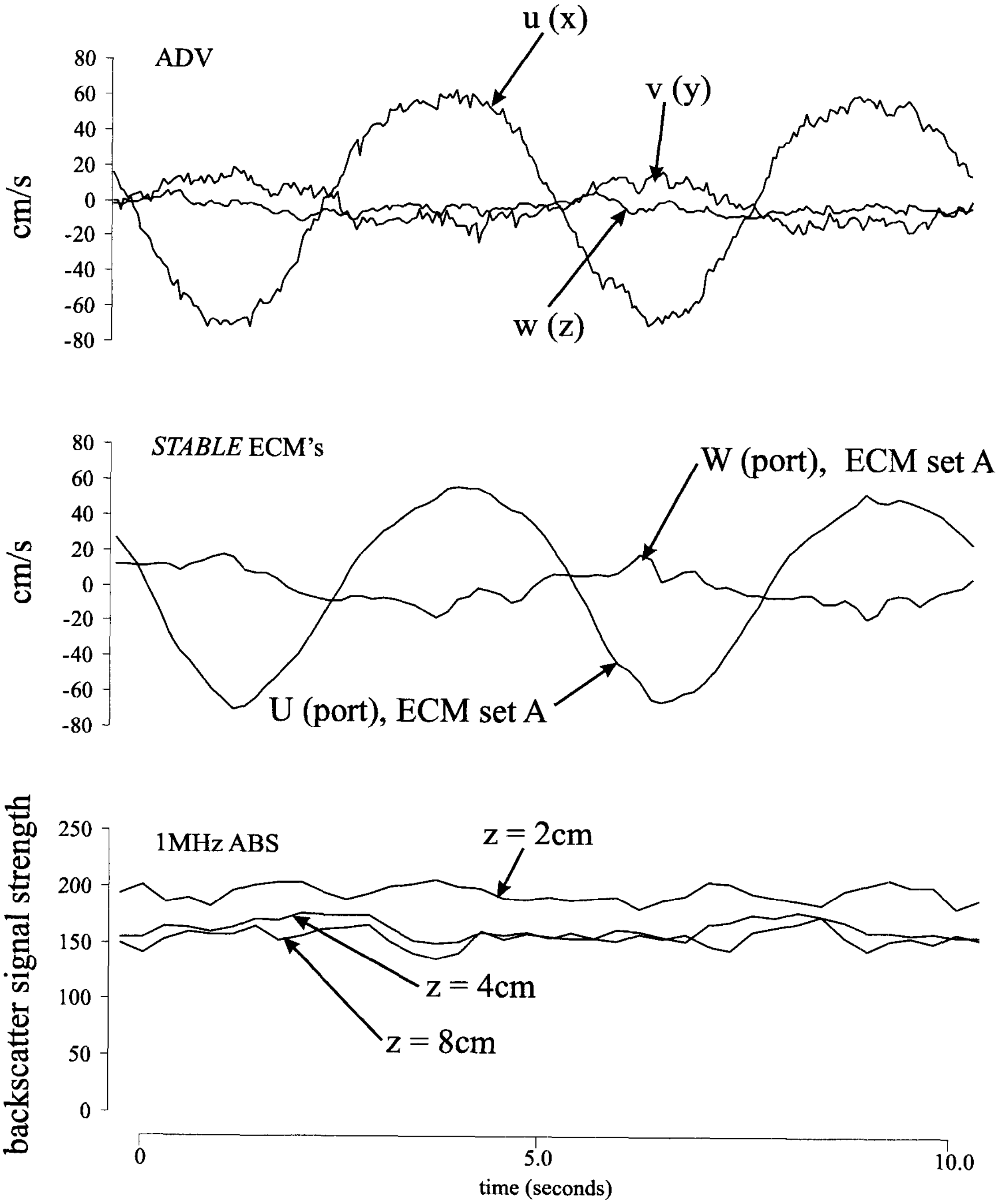

Figure 13 (a) Zero-mean orthogonal flow components u, v and w measured by the SonTec *ADV*; (b) uncorrected horizontal (U) and vertical (W) flow components measured by *STABLE* and; (c) 1MHz ABS time-series measured at z = 2cm, 4cm and 8cm for regular waves in test *A11a* (H = 1.299m, T = 5.0s).

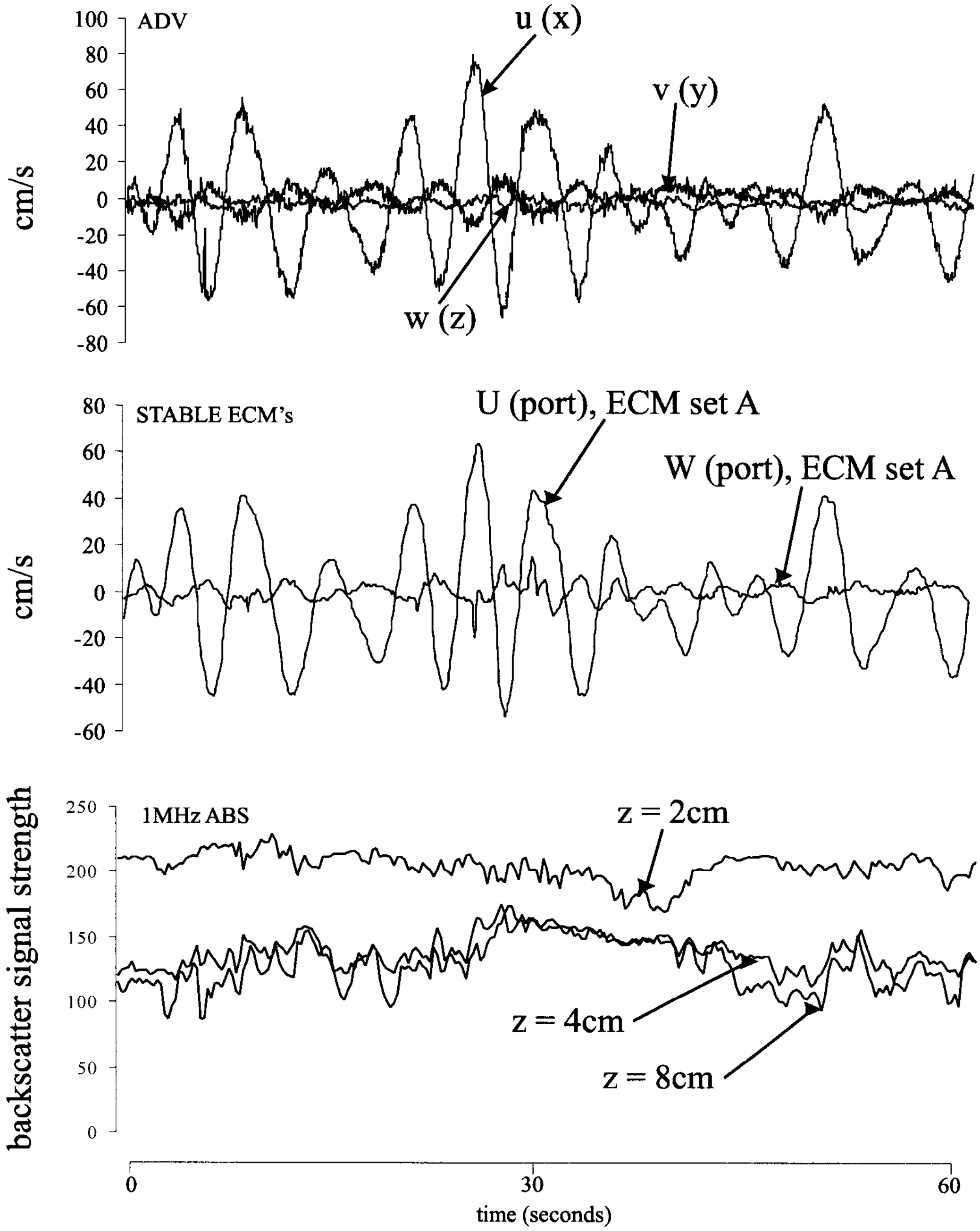

Figure 14 (*a*) Zero-mean orthogonal flow components *u*, *v* and *w* measured by the SonTec *ADV*; (*b*) uncorrected horizontal (*U*) and vertical (*W*) flow components measured by *STABLE* and; (*c*) 1MHz ABS time-series measured at z = 2cm, 4cm and 8cm for irregular waves in test *A12a* (H_s = 1.223m, T_p = 5.1s).

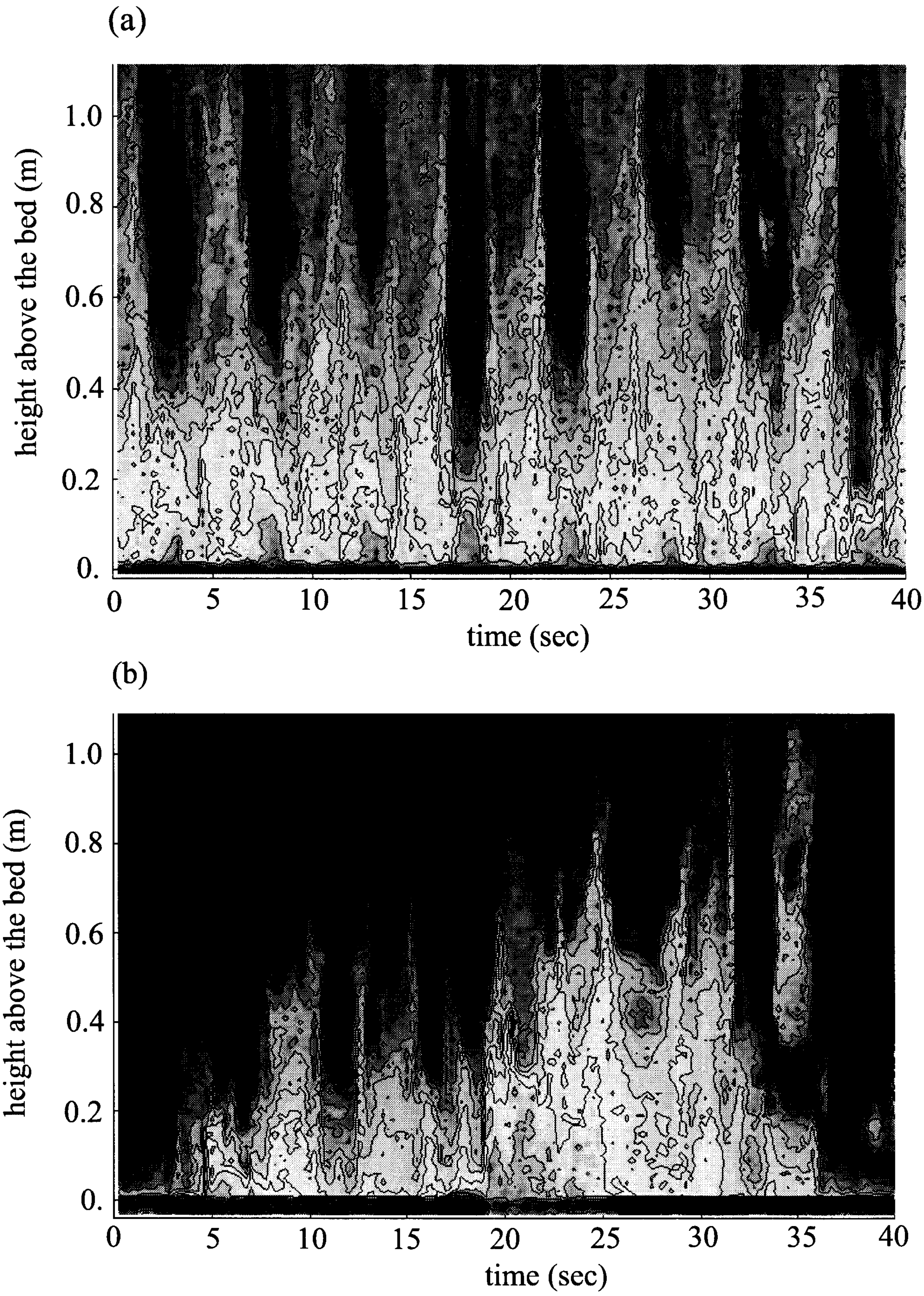

Figure 15 4MHz ABS records for: (a) regular waves, test *A11a*; and (b) irregular waves, test *A12a*. (Dark grey shades indicate low suspended sediment concentrations).

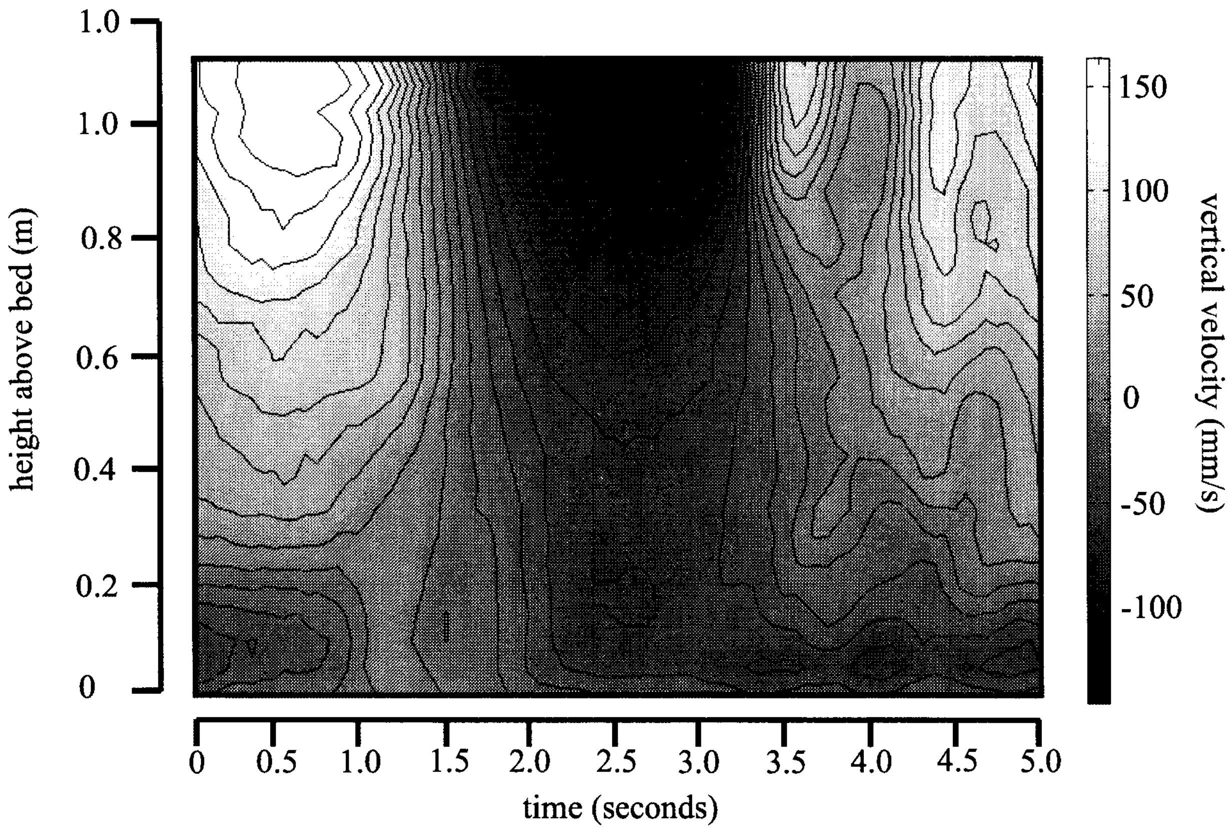

Figure 16 Vertical velocities (mm/s) measured with coherent Doppler averaged over 200 waves, regular waves, test *A11a*.

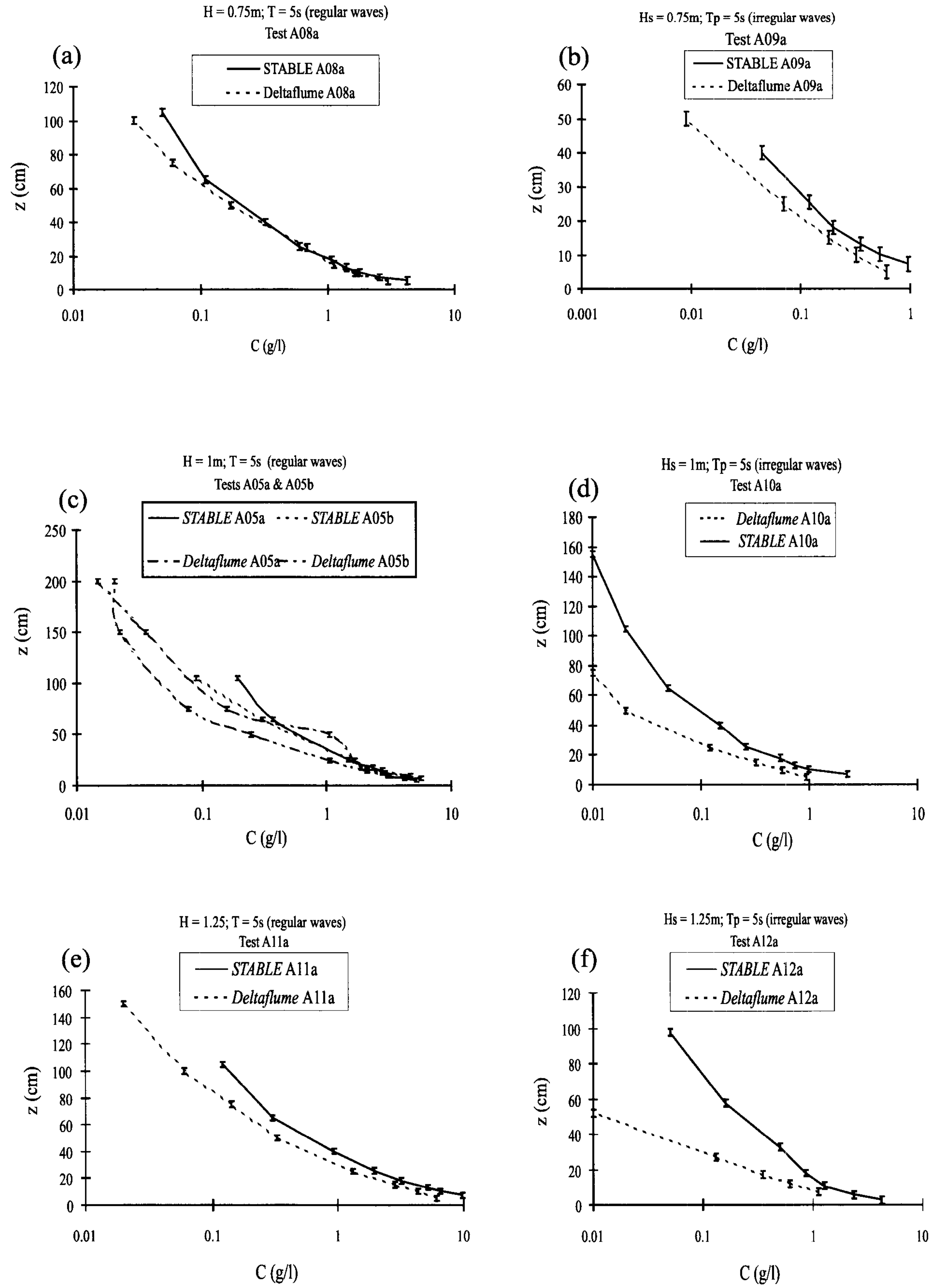

Figure 17 Suspended sediment concentration profiles measured using pump-sampling apparatus above the medium sand bed.

Appendix 1 **Useful linear wave theory formulae for the *Deltaflume***

Wave potential and velocities

$$\phi = \frac{gH}{2\omega}\frac{\cosh k(h+z)}{\cosh kh}\cos(kx-\omega t)$$
$$u = -\frac{\partial\phi}{\partial x} = \frac{gHk}{2\omega}\frac{\cosh k(h+z)}{\cosh kh}\sin(kx-\omega t) = \frac{\omega H}{2\sinh kh}\cosh k(h+z)\sin(kx-\omega t) \qquad (A1)$$
$$w = -\frac{\partial\phi}{\partial z} = -\frac{gHk}{2\omega}\frac{\sinh k(h+z)}{\cosh kh}\cos(kx-\omega t) = -\frac{\omega H}{2\sinh kh}\sinh k(h+z)\cos(kx-\omega t)$$

Dispersion relation

$$\omega^2 = gk\tanh kh \qquad (A2)$$

Particle orbits

$$X = \int_0^t u\,dt = \frac{H}{2}\frac{\cosh k(h+z)}{\sinh kh}\cos(kx-\omega t)$$
$$Z = \int_0^t w\,dt = \frac{H}{2}\frac{\sinh k(h+z)}{\sinh kh}\sin(kx-\omega t) \qquad (A3)$$

Maximum velocity at bed (z = -h)

$$u_{bed} = \frac{\omega H}{2\sinh kh} = \omega A \qquad (A4)$$

Maximum amplitude of particle excursion at bed (z = -h)

$$A = \frac{H}{2\sinh kh} \qquad (A5)$$

Wave generator (piston) characteristic

$$\frac{H}{S} = \frac{2\sinh^2 kh}{(kh+\sinh kh\cosh kh)} = \frac{2\omega^2\sinh 2kh}{gk(2kh+\sinh 2kh)} = \frac{\omega^2}{gkn} \qquad (A6)$$

The stroke, S, is limited to 2.5m less 10% for absorption etc.

Practical maximum wave height.

The usual limiting height is given as either:

$$\left(\frac{H}{\lambda}\right)_{max} = 0.14\tanh kh \quad \text{(Intermediate depth)} \qquad (A7)$$

or

$$\left(\frac{H}{h}\right)_{max} = 0.78 \quad \text{(Shallow water waves)} \qquad (A8)$$

The shallow water limit is not likely to be exceeded in the working section of the *Deltaflume*. The intermediate depth result for regular waves corresponds to non-linear waves at the point of breaking. If a significant wave height > 1.5m is used then many waves will exceed the breaking limit. The equations given above can be used to create graphs showing the maximum wave heights achievable for regular waves. The effects at the bed are likely to peak at a different period because of the trade-off between the generator characteristic and the usual decay with depth.

Transverse instabilities

One limitation of the *Deltaflume* is the possibility of exciting transverse oscillations at the natural frequencies of the flume. The lowest frequency will correspond to a wavelength of twice the flume width, which is just on the limit for deep-water waves. Eigenvalues correspond to:

$$kW = m\pi \qquad (A9)$$

where W is the flume width, m is an integer and therefore

$$T = \sqrt{\frac{4\pi W}{mg}\frac{1}{\tanh\left(\frac{m\pi h}{W}\right)}} \qquad (A10)$$

from the dispersion relation. The first solution (m = 1) is therefore 2.536 secs. However, for the specific dimensions of this flume the above formula simplifies as follows:

$$T = \sqrt{\frac{4\times\pi\times 5}{m\times 9.807}\frac{1}{\tanh\left(\frac{m\times\pi\times 5}{5}\right)}} = \sqrt{\frac{6.407}{m\tanh m\pi}} \qquad (A11)$$

$$\cong 2.53m^{-1/2}$$

because the waves are essentially 'deep water' and do not feel the bed.

Figure A1 illustrates a range of possible wave conditions in the *Deltaflume*. However, as various assumptions have been made about the efficiency of the wave generator, zero wave attenuation this figure is included as a guide only. These data are also summarised in *Table A1*.

It will be noted that:

- Below a period of approximately 4.5s, the wave height is limited by the breaking criterion. It is therefore physically impossible to generate waves higher than this as they will break at the generator.
- Above a period of approximately 4.5s, the wave height is limited by the maximum stroke of the piston. Although it seems possible to generate waves of 10s period, the wave height cannot exceed about 1m and even this may place impossible demands on the power of the hydraulic actuators.
- The maximum wave height seems to be approximately 2.6m for regular waves.
- The amplitude of particle motion at the bed, A, appears to approach a limiting value as the wave period increases. This value is caused by a balance between the reduction in the efficiency of the piston and the fact that for longer wavelengths the difference between free surface and bed activity reduces. This limit may be deduced as follows:

For small kh the generator characteristic reduces to:

$$\frac{H}{S} = \frac{2(kh)^2}{(kh + kh\times 1)} = kh \qquad (A12)$$

For small kh the amplitude of oscillation simplifies to:

$$A = \frac{1}{2}\frac{H}{kh} = \frac{S\times kh}{2kh} = \frac{1}{2}S \qquad (A13)$$

which shows that the amplitude of oscillation at the bed becomes equal to the amplitude of oscillation of the piston, as expected. The maximum bed velocity is about 1.2 m/s.

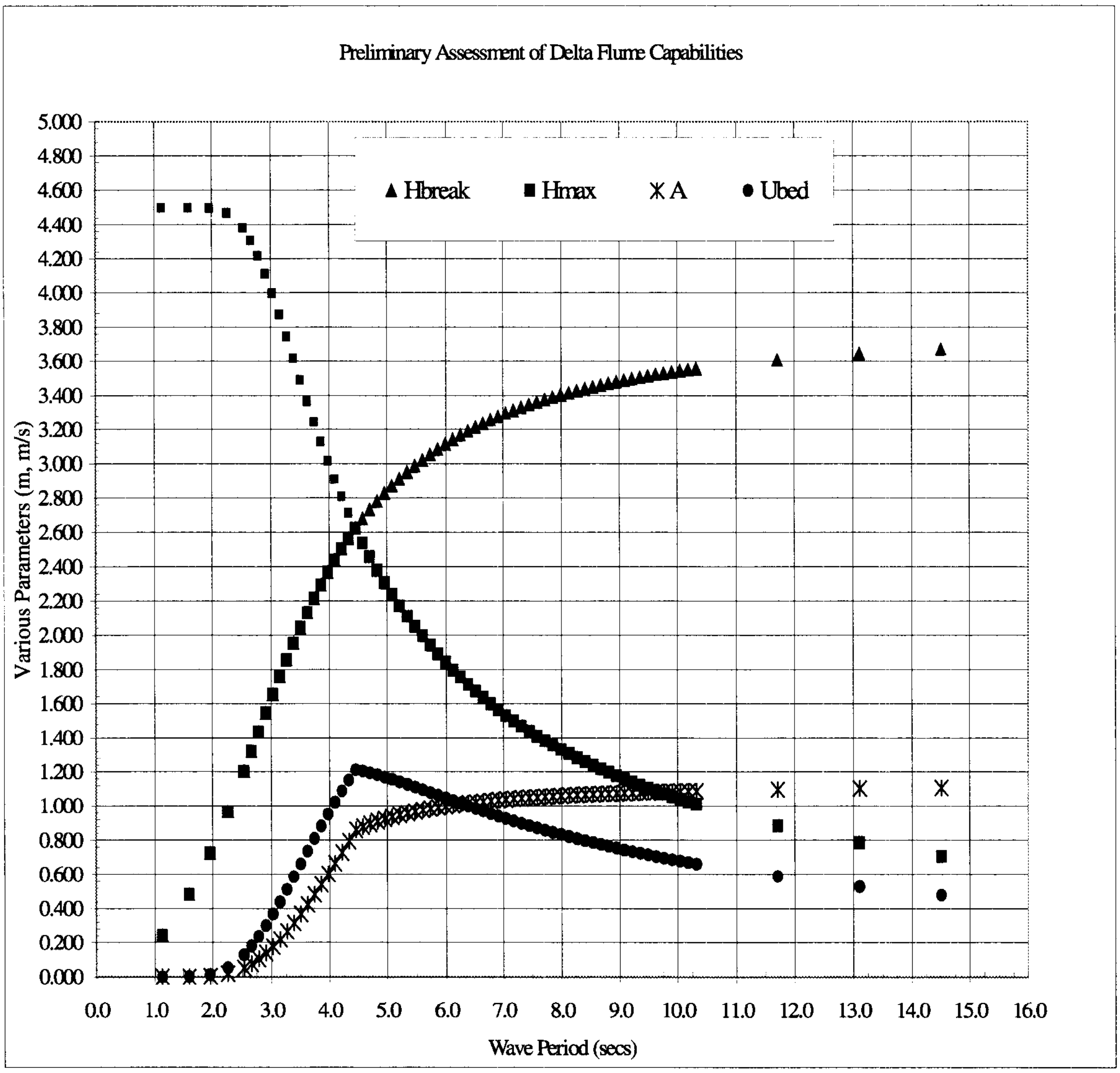

Figure A1 Assessment of wave generation capability, *Deltaflume*

Wavelength (m)	Period (s)	kh (m)	Hgen (m)	Hbreak (m)	Hmax (m)	A (m)	Ubed (m/s)
10	2.536	3.142	4.380	1.203	1.203	0.052	0.129
12	2.788	2.618	4.217	1.433	1.433	0.105	0.237
14	3.029	2.244	3.997	1.652	1.652	0.177	0.368
16	3.265	1.963	3.746	1.857	1.857	0.266	0.512
18	3.501	1.745	3.490	2.044	2.044	0.368	0.661
20	3.738	1.571	3.245	2.214	2.214	0.481	0.809
22	3.977	1.428	3.017	2.367	2.367	0.602	0.951
24	4.219	1.309	2.809	2.503	2.503	0.729	1.086
26	4.463	1.208	2.623	2.624	2.623	0.860	1.211
28	4.711	1.122	2.455	2.732	2.455	0.894	1.193
30	4.962	1.047	2.306	2.827	2.306	0.923	1.168
32	5.215	0.982	2.171	2.912	2.171	0.946	1.140
34	5.471	0.924	2.051	2.987	2.051	0.966	1.110
36	5.729	0.873	1.942	3.053	1.942	0.983	1.078
38	5.989	0.827	1.843	3.113	1.843	0.997	1.046
40	6.251	0.785	1.754	3.166	1.754	1.010	1.015
42	6.515	0.748	1.673	3.214	1.673	1.020	0.984
44	6.780	0.714	1.598	3.256	1.598	1.029	0.954
46	7.047	0.683	1.530	3.295	1.530	1.037	0.925
48	7.315	0.654	1.467	3.330	1.467	1.045	0.897
50	7.584	0.628	1.409	3.361	1.409	1.051	0.871
52	7.855	0.604	1.356	3.389	1.356	1.056	0.845
54	8.126	0.582	1.306	3.415	1.306	1.061	0.821
56	8.398	0.561	1.260	3.439	1.260	1.066	0.797
58	8.671	0.542	1.217	3.460	1.217	1.070	0.775
60	8.945	0.524	1.176	3.480	1.176	1.073	0.754
62	9.219	0.507	1.139	3.498	1.139	1.077	0.734
64	9.494	0.491	1.103	3.514	1.103	1.080	0.715
66	9.770	0.476	1.070	3.529	1.070	1.082	0.696
68	10.046	0.462	1.038	3.543	1.038	1.085	0.679
70	10.322	0.449	1.009	3.556	1.009	1.087	0.662
80	11.712	0.393	0.883	3.608	0.883	1.096	0.588
90	13.109	0.349	0.785	3.645	0.785	1.102	0.528
100	14.512	0.314	0.707	3.672	0.707	1.106	0.479

Table A1 Likely wave conditions in the *Deltaflume*. (Water depth = 5m, flume width = 5m, piston stroke = 2.25m, $g = 9.807m/s^2$ and pi = 3.141593)