Sediment suspension and turbulence in the swash zone of dissipative beaches

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Abstract

This paper investigates mechanisms for stirring and transport of suspended sediment by infragravity-scale swash using high-frequency field measurements of horizontal and vertical flow velocities, water depths and sediment concentration profiles. The field data suggest that vertical velocity fluctuations generated by coherent eddies can be important to the process of sediment suspension and can contribute to asymmetrically distributed sediment transport rates between the uprush and backwash phases of the swash cycle. This result indicates that the traditional and often used proxy for bed shear stress based solely on measurements of the horizontal component of flow, \( \tau_b \propto \rho u^2 \) where \( \rho \) is the water density and \( f \) is a friction factor may be inadequate when used in energetics-type sediment transport models applied to the swash, which is indeed the case. We demonstrate that a bed shear stress formulation which is more consistent with the physics leads to improved predictive capability for energetics-type transport models. This formulation is based on the correlation between the horizontal and (turbulent) vertical components of the flow (i.e. \( \tau_b \propto \rho u'w' \)). Despite the improvement, it is evident that considerable amounts of calibration data are still required before each application of this model type. Moreover, our data shows that the issue of calibration coefficients is more problematic than generally appreciated. The calibration coefficients for energetics-type models on a given beach not only differ between uprush and backwash, but also vary with position within the swash zone, particularly on the uprush phase.

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1. Introduction

The swash zone is defined as that part of the beach profile where the shoreline sweeps back and forth at frequencies related to incident short waves (sea and swell) and infragravity waves. In the swash zone, the profile is therefore subaerially exposed for part of each swash cycle. The swash zone is an important and integral part of the beach/shoreface environment, because swash processes largely determine whether the subaerial beach erodes or accretes and large amounts of sediment are suspended and transported in continuous exchange between the nearshore and the foreshore.

Basically two types of swash regime exist: On steep beaches swash is predominantly driven by short waves (sea and swell) whereas on gently sloping dissipative beaches it is predominantly driven by infragravity waves. Foreshore accretion and an increase in beach face slope against the force of gravity require an asymmetry in the sediment transport field caused by
either asymmetric uprush/backwash velocities or an asymmetry in the amounts of sand suspended on the uprush and the backwash. Accordingly, field observations show that suspended sediment concentrations are often larger on the uprush than in the backwash (Puleo et al., 2000; Butt et al., 2002; Masselink et al., 2005; Hughes et al., in press).

A considerable effort has been invested in attempting to model sediment transport in the swash zone. Bagnold-type energetics models for bedload (Bagnold, 1963), which predict a dependence of sediment transport on velocity skewness, have been particularly popular (e.g. Hughes et al., 1997a; Masselink and Hughes, 1998; Puleo et al., 2000). These models relate sediment transport, $q$, to velocity cubed through $q = ku^3$, where $k$ is a calibration coefficient incorporating friction that is expected to be constant for a given beach. In general, mixed results have been obtained, because field tests suggest that the uprush is more ‘efficient’ than the backwash, i.e. $k_{up} > k_{back}$ (e.g. Masselink and Hughes, 1998; Puleo et al., 2000). Such results are consistent with the laboratory findings of Cox et al. (2000) and Conley and Griffin (2004) who observed larger mean bed shear stresses and friction factors in the uprush compared with the backwash, suggesting that Bagnold-type models omit some important physics. Several explanations have been offered for larger bed shear stresses and sediment transport in the uprush. These include: (a) acceleration effects induced by landward directed pressure gradients (Butt and Russell, 1999; Nielsen, 2002; Puleo et al., 2003); (b) turbulence impinging on the bed caused by bores overrunning the preceding swash lens or advected from bore collapse (Puleo et al., 2000; Petti and Longo, 2001; Butt et al., 2004); (c) sediment advection from the point of bore collapse (Hughes et al., 1997b, in press; Pritchard and Hogg, 2005); and/or (d) groundwater in/exfiltration modifying the fluid boundary layer (Turner and Masselink, 1998; Butt et al., 2001). Added to the omission of these potentially important processes in existing bedload models is the uncertainty of their relevance in situations when large amounts of sand are transported in suspension.

As listed above, turbulence is one of the potentially important contributors to sediment suspension in the nearshore/swash zones. Surf zone breakers generate large vortices that can penetrate to the bed and generate large vertical velocity oscillations (Nadaoka et al., 1988; Smyth et al., 2002) and Reynolds-stresses (Yu et al., 1993; Cox and Kobayashi, 2000). This bore-related turbulence can be injected into the swash zone at bore collapse and can be advected along by the swash front with the turbulent face in contact with the bed. Additional sources of turbulence generated within the swash zone include hydraulic jumps at the end of long infragravity backwash events; incoming bores overrunning the preceding swash lens, and friction at the bed. In most previous field studies of swash zone sediment transport, only horizontal flow components have been obtained, exceptions being the data sets of Osborne and Rooker (1999) and Butt et al. (2004). As a result, the effects of bore-generated turbulence and eddies, including vertical velocity fluctuations, have not been directly quantified in the context of sediment resuspension and transport in the field.

In this paper, observations are reported on near-bed horizontal and vertical velocity structure and the ensuing sediment resuspension and transport on two (dissipative) beaches dominated by uprush/backwash at infragravity time scales. The aims of the paper are: (i) to examine the spatial structure of sediment transport in dissipative swash and to identify zones of erosion and accretion, (ii) to examine the nature of turbulence in the swash and to quantify its importance to sediment resuspension and transport and (iii) to test a new model for sediment concentration in which bed shear stresses, calculated as the covariance of the horizontal and vertical velocity components, are used to parameterize sediment stirring. While still not satisfactory, this model shows significantly improved skill compared with the widely used Bagnold-type model.

2. Theoretical background

Several existing sediment transport models for the surf zone (e.g. Bagnold, 1963; Bailard, 1981) predict sediment concentration/load ($c$) as a function of a sediment stirring term which is parameterized through the horizontal velocity variance

$$c = k_1 U^2 \quad (1)$$

where $U$ is the vector product of cross-shore and longshore velocity ($U = (u^2 + v^2)^{1/2}$) and $k_1$ is a constant of proportionality incorporating friction. If the longshore velocity component is zero, sediment transport ($q$) is then the product of the stirring term and a transport term which is the fluid velocity, i.e.

$$q = k_3 u^3. \quad (2)$$

This formulation is based on the concept that bed shear stress ($\tau_b$) which is responsible for sediment stirring, can be expressed through

$$\tau_b = \rho c_f u^2 \quad (3)$$

where $\rho$ is fluid density and $c_f$ is a coefficient of friction.
In the present work we are primarily concerned with suspended load. Furthermore, instead of using a bed shear stress proxy such as Eq. (3) we consider an explicit formulation for bed shear stress. Using the Reynolds equation for combined wave–current flow in a turbulent oscillatory boundary layer and neglecting the steady current contribution, the turbulent momentum flux in the cross-shore dimension is defined as

$$\frac{dv}{dz} = \frac{\tau}{\rho} = -(\bar{u} \bar{w}) - (u'w') + v$$  \hspace{1cm} (4)

(e.g. Nielsen, 1992, p.31), where $v_1$ is eddy viscosity, $\tau$ is horizontal (bed) shear stress, $u,w$ are the cross-shore and vertical velocity components, $v$ is kinematic (laminar) viscosity and tildes and primes denote orbital and turbulent velocity contributions, respectively. Assuming laminar viscosity is negligible, the bed shear stress is made up of two terms: one due to wave motions and one due to turbulence (Reynolds stresses) and based on Eq. (4), a model for sediment concentrations in the swash zone can be expressed as

$$c = k_2|uvw|$$ \hspace{1cm} (5)

In principle, $|uvw|$ includes orbital as well as turbulent velocity components. Multiplying Eq. (5) by the cross-shore velocity results in a crude model for sediment transport in the swash zone which is analogous to the Bagnold-type formulation (Eq. (2)) consisting of a stirring term and a transport term,

$$q = k_2|uvw|u$$ \hspace{1cm} (6)

To specifically examine turbulence characteristics and the significance of turbulence to sediment resuspension, the turbulent signal must be extracted from the measured time series of $u$ and $w$ to isolate the turbulent kinetic energy,

$$\text{TKE} = \frac{1}{2} \rho (u'^2 + v'^2 + w'^2)$$ \hspace{1cm} (7)

However, the separation of orbital and turbulent velocity terms using measurements from a single instrument in irregular and strongly nonlinear wave conditions with potentially slight misalignments in sensor orientation is not a trivial task (Trowbridge, 1998). Various methods have been proposed often employing a high-pass filter with a specified frequency cut-off to remove orbital motions. This cut-off has been based on either coherence between the velocity and surface elevation signals (Thornton, 1979), excess measured velocity variance relative to predicted orbital velocity variance (Rodriguez et al., 1999), or spectral slope breaks (Smyth and Hay, 2003; Scott et al., 2005). At the outset, we take the pragmatic view that close to the bed, contributions to the vertical velocity from wave-orbital motions ($\tilde{w}$) are expected to become small, especially in the very shallow water depths of the swash zone where vertical wave orbital velocities tend to zero. This is consistent with the data presented in Section 4.3. As the assumption is equivalent to making the assumption that the flow is hydrostatic, it is also consistent with several numerical models which make that latter assumption and successfully describe the essential features of the flow in the inner surf and swash zones with a good degree of accuracy (e.g. Hibberd and Peregrine, 1979; Kobayashi et al., 1989; Watson and Peregrine, 1992 and several others). Furthermore, if we assume that $w'$ is some fixed proportion of $u'$ (and $v'$) on the time scale of turbulent vortices (Svendsen, 1987), the turbulent kinetic energy (and the sediment concentration in the water column due to Reynolds stresses) should scale as the vertical velocity variance,

$$\text{TKE} \propto w'^2 \propto w^2$$ \hspace{1cm} (8)

### 3. Field sites and instrumentation

#### 3.1. Field experiments

Two field experiments were conducted at Skallingen on the Danish North Sea coast during August–September 2002 and at Egmond aan Zee on the Central Dutch coast during October–November 2002. Skallingen is a dissipative beach with a gently sloping, low-relief double-barred inner nearshore (surf) zone. The mean annual significant wave height is 1.0m and the mean tidal range is 1.5m, which increases to 1.8m during spring tides and the intertidal zone typically exhibits one or more intertidal bars. At the time of the experiment, the foreshore sediment was moderately sorted with a mean grain size of 240 $\mu$m and the beach face slope was $\beta=0.032$ (Fig. 1). Wave energy levels during the experiment were quite low; significant offshore wave heights mostly remained below 0.5–0.6m, but increased briefly up to 2.1m, and the incident wave periods ranged from 4 to 8s (Aagaard et al., 2005). Measurements from a pressure sensor installed at $x=120$m (Fig. 1) showed that the significant wave height at the base of the swash zone did not exceed 0.6m and the Iribarren number at the foreshore was between 0.3 and 0.4, which indicates spilling breakers and dissipative conditions in the inner surf/swash zone.
At Egmond the longshore bars are larger and higher than at Skallingen, with deep intervening troughs and the surf zone morphology is modally intermediate. The average annual significant wave height is approximately 1.2m and the mean semi-diurnal tidal range is 1.65m, which increases to 2.1m at springs. The tidal curve is asymmetric with a 4-h flood period and an 8-h ebb-period. The mean sediment grain size in the intertidal zone was slightly coarser than at Skallingen, 260 \( \mu \text{m} \), and the sand was very well-sorted. The beach face slope was \( \beta = 0.036 \). Wave energy conditions during the period of data collection were much more energetic than at Skallingen. Significant offshore wave heights were up to 3.75m with wave periods of 6–9s and maximum inshore wave heights at \( x = 126\text{m} \) (Fig. 1) were 1.25m (Aagaard et al., in press) with a foreshore Iribarren-number of approximately 0.3, again indicating dissipative conditions in the inner surf/swash zone.

3.2. Instrumentation

Cross-shore instrument arrays were deployed across the intertidal and inner nearshore zones at both sites. However, only results from the intertidal stations (shown in Fig. 1) are reported here. Instruments were mounted on a stainless steel H-frame (Fig. 2) and consisted of a 3D sideways-looking Sontek 10MHz Acoustic Doppler Velocimeter (ADV) mounted with the horizontal axes parallel to the bed at a nominal elevation of 0.025–0.03m and a vertical array of five D&A Instruments UFOBS-7 fibreoptical backscatter sensors. The UFOBS-7 uses an infrared laser beam with a pass band of 810–850nm to detect sediment concentration within a very small sampling volume (nominally \( \approx 10\text{mm}^3 \)) that is centred 10–15mm away from the sensor head. Due to the small size of the sensor head (8mm O.D.) and the remote sampling volume, the instrument is capable of recording sediment concentrations very close to the bed. In this experiment sampling volumes were nominally centred at \( z = 0.01, 0.02, 0.03, 0.04 \) and 0.05m. Similar to the ordinary D&A Instruments OBS-sensors, the UFOBS is not sensitive to visible light. Infrared radiation from the sun can saturate OBS-sensors when exposed to direct sunlight, or sunlight reflected from the water surface or foam. This is easily identified in the records, which become...
extremely spiky and concentration profiles become inverted as the uppermost sensor is most strongly affected. In the present experiment, such problems were avoided by pointing the sensors downwards and/or away from the sun. No cases of measurement errors due to ambient infrared/daylight exposure could be identified for the UFOBS-7 sensors.

ADVs can accurately measure mean currents and orbital velocities at elevations equal to, or larger, than the vertical extent of the sampling volume (Voulgaris and Trowbridge, 1998) which is 9 mm for the instrument in question. With the deployment elevations used here, the ADV was capable of recording horizontal and vertical flows in water depths of \( \approx 0.03 - 0.04 \) and \( 0.07 \) m, respectively.

Ancillary instruments consisted of a pressure sensor (Druck Model PTX1830) which was deployed at, or slightly below, bed level in order to measure water depths, a Marsh-Mc Birney OEM512 electromagnetic current meter (EM) at a nominal elevation of 0.20 m above the bed, and an array of three D&A Instruments OBS-1P optical backscatter sensors at nominal elevations of 0.05, 0.10 and 0.20 m above the bed. Instrument elevations were measured prior to and after each instrument run and elevations were adjusted if required and when possible. Sensors were hard-wired to shore where the signals were recorded on laptop computers.

### 3.3. Data collection, processing and analysis

(UF)OBS-sensors were post-calibrated in a large recirculation tank using sand samples from the deployment locations. Known quantities of sand were cumulatively added to the tank, water samples were drawn off and sensor output recorded to construct a calibration curve for the particular sand grain reflectance characteristics at the two sites. Field offsets were determined from distinct breaks in the cumulative frequency distribution of sediment concentration. These offsets were close to the 2nd and 5th percentile frequency output voltages for the UFOBS- and OBS-sensors, respectively, and to maintain consistency these percentiles were applied to all records.

During periods of data collection, instruments were sampled almost continuously at 10 Hz. The duration of individual records was 45 min and records were separated by 2–5 min breaks to back up data. Instrument outputs were screened and checked for data quality and records containing instrument noise and/or erroneous data were rejected. The saturation level of the UFOBS-sensors was 100–120 kg m\(^{-3}\) for the grain sizes at Egmond and Skallingen while OBS-sensors saturated at 105–140 kg m\(^{-3}\). Records containing >2% of clipped values due to sensor saturation were discarded as the sensor in question was probably within, or at, the bed. It is possible that extreme suspension events also resulted in saturation, thus these events are excluded from our data.

Velocity time series from an ADV tend to become noisy in highly turbulent or aerated flows. At such times, signal correlation values recorded by the ADV were used to quality control the data. For the sampling frequency used here the threshold signal correlation indicating potentially inaccurate data for a particular acoustic beam was <55% (Raubenheimer, 2002). A low-pass filtered record of the original velocity time series was obtained using a filter cut-off frequency of 2.5 Hz. Observations in the original velocity time series that had a signal correlation below the threshold were replaced with the corresponding observation from the filtered time series. Furthermore, a conservatively selected signal-to-noise ratio of <20 (SonTek, 2001) was employed to identify occasions when the sensor became emergent; at such times, the flow velocity is undefined (Hughes and Baldock, 2004).

Pressure sensors were calibrated in a stilling well at the field site and pressure records were detrended prior to computing wave heights. Mean water depths and water levels were determined through repeated surveys of instrument positions and measurements of sensor elevations relative to the bed. Instantaneous sediment flux at a point was calculated as the product of local sediment concentration \( c \) and fluid velocity \( u \). Net cross-shore suspended sediment fluxes at the respective sensor elevations were then calculated as

\[
q_z = \langle uc \rangle
\]  

where \( \langle \cdot \rangle \) denotes the time-average. The fluxes determined from the UFOBS-sensors each represented a 0.01 m vertical bin while the two upper OBS-sensors each represented 0.10 m bins. Fluxes were subsequently summed across the instrument array and linearly extrapolated to the water surface to yield approximate run-averaged net suspended sediment transport rates. The sediment transport was computed using velocities from the ADV with sediment concentrations determined from the UFOBS-array, and velocities from the EM with concentrations from the OBS-array. Coupling velocity measurements at one elevation with measurements of suspended sediment concentration at another can potentially result in erroneous estimates, particularly within the bottom boundary layer (e.g. Ogston and Stemberg, 1995). We sought to minimise this potential problem by matching the ADV-elevation to the middle
sensor in the UFOBS-array. In addition, the shallow, rapid flows in the swash zone can be expected to be very well mixed.

4. Results

4.1. Observed sediment transport rates in the swash zone

A total of 25 swash zone records (each of 45 min duration) containing reliable velocity and sediment concentration data were obtained. Net sediment transport rates depended strongly upon relative position within the swash zone. To distinguish such different relative positions, the upper, mid and lower swash zones were separated on the basis of the fraction of time that the ADV was immersed during a run (i.e. a signal-to-noise ratio \( > 20 \) on the cross-shore acoustic beam). Upper swash zone conditions were assigned when the ADV was immersed for \( 1–40\% \) of an instrument run, mid swash conditions for \( 40–75\% \) and lower swash conditions for \( 75–95\% \) immersion.

The net suspended sediment transport exhibited similar overall characteristics at the two beaches (Fig. 3). Transport was relatively small and onshore directed when sensors were located in the uppermost swash zone at low tidal stages. With an increased fraction of instrument immersion, i.e. for increasing mean water levels, onshore transport rates also increased whereas the transport reversed and became large and offshore directed when instruments were located in the lower swash zone. Net transports in the inner surf zone were also seaward directed (Aagaard et al., 2005, in press). There was no obvious difference in net transport rates recorded on rising and falling tides (Fig. 3).

A second-order polynomial was fitted through all data points to define a sediment transport shape function for the swash zones of these two dissipative beaches. The empirical function is

\[ y = -0.00043x^2 + 0.032x - 0.08 \]

where \( y \) is net sediment transport rate and \( x \) is percentage of immersion. Maximum onshore transport rates occurred around the transition between the mid and upper swash zones (as defined here), and maximum offshore transport rates occurred at the base of the swash (Fig. 3).

4.2. Fluid velocity and sediment concentration in the swash zone

In order to examine the relationships between fluid velocity and sediment concentration, six example time series were selected to represent respectively upper swash (runs EG07; 24% instrument immersion and EG44; 38% immersion), mid swash (runs EG59; 53% immersion and EG45; 66% immersion) and lower swash (runs EG46; 90% immersion and EG68; 94% immersion) conditions. The time series were selected on the basis of four criteria: (a) swash flows had to be sufficiently deep to yield reliable estimates of \( w \); i.e. time series of vertical velocities should be continuous through individual swash events, although this criterion had to be relaxed for upper swash records; (b) the ADV should be within 4cm from the level of the bed; (c) the lowermost fibreoptical sensor should be within 2cm from the bed, and (d) signal saturation in fibreoptical sensors should be \( < 2\% \) of the record length for at least 4 of the sensors. Fig. 4 illustrates an example of recorded cumulative frequency distributions of sediment concentration at different levels above the bed. For this particular record, the lowermost UFOBS-sensor saturated for 1.1% of the record, indicated by the break-off at the top of the curve, the uppermost sensor (which had a significantly higher gain than the rest of the sensors) saturated for 2.3% of the time whereas the middle sensor did not saturate.

All examples selected on the basis of these criteria were from the Egmond-experiment because swash flows

Fig. 3. Net suspended sediment transport rates (\( q_s \)) at Egmond (E) and Skallingen (S), as a function of the fraction of time that the ADV-sensor was immersed. The data have been separated into rising and falling tidal stages. The solid line is a second-order polynomial fit through all data points.
were deeper and vertical velocity estimates were more continuous and reliable during swash events. Representative 2 min time series of cross-shore (\(u\)) and vertical (\(w\)) velocities, and sediment concentrations at \(z=0.01\) m and 0.03 m are illustrated in Figs. 5, 6 and 7. In all examples, the velocity sensor was located \(\approx 0.025–0.035\) m above the bed and positive velocities are directed onshore and upwards in the figures.

Uprush velocities were large in the upper swash zone, up to \(\approx 1.5\) m s\(^{-1}\) (Fig. 5). Velocity distributions were characteristically asymmetric, which may, at least in part, be due to the fact that the sensor became emerged in the final stages of the backwash. Sediment concentration events were also asymmetrically distributed, however, with conspicuously larger concentrations during the uprush (up to 100 kg m\(^{-3}\)) compared with the backwash (20–40 kg m\(^{-3}\)). Vertical velocities observed during the backwash in this record from the upper swash zone did not meet the data quality criteria and have been omitted.

In the mid swash (Fig. 6), the cross-shore velocity field was more symmetric with respect to peak velocities although the uprush flow was of shorter duration. In general, sediment concentrations were still asymmetrically distributed with larger concentrations during the uprush, which resulted in a net onshore directed suspended sediment transport. The time series of vertical velocities reveals significant amounts of high-frequency turbulence throughout swash events. More prolonged, predominantly downward directed vertical velocity fluctuations with speeds up to \(\approx 1\) m s\(^{-1}\) occur at the leading edge of the swash and at the end of prolonged backwash cycles. Downward directed velocities on the uprush are inconsistent with wave motions and the time scale of the vertical fluctuations (1.5–3.5 s) is distinctly shorter than the cross-shore orbital wave velocity time scale. Hence, it is unlikely that these vertical fluctuations were directly associated with local wave orbital motions.

The lower swash zone (Fig. 7) was characterized by extended backwash events during which the cross-shore velocity sometimes exceeded 1.5 m s\(^{-1}\). Such events

Fig. 4. Cumulative frequency distributions of sediment concentrations measured by the UFOBS sensors at \(z=0.01, 0.03\) and 0.05 m in the mid swash zone; run EG59.
have been observed earlier on dissipative beaches dominated by swash at infragravity time scales (e.g. Beach and Sternberg, 1991). In the lower swash zone, the near-bed uprush velocities were notably smaller than backwash velocities. Very large sediment concentrations were generated towards the end of the high-velocity backwash events, which resulted in a net offshore directed sediment transport in the lower swash zone. Also in the lower swash, the vertical velocity trace reveals large amounts of high-frequency turbulence and very large, downward directed velocities in the final stages of the backwash. Hydraulic jumps were often observed visually in the vicinity of the instrument station during this instrument run.

In order to investigate persistent patterns between individual swash events, velocity, sediment concentration and surface elevation time series were ensemble-averaged. Following earlier workers (e.g. Puleo et al.,
Single swash events were extracted from the time series and re-sampled on a normalized time scale, \( t/T \), where \( T \) is the duration of the individual swash event. Twenty averaging bins at intervals of \( t/T = 0.05 \) were used. Table 1 lists the number of individual swash events extracted and the mean swash duration for the six example time series as well as offshore and inshore wave conditions. Ensemble-averaged time series of cross-shore velocity (\( u \)), vertical velocity variance (\( w^2 \), which is proportional to the turbulent kinetic energy (Eq. (8)) and the (turbulent) bed shear stress), surface elevation (\( z \)), Froude number (\( Fr \)) and sediment concentration (\( c \)) were obtained. \( w^2 \) has been recast in terms of \( |w|w \) in order to illustrate the dominant direction of the vertical velocity component.

The ensemble-averaged time series from the upper swash zone are illustrated in Fig. 8. Wave conditions were moderate with offshore significant wave heights and peak spectral wave periods of 1.8 m and 5.6 s, respectively (Table 1). The plots illustrate that mean sediment concentrations were very large during the uprush and small during the backwash, in correspondence with the relatively large uprush velocities compared to the backwash. The flow was subcritical throughout the swash cycle. The vertical velocity variance has not been included during the backwash due to the shallow water depths which prevented reliable \( w \)-estimates. During the uprush there was no relationship between sediment concentration and the recorded vertical velocity variance, which had no clear structure.

The example representing the mid swash zone (Fig. 9) was obtained under high-energy conditions with offshore wave heights and periods of \( H_{s,0} = 3.5 \text{ m} \) and \( T_{p,0} = 7.1 \text{ s} \) (Table 1). Sediment concentrations were asymmetrically distributed with larger concentrations during the uprush, even though the cross-shore velocity field was skewed offshore. Visually, it appears that there is a good correspondence between the concentration records and both the \( u \) and \( |w|w \)-traces. However, the increase in \( c \) at \( t/T = 0.875 \) is more in accordance with the turbulent signal (\( |w|w \)), which increases rapidly at the same relative phase and in association with a transition to supercritical flow. In the mid swash, the \( |w|w \)-trace is consistently exhibiting large downward directed velocities at the leading edge of the uprush and at the termination of backwash, as also observed in the instantaneous velocity time series (Fig. 6). There is a clear hysteresis effect evident: during the uprush \( c \) is slow to decrease during the waning of the large vertical velocities and during the backwash \( c \) is slow to increase during the waxing of the large vertical velocities. The surface elevation trace from this record (\( z \)) is irregular due to the superposition of several short wave bores on the infragravity-scale swash events.

The example selected for lower swash zone conditions (Fig. 10) was obtained under decaying storm wave conditions with \( H_{s,0} = 2.4 \text{ m} \) and \( T_{p,0} = 7.1 \text{ s} \) (Table 1). The cross-shore velocity and surface elevation traces are again quite irregular due to several short wave cycles occurring during an individual infragravity swash event. Sediment concentrations are comparatively large throughout the swash cycle with maxima at the leading edge of the uprush and, in particular, at the termination of the backwash. Throughout the cycle, changes in concentration agree qualitatively well with fluctuations in \( |w|w \) although concentrations seem to be disproportionately large at the leading swash edge and hysteresis is again evident. The Froude number exceeds 1 in the late stages of the backwash, but sediment concentrations clearly increase prior to the onset of supercritical flow conditions and they follow more closely the \( |w|w \)-trace.

### 4.3. Vertical velocity structure

Visual comparisons between velocity and sediment concentration traces in Figs. 8, 9 and 10 suggest that vertical velocity variance may be important to sediment suspension in the mid and lower swash zones. The question is whether these velocity fluctuations are indeed due to turbulence, i.e. whether \( w^2 \) is a suitable surrogate for the turbulent kinetic energy (Eq. (8)). At the leading edge of the uprush, large, downward directed velocities occurred. Their magnitude (0.5–1 m s\(^{-1}\)) and time scale (several seconds, but shorter than the cross-shore velocity time scale; Figs. 6 and 7) suggest that they are not due to ordinary wall turbulence generated by bed friction. On the other hand, the vertical velocity is mainly negative in sign (i.e. directed towards the bed), which suggests that the velocity

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**Table 1:** Summary statistics of selected swash time series and offshore and inshore wave conditions

<table>
<thead>
<tr>
<th>Run</th>
<th>No. of swash events</th>
<th>Mean duration (s)</th>
<th>( H_{s,0} ) (m)</th>
<th>( T_{p,0} ) (s)</th>
<th>( H_{s,i} ) (m)</th>
<th>( T_{p,i} ) (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EG07</td>
<td>43</td>
<td>12.5</td>
<td>1.8</td>
<td>5.6</td>
<td>0.29</td>
<td>38</td>
</tr>
<tr>
<td>EG44</td>
<td>18</td>
<td>22.6</td>
<td>2.9</td>
<td>7.7</td>
<td>0.41</td>
<td>50</td>
</tr>
<tr>
<td>EG45</td>
<td>31</td>
<td>27.5</td>
<td>3.5</td>
<td>7.1</td>
<td>0.42</td>
<td>50</td>
</tr>
<tr>
<td>EG59</td>
<td>29</td>
<td>22.8</td>
<td>3.3</td>
<td>7.1</td>
<td>0.44</td>
<td>58</td>
</tr>
<tr>
<td>EG46</td>
<td>20</td>
<td>41.0</td>
<td>3.3</td>
<td>7.1</td>
<td>0.50</td>
<td>55</td>
</tr>
<tr>
<td>EG68</td>
<td>40</td>
<td>44.9</td>
<td>2.4</td>
<td>7.1</td>
<td>0.39</td>
<td>58</td>
</tr>
</tbody>
</table>

Offshore wave parameters are indicated by subscript 0 and wave parameters measured at the base of the swash zone are indicated by subscript i.
fluctuations are also not due to wave orbital motion. At the termination of the backwash, even more prolonged (5–8s), high velocity (−0.5 to 1m s \(^{-1}\)) fluctuations were observed at times when the flow became supercritical (e.g. Figs. 7 and 10).

The individual swash events were concatenated to form continuous time series of cross-shore and vertical velocity. Spectra from these time series (Fig. 11) show that vertical velocity variance decreased approximately as \(f^{-5/3}\) between 0.1 and \(\approx 2\)Hz, consistent with an inertial subrange which further indicates this frequency band is in fact dominated by turbulent motions (Kundu, 1990; Smyth and Hay, 2003). Beyond 2Hz, vertical velocity variance appears to approach a background noise floor; this break-off frequency is somewhat lower than the 4.5Hz observed by Raubenheimer et al. (2004). In contrast, the slope of the cross-shore velocity spectrum at frequencies 0.1–2Hz is intermediate between \(f^{-3}\) and \(f^{-5/3}\), which is consistent with a mixture of turbulence and saturated wave motion which is expected to decay as \(f^{-3}\) (e.g. Thornton, 1979).

As the frequency band characterized by an \(f^{-5/3}\) spectral roll-off (i.e. 0.1–2Hz) was probably dominated by turbulent motions, turbulence constituted 74–95% of the total vertical velocity variance (after subtracting the noise floor) in the four example time series from the mid and lower swash zones. Thus, a major fraction of the vertical velocity fluctuations had a short-wave time scale, but were not directly due to wave orbital motions. It seems reasonable, therefore, to include the prolonged
(several seconds duration) high-speed events in estimates of swash zone turbulence.

4.4. Sediment resuspension mechanisms

To more quantitatively examine the relationships between sediment concentration and resuspension mechanisms, Eqs. (1) and (5) were tested through calculation of the total sediment load \( C \) in the water column by summing the loads in each measurement bin:

\[
C = \sum_{z=0.05}^{h} c(z) \Delta z
\]  

where \( h \) is water depth and \( \Delta z \) is 0.01 m for the UFOBS-sensors and 0.10 m for the OBS-sensors with the constraint that \( c=0 \) at the water surface. Instantaneous loads were correlated with instantaneous values of \( U^2 \), \( U^3 \) and \( |Uw| \) where \( U \) is computed as the vector product of cross-shore and longshore velocity and \( |Uw| \) includes orbital motions, contained in \( U \) and turbulent motions which make up the majority of \( w \). This approach follows earlier attempts at estimating relationships between energetics-type models and sediment transport, but in this case we consider the sediment concentration and avoid the spurious correlations introduced by including cross-shore velocity in measurements of \( q \) (Puleo et al., 2005). Because \( w \) consists mainly of turbulent motions,

Fig. 9. Ensemble-averaged records of cross-shore velocity \( (u) \), surface elevation \( (z) \), vertical velocity variance \( (w|w|) \), Froude number \( (Fr) \) and sediment concentration \( (c) \) at \( z=0.01 \) m (solid), \( z=0.03 \) m (small dashes) and \( z=0.05 \) m (large dashes); mid swash zone conditions, run EG45.
$|Uw'|$ might be a more appropriate expression here than $|Uw|$ but the latter is maintained because in principle $w$ contains contributions from all frequency bands.

An example of these relationships is illustrated in Fig. 12. While the correlations are statistically significant, they are certainly not convincing with $r^2$ ranging from 0.081 ($U^2$), 0.075 ($U^3$) to 0.098 ($|Uw|$). The reasons for the poor correlations are probably due to the different time scales of velocity structure and sediment resuspension events, partly demonstrated by the hysteresis observed in the ensemble-averaged time series (Figs. 9 and 10), but much more evident and more variable in the individual time series. Sediment concentrations remain high even after velocity has decreased (Figs. 6 and 7), probably due to settling lag (Baldock et al., 2004) and the persistence of high-frequency, low-magnitude turbulence maintaining sand in suspension (see also Nielsen, 1993; Leeder et al., 2005). Additionally, on the stirring phase, it takes a finite time for the sediment to diffuse upward to the elevation of the optical sensors.

To reduce the problem of different time scales, the correlations were also performed with ensemble-averaged values of the different variables, i.e. averages of $U^3$, $|Uw|$ and $C$ were computed for the 20 phase bins (see also Masselink et al., 2005). The reason for selecting $U^3$ instead of $U^2$ is that Bagnold-type models (as applied to the surf zone) predict a dependency of suspended sediment transport on the fourth moment of horizontal velocity (e.g. Bailard, 1981) and hence sediment

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**Fig. 10.** Ensemble-averaged records of cross-shore velocity ($u$), surface elevation ($z$), vertical velocity variance ($|w|w|$), Froude number ($Fr$) and sediment concentration ($c$) at $z=0.01$ m (solid), $z=0.03$ m (small dashes) and $z=0.05$ m (large dashes); lower swash zone conditions, run EG68.
concentration should depend on the third moment. Tests (not shown) also demonstrated that in general, correlations between $U^3$ and $C$ were marginally superior to relationships involving the squared velocity moment.

Ensemble-averaged suspended sediment loads were least-squares fitted to ensemble-averaged $|U_w|$ and $U^3$ for the 20 phase bins in the six example runs. The data was separated into the uprush and backwash phases and $r^2$-values for the least-squares regression models are listed in Table 2. Using ensemble-averaged values vastly improves the functional relationships. With respect to the mid and lower swash zones, $|U_w|$ is a significantly better predictor than $U^3$ except for backwash in the lower swash zone where the latter performs slightly better. In the upper swash zone, the (uprush) predictions using $|U_w|$ are poor as vertical velocities were not well resolved in these shallow water depths whereas the cubed horizontal velocity moment provided a reasonable fit.

The results of the regressions on $|U_w|$ and $U^3$ are illustrated graphically in Figs. 13 and 14. The figures amply demonstrate that $|U_w|$ is a significantly better predictor than $U^3$, particularly in the uprush. However, calibration coefficients are different not only in the uprush and the backwash (as previously reported by e.g. Masselink and Hughes, 1998; Puleo et al., 2000) but also at different relative positions within the swash zone, particularly during the uprush (Table 3). For the mid and lower swash zone data, $k_2$ (Eq. (5)) ranges from 8.2 to 23.6 for the uprush. For the backwash, the spread in $k_2$ is smaller; 1.1–2.2.

All data from the mid and lower swash zones were combined in Fig. 15 to assess the merits of a transport model based on estimated bed shear stress, including turbulent Reynolds-stresses, as the stirring term. The data suggest that a sediment concentration model based on $|U_w|$ (mean skill = 0.85 and 0.61 on the uprush and backwash, respectively; Table 2) is clearly superior to a model using $U^3$ as the stirring mechanism. However, we are still faced with the problem of different calibration coefficients on the uprush ($\bar{k}_2 = 9.5$) and the backwash ($\bar{k}_2 = 1.3$) and it is indeed questionable whether the relationships obtained are generally applicable. It would appear that non-local factors contribute significantly to sediment concentrations observed within the swash zone.

5. Discussion

Measurements of suspended sediment transport at elevations of 1–20 cm from the bed at two dissipative beaches, dominated by swash at infragravity time scales, have indicated that this transport is almost always landward directed in the mid and upper swash zones, and offshore directed in the lower swash zone (Fig. 3). This is consistent with sediment transport measurements reported by Butt et al. (2002) and by Cox et al. (2000) who observed onshore directed mean bed shear stresses in the upper swash and offshore directed stresses in the lower swash. The swash zone of dissipative beaches thus seems to be segregated with respect to sediment transport and consequently such beaches should display a tendency for accretion at the landward edge of the swash if accommodation space is available. With a rising tide, the morphological change resulting from a sediment transport ‘shape function’ such as the one depicted in Fig. 3 is likely to be a progressive onshore translation of a wedge of sediment located at the upper...
edge of the swash. With a falling tide, an offshore progressive erosion/accretion couplet should occur. Such morphological changes would agree with the observations of Strahler (1966).

The reason for the onshore-directed sediment transport asymmetry was the increased sediment concentrations during the uprush relative to the backwash and, for the upper swash zone, an onshore asymmetric cross-shore velocity field (Figs. 5 and 8). Because of the larger sediment concentrations and larger water depths, sediment loads during the uprush were therefore larger than during the backwash. In the mid swash, the concentration asymmetry led to an onshore net sediment transport in spite of the larger offshore directed velocities (Figs. 6 and 9). In the lower swash zone, however, the net suspended sediment transport was seaward directed at both beaches, due to large sediment concentrations and turbulence generation during the backwash, associated with the transition to supercritical flow conditions as well as an offshore directed velocity asymmetry (Figs. 7 and 10).

Examination of the time series of velocity and sediment concentration revealed that large concentrations were associated with prolonged large-magnitude vertical velocity fluctuations (Figs. 6–10) which, despite their incident wave time scale, were primarily
of turbulent origin (Fig. 11). The exact source of these large-magnitude turbulent events is impossible to ascertain from a single measurement location. In the backwash, visual observations suggested that the events were associated with the formation of hydraulic jumps. With respect to the uprush, it is likely that the vertical velocity fluctuations represent coherent, low-frequency turbulent flow structures associated with large eddies or breaker vortices (Svendsen, 1987). Such vortices may be generated by bores and subsequently advected onshore by the swash front while decaying, or they may be due to ‘downbursting’ consisting of a vertical downrush of water from the free surface that diverges at the bed as observed in the laboratory by Kubo and Sunamura (2001) and numerically by Rogers and Dalrymple (2005).

The data in Fig. 9 from the mid swash zone show that cross-shore velocity as well as water depth continued to increase behind the leading edge of the swash. Conceptually, this should result in large horizontal shears within the water column and the generation of large eddies. Accordingly, large downward directed velocities are observed on the uprush (Figs. 6 and 9). On the other hand, the corresponding record from the lower swash (Fig. 10) exhibits decreasing uprush velocities behind the leading swash edge and accordingly the vertical velocity fluctuations are much smaller.

In order to quantitatively examine the relationships between sediment concentration/sediment load in the

| Run       | $|U_w|$ | $U^3$ | $|U_w|$ | $U^3$ |
|-----------|--------|-------|--------|-------|
| Upper     |        |       |        |       |
| EG07      | 0.87   | –     | –      | –     |
| EG44      | 0.81   | –     | –      | –     |
| Mid       |        |       |        |       |
| EG45      | 0.81   | 0.54  | 0.91   | 0.74  |
| EG59      | 0.99   | 0.65  | 0.97   | 0.80  |
| Lower     |        |       |        |       |
| EG46      | 0.96   | 0.62  | 0.81   | 0.90  |
| EG68      | 0.96   | 0.87  | 0.93   | 0.95  |
| Mid+lower | all    | 0.85  | 0.31   | 0.61  | 0.42  |

Optimum predictors for individual runs are underlined.

![Graph](image_url)

Fig. 13. Ensemble-averaged sediment load in the water column plotted against the absolute value of the bed shear stress estimator ($|U_w|$) for the mid (EG45—crosses; EG59—dots) and lower (EG46—crosses; EG68—dots) swash zones. The data have been separated into uprush and backwash phases. Note the different slope of the lines-of-best-fit on the uprush and backwash.
water column and potential sediment resuspension mechanisms, as well as the causes of the excess sediment concentrations in the uprush relative to the backwash, computed sediment loads were regressed against horizontal velocity skewness \( (U^3) \) and bed shear stress, parameterized through \( |Uw| \). Errors in the ensemble-averaged estimates may occur if sensor gain changes temporally, e.g. due to systematically varying sediment grain sizes through swash events, or if sensors temporally saturate and signals are clipped. This latter problem did occasionally affect measurements during the terminal stages of the backwash in the lower swash zone when sediment concentrations sometimes exceeded 100–120 kg m\(^{-3}\). As mentioned earlier, however, the selected records contained less than 2% clipped values in at least four of the UFOBS-sensors.

For the ensemble-averaged records, the third-order horizontal velocity moment performed reasonably well in the upper swash zone (Fig. 14) where we were unable to quantify the bed shear stress because of the
incomplete $w$-time series. In the mid and lower swash zones, however, the $|U_w|$-estimates ($r^2 = 0.81–0.99$; Table 2) were clearly a much better predictor of mean sediment concentrations and sediment loads than horizontal velocity moments. As the majority of the vertical velocity variance consisted of turbulent motions (Fig. 11) and because of the phase coupling between $u$ and $w'$, turbulence is a critical ingredient in this bed shear stress estimator.

Hence, our observations are broadly consistent with Kobayashi and Tega (2002) who found that sediment was primarily suspended by wave breaking in the lower/mid swash zone while suspension was primarily caused by bed friction in the upper swash. At least for the lower and mid swash zones, the results from that study and the present favour the more rigorous relationship between shear stresses and sediment concentrations (and suspended sediment transport) expressed through Eq. (4) compared to the traditional energetics approach (e.g. Eq. (3)).

Merging all data from the mid and lower swash zones degraded model skill, but estimates were still statistically significant (Table 2). Nevertheless, even when including turbulent motions in the predictor, sediment concentrations/loads and by extension suspended sediment transport rates were disproportionately large during the uprush compared to the backwash (Fig. 15 and Table 3). In this respect, the proposed model is not an improvement on previous models using only horizontal velocity moments since the uprush is still somehow more ‘efficient’ than the backwash in some undetermined way (i.e. $k_{up} > k_{back}$; Masselink and Hughes, 1998; Puleo et al., 2000; Butt et al., 2002).

Potentially, the uprush data reflect an influence from non-local sediment resuspension processes with the sediment subsequently being advected to the instrument position, and/or being affected by settling lag. Several authors (e.g. Hughes et al., 1997a; Puleo and Holland, 2003; Butt et al., 2004; Pritchard and Hogg, 2005; Hughes et al., in press) have discussed the potential role of sediment advection originating from bore collapse and Longo et al. (2002) observed that turbulence from the inner surf zone, potentially carrying pre-suspended sediment, may be advected into the swash. In the present experiments, hydraulic jumps often formed at the end of long infragravity backwash events, producing large amounts of turbulence and suspending large amounts of sand (Fig. 7), which could then have become advected landward by the subsequent decelerating uprush flow while slowly settling out of the water column. Such ‘moving carpets’, or clouds of sand were frequently observed visually immediately behind the swash front. Given the sediment grain sizes in the swash zone at Egmond, this sediment should theoretically settle out of the water column within a few seconds. However, because of the large sediment concentrations hindered settling may have occurred,

![upwash vs backwash](image)

**Fig. 15.** Ensemble-averaged sediment load in the water column plotted against the bed shear stress estimator ($|U_w|$) for the four selected examples from the mid and lower swash zones.
reducing settling to velocities on the order of 50% of clear water values (cf. Baldock et al., 2004). Additionally, suspended sand particles can be trapped in vortices virtually indefinitely if turbulent production is sustained (Nielsen, 1993) which generally appears to have been the case (Figs. 6 and 7). Consequently, sediment concentration (and sediment load) on the uprush may depend on locally generated turbulence plus an additional contribution from advection and/or delayed settling.

In contrast to the decelerating uprush, the accelerating backwash has no free-surface turbulence production and contains only little pre-suspended sediment at its initiation. Consequently, sediment advection from a point source is unlikely and hence the bed shear stress may appear less ‘efficient’; in other words, the line of best fit between forcing (bed shear stress) and response (sediment concentration/load) should be less steep, as is the case (Fig. 15).

6. Conclusions

Swash zone sediment transport has been investigated on two fine-grained, gently sloping, dissipative beaches. Shoreline oscillations on the two beaches predominantly occurred at infragravity periods (of the order of 50 s), the related flows had durations in the mid swash of the order of 20–40 s and they carried maximum suspended sediment concentrations of the order of 100 kg m\(^{-3}\). Short wave interaction with the infragravity swash motion (involving overrunning bores and stationary hydraulic jumps) was persistent on the lower beach face. These experimental conditions therefore differ considerably from most of the recent studies that have tested energetics-type transport models in the swash zone (with the exception of Masselink et al., 2005). Previous studies were mainly undertaken on medium-coarse grained, steep beaches where short waves primarily drive the swash.

Sediment loads, computed from measured suspended sediment concentrations at several elevations above the bed were correlated with sediment stirring parameters, including bed shear stress (expressed as the covariance of horizontal and vertical velocity, \(|U_w|\)) and bed shear stress proxies formed by higher-order moments of the horizontal flow velocity. In the mid and lower swash zones where vertical velocities could be estimated, the former performed significantly better than the shear stress proxies which is a clear indication that the vertical (turbulent) velocity component is important to sediment resuspension and should be included in models for sediment concentrations in the swash zone.

While we were unable to demonstrate the exact sources of turbulent fluctuations, the turbulence at the leading edge of the uprush appears to be generated by coherent eddies, which may have (a) originated with bores in the inner surf zone, (b) been due to ‘down-bursting’ at the leading edge of swash bores and/or (c) originated from the large shear expected in the shallow water depths at the swash front. In the backwash, turbulence was seemingly mainly associated with hydraulic jumps.

Even though the functional relationships between bed shear stress and sediment load were reasonable, the constants relating the two parameters were different between the uprush and the backwash, and also differed with relative position in the swash zone. Our data suggest, therefore, that there is limited value in pursuing energetics-type transport models much further. New sediment transport models are required that explicitly account for both locally suspended and advected sediment, as well as the role of coherent turbulence as a stirring mechanism.

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