CHAPTER 166

Wave Entrainment of Sand from a Rippled Bed Malcolm O. Green¹ and Christopher E. Vincent²

<u>Abstract</u>

Wave-orbital velocities at 20 cm above the bed and continuous vertical profiles of near-bed suspended-sediment concentration were measured seaward of the surfzone over a rippled bed. Sand was intermittently entrained from the bed and ejected upwards in discrete The typical sequence of events in the clouds. entrainment cycle, with sand being rolled up in a thin near-bed layer and ejected into the flow on alternating wave strokes, is attributed to the action of vortices shed from the bed ripples by the reversing flow. The orderly cycle of events causes a time-domain correlation between the wave fluctuations of velocity and concentration, and the resulting sediment flux is comparable in size, and at some elevations directed opposite to, the mean sediment flux.

Introduction

Time-averaged horizontal suspended-sediment flux in a combined wave and current flow may comprise two terms: a "mean" term, which is readily understood, and a "correlation" term, which arises from correlation in time of the wave fluctuations in suspended-sediment concentration and horizontal velocity (e.g., Jaffe et al., 1984; Vincent and Green, 1990). The latter component of the total flux is analogous to the vertical turbulent flux of horizontal momentum that occurs in the benthic boundary layer. In the case of the boundary layer, sublayer bursting drives the momentum flux; in the

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²School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ, England. case of the sediment transport, the correlation flux is driven by the orderly process of flow separation and vortex-shedding associated with reversing flows over ripples.

The process of vortex shedding from rippled beds by reversing flows has been studied using flow visualization techniques in the laboratory (e.g., Bijker et al., 1976; Honji et al., 1980); Eulerian measurements of the resulting suspended-sediment concentrations and fluid velocities have been made in the laboratory by several workers (e.g., Hom-ma et al., 1965; Nakato et al., 1977; Sleath, 1982); and theoretical models of the velocity and suspended-sediment fields have been developed (e.g., Tunstall and Inman, 1975; Nielsen, 1984). Although rippled beds are virtually ubiquitous in nature, and vortex shedding has been invoked to explain the cause of measured correlation fluxes that were a significant fraction of the total flux (e.g., Vincent and Green, 1990), there have been few descriptions of the process in the field from either a Lagrangian or Eulerian point of view.

Our objective is to describe field observations of the cycle of vortex-entrainment and ejection into the flow of sand by waves from a rippled bed. Vincent and Green (1990) used part of the same data set in an analysis of the time-averaged suspension profile and of the distribution of the two components of the total sediment flux close to the bed. In that analysis, we hypothesized that vortex-shedding was the underlying cause of the measured correlation fluxes. Our objective here is to describe in more detail, using wave-by-wave and statistical analyses, the temporal variability of the entrainment process and the vertical and temporal structure of the individual clouds of suspended sediment.

<u>Data</u>

The data are from an experiment conducted over a rippled sand bed in 1.7±0.2 m water depth seaward of the surfzone on the North Norfolk coast of England. The modal grain size of the bed sediment was 0.023 cm, which is a fine to medium noncohesive sand, and bed ripples were a few centimeters high by several tens of centimeters long. The ripple dimensions were not measured, however Vincent and Green (1990) estimated, using Grant and Madsen's (1982) model, that the ripple height was ~3 cm.

Continuous profiles of suspended-sediment concentration from 48 cm above the bed down to the bed level were obtained every 0.58 s using an acoustic backscatter sensor (ABS). The ABS emitted 2.8-MHz acoustic pulses and the backscattered acoustic pressure was sampled at 13 μ s intervals, which provided a vertical resolution of 1 cm. A calibration equation was applied to convert the measurements of backscattered pressure into estimates of suspended-sediment concentration. The particular calibration equation used was based on the grainsize distribution of the bed sediment, thus we make an implicit assumption that the suspended-sand population is the same as the bed-sediment population.

Simultaneous measurements of horizontal current velocity at 20 cm above the bed were obtained with an electromagnetic current meter. In this analysis, we use one record, termed run 2046, of 12-min duration, which consists of 1250 measurements of velocity and concentration at 1-cm intervals above the bed. The wave period during the deployment was ~6 s, and the significant on-offshore velocity was 60 cm/s, which was superimposed on an alongshore current of 15 cm/s.

The ABS was positioned 2 m seaward of the current meter, thus a correction had to be made to align the velocity and concentration time series. This is required in order to compute cross-correlation functions and ultimately to estimate correlation sediment fluxes. In order to align the two series, the phase spectrum, $\phi_{UwCz}(\omega)$, was examined, where U_w is on-offshore zero-mean velocity (which is taken to be the wave-orbital velocity) and C_z is concentration at an elevation z above the bed. If the estimated phase function approximates a straight line through the origin (i.e., 0 or 360 degrees):

 $\phi_{II \omega C_{\tau}}(\omega) = -d\omega$

then this indicates a delay or constant offset of $d.\Delta t$ seconds between U_w and C_z where -d is the slope of the phase function and Δt is the sampling interval (Chatfield, 1980). Shown in Figure 1a are the phase spectra for U_w crossed with concentration at 5 levels.

Each phase spectrum falls off at a rate that indicates a constant offset of $2\Delta t$ between the velocity and concentration series. The velocity series was thus shifted forward by $2\Delta t$ relative to the concentration series, and the phase spectra were recomputed. The rolloff is thus removed from the phase function (Figure 1b). This shift is applied throughout this analysis; note that an identical offset was indicated by consideration of the average phase speed of the waves and the measured separation of the sensors.

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Figure 1. (a) Phase spectra $\phi_{U_wC_z}(\omega)$. All spectra appear to roll off at a constant rate indicated by the dashed line, the slope of which is consistent with a constant offset of 2At between the velocity and concentration series. (Note that only the statistically significant estimates of phase are shown. $o = U_w vs. C_2$, $\Box = U_w vs. C_3$, $\Delta = U_w vs. C_5$, $+ = U_w vs. C_{10}$, $x = U_w vs. C_{20}$.) (b) The same spectra as in (a) but with the velocity series shifted forward in time by 2At.

Description of Time Series

Shown in Figure 2 are time series of U measured at z = 20 cm and concentration measured at 5 elevations above the bed. The elevations are shown normalized by the ripple height of 3 cm, i.e. $z^{*} = z/\eta$, where η is the wave-ripple height.

Sand was intermittently entrained from the bed and ejected upwards into the water column. Although the intermittency appeared to be related to the waves, not every wave initiated a suspension event. The intermittency leads to unacceptably large amounts of leakage when computing energy spectra, thus we avoid frequency-domain analyses of the data and instead use wave-by-wave and other statistical methods.



Figure 2. Time series of wave-orbital velocity (U_w) and concentration at 5 elevations above the bed. Elevation is nondimensionalized by the ripple height (3 cm).

Wave-By-Wave Analyses

The shapes of individual sediment clouds are shown in Figure 3 for two elevations above the bed. For these plots, zero-downcrossings of on-offshore velocity were used to identify 123 individual waves in the 12-min record, but waves were selected for analysis only if the concentration at z = 1 cm, which was the lowest usable bin, exceeded a certain threshold value. In this way, 26 well-developed sediment pulses were chosen for display. Also shown are the corresponding cycles of zero-mean velocity (U_w) measured at z = 20 cm. Note that a lot of the "noise" in the plots is due to the fact that wave periods varied from wave to wave and so the effective resolution also varies from wave to wave.



WAVE PHASE, DEGREES

Figure 3. Wave cycles of zero-mean velocity and concentration at $z^* = 0.7$ and $z^* = 3.3$. The horizontal axes are wave phase in degrees, with zero phase defined as the instant of velocity zero-downcrossing. Each cycle of velocity has been nondimensionalized by the maximum onshore velocity that occurred in the cycle. Each cycle of concentration has been nondimensionalized by the maximum concentration that occurred in the cycle. The wave-orbital velocities were skewed onshore: note that in any one cycle the onshore stroke was usually the stronger of the two, and the offshore velocities typically persist for longer than half of the wave period (Figure 3). At $z^{\star} = 0.7$, there are often two peaks in the concentration cycle. The first, which occurs while the orbital velocity is directed onshore, is stronger, and corresponds to the initiation of a sediment pulse at the bed. The second, which occurs while the orbital velocity is directed offshore, is weaker and corresponds to the advection back through the beam of the sediment pulse generated on the previous shoreward stroke. This second pulse is weaker since sand has settled back to the bed since the pulse was generated half a wave period previously.

At $z^{\dagger} = 3.3$ the picture is quite different: the water column is clear whilst the orbital velocity is directed onshore, and the sediment cloud only arrives at this elevation after the orbital velocity has reversed. Thus, ejection from the bed of the sediment cloud that is initiated during the onshore wave stroke only occurs after the flow has reversed.

Cross-Correlation Analyses

Cross-correlation functions were computed to investigate the phasing of the peak concentration in the sediment cloud with the peak orbital velocity.

At $z^{+} = 0.7$, the peak suspension is exactly coincident with the peak onshore orbital velocity (Figure 4). In a fully rough turbulent flow, the peak bed shear stress leads the orbital velocity by approximately 10° , however the sampling rate was insufficient to resolve any such lead of the concentration over the velocity. We conclude then that, within the resolution of the data, the peak concentration very close to the bed was exactly in phase with the peak bed shear stress and that there was therefore a causal relationship between the two.

For $z^* > 1.0$, the results of the cross-correlation analyses show that the peak concentration occurs during the offshore wave stroke and furthermore that the cloud arrives slightly earlier at higher elevations. This result is consistent with the horizontal advection of the cloud from a distant source - if the clouds were propagating upwards from the bed directly underneath the sensor then they would arrive earlier at lower elevations (e.g., Hanes and Huntley, 1986). Thus, the clouds arriving on the offshore wave stroke above the ripple tops have been released from distant (shoreward) parts of the bed.

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Figure 4. Cross-correlation function, U versus C at $z^* = 0.7$. The peak concentration occurs at the same time as the peak onshore orbital velocity.

The field observations so far described are consistent with a vortex model of sediment entrainment in which sediment clouds are initiated at the bed and ejected into the flow on alternating wave strokes (e.g., Sleath, 1982). The roll-up of the cloud during the onshore wave stroke was restricted to $z < \eta$ (i.e. $z^{+} <$ 1): since flow visualization experiments have demonstrated that the vortex fills the ripple trough (e.g., Honji et al., 1980), it seems feasible that the ABS was looking down into a ripple trough.

Magnitude of Events

The fact that peak bed shear stress is synchronous with peak concentration in the vortex points the way to predicting the size of the sediment clouds that are ejected from the bed when the orbital velocity reverses. For this, we draw from well-known time-averaged theory in which the suspended-sediment reference concentration close to the bed is hypothesized to be a function of the skin friction that is in excess of critical stress:

$$C = \gamma_{o} C_{b} S^{n} / X , S = (|\tau'| - \tau_{cr}) / \tau_{cr}$$
(1)

(Smith, 1977). In equation (1), C is the time-averaged reference concentration which is specified at the top of the bedload layer; S is the time-averaged skin friction, τ' , in excess of the critical stress, τ_{cr} ; C is the bed sediment concentration; γ_{cr} is an empirical constant, $O(10^{-4})$. Smith and McLean (1977) used X = $(1 + \gamma_{cr})$ and proposed n = 1, although others have used different values for n (e.g., Shi et al., 1985). We hypothesize that, by analogy, the peak concentration in the vortex is related to the peak excess skin friction.

To evaluate the model, we replace C in equation (1) with C the peak concentration in the vortex (i.e. from the region $\hat{z}^{\dagger} < 1$, and S by $\hat{S} = (|\tau'_{cy}| - \tau'_{cr})/\tau_{cr}$, where τ'_{cw} is the total maximum skin friction, which is the sum of the maximum wave-induced and time-averaged components. au_{i}^{\prime} was calculated by a combined-flow boundary layer model using the maximum observed half-cycle velocity and observed zero-downcrossing wave period. The roughness length was taken as proportional to the grainsize of the bed sediment, thus these estimates are meant to represent the skin friction. The critical stress applicable to fully rough turbulent flow was found from a classical Shields curve, which has been shown to apply to rippled beds in combined wave and current flow provided the grain texture is used to scale the hydraulic roughness (Larsen et al., 1981). Finally, since the observed values for \hat{S} are $O(10^{\circ})$ or less, X in equation (1) is set to 1.

Shown as the crosses in Figure 5 are the observed values of C plotted against S for the shoreward-directed cycle of 103 waves in which critical stress was exceeded. The line in the figure is the fit of the model to the data, which yielded an r^2 of 0.73, which is significant at the 95% level. The best-fit exponent, n, was 1.33 \pm 0.23 at the 95% level, which is similar to Smith's proposed value of 1 for the time-averaged case. The corresponding value for γ was 0.91x10⁻⁴ with a lower bound of 0.59x10⁻⁴ and an upper bound of 1.40x10⁻⁴ at the 95% confidence level.

Also shown in Figure 5 are 13 data points from offshore-directed wave strokes in which vortices were initiated at the bed. These points cluster around the model fit derived from the onshore data. This result is



Figure 5. Fit of equation (1) to data. The crosses represent peak concentration in the vortex generated on the onshore wave stroke and the filled circles represent peak concentration generated on the offshore wave stroke.

counter to Bijker et al.'s (1976) and Hanes and Huntley's (1986) suggestions that the local acceleration governs the size of the sediment cloud generated at the bed and ejected into the flow. If this were the case, the data from the two half-cycles, which exhibit markedly different accelerations on account of the wave skewness, would not cluster in this way.

Sleath (1982) suggested a mechanism that accounts for a link between bed shear stress and concentration in the vortex: he showed that the vortex is fed by a thin bedload layer that cascades over the ripple crest and into the developing vortex; equation (1) can be used to predict the size of the sediment cloud that is ejected into the flow when the orbital velocity reverses.

Discussion

Vincent and Green (1990) showed that the correlation flux for run 2046 contributed a significant fraction of the total flux, and was sufficient close to the bed to cause reversals in the direction of the total flux (Figure 6). The size of the correlation term is dependent on the phasing of the sediment cloud relative to the wave-orbital velocity: the magnitude of the correlation varies with elevation above the bed, becoming smaller at higher elevations as the sediment clouds disperse and lose their wave-scale structure. The sign of the correlation term also changes: below an elevation approximately equal to the ripple height, the peak suspension is in phase with the onshore motion in the potential-flow region of the wave, and above this elevation the onshore motion and suspension are ~180° out of phase.



SUSPENDED-SEDIMENT FLUX IN MG/S/CM-WIDTH

Figure 6. Vertical profiles of cross-shore suspended-sediment flux, run 2046. UC is the mean cross-shore flux, where U is the mean velocity and C is the mean concentration. UC is the correlation flux, where U and C are the wave (i.e. zero-mean) fluctuations in velocity and concentration respectively (see Vincent and Green, 1990, for details of how the flux profiles were estimated).

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Since the bed shear stress controls the size of the sediment cloud ejected from the bed when the flow reverses, the vertically-integrated correlation flux above the level of the ripple crests will be opposed to the direction of wave skewness (assuming the mean current is negligible). Furthermore, since the vertically integrated flux below the ripple crest depends upon the characteristics of the vortices and the vortices are distributed periodically in space, then there exists the possibility of a periodic divergence in sediment flux close to the bed which could govern the bedform migration and modify the net flux close to the bed.

<u>Conclusions</u>

The periodic vortex entrainment and release of sand from a rippled bed causes a flux of sediment that may be comparable in magnitude and opposite in sign to the mean suspended-sediment flux. Transport predictions based on the time-averaged distributions of velocity and sediment concentration will neglect this component of the sediment flux and may therefore be in serious error.

Contribution ES1768, Department of Earth Sciences, University of Cambridge.

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