15. MEASURED AND PREDICTED WAVE-GENERATED BEDFORMS

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Abstract

The paper presents an overview of results obtained from experiments in the large-scale Delta flume facility in the Netherlands examining hydrodynamic conditions, wave-generated ripples and sediment entrainment above sand beds. A sequence of experiments were undertaken in random wave conditions on two different test beds composed of sand with D50 = 0.349 mm and 0.220 mm under conditions. During the tests the significant wave height, Hs, was gradually increased allowing investigation of processes resulting in ripple formation and destruction and sheet flow conditions. A combination of advanced and traditional measurement techniques from the field and the laboratory were used to quantify the near-bed hydrodynamics, suspended sediments and ripple dynamics. The data have been widely disseminated through BODC1 to research partners in Europe and analyses to date are providing new insight into sediment dynamics in wave conditions.

15.1 INTRODUCTION

Due largely to advances in acoustic technology over the past decade, significant progress has been made in measurement of sediment resuspension processes and sediment transport by waves in near-shore and continental shelf environments. Whilst the use of the new technology in the field has advanced the understanding of these processes, it has not yet been possible to undertake a series of controlled experiments at full-scale using a range of sediments and hydrodynamic conditions. As a result there are a number of gaps in knowledge that prevent full description of sediment resuspension and transport in oscillatory flows. In a previous study (Williams et. al 1999 and 2003a), it has been demonstrated comprehensively that field measurement devices mounted on the benthic tripod STABLE accurately measure near-bed hydrodynamics, suspended sediments and bed dynamics. The data gathered have enabled for the first time quantification of the degree to which frames such as STABLE affect processes interfering with the near-bed processes of bedform formation and maintenance, resuspension and diffusion. These studies have examined bedforms beneath and adjacent to a suite of instrumentation and the support frame. Differences between different bed
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locations were not detected thereby inferring processes resulting in bedform evolution and maintenance remains essentially unaffected by measurement devices.

The work reported here concerns deployment of field equipment in the Delta flume in a focused study examining oscillatory suspended sediment transport processes at full-scale in controlled conditions. The experiments have addressed the following topics: 1) sediment resuspension and transport by random waves; 2) the vortex ejection mechanism and vortex pairing; 3) inter- and intra-wave suspended sediment concentration and grain size profiles; and 4) bedform dynamics. Analysis of the resulting data sets are still at an early stage, and thus only preliminary results are set out here. However, they serve to illustrate well the quality of the data and highlight some potential applications in process studies and numerical modelling.

15.2 METHODOLOGY AND INSTRUMENTATION

A series of experiments to examine the formation and morphology of wave-generated ripples were undertaken in the large-scale Delta flume facility of Delft Hydraulics (230 m long, 5 m wide and 7 m deep) using a carefully levelled bed of sand of depth 0.75 m which spanned the 5 m width of the flume and extended a length of 30 m (Figure 15-1a). Drainage pipes were laid beneath the sand bed to minimise disturbance of the sediments during filling of the flume. Each end of the test bed was smoothed out to form a ramp between the floor of the flume and elevated surface of the test area. The D50 values for sand used in experimental series Delta-2a and Delta-2b were 0.349 mm (medium sand) and 0.220 mm (fine sand), respectively. Instruments to measure waves, turbulence, bedforms and suspended sediments were mounted in close proximity onto a purpose-built frame and deployed in the Delta flume approximately mid-way along the sand bed (Figure 15-1b). Spacing between adjacent acoustic sensors was sufficient to ensure no acoustic interference. When necessary, the instrument support frame could be driven backwards and forwards to a desired location above selected bed features in response to local bed elevation changes.
Figure 15-1. Deltaflume and POL frame: a) leveling the medium sand bed; b) deploying the frame; c) frame showing 1) pressure sensor; 2) stepper motor; 3) ARP; 4) SSS; 5) ECMs; 6) LISST-100; 7) 3DCD; 8) ABS; 9) ADV 10) pump sampler; and 11) ADV

The still water depth, $h$, above the test bed of sand was 4.0 m during all the experiments. The wave height was increased systematically to a point where sheetflow conditions might be expected and thereafter decreased to the starting value. In all tests waves passed above the test beds of sand for at 1 hour before taking measurements. Previous tests reported by Williams et al. (2003a) showed that $\lambda$ and $\eta$ values remained statistically stationary after this time. The significant wave height, $H_s$, and peak period, $T_p$, of the waves were measured by surface following wave gauges deployed above the sand bed. Table 1 details the various test runs together with the measured wave heights and periods. Current meters were also sited on the sidewall of the flume to provide independent measurements of the wave-induced flow at a location remote from the frame.
<table>
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<th>Fine Sand</th>
<th>$T_p$ (s)</th>
<th>$H_s$ (m)</th>
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Table 1: Summary of all test runs

Field and laboratory instruments were deployed using a specially designed frame above a given test bed (see Figure 15-1c). Digiquartz pressure sensor, PS (0.5 bar to 10 bar ± 10^{-5} bar) measured $h$, (waves, sampling frequency, $f_s$ = 8 Hz). Two Acoustic Doppler Velocimeters, ADV, ($f_s$ = 25 Hz) and the POL 3D coherent Doppler system, 3DCD, ($f_s$ = 16 Hz), (Wilson et al., 2000) measured turbulence at a point and at other locations in a vertical profile up to a height of approximately 0.6 m above the bed at vertical intervals of 0.046 m. Vertical suspended sediment concentration profiles were measured at intervals of 0.01 m over the range 0.01 m < $z$ < 1.0 m using a 1.0 MHz, 2.0 MHz and 4.0 MHz acoustic backscatter system, ABS, ($f_s$ = 4 Hz), (Thorne & Hardcastle, 1997). Measurements of the time-averaged suspended sediment concentration and composition were obtained at 5 heights above the bed from pump-samples (Bosman et al., 1987) aligned normal to the flow. A LISST-100 was used to measure particle size and concentration \textit{in situ}. Instruments to measure bedform morphology in the wave flume consisted of an acoustic ripple profiler, ARP, comprising of a 2 MHz transducer mounted onto a motor (Bell & Thorne, 1997), and high-resolution sector-scanning sonar, SSS, consisting of a small, fan beam acoustic transducer mounted on a stepper motor (Bell et al., 1998). The ARP measured the morphology of the bed along a single line of length 4 m centred beneath the deployment frame described below and running along the x-axis of the flume. Approximately 33 bed profiles were measured during each test. The SSS recorded an image of the bed morphology in a circular area of radius approximately 5 m beneath the deployment frame at 1-minute intervals. In all cases a time of at least 1 hour was allowed for ripple development before measuring bed morphology. The frames used to deploy these instruments is shown by Williams et al., (2002) and Williams et al., (2003a) to cause only minor disturbance to the local near-bed hydrodynamics and sediment processes. The streamwise and spanwise location of all the instruments with reference to the measured bed location during test M071 is shown in Figure 15-2.
15.3 DATA ANALYSIS

The pressure sensor data were corrected for depth-attenuation using linear wave theory before converting it into time-series of water depth, \( h \). The ABS instruments were calibrated using \textit{in situ} pump-samples and laboratory tests were used to provide calibration information necessary to process the SSS and ARP data. Manufacturers’ calibrations and software were used for the ADV and ECM instruments. Being reliant upon a measured shift in frequency, the 3DCD required no special calibration (Wilson et al., 2000). The orthogonal turbulent flow components measured by the ADVs and the 3DCD were then corrected for slight misalignment in the vertical and horizontal planes using an axes rotation algorithm and corrected zero-mean flow component time-series \( u \), \( v \) and \( w \), comprising wave-induced fluid motion and turbulence were calculated. The wave-induced fluid motion was removed effectively from the \( u \), \( v \) and \( w \) time-series to leave turbulence using a moving average, MA, filter in the form

\[
F_{j(t+1)} = \frac{1}{N} \sum_{j=1}^{N} A_{t-j+1}
\]  

Figure 15-2. Streamwise (X) and spanwise (Y) locations of instruments on the POL frame
where $F_j$ is the forecasted value at time $j$, $N$ is the number of prior periods to include in the MA and $A_j$ is the actual value at time $j$. Parameter values in Eq. 1 were chosen to give 1 s average values of $u$, $v$ and $w$ and the resulting 1 Hz MA series comprising wave motion, $u_w$, $v_w$ and $w_w$ were then re-sampled at the original sampling frequency and subtracted from the original signal to obtain the time-series $u_t$, $v_t$ and $w_t$ comprising principally turbulence. ARP profiles of bed morphology were edited to remove infrequent noise spikes attributable to local resuspension events and smoothed using a digital low pass filter. Spatially average values for $\eta$ and $\lambda$ were then obtained for each ARP profile using zero down-crossing analysis$^2$. These were subsequently combined to give average and standard deviation, $\sigma$, values for $\eta$ and $\lambda$ for each test. Further details of data analysis approaches used for the data are given by Williams et al., (2003b).

15.4 RESULTS

In the present paper we focus attention upon results obtained from experiment M07_1 on the medium sand bed. This illustrates the principal features of the much larger data set that is currently the subject of further investigation.

15.4.1 Hydrodynamics

Power spectra of flow components $u$, $v$ and $w$ and co-spectra $uw$ measured by the ADVs, the ECM ($z = 25$ cm) and the 3DCD are shown in Figure 15-3. With the exception of the ECM which shows the characteristic insensitivity to high-frequency motions attributable to the sampling volume, spectra and co-spectra from the acoustic instruments show close agreement across a broad range of frequencies. Thus the 3DCD is shown to have a capacity to measure the wave-induced flow field with accuracy comparable to an ADV. Since this instrument has the added advantage of providing a vertical profile of flow conditions, attention will now focus on data from this instrument. It should be noted that the peak associated with the waves occurs at a frequency of about 0.17 Hz, which corresponds to a period of approximately 6 s.

The effectiveness of Eq. 1 in separating wave-only motion from turbulence is presented in Figure 15-4 and Figure 15-5. Figure 15-4 shows waves + turbulence [$u$, $v$, $w$], turbulence-only [$u_t$, $v_t$, $w_t$] and waves-only [$u_w$, $v_w$, $w_w$] flow component time-series measured at 11 locations above the bed approximately in the range $2$ cm $< z < 70$ cm. For clarity, the time-series have been offset. Figure 15-4 shows a high degree of vertical coherence of the flow components. Figure 15-5 shows vertical profiles of the wave-period averaged flow components [$u$, $v$, $w$], [$u_t$, $v_t$, $w_t$] and [$u_w$, $v_w$, $w_w$]. Each wave was split into 14 parts to shown the variation in the flow components over one period. In all cases, measured parameters conform approximately with theoretical expectations and with a simple 1DV numerical wave boundary layer model. It is clear therefore that the acoustic instruments on the frame are able to resolve the wave-induced flow field with consistency and in great detail.

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Figure 15-3. Power spectra for u, v and w and co-spectra uw measured by ECM, ADV and 3DCD

Figure 15-4. Separation of turbulence from wave-only flow measured by the 3DCD
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15.4.2 Bedforms

A time-stacked image of ARP data is illustrated in Figure 15-6 together with some examples of individual ARP bed profiles in Figure 15-6b. Figure 15-6 shows ripples with a height, $\eta \sim 4$ cm, and wavelength, $\lambda \sim 100$ cm, which remain approximately static in the present irregular wave regime for the first 750 seconds of the experiment. At that time, the instrument carriage was moved forward by means of the stepper motor and drive train illustrated in Figure 15-1c to relocate instruments to a different measurement location. Following this the ripple locations are once again observed to remain fixed. During a sequence of experiments where $H_s$ was increased to a maximum value of circa 1.5 m and then decreased, a range of ripple geometries were measured. To investigate relationships between ripple morphology and hydrodynamic forcing, $\eta$ and $\lambda$ values are related here in a non-dimensional form to the wave mobility number, $\psi$, in Figure 15-7 which shows plots of $\eta/D_{50}$ against $\psi$ and $\lambda/D_{50}$ against $\psi$. Also included here are $\eta$ and $\lambda$ values obtained from tests in regular waves reported by Williams et al., (2003c) and field data (mainly for anorbital ripples) reported by Inman (1957). Here a fit to the data gives the relationships

$$\frac{\eta}{A_o} = \exp[-0.315 \ln(\psi)^2 + 2.121 \ln(\psi) - 6.098]$$  \hspace{1cm} (2)$$

$$\frac{\lambda}{A_o} = \exp[-0.028 \ln(\psi)^2 + 0.00342 \ln(\psi) + 0.0349]$$  \hspace{1cm} (3)$$

Figure 15-5. Wave-period average profiles of $[u, v, w], [uw, vw, ww]$ and $[ut, vt, wt]$ measured by 3DCD

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where

$$\psi = \frac{\rho u_w^2}{(\rho_s - \rho)gD_{50}}$$

(4)

$u_w$ is the peak semi-orbital velocity close to the bed, $\rho_s$ is the sediment density, $\rho$ is the fluid density and $g$ is the acceleration due to gravity. $u_w = \pi d_o / T$ and $d_o = H_s / \sinh(kh)$, where $k$ is the wavenumber, $2\pi / L$, and $L$ is the wavelength of the surface gravity wave. Further analyses of these data by Williams et al. (2003c) shows the present ripples to fall within the suborbital range defined by Wiberg & Harris (1994) and consequently, predicted values for $\eta$ and $\lambda$ given by empirical formulae from, for example Nielsen (1981), Grant & Madsen (1982) and Van Rijn (1989) do not perform well for these bedforms. Further, the data of Inman (1957) for field conditions are quite distinct on these plots indicating the present data are not typical of bedforms found in relatively deep coastal water and have more in common with the bedforms observed in shallow coastal environments. A paucity of data relating to this bed morphology makes the present data set of particular relevance to applications in the near-shore region. It is noted also that during the present sequence of tests, bed morphology at the start and end of the wave sequences was different despite the start and end wave conditions being identical. This hysteresis effect, shown in Figure 15-8 for the medium sand, appears to be a ubiquitous feature of mobile bed-wave interactions and explains in part why prediction of $\eta$ and $\lambda$ values based on measured hydrodynamics are inherently unreliable in most situations.

*Figure 15-6. Wave-generated bedforms measured by the ARP*
15.4.3 Suspended sediments

The suspended sediment concentration fields measured by the 1.0 MHz, 2.0 MHz and 4.0 MHz ABS transducers over a time of 1500 seconds and height range of $0 \text{ cm} < z < 60 \text{ cm}$ presented in Figure 15-9 show essentially the same features. This provides strong evidence that the acoustic approach to measurement of suspended sediment has a capacity to give reproducible results. Each shows the rapid, high concentration intermittent resuspension of the bed sediments by individual waves well documented by, for example, Villard & Osborne (2002) and the lower frequency modulations in average concentration associated with groups of waves (Vincent & Hanes, 2002). The vertical coherence of resuspension events is illustrated by the time-series in Figure 15-10 of suspended sediment concentration, $C$, measured in the range $1 \text{ cm} < z < 10 \text{ cm}$. Here, each $C$ series has been offset in the vertical by $20 \text{ cm}$ to show the important features of the data. This figure shows that resuspension events are vertically coherent and exhibit a lag between lower and upper regions of the flow.
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Time-averaged suspended sediment concentration profiles for each ABS frequency obtained over periods of 32 s (c-profiles) and for a whole 30 minute run (C-profiles) are shown in Figure 15-11 together with C values from pump-samples. These later data are time-averaged values for a period of approximately 10 minutes during the middle of a run. Whilst scatter is evident in the 32 s average c-profiles, good agreement between the C-profile and the pump sample values is evident. Following work reported by Thorne et al. (2002), the shape of the near-bed C-profile is best characterized by pure diffusion and a height invariant eddy viscosity up to approximately 2 ripple heights above the bed. Above this region, the shape of the C-profile conforms Nielsen’s (1992) convective-diffusive description or a pure convective solution alone. Further discussion of this is given by Thorne et al., (2002).
Preliminary investigations have also examined the role of wave groups in the resuspension process. Figure 15-12 shows: a) a wave record and the associated wave group envelope function; b) a sequence of C-profiles measured for each successive forward and reverse wave stroke within the group; and c) a time series of total suspended sediment for the time period commensurate with the wave record in a). The well-documented wave-pumping effect is evident in Figure 15-12b. In common with observations reported by Villard et al. (2000) high concentrations of suspended sediment are observed towards the end of a wave group as the wave height dropped rapidly. Present data indicate that this is associated with changes occurring to the bedforms during the passage of a wave group promoting more effective sediment entrainment, and more efficient diffusion by enhanced turbulence production at the bed. It seems likely also that settling of suspended grains may also be hindered by enhanced turbulence described by Nielsen (1992).
Figure 15-10. Suspended sediment concentration time-series measured by the ABS system

Figure 15-11. Measured time-averaged vertical suspended sediment concentration profiles
15.5 CONCLUSIONS

The present paper has given a small insight into the ongoing analysis of the large data set during experiments in the Delta flume. Analyses of previous data suggested that there is no influence of large scale deployment frames on measurements obtained by sensors mounted on the frames. This allowed the focus of the data analysis on the interaction between hydrodynamics and morphodynamics. The deployment of the Coherent Doppler sensor with a vertical resolution of about 4 cm in conjunction with the ABS measurements has, for the first time, provided the opportunity to determine sediment transport within about 50 cm above the bed. The systematic analysis of the deployment of bedforms has highlighted the problems associated with the prediction of bedform dimensions based on the driving hydrodynamic parameters. The present systematic investigation of bed response to changing hydrodynamic forcing has wider applications in aiding parameterisation of numerical models of coastal systems, which must consider the relationship between the present bed morphology and antecedent wave conditions. The results are helpful also in investigations of the dynamic feedback linking hydrodynamics, suspended sediments and bed morphology in natural situations.
15.6 ACKNOWLEDGEMENTS

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15.7 REFERENCES

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