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Sediment resuspension on beaches: response to breaking waves

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Abstract

Field data of time-averaged suspended sediment concentration (ssc) are presented from three different UK beaches and a variety of wave conditions. The data are collated into a single analysis to examine the mechanisms associated with sand resuspension in the surf zone. Emphasis is placed upon the relative contribution of bottom and surface generated turbulence in controlling suspended sediment concentration distribution. Inside the surf zone, vortices induced by breaking waves and bores are the main mechanism for sediment resuspension; this process dominates over bottom boundary layer processes. Time-averaged reference concentration, defined as the ssc at 3.5 cm above the bed, does not correlate with bottom-induced shear stress or predicted ripple steepness. Both reference concentration and vertical distribution of sediment are controlled by the breaking wave (plunging, spilling) characteristics. Within the inner surf zone, hydraulic jumps (associated with strong offshore flows) are responsible for sediment resuspension. Vertical distribution of sediment is parameterised using a convective type time-averaged suspended sediment concentration profile. Reference concentration is highly correlated with wave breaking type, as defined by the local breaker parameter. The mixing parameter depends also on the wave breaking type and may be expressed as a fraction of the local water depth. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Surf-zone; Suspended sediment; Bottom turbulence; Breaking waves; Sediment transport

1. Introduction

Natural beaches change constantly in response to natural conditions (i.e. wind and wave forcing) or human interference (e.g. breakwater, groin construction). Modelling and prediction of such bathymetric changes requires an accurate knowledge of sediment transport processes in the nearshore and in particular within the surf zone. These processes are controlled by the physical mechanisms of sediment mobilisation, as it is influenced by the prevailing hydrodynamic and bottom boundary layer conditions, by the coupling of sediment and fluid motion (sediment fluxes) and their variability in space and time.

Sand transport occurs adjacent to and within the bed and in suspension. Bedload is the transport of sand, by saltation or rolling on the stationary bed and in a thin layer with thickness of the order of a few grain diameters (Francis, 1973). Sand is placed and maintained into suspension by turbulence and advected within the overlying water as suspended load. There is an ill-defined boundary between bedload and suspended load. The use of sediment traps, for the measurement of sediment transport in the surf zone, has led earlier investigators to conclude that bedload is more significant than suspended load. In particular, early estimations of the contribution of suspended load varied between 7 and 26% of the total

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load (Komar, 1978; Inman et al., 1980). However, the development of instrumentation capable of measuring suspended sediment concentrations within a few centimetres from the sea bed (Downing et al., 1981) has shown its contribution to vary between 80 and 100% (Kraus and Dean, 1987; Sternberg et al., 1989; Russel, 1990). Nielsen (1992), using Horikawa et al.'s (1982) laboratory measurements of total sediment concentration (bedload and suspended load) and Bagnold's (1956) definition of bedload, showed that the total sediment concentration equals the suspended sediment concentration at elevations (z) greater than 5 mm above the undisturbed bed. Below 5 mm, movement in suspension is still the dominant mode of transport i.e. some 20 times greater than bedload, at $z = 1$ mm. On the basis of the above, near-bed measurements of suspended load are seen to be adequate for accurately representing sediment availability for transport by the prevailing currents.

Currents transport sediment in suspension and divergence and/or convergence of the transport patterns result in bathymetric changes. Beach profile changes occur at short time-scales (i.e. hours to days) and are dependent upon the incoming wave characteristics (i.e. height, period, asymmetry) and cross-shore wave-induced steady flows (i.e. undertow). Cross-shore sand transport in some cases is simply a local re-arrangement of sediment rather than a net loss. On the other hand, shoreline changes are associated with sediment transport in an alongshore direction. This involves an extensive alongshore displacement of sand material (littoral drift). Its loss (assuming no replacement) from the system results in permanent shoreline changes. Littoral drift is mainly the result of the coupling of the semi-steady longshore current and the time-averaged suspended sediment concentration and its accurate prediction require information on both longshore currents and sediment load.

In modelling longshore transport, emphasis has been placed upon the hydrodynamic component and in particular upon wave propagation and wave-induced steady current variation throughout the surf-zone zone (see Komar, 1976; Deigaard et al., 1986; Watanabe, 1993). Longshore current generation is attributed mainly to the longshore component of the radiation stress (Longuet-Higgins, 1970). Additional mechanisms include: wind-driven longshore currents (Whitford and Thornton, 1993); a tidally driven component (Voulgaris et al., 1998); and alongshore variation in wave height distribution (Komar, 1976). Despite the advances in the study of hydrodynamics, sediment transport is represented by either empirical formulae or those requiring an empirical coefficient without accounting for the different turbulence characteristics that occur in the different parts of the surf zone. Kana (1979) was the first to question the validity of longshore sediment transport models that relate the longshore component of wave energy flux to longshore sediment transport because they do not account for the variation of suspended load with breaker type.

The present investigation aims at contributing toward the improvement of the suspended sediment component of such models; it examines the processes controlling sediment resuspension in the surf zone under breaking waves. The specific objectives are to: (i) examine the relative importance of bottom generated turbulence (benthic boundary layer) and turbulence induced by the breaking waves in sediment resuspension; and (ii) derive a parameterisation of reference concentration and vertical distribution of suspended sediment concentration as a function of breaking wave characteristics. In order to achieve the objectives stated above, field experimental data, from three different UK beaches with different morphological and sedimentary characteristics are combined in a single analysis.

In the following section, background information is given on sediment resuspension processes under wave conditions. Then the three different experimental sites are described together with the data collection and analysis procedures. Finally the experimental results are described and discussed in sub-sections dealing with the reference concentration and the bottom boundary layer conditions, breaking characteristics and the vertical distribution of sediment in suspension.

2. Background

The modelling of suspended sediment concentration requires the precise definition of two fundamental parameters. The first is the definition of a sediment "pick-up" (entrainment) function and the second is to define the mechanisms that distribute the sediment through the water column. For purely steady flows the pick-up function has been defined assuming equilibrium between the bottom shear stress and the near bed sediment concentration which is usually defined as the concentration (C_a) at a reference level z_a (Smith, 1977). Once the sediment is entrained from the seabed its vertical distribution in the water column can be attributed to either diffusive, convective or a combination of both processes (Nielsen, 1992). The convective or diffusive character of sediment resuspension is defined by the magnitude of the mixing length (l). When the mixing length is small in relation to the mean water depth then the suspension is diffusive, whilst when l is large in relation to the water depth, convection is the dominant process.

Nielsen (1984) showed experimentally that the process of sediment suspension is convective rather than diffusive and is dominated by such features as travelling vortices, jets and turbulent bursts. In the case of non-breaking waves, the following relationship was given for the time-averaged vertical distribution of suspended sediment concentration (Nielsen, 1992):

$$C(z) = C_a \exp\left(-\frac{z}{l}\right) \quad (1)$$

where C_a is the reference concentration near the sea bed and l is the vertical scale of decay (mixing length) set equal to the ripple height for a rippled bed or $20D$ (where D is the mean sediment particle diameter) for the case of sheet flow. Bottom generated turbulent diffusion and travelling vortices are probably the most dominant mechanisms responsible for sediment suspension under shoaling (non-breaking) wave conditions.

Observations of the time-averaged vertical distribution of suspended sediment concentration in a nearshore zone have been compared with model predictions (Lee and Hanes, 1996). Wikramayake's (1993) pure diffusion model was found to be in good agreement with the field observations under high wave energy conditions when the bed was flat. Nielsen's (1992) pure convection model was found to be in good agreement with the observations under low wave energy conditions when vortex ripples were present. The lee vortex released from the ripple at the free stream reversal is one of the plausible mechanisms that support the convection model. Analysis of the collected data (Lee and Hanes, 1996) showed that turbulent diffusion is probably the most dominant mechanism responsible for sediment suspension under high (non-breaking) wave conditions. Although the diffusion model was found to be sensitive to the sediment fall velocity, the convection model was relatively insensitive.

Inside the surf zone, wave breaking accounts for most of the sediment suspension through the introduction of eddies associated with breaking waves (Miller, 1976; Zhang and Sunamura, 1990), with increasing levels of turbulence coming towards the boundary layer from the water surface. Bosman (1982), cited by Stive and Battjes, 1984) has presented a double layer model for breaking waves. According to this model the whole depth is divided into two layers (upper and lower) with two different but constant diffusion coefficients. Deigaard et al. (1986) presented a similar model by which the diffusion coefficient in each layer was given as a function of total turbulent energy, mean water depth and height above the seabed. However, all of the above models treat sediment resuspension as a diffusive rather than a convective process.

Experimental results on sediment resuspension have shown that the magnitude of sediment in suspension and subsequently of the reference concentration is a function of wave type (plunging, spilling breakers, Kana, 1977, 1978, 1979; Inman et al., 1980; Beach and Sternberg, 1996) and position in the surf zone (Brenninkmeyer, 1974, 1976; Kana 1977, 1978; Shib ayama and Horikawa, 1982; Beach and Sternberg, 1996). Nielsen (1984) has discussed the effect of wave breaking on the concentration profile in terms of turbulence associated with each breaker type. Suspended sediment concentration inside the surf zone was recognised as being determined by entrainment and mixing due to wave breaking. In the case where waves plunge on shallow bars or steep beaches strong jets can be formed. These penetrate through to the bed, introducing turbulence external to the boundary layer. Through this procedure, large amounts of air are entrained into the boundary layer; when this rises it generates large upwards-localised velocities (i.e. hundreds of times greater than the sediment settling velocity). This procedure can explain the difference in the shape of the profiles of suspended sediment concentration for the different breaker types. Near the bed though, experimental results have shown that the sediment concentration profiles are very similar, thus suggesting that the near bed reference concentration is independent of the external turbulence (breaking waves) and is controlled mainly by the bottom boundary layer.

Analysis of individual waves in the surf zone (Yu et al., 1993) has shown that for unbroken waves sediment suspension can be high under the crest, but occur within several centimetres of the sea bed. For breaking waves, suspended sediment concentration increases dramatically and sediment is mixed to higher levels in the water column. Also, the role of eddy motions impinging directly on the seabed were observed to create sediment inversions and high sediment concentration patches. The suspended load under breaking waves was found to be 2.9 times larger than that under non-breaking waves, while for bores it was 4–1.3 times larger depending on the position in the surf zone. Beach and Sternberg (1996) used OBS measurements to examine the role of breaking waves in sediment resuspension. Their results are similar to those of Kana (1979) suggesting that plunging waves are responsible for high sediment concentrations.

The above ideas regarding the relation between sediment-stirring vortices and breaker types are supported by the results of tracer experiments. Tracer data from a variety of beaches have shown that the depth of activation tends to be greater at steep beaches than at gentle beaches (i.e. Kraus, 1985; Jackson and Nordstrom, 1993; Sherman et al., 1994; Ciavola et al., 1997a,b). This can be attributed to the different breaking types associated with different beach slopes. Ciavola et al. (1997b) synthesised published sand-mixing depths data with data they collected on beaches with steep upper shoreface and under plunging wave conditions. They presented a direct relationship by which sand-mixing depth is proportional to the breaker wave height ($Z_m = 0.27H_b$ where Z_m is the sand-mixing depth and H_b the wave height in the breaker zone). Hanes (1988) discussed the physical meaning of the mixing-depth and argued that is related to the intermittent character of sediment resuspension. He re-interpreted the results of tracer experiments and suggested that the mixing-depth does not indicate the thickness of a moving bedload layer, but is the result of processes of local erosion and accretion. Thus, based on Hanes (1988) results, the mixing-depth can be considered as a proxy for the intensity of intermittent resuspension events.

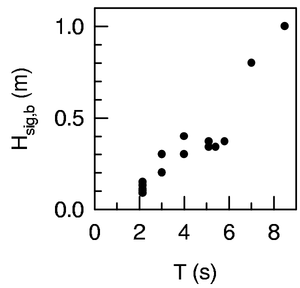

Fig. 1. Correlation between significant wave height at breakers and wave period for the data used by Ciavola et al. (1997b) to examine the relationship between tracer mixing-depth and wave conditions.

On the basis of the existing information, although the effect of breaking waves in the distribution of suspended load in the surf zone is evident, no clear parameterisation has been put forward to describe these processes. Ciavola et al.'s (1997b) parameterisation of mixing-depth (here used as a proxy of sediment resuspension intensity) with wave height reflects the intensity of the hydrodynamic forcing and does not account for the different breaker characteristics. Ciavola et al. (1997b) found that Z_m is also a function of wave period; however, a closer examination of the data used in their paper reveals that the suggested correlation is due to a strong correlation between wave height and period (Fig. 1).

An efficient model of time-averaged suspended sediment concentration should be related to the breaking characteristics of the waves. A commonly used parameter to define the onset of wave breaking is the ratio of wave height to water depth. Beach and Sternberg (1988) noticed that plunging waves have significant higher values than other types of breakers. Galvin (1972) defined another simple wave breaking parameter that is a function of breaking wave height (H_b), beach slope ($\tan\beta$) and wave period (f):

$$B_b = \frac{H_b}{gT^2 \tan\beta} \tag{2}$$

For $B_b > 0.068$ the breaking waves are spilling, for $0.003 < B_b < 0.068$ the waves are plunging, while surging breaking waves are present when $B_b < 0.003$.

Galvin's parameter has been used extensively in the study of the effect of the breaking wave-induced vortices in sediment resuspension (Zhang and Sunamura, 1990; Zhang, 1994). An oblique and four

Table 1
Morphological and sedimentary characteristics of experimental sites: mean beach slope; mean particle size (D); and settling velocity (W_s) of the mean particle size, derived experimentally using a settling tower

Location	Slope ($\tan\beta$)	D (mm)	W_s (mm/s)	Sediment type
Bournemouth beach	0.057	0.215	26.27	Well sorted, fine-medium sand
Caswell Bay	0.014	0.261	35.56	Very well sorted, fine-medium sand
Rhossili Bay	0.020	0.329	46.71	Very well sorted, medium sand

types (A–D) of rolling vortices were identified. The conditions for the occurrence of the observed types of vortices were defined as a function of Galvin's breaker parameter (Eq. (2)) and the breaking wave Reynolds number ($R_e = H_b L_b / \nu T$, where L_b and ν are the wavelength at the breaking position and the seawater kinematic viscosity, respectively).

On the basis of laboratory experiments, Zhang (1994) found that Types A and B vortices last longer than Types C and D. Oblique vortices whirl the bed material and lift the sediment up into suspension acting as a tornado. Type-A horizontal vortices act in a similar manner as the oblique vortices, but are capable of resuspending more sediment. Type-B horizontal vortices dig the bed material like a cultivator so that a larger amount of sand is lift up into suspension and is entrapped in the vortex. Types C and D do not reach the bottom and thus do not contribute to sediment resuspension. Considering the duration that the vortex is in contact with the bed, the strength of the vortex and thus its capability to resuspend sediment has been found to be highest in the B-type horizontal vortex and it decreases in the A-type horizontal vortex and oblique vortex in this order.

In summary, both bottom boundary layer and wave breaking processes appear to be important in sediment resuspension in the surf zone. However, the relative contribution of those two mechanisms remains unclear.

3. Experimental sites

Data were collected from three different beaches situated in southern England (Bournemouth, Fig. 2a) and the west coast of South Wales (Rhossili and Caswell bays (Fig. 2b and c, respectively). The beach slope and sedimentary characteristics (mean particle size and settling velocity) for each site are listed in Table 1.

3.1. Bournemouth beach

Bournemouth beach (Fig. 2a) is located in Poole Bay; it consists of a groaned sandy beach system, backed by Tertiary sequences (cliffs). The embossment is exposed to SW and SE winds, with large fetches. Offshore wave climate studies (Hydraulics Research, 1989) have shown that the most frequently occurring wave heights are less than 0.6 m, but in extreme cases, wave heights of up to 6 m can occur. Tides over the area are seem-diurnal in character. However, the amplitude of the seem-diurnal (M_2) component is weak and at spring tides a combination with a significant shallow water constituent (M_4) results in a "double high". Neap and spring tidal ranges are 0.6 and 1.6 m, respectively.

The area is one of strong erosion. Following the construction of a promenade and the stabilisation of the cliff, which was the original source of beach sediments, two beach replenishment schemes have been undertaken. The nourished beach material consists of well-sorted fine to medium grained sand (mean size 215 μm). The beach appears to behave as a dissipative beach for during storms; for lower wave heights or very long periods the beach behaves as an intermediate system (c.f., Wright and Short, 1984).

3.2. Caswell Bay

Caswell Bay is located on the southern coastline of the Gower Peninsula, in South Wales (Fig. 2b); it is a small "pocket type" beach, constrained by headlands. Because of the east–west orientation of the coastline, the bay is exposed to swell from the Atlantic (with a 7500 km fetch) and together with locally generated wind-waves in response to southeasterly winds. The tides are semi-diurnal in character, with spring and neap tidal ranges of around 8 and 4.3 m, respectively. The beach width at the measurement site was 40 m (at

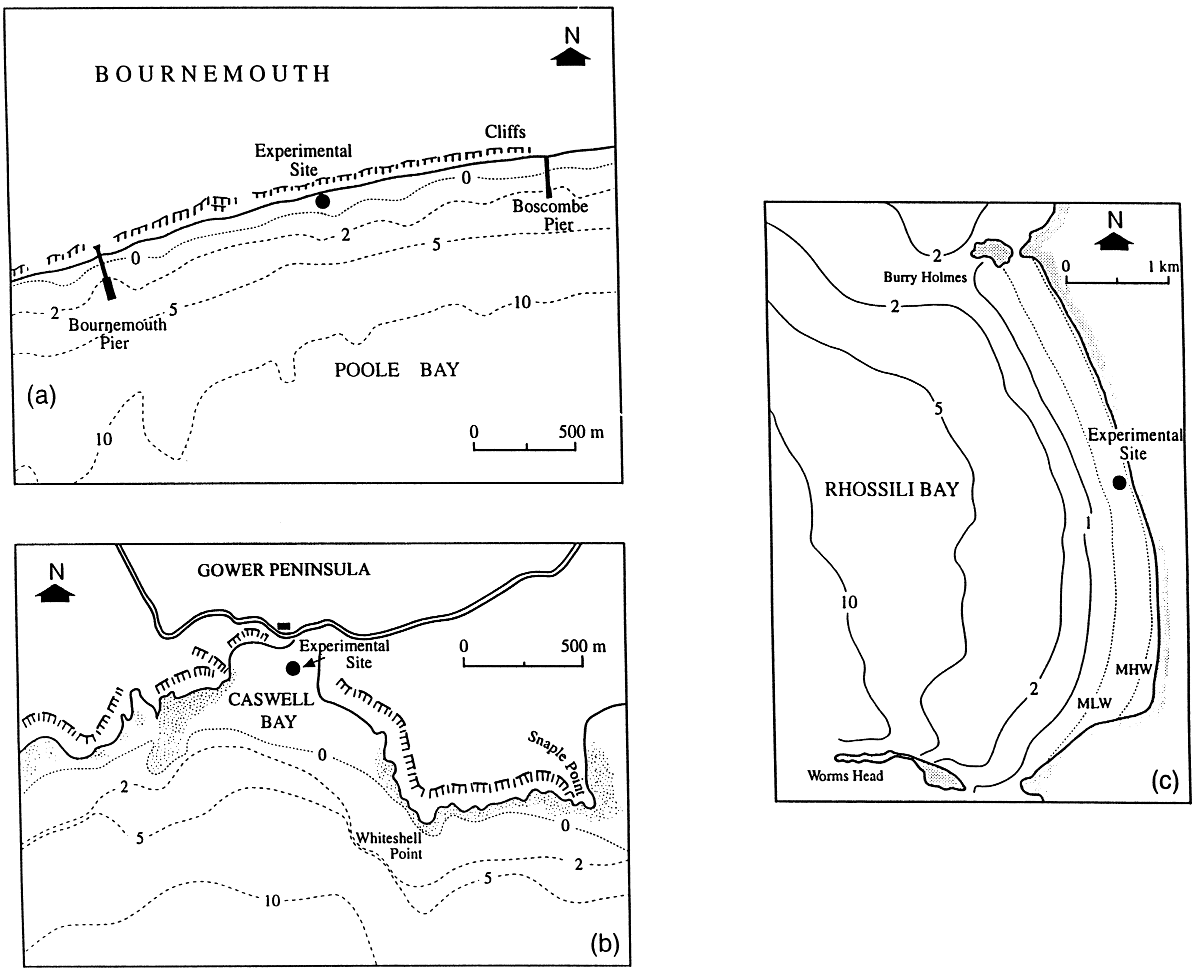

Fig. 2. Location of experimental sites for the present investigation: (a) Bournemouth beach, south coast of England; (b) Rhossili Bay, western Gower Peninsula, S. Wales; and (c) Caswell Bay, Gower Peninsula, S. Wales. Bathymetric contours are in metres representing water depths relative to LAT.

low tide); it is characterised by a low slope (0.014) and compacted well-sorted medium to fine-grained sand (261 μm). There is absence of any bedforms, and both plunging and spilling type breakers occur. The beach is a dissipative morphodynamic system, except at high spring tides when a strong reflection takes place from a seawall.

3.3. Rhosilli Bay

Rhossili Bay is situated at the western extremity of the Gower Peninsula, in South Wales (Fig. 2c); it is a stable, straight natural beach, 5 km in length. The beach faces towards the west and it is backed by sand dunes. There is an absence of artificial structures and major bathymetric irregularities; it is associated with a gentle offshore slope. The beach is exposed to prevailing southwesterly winds, locally wind-driven and longer period (Atlantic) swell waves. Tidal characteristics are semi-diurnal with the mean spring tidal range 8.5 m whilst the mean neap tidal range is 4.1 m. The beach is highly dissipative (mean slope 0.020) and consists of fine-medium (329 μm) and well-sorted sand (see Table 1).

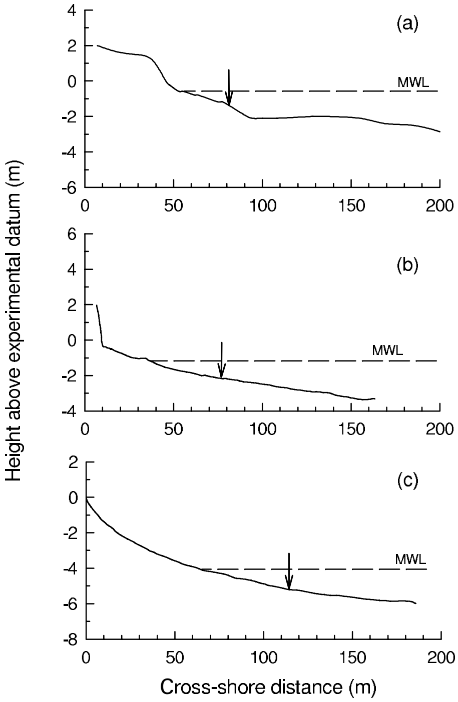

Fig. 3. Beach profiles showing the data collection positions (arrow) for: (a) Bournemouth beach; (b) Caswell Bay; and (c) Rhossili Bay. Mean water level (MWL) is shown.

Table 2
Dates and times of data collection. The duration of each data set was 17 min

Experimental site	Data set reference	Date	Time (GMT)
Bournemouth	1	25/05/90	07:20
Bournemouth	2	25/05/90	09:10
Bournemouth	3	25/05/90	11:40
Bournemouth	4	25/05/90	13:00
Caswell	5	11/12/89	03:15
Caswell	6	16/12/89	09:00
Caswell	7	16/12/89	09:30
Caswell	8	16/12/89	10:00
Rhossili	9	14/06/90	22:35
Rhossili	10	15/06/90	10:15
Rhossili	11	15/06/90	22:00
Rhossili	12	16/06/90	11:00

4. Data collection

Instantaneous horizontal velocities were measured using electromagnetic (EM) current meters. Wave-induced pressure was measured using a pressure transducer. Suspended sand concentrations were measured using an array of three optical backscatter sensors (OBS). The EMs and OBS array were cantilevered from a steel pipe, set vertically into the beach sand in the intertidal zone. In each case, the current meter was set about 20 cm above the seabed, and oriented in such a way that the steel pipe did not obstruct the longshore or cross-shore flow. Suspended sediment concentration (ssc) measurements were obtained at elevations of 3.5, 9.5 and 20.5 cm above the seabed, during the Caswell and Rhossili Bay experiments; at Bournemouth the heights were 3.5, 6.5 and 10.5 cm above the sea bed. The locations of the instrument package, for each experimental site, are shown in Fig. 3, while the data collection times are listed in Table 2.

Cables from the shoreline, some 70 m away, were used to provide power to the sensors. The output signal was recorded on a shore-based PC; this was equipped with a 12 bit analogue to digital conversion card. Data collection was carried out when all the instruments were inundated, mainly around high water. Data were collected continuously over periods of 17 min and at a sampling frequency of 2 Hz. The OBS output was converted to ssc (g/l) using a calibration curve derived experimentally in the laboratory. The calibration was undertaken with sediments obtained from the experimental sites (Table 1), using a recirculating calibration chamber (Voulgaris, 1992). The data presented here were collected between December 1989 and June 1990 (Table 2). The relative position of the measuring station in the surf zone was determined visually. Also, visual observations of the seabed, prior and after instrument inundation, were carried out to obtain information on bottom morphology. No ripples or scours were observed for the data presented here and the elevation of lower sensor above the bed remained constant within 1 cm. Black and Rosenberg (1991) reported that placing OBS sensor close to bed (<5 cm) flow-sensor interference results in scouring producing enhanced levels of sediment concentration. However, in their studies the maximum oscillatory velocity was much larger (1.5 m/s) than the velocities (0.2–0.5 m/s) encountered during the present study. Also, no scouring effects were observed under the sensor location and finally flow-sensor interference is associated

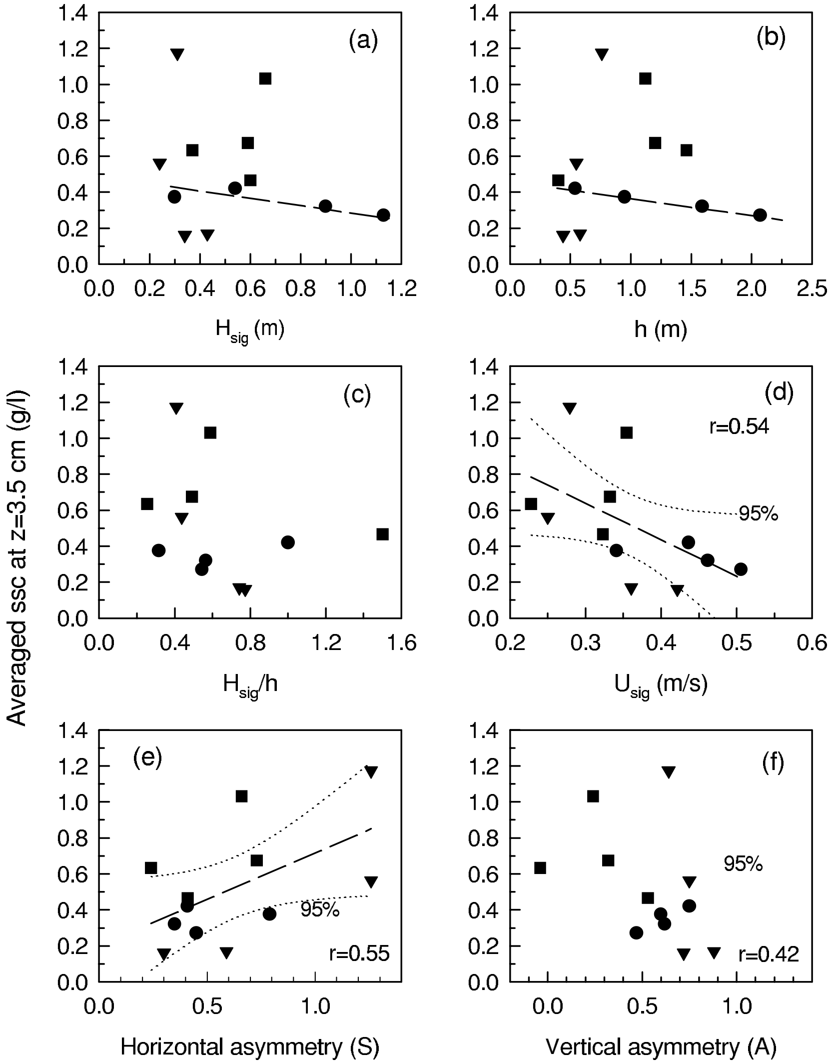

Fig. 4. Variation in time-averaged sand concentration, at 3.5 cm above the sea bed (reference concentration), against: (a) local significant wave height (H_{sig}); (b) local mean water depth (h); (c) ratio of H_{sig}/h; (d) significant orbital velocity (U_{sig}); (e) asymmetry of the waves in the horizontal axis (S); and (f) vertical asymmetry of the waves (A). Key: ● Caswell Bay; ■ Bournemouth beach; and ▽ Rhossili Bay.

with sharp spikes in concentration that occur near the velocity zero-crossing and into the following half cycle (Black and Rosenberg, 1991). This type of correlation between spikes in ssc and flow phase was not observed in our records. On the contrary ssc was correlated with the onshore phase of the wave cycle as the co-spectral analysis of the instantaneous ssc and current velocity indicated (Voulgaris, 1992). From the above and the fact that the level of ssc is inverse related to orbital velocity (see results section and Fig. 4d) we concluded that no flow-sensor interference was present that could contaminate our data.

To define the local hydrodynamic conditions associated with each of the data sets, time-averaged statistics (mean, standard deviation) were calculated. These included: mean cross-shore ($\langle u \rangle$) and longshore ($\langle v \rangle$) currents; mean suspended sand concentration ($\langle c \rangle$) at each measurement height above the sea bed; mean water depth (h); standard deviation of cross-shore (σ_u), longshore (σ_v) current and sea surface elevation

(σ_η). Significant values of the local wave heights ($H_{sig} = 4\sigma_\eta$), cross-shore and longshore oscillatory currents ($U_{sig} = 2\sigma_u$ and $V_{sig} = 2\sigma_v$), together with the maximum oscillatory currents ($U_b = 2.8\sigma_u$, $V_b = 2.8\sigma_v$), were also determined (Thornton and Guza, 1989). Wave period (T) is described on the basis of zero up-crossing period, calculated from the demeaned and de-trended cross-shore current time-series.

The asymmetry of the wave profile about the horizontal (S) and vertical (A) axis were estimated as (Elgar et al., 1988):

$$S(u(t)) = \frac{\langle u^3(t)\rangle}{\langle u^2(t)\rangle^{3/2}}, \qquad A(u(t)) = -S(H(u(t))) \quad (3)$$

where $H(u(t))$ is the Hilbert transform of the cross-shore velocity time-series ($u(t)$) with the angle brackets denoting time-averaging over the record length. A “saw-tooth” wave shape (steep front faces and gently sloping rear faces, but with crests and troughs of equal amplitudes) has $S = 0$ and $A \neq 0$. A “Stokes wave” shape (broad low troughs and narrow tall crests, but with symmetrical front and back faces, has $S \neq 0$ and $A = 0$. For near-breaking and breaking waves, $A(u) > S(u)$ (Elgar et al., 1988).

5. Results and discussion

The complete data set collected from the experimental sites is used in this contribution. The time-series and a description of the analytical approach can be found in Voulgaris (1992). However, only time-averaged suspended sediment concentration profiles are examined here.

The instruments were inundated only for a few hours on either side of high water. Hence, no data were collected extending over the whole of the surf zone (relative position) for the same incident wave characteristics (except for Caswell Bay, where runs 6, 7 and 8 (see Table 2) were collected during a falling tide). Similarly, in response to changes in weather conditions, the incident wave regime changed during the course of the experiments; this resulted in changes in the breaker zone position and, subsequently, to the relative position of instrumentation within the surf zone. Local wave height, mean water depths and the relative location within the surf zone, for each of the experimental runs are listed in Table 3.

In accordance with existing models for the vertical distribution of ssc, a reference concentration (C_a) has to be defined. Elsewhere (Drake and Cacchione, 1989), ssc measurements at high elevations above the seabed were extrapolated to elevations very near to the seabed. Such an approach requires a priori knowledge of a vertical distribution model for the ssc. To avoid the reference concentration being dependent upon the model used, the mean concentration measured at 3.5 cm above the sea bed is used here (Table 3). Although this elevation is higher than that used in the literature (i.e. height of saltating grains or concentration at a height equal to the flow roughness scale), is adopted for practical reasons. It is consistent with similar elevations used by other investigators to measure the concentration of sediment on beaches.

Given the proximity to the bed, the reference concentration is sensitive to the elevation above the seabed. In the absence of simultaneous bed elevation measurements, the averaged erosion depth required to support the material in suspension load was estimated from (Sternberg et al., 1989):

$$b = \frac{\int_{z=0}^{z=h} C(z)\,\mathrm{d}z}{\rho_s C_b} \quad (4)$$

where C_b (= 0.65) is the bed volume concentration, ρ_s is the density of the sand (= 2675 kg/m^3) and h is the total water depth. A box integration method was used to calculate the integral in Eq. (4) from the ssc data (see Voulgaris 1992). The maximum estimate of time-averaged erosion depth was 0.17 mm while the maximum instantaneous erosion depth (i.e. erosional depth required to support the material in suspension from an individual resuspension event) was 2.5 mm. These depths were used in the suspended sediment concentration profile equation (Eq. (1)) to estimate the error in measured C_a due to bed elevation uncertainty. Assuming a small mixing length (0.1 m, i.e. the majority of the sediment is near the bed) it was found that the maximum error in the measured time-averaged and instantaneous reference concentration, due to possible bed elevation changes, was less than 0.5 and 2.5% for the time-averaged and instantaneous values, respectively. The above error estimations do

Table 3
The prevailing wave conditions for each experimental run, together with the estimated parameter *b* (see text for details) and the ripple geometry predicted by the Wiberg and Harris (1994) model

Site	H (m)	H_{sig} (m)	T (s)	U_b (m/s)	C_a (g/l)	b	Breaker type	Position in surf zone	Ripple height (η, cm)	Ripple length (λ, cm)	Ripple types
Bournemouth	1.20	0.59	4.7	0.43	0.675	0.078	Plunging	Outer surf zone	3.6	24.3	Suborbital
Bournemouth	1.12	0.66	5.3	0.51	1.031	0.066	Plunging	Breaker zone	2.9	20.8	Suborbital
Bournemouth	0.40	0.60	4.3	0.46	0.466	0.507	Plunging	Inner surf zone	3.7	24.8	Suborbital
Bournemouth	1.46	0.37	3.2	0.32	0.634	0.090	Spilling	Outer breaker zone	3.4	20.2	Orbital
Caswell	0.95	0.30	4.0	0.34	0.374	0.042	Spilling	Outer breaker zone	4.8	29.9	Suborbital
Caswell	2.07	1.13	5.8	0.80	0.270	0.637	Spilling	Middle surf zone	1.6	13.9	Anorbital
Caswell	1.59	0.90	5.5	0.73	0.320	0.602	Spilling	Middle/inner surf	1.7	14.3	Suborbital
Caswell	0.54	0.54	6.1	0.67	0.420	0.851	Plunging	Middle/inner surf	1.6	13.9	Anorbital
Rhossili	0.76	0.31	9.1	0.39	1.174	0.118	Plunging	Breaker zone	5.9	38.5	Suborbital
Rhossili	0.55	0.24	5.2	0.35	0.563	0.264	Plunging	Outer surf zone	5.8	34.5	Orbital
Rhossili	0.58	0.43	8.3	0.50	0.170	0.446	Plunging	Middle /inner surf	5.2	36.1	Suborbital
Rhossili	0.44	0.34	8.1	0.59	0.162	–	Plunging	Inner surf zone	4.3	31.2	Suborbital

not take into consideration the time-history of seabed changes. The elevation of the sensor was checked at every tidal cycle prior and after sensor inundation. The maximum elevation difference, during all the experimental runs presented in this paper, was approximately 1 cm. Assuming the same mixing length as above ($l = 0.1$ m) this corresponds to a 10% underestimation in ssc. However, other investigators have documented that seabed elevations can change up to 5 cm (i.e. Davidson et al., 1993). Although no evidence exists indicating that this might be the case during our study, this possibility should not be disregarded in our analysis. The effect of such an error is discussed in subsequent sections.

5.1. Reference concentration and bottom boundary processes

The data presented here were collected inside the surf zone, under breaking wave conditions. Thus, turbulence was generated at the bottom boundary layer and from the water surface. Nielsen (1984) has stated that, with the exception of plunging waves, the reference concentration (C_a) is unaffected by wave breaking: hence, it is controlled by the bottom-generated turbulence. In order to test this assumption, C_a is examined as a function of various hydrodynamic conditions: local wave height (H_{sig}); total mean water depth (h); the ratio H_{sig}/h; wave orbital velocity (U_{sig}); horizontal (S) and vertical (A) wave asymmetries; total mean current speed ($\langle U \rangle = (\langle u \rangle^2 + \langle v \rangle^2)^{1/2}$); the relative wave strength $U_{sig}/\langle U \rangle$; the ratio of orbital to settling velocity (U_{sig}/W_s); the ratio of "stirring" over "stabilising" forces ($U_{sig} \tan \beta / W_s$); the ratio of wave orbital excursion over sediment diameter (A_b/D); and, finally, the mobility parameter for the maximum orbital velocity ($U_b^2/((s-1)gD)$. The time-averaged reference concentrations, in relation to the above parameters, are shown in Figs. 4 and 5. The selected parameters represent either bottom boundary layer conditions, those associated with breaking waves (height, local depth), sediment (W_s, D) or beach characteristics (slope).

No relationship appears to exist between C_a and wave height (Fig. 4a) for the Rhossili and Bournemouth data, whilst C_a tends to decrease with increasing wave height for Caswell bay (see dotted line on Fig. 4a). The correlation found for Caswell could be due to the fact that these data were collected under the same incident wave conditions: hence, the relationship shown is that between C_a and wave saturation (i.e. depth-controlled wave height) inside the surf zone. This interpretation is confirmed by the negative correlation between the Caswell C_a data and local mean water depth (Fig. 4b, see dotted line). Such a relationship is in agreement with Kana's (1978) observations that more sediment is set into suspension due to interaction between backwash and the incoming waves in very shallow water (see in Fig. 4b more sediment in suspension in 0.5 water depth than in deeper water depths). Also, Downing's (1984) observations from a dissipative beach showed that sand suspension is correlated with strong, low frequency offshore flows that occur in the inner surf zone. The absence of any relationship for the other sites may be attributed to differing incident wave regimes. In an earlier study, Galloway (1984) observed a relationship between mean water depth and sediment concentration: the ratio of wave height to water depth was found to be the best parameter to correlate ($r = 0.77$) with sediment concentration. This interpretation is not consistent with the present data (Fig. 4c) where higher C_a values are related to low H/h values. A similar conclusion applies to the comparison between sand concentration and orbital velocity (Fig. 4d) where higher C_a values are related to lower orbital velocities (correlation significant at a 10% level, t-test).

Also reference concentration (C_a) tends to increase with increased asymmetry about the horizontal axis (Fig. 4e, significant at a 10% level, t-test). Although no statistically significant, an inverse trend is shown for the vertical asymmetry (Fig. 4f). Inside the surf zone, the highest horizontal asymmetry is achieved within the breaker zone where the waves become unstable. On the other hand, lower horizontal asymmetry is encountered within the inner surf zone (i.e. "bore-like" waves). However, wave asymmetries also depend on breaker type types (i.e., spilling breakers are less symmetrical than plunging waves) and position in surf zone (bores in the inner surf are characterised by a crest and lack of wave trough). Thus the correlation between reference concentration and wave asymmetries is related both to position in the surf zone and breaker type.

C_a does not appear to be related neither to total

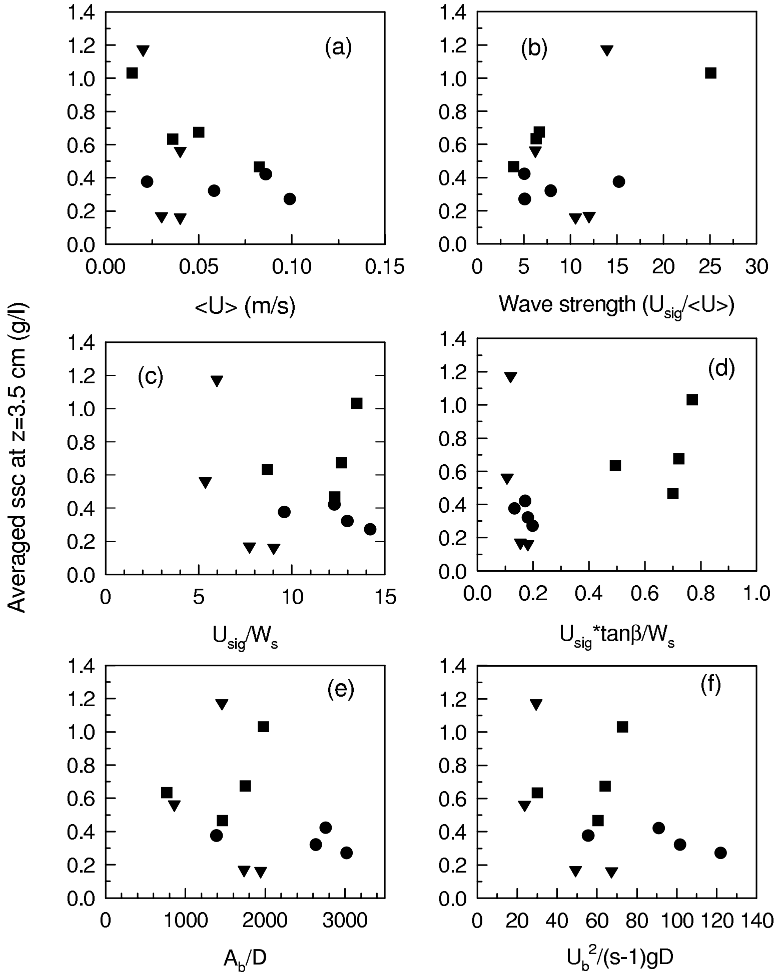

Fig. 5. Variation in time-averaged sand concentration at 3.5 cm above the sea bed (reference concentration), against: (a) mean current velocity ($\langle U \rangle$); (b) local strength of the waves over the mean currents, expressed as the ratio $U_{sig}/\langle U \rangle$; (c) dimensionless parameter U_{sig}/W_s, where W_s is the particle settling velocity; (d) the ratio between stirring and stabilising forces ($U_{sig} \tan \beta / W_s$); (e) ratio of orbital excursion over particle diameter (A_b/D); and (f) the mobility parameter ($u_b^2/(s-1)gD$). Key: ● Caswell Bay; ■ Bournemouth beach; and ▽ Rhossili bay.

mean velocity speed (Fig. 5a) nor to wave strength (ratio of wave to mean current, Fig. 5b). Even when the reference concentration is compared with dimensionless parameters, that express the ratio of stirring to stabilising forces (Fig. 5c–f), no clear relationship is apparent.

All the above results indicate that parameters related to the wave boundary layer do not explain efficiently the measured variation in reference concentration. Even when these parameters are normalised, by reference to sediment (i.e. D, W_s) or beach characteristics (i.e. $\tan\beta$), the situation remains inconclusive. Similar results have been obtained comparing the measured reference concentration to the maximum skin friction shear stress (Fig. 6a) and Shields parameter (Fig. 6b), derived using the wave current interaction model of Grant and Madsen (1979). The bottom generated turbulence and data from individual locations show higher concentrations for lower shear stresses (see Rhossili and Caswell data in Fig. 6); this suggests higher concentrations for lower values of bottom generated turbulence. However, this approach assumes that all resuspension processes are connected solely to bottom boundary

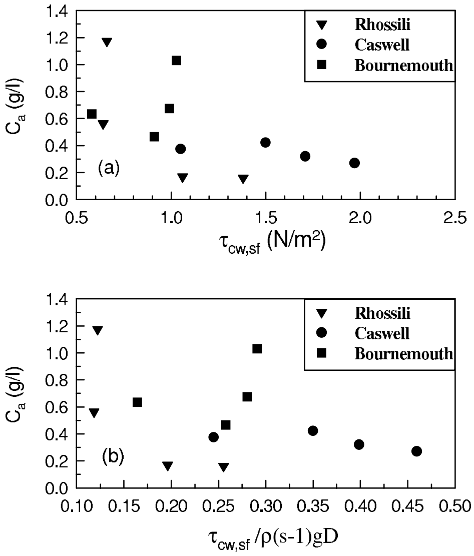

Fig. 6. Variation in time-averaged reference concentration C_a, against: (a) maximum bottom skin friction ($\tau_{cw,sf}$); and (b) the Shield's parameter ($\tau_{cw,sf}/\rho(s-1)D$).

processes; the bed is flat (i.e. no ripples) and ignores the effect of breaking waves.

Although, no signs of ripples were evident during the sea bed inspection periods between data collection, no one can warranty that this was the case during data collection (high water). If ripples were present, then the reference concentration observed might be associated with the vortex ripples and the ejection of the vortex during the return phase of the wave cycle (Vincent and Green, 1990). Since no diver observations exist for the experimental period, the measured hydrodynamic conditions and sediment size were utilised to predict ripple dimensions. The Wiberg and Harris (1994) model for ripple geometry in wave-dominated environments predicted that ripples of different types (i.e. suborbital, orbital and anorbital) could had been present during the period of the measurements. The predicted ripple heights and lengths varied between 1.6–5.9 and 13.9–40 cm, respectively (Table 3). At this juncture, it should be noted that the model was developed for use under non-breaking wave conditions. Its application in surf zone conditions exceeds the limits of applicability of the model. Dick et al. (1994) found that the Wiberg and Harris (1994) model predicted ripples for shoaling wave condition while divers observed a flat bed. The predicted ripple dimensions are used here in a diagnostic mode to identify if the bottom reference concentration values measured might be related to vortex-ejection from a rippled bed. If the predicted ripples were present then suspended sediment concentration (C_a) should be related either to the total shear stress (including form drag) or to the asymmetry of the ripples. The predicted ripple dimensions were used to calculate the total shear stress using Wiberg and Nelson (1992) formula:

$$\frac{\tau_o}{\tau_{sf}} = 1 + \frac{1}{2} C_D \frac{1}{\kappa^2}\left[\ln\frac{\eta}{z_{o,sf}} - 1\right]^2 \frac{\eta}{\lambda} \tag{5}$$

where $\kappa = 0.41$ is von Karman's constant, C_D a bed form drag coefficient ($= 0.1$); η and λ are the ripple height and length, respectively.

The measured reference concentration is compared to maximum total shear stress and Shields parameters, assuming that the predicted ripples were present during the measurement periods, in Fig. 7. As in the case of skin friction (Fig. 6) the bottom generated turbulence, assuming a rippled bed show higher concentrations for lower shear stresses. This, once more, suggests higher reference concentrations for lower bottom generated turbulence.

Nielsen (1986) showed that sediment resuspension is enhanced by the presence of ripples and that higher ripple steepness (η/λ) contributes to a higher sediment concentration. This process is parameterised in the following equation for the reference concentration under ripples (Nielsen, 1986):

$$C_a = 0.005\left[\frac{\tau_{cw}/\rho(s-1)gD}{1 - \pi(\eta/\lambda)^2}\right]^3 \tag{6}$$

In Fig. 7c, the reference concentration is plotted against the right hand term of Eq. (6). It is worth noting that no relationship exists between ripple-induced resuspension and measured suspended sediment concentration.

The results indicate that intensity of the flow or bottom-generated turbulence are not adequate mechanisms to explain the observed near-bed concentrations. This seems to hold for both cases of flat and rippled bed. The relationships between reference concentration and wave asymmetry suggest that sediment resuspension is controlled mainly by processes

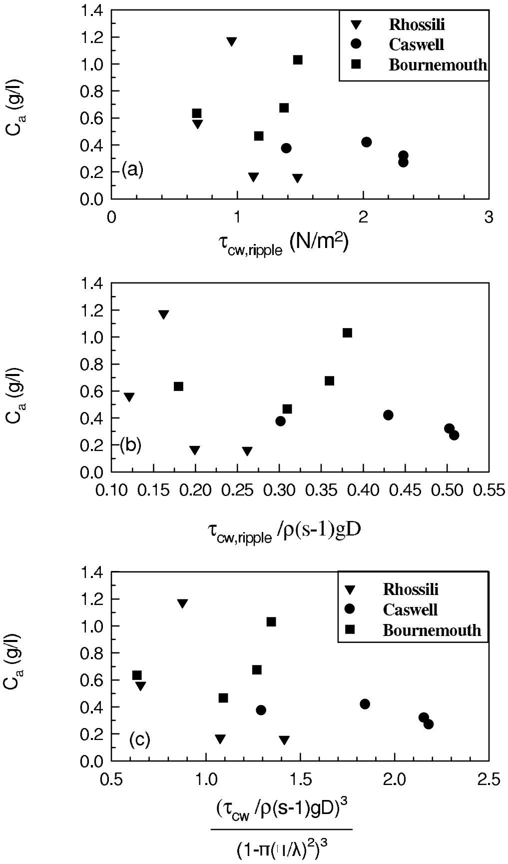

Fig. 7. Variation in time-averaged reference concentration C_a, against: (a) total maximum bottom stress ($\tau_{cw,ripple}$); (b) the Shield's parameter ($\tau_{cw,ripple}/\rho(s-1)D$); and (c) Shields parameter normalised by the ripple steepness (see Eq. (6) in text). Note: Ripple dimensions predicted using the Wiberg and Harris (1994) model is used to calculate total stress.

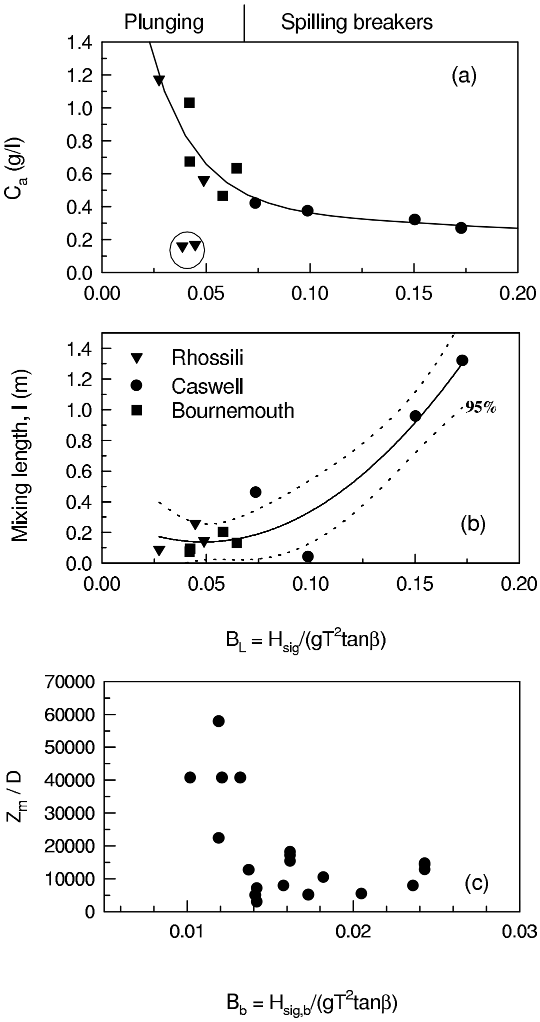

Fig. 8. Relationship between the local breaker parameter (B_L) and: (a) the time-averaged reference concentration (C_a, measured at a height $z_a = 3.5$ cm above the sea bed); and (b) the mixing length (l). Note: the lines of "best fit" are also shown in the diagram. (c) Relationship between tracer mixing-depth normalised by the mean particle size and breaker parameter (B_o) (data used the same as in Ciavola et al., 1997b).

associated with individual wave breaking as these may vary throughout the surf zone.

5.2. Reference concentration and wave breaking

Miller (1976) has demonstrated the relationship between turbulence and wave breaking type. Furthermore, experimental work (Zhang and Sunamura, 1990) has quantitatively associated the breaking characteristics, expressed through Galvin's (1972) breaker parameter, and the wave Reynolds number (R_e) with the type of vortices which are expected to be present. Here, breaker type is expressed through the use of the local breaker parameter (hereafter, denoted as B_L). This is similar to Galvin's (1972) breaker parameter, but with the wave height at the breaker zone (H_b) being replaced with that at the point of measurements (H_{sig}).

The relationship between the local breaker parameter (B_L) and reference concentration (C_a) is shown in Fig. 8a. High concentrations are correlated with a low parameter (highly plunging characteristics); they

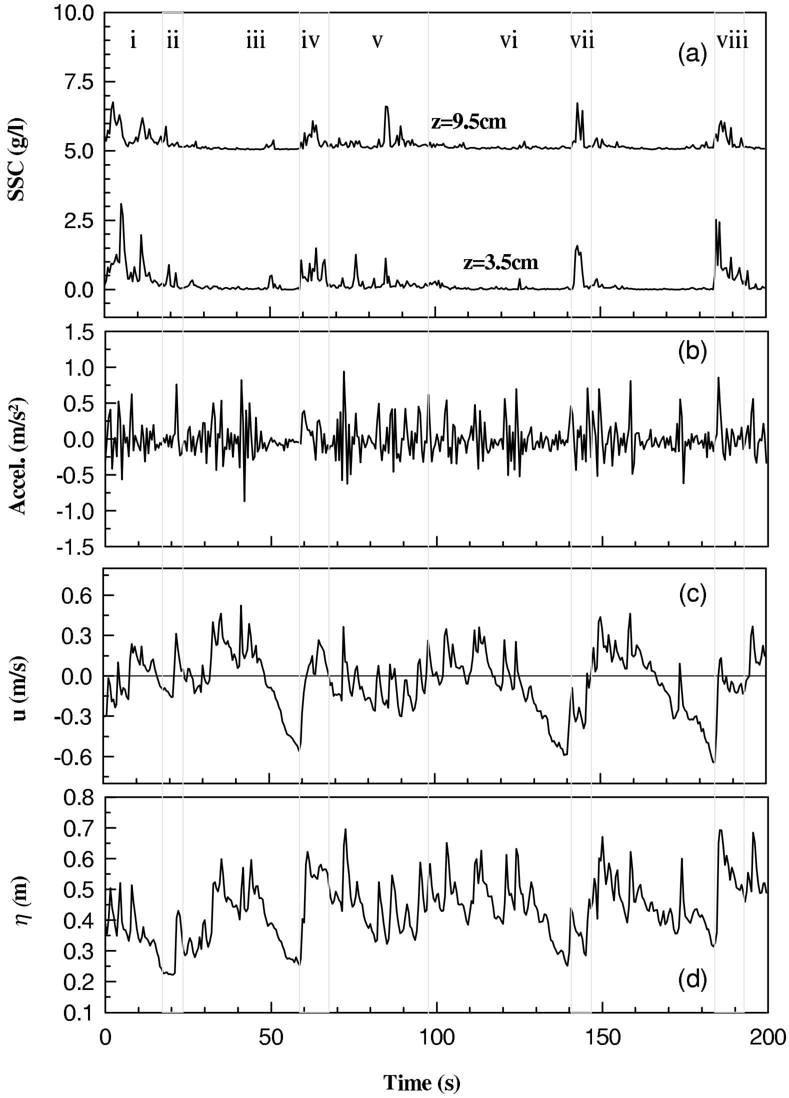

Fig. 9. Typical time-series obtained from the inner surf zone during the experiment undertaken at Rhossili Bay: (a) suspended sediment concentration at 3.5 and 9.5 cm above the sea bed (note: the vaues from the 9.5 cm sensor have been offset by 5 g/l); (b) acceleration of horizontal flow; (c) cross-shore velocity; and (d) instantaneous water surface elevation. HJ indicates hydraulic jump conditions, associated with sediment resuspension events. W indicates conditions where individual waves are associated with the resuspension of sediment.

decrease exponentially for an increase in breaker parameter (increasing spilling characteristics). Only two of the experimental points on the figure, from Rhossili Bay, do not follow the observed trend. These points correspond to measurements in the inner surf zone, at low water depths (data sets 7 and 8, see Tables 2 and 3). At such a time, the resuspension processes relate to hydraulic jump conditions caused when the incoming waves interact with strong offshore currents (generated by the backwash of the run-up) as shown in Fig. 9.

Time-series of instantaneous values of suspended sediment concentration (Fig. 9a), cross-shore velocity (positive values indicate onshore flow, Fig. 9c) and sea surface elevation (Fig. 9d) are shown for inner surf zone conditions in Rhossili Bay. Strong offshore flows coupled with individual wave crests correspond to significant resuspension events (see periods marked as ii, iv, vii and viii in Fig. 9d). These occur every 50–60 s and correspond to the infragravity band of motions, usually observed in the inner surf zone. Also, in the same figure (Fig. 9) periods of the record, where strong onshore flow coincides with peak in sea surface elevation (marked as i, iii, v and vi), are characteristic of the passage of individual waves (bores). During these periods, resuspension occur only when the instantaneous water depth is low (see periods i and v); when the water depth is higher (see periods iii and vi) no sediment resuspension events are observed. The above details demonstrate that in the shallow waters of the inner surf zone sediment resuspension is not related strictly to wave height. The instantaneous water depth and the creation of hydraulic jump conditions occurring when strong offshore flows during the backwash meet the incoming bores are more significant parameters in determining resuspension.

Excluding the two data points from Rhossili Bay, the reference concentration is related to the local breaker parameter (B_L) through a double decay exponential relationship (correlation coefficient 0.92, significant at 0.2% level):

$$C_a = 2.79\,e^{-45.57B_L} + 0.42\,e^{-2.19B_L} \tag{7}$$

The derived relationship is empirical and valid only for B_L values ranging from 0.0001 to 0.2 (as given by Galvin, 1972). The first term relates to plunging waves while the second to spilling characteristics. This statistical model agrees with previous observations that plunging breakers contain up to an order of magnitude more sediment in suspension, than spilling waves (Kana, 1977, 1978; Inman et al., 1980; Galloway, 1984; Nielsen, 1984; Beach, 1989; Beach and Sternberg, 1996). Although Eq. (7) relates the reference concentration to breaking wave characteristics only, bottom boundary layer induced turbulence is included implicitly as the height of the wave in the breaker parameter. Also, Eq. (7) does not imply a direct relation with sediment size. A statistical relationship that includes particle size could be established from Fig. 5d, if we exclude the same 2 data points from Rhossili for the reasons described above. A linear relationship between C_a and the ratio of stirring over stabilising forces ($U_{sig} \tan \beta / W_s$) can be derived with a correlation coefficient $r = 0.69$. This correlation although significant at 2% level is significantly lower than that found for Eq. (7) and insignificant at the 0.2% level. This concludes that Eq. (7) explains best the variance of the observed ssc despite the fact that no information on sediment characteristics are included. This is attributed to the limited range of sediment sizes (fine-medium to medium sand) commonly found on sandy beaches, thus the settling velocity is of a limited range and its effect is included in the coefficients of the model shown as Eq. (7).

At this juncture it should be noted that uncertainties in the actual distance between sensor and bed might be influencing the accuracy of the above correlation. In order to evaluate the effect of this uncertainty, a maximum error of 5 cm in distance was assumed and the error in ssc was estimated using Eq. (1) with the mixing parameter obtained from the experimental data (see next section). It was found that the maximum error would be 72% for the last run form Caswell bay while the remaining of the runs will exhibit an error varying from 44 to 5%. The errors reduce to 22, 13 and 1%, respectively, if a more realistic 1 cm error in vertical elevation is assumed. Correcting the data even for the 5 cm offset does not alter the shape of the curve although it changes the coefficients in Eq. (7). The results of smaller differences in elevation are considerable smaller.

Similar trends are shown using the tracer mixing-depth data presented in the work of Ciavola et al. (1997b). In Fig. 8c, the recorded mixing-depth is plotted as function of the breaker parameter (B_b) revealing that higher mixing-depths occur at lower values of B_b. All data used in Ciavola et al. (1997b) are from experiments under the plunging wave conditions; also the breaker parameter is for the breaker zone and not for the location of the tracer release. Thus, the data represent averaged conditions in both time and space; however, the trend is similar to that shown in Fig. 8a for the reference concentration measured locally using OBS sensors. The similarity between the results from the tracer experiments and the present data offer an additional degree of confidence to the interpretation of the OBS data and the use of the local breaker parameter as an indicator of resuspension intensity. However, the uncertainty regarding the elevation of the seabed and exact ripple

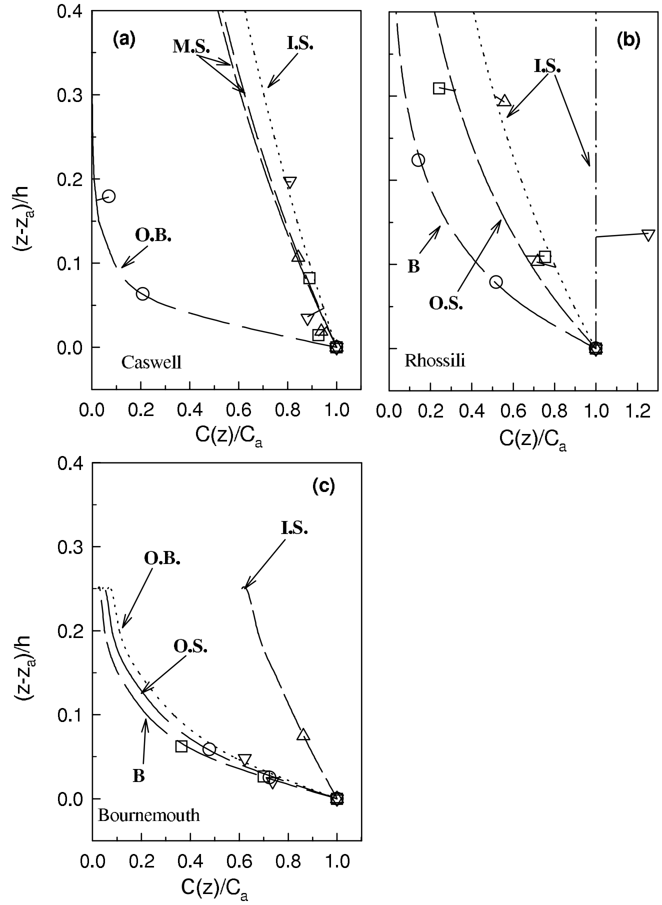

Fig. 10. Dimensionless vertical distributions of measured time-averaged suspended sediment concentration, from: (a) Caswell Bay; (b) Rhossili Bay; and (c) Bournemouth beach. The best fit exponential decay curves (Eq. (5)) are shown for each experiment with their relative position in the surf zone indicated (O.B.: outer breaker zone; B: breaker zone; O.S.: outer surf zone; M.S.: middle surf zone; I.S.: inner surf zone). Within each diagram data with the same symbols represent data used for the fit of a single curve—when no clear a line is used to connect symbol with the corresponding curve.

dimensions (if any) limits Eq. (7) to qualitative or semi-quantitative applications.

5.3. Vertical distribution of time-averaged suspended sediment concentration

The vertical distribution is required in the estimation of sediment fluxes, throughout the water column. The normalised (in relation to the reference concentration) sand concentration ($C(z)/C_a$) is plotted against normalised elevation $(z - z_a)/h$ (where z_a is the reference level, 3.5 cm) in Fig. 10. Despite the limited measurement points (minimum 2, maximum 3), a best-fit technique was applied to the profile. Such a curve-fit is similar to that suggested by Nielsen (1984) (see Eq. (2)); it assumes that the distribution of sediment in the vertical is due to convection, with the mixing length (l) being a function of local mean water depth ($l = bh$):

$$\frac{C(z)}{C_a} = e^{-(z-z_a)/bh} \tag{8}$$

The purpose of fitting Eq. (8) to the data is to: (i) identify trends in the vertical distribution of time-averaged suspended sediment concentration as these

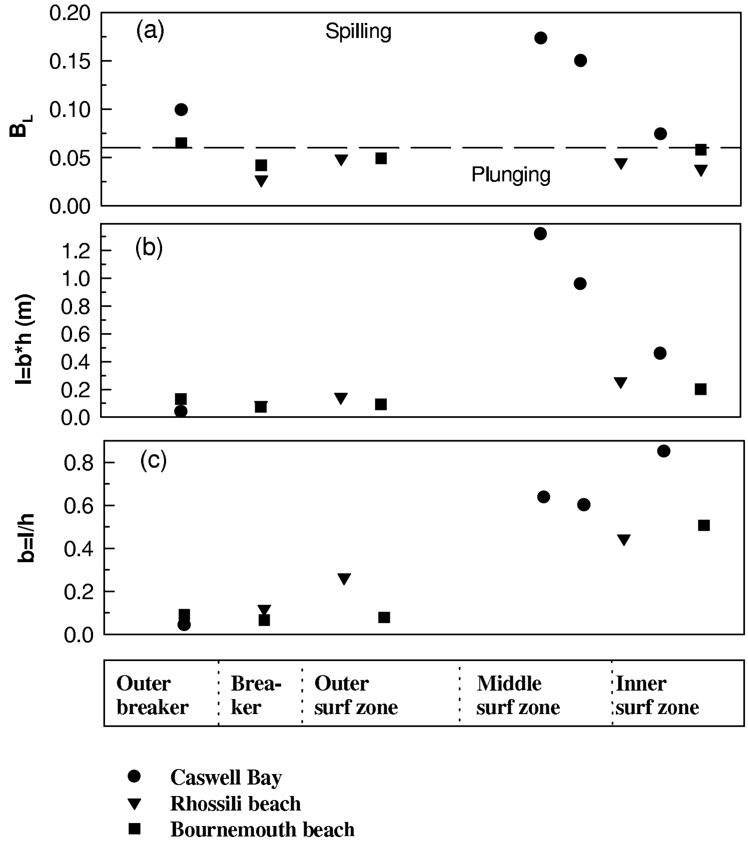

Fig. 11. Variation in the local breaker parameter, B_L (a), mixing length parameter, l (b), and parameter $b = l/h$ (c) in terms of relative position in the surf zone (as observed visually).

are indicated by the data; and (ii) examine the relation of the mixing parameter to position in the surf zone.

Characteristically, the less steep profile occurs near the breaker zone (B): slightly steeper dimensionless profiles are associated with locations to seawards (outer breaker, O.B.) and shoreward (outer surf zone, O.S.) of the breaker zone. An implied reversal in the profile is observed during one of the inner surf experiments from Rhossili (Fig. 10b, inner surf zone, I.S.); this reversal is similar to that observed in a dissipative beach by Beach (1989).

The analysis revealed various values for the mixing length (l) and the ratio of mixing length to local water depth ($b = l/h$); these are plotted (Fig. 11) as a function of position in the surf zone. The mixing length in the outer breaker, breaker and outer surf zone varied from 0.03 to 0.15. Significant higher values were obtained in the middle and inner surf zone (see Fig. 11b). The values obtained here are of the same order to those obtained by Black and Rosenberg (1991) (i.e. 0.066–071 beyond the breaker zone, rising to a maximum of 0.386 inside the surf zone) but with much higher values (approx. 1.0) associated with spilling breakers in the middle surf of Rhossili.

The value of b (the ratio of mixing length to local water depth) may be seen to increase shoreward of the breaker zone corresponding to an increase in the steepness of the concentration profile. Such an observation is consistent with the information on profile steepness as descriptively shown by Sternberg et al. (1989) and Beach (1989). The local breaker parameter appears to be independent of location within the surf zone, suggesting specific site dependence (i.e. beach slope).

The reference concentration has been shown to be very high for plunging waves, suggesting that large quantities of sediment are set in suspension (Fig. 8a). At the same time, the mixing length $l = bh$ is small (Fig. 8b); it is indicative of a low vertical gradient, compared to that of spilling waves. These results are in accordance with the turbulence structure associated with various breaking wave types. The ejection of the jet towards the sea bed at plunging could be laminar up to the point of impact (Cokelet, 1977); it sets, at plunging, large amounts of sediment into suspension (Miller 1976; Nielsen, 1984). In the case of spilling waves, turbulence is generated at the top of the wave by a roller (Deigaard et al., 1986; Battjes, 1988; Roelvik and Stive, 1989); this then decays exponentially with depth. The mixing length has been given by other investigators to be of the order of 0.07 (Deigaard et al., 1986) or 0.25–0.35 times the local water depth(Svendsen et al., 1987). The results of the present study give a turbulence mixing length from near zero, for plunging conditions, to >0.8 times the local water depth, for extreme spilling waves.

Local breaker parameter and wave Reynold's number, corresponding to the present data sets, are plotted on Zhang and Sunamura's (1990) diagram for the occurrence of various types of vortices. Conditions during the experiments can be seen to be generally favourable for the creation of vortices. Oblique vortices at Bournemouth beach (points 1–4); horizontal vortices Type A (horizontal vortex changing into vertical) were present at Rhossili; and between Type A and B (horizontal vortices that develop in sequence) at Caswell.

The favourable conditions for the creation of vortices, as shown in Fig. 12, reinforce the findings of this study that sediment resuspension in the surf zone is controlled by the turbulence injected by the breaking waves. However, no consistent relationship was identified between the vortex type as identified in Zhang and Sunamura's (1990) diagram and neither reference concentration or mixing length. This is indicative of the difficulty in quantifying sediment resuspension as a function of vortex characteristics and the need to incorporate this process to any general model of surf zone sediment transport.

6. Conclusions

Measurements on suspended sediment concentration from three different fine-medium to medium sandy beaches have been combined, in order to identify processes controlling sediment resuspension in the surf zone.

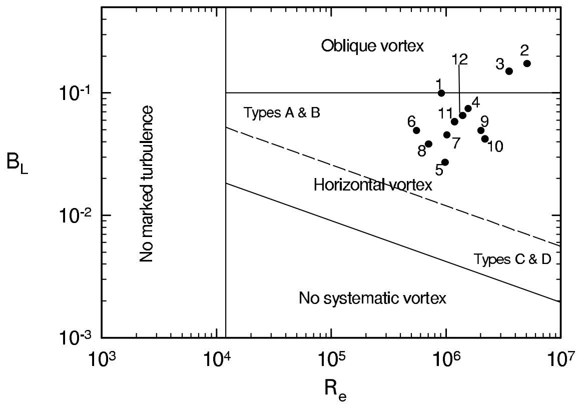

Fig. 12. Zhang and Sunamura's (1990) diagram showing the conditions for the occurrence of various types of vortices, under breaking waves. The points represents conditions from the experimental data presented here while the numbers correspond to different experimental data sets: 1–4 Bournemouth beach; 5–8 Caswell Bay; and 9–12 Rhossili Bay.

Sediment resuspension is highly dependent on breaking wave processes, rather than bottom boundary layer turbulence. Reference concentration and vertical distribution of ssc are controlled by vortices induced by breaking waves.

Plunging waves set more sediment in suspension near the bed, but the laminar character of the vortices associated with these types of waves limits the vertical distribution of the resuspended material; the opposite is valid for spilling waves.

Vertical distribution of sediment is parameterised using a convective type time-averaged suspended sediment concentration profile (Eq. (8)). Both reference concentration and mixing parameter are highly correlated with wave breaking type, as defined by the local breaker parameter.

The data presented here support: (i) the findings of Kana (1979) and Beach and Sternberg (1996) that emphasise the importance of breaking wave types in sediment suspension; and (ii) the use of Galvin's (1972) breaker parameter to parameterise the efficiency of breaker type to set sediment in suspension.

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