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Measurements of suspended sediment transport on a reflective mesotidal beach in southern Portugal

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ABSTRACT

The present paper reports the results obtained in a field experiment carried out on a medium-energy, mesotidal, reflective beach on Culatra Island (southern Portugal). Simultaneous time-series measurements of waves, currents and sediment concentration were taken during 1.5 tidal cycles using a pressure transducer, two bidirectional electromagnetic current-meters and three optical backscatter sensors. Measurements of suspended sediment transport were compared with fluorescent sand tracers. Total longshore sediment fluxes measured with optical techniques and sand tracers were found to give similar results, if their major limitations are considered. The present experiment confirms the different sedimentary behaviours of steep reflective beaches with plunging breakers, as opposed to the low-gradient beaches with spilling breakers where most previous studies have been performed, and supports the idea that one of the major limitations of longshore sediment transport models is their lack of dependency on breaker/beach type.

Key words: Suspended sediment, plunging break, longshore transport, mesotidal beach, physical measurements, Portugal.

RESUMEN

Mediciones del transporte sedimentario en suspensión en una playa mesomareal reflectiva en el sur de Portugal

Se presentan los resultados de un experimento realizado en una playa reflectiva, mesotidal y de media energía, en la isla de Culatra (sur de Portugal). Se llevaron a cabo mediciones de series temporales de olas, de corrientes y de concentración de sedimento en suspensión durante un ciclo tidal y medio, utilizando un transductor de presión, dos correntímetros bidireccionales electromagnéticos y tres sensores ópticos. Se constató que los resultados de medir los flujos sedimentarios con las técnicas ópticas y con arenas marcadas eran semejantes, teniendo en cuenta las respectivas limitaciones. El presente experimento ha confirmado el desigual comportamiento sedimentario de playas reflectivas con fuerte inclinación y rompiente en voluta, en oposición a las playas con pequeña inclinación y rompiente en derrame, apoyando, pues, la idea de que una de las mayores limitaciones de los modelos de deriva litoral es la ausencia de dependencia en relación al tipo de playa/rompiente.

Palabras clave: *Sedimento en suspensión, rompientes en voluta, deriva litoral, playa mesotidal, medidas físicas, Portugal.*

INTRODUCTION

The determination of patterns of suspended sediment in the surf zone and the calculation of longshore sand transport are of utmost importance in coastal oceanography. However, despite the research effort that has been expended on these subjects over the last 50 years, their underlying mechanisms are still poorly understood. Calculations have to rely mostly on empirical formulations calibrated for a limited set of environmental conditions, and field data obtained using different methodologies that are subject to different kinds of error. Bodge and Kraus (1991) pointed out, the scatter in the proportionality coefficients obtained from field data may be a result of inadequate recognition of the surf or beach conditions that control longshore sediment transport, or error in the field database.

Due to the high degree of uncertainty involved in longshore sand transport determination, in order to verify the applicability of the most widely-used empirical equations to the Portuguese coast, a series of field experiments has been carried out since 1992 by the DISEPLA Group to assess longshore sand transport rates under a wide range of environmental conditions (Dias *et al.*, 1992; Ciavola *et al.*, submitted).

The field experiment described in the present paper (LUAR-Culatra 93) was conducted in southern Portugal on Culatra Island, part of the Ria Formosa barrier-island system, as part of a joint project involving several universities from Portugal and the rest of Europe (Algarve, Southampton, East Anglia, Lisbon, Liverpool, Bordeaux) with the support of local and national authorities (Portuguese Hydrographic Institute, Ria Formosa National Park, Faro-Olhão Port Authority). During this field exercise, simultaneous measurements of time-series of waves, currents and sediment concentrations were obtained during 1.5 tidal cycles. Measurements of suspended sediment transport were also taken, using sediment traps, and of total transport, using fluorescent sand tracers.

Fluorescent tracer results have already been discussed by Ciavola *et al.* (1997a), who found that previous empirical formulas underestimated the measured transport rates by more than one order of magnitude. These findings confirmed that the morphodynamics of steep beaches are very different from those of low gradient beaches, against which most longshore formulas had been calibrated. The present paper extends that work, with two main objectives: first, to understand the patterns of suspended sediment transport observed in the surf zone, in an effort to understand the underlying mechanisms; second, to compare the estimates of total longshore sand transport using different methods in order to verify their reliability.

MATERIALS AND METHODS

The field measurements were obtained at Culatra beach, Algarve, southern Portugal (figure 1). The beach is mesotidal, with a moderate- to high-energy wave climate. The measurements were made using one instrument rig, deployed in the intertidal zone, with two biaxial electromagnetic current-meters (EMCM), three infrared optical backscatter sensors (OBS) and one pressure transducer (PT). The two electromagnetic current-meters, denoted EMCM1 and EMCM2, were arranged to measure instantaneous horizontal currents at 17 cm and 45 cm above the bed. The OBS sensors were installed at elevations of 5 cm (OBS1), 19 cm (OBS2) and 41cm (OBS3) from the bed. Data were recorded on a shore-based personal computer, and sampled continuously at a rate of 5Hz in time-series of approximately 10 min, giving 3 072 data points. This record length was chosen to ensure stationarity in this rapidly-changing environment. Calibration of the OBSs, which was necessary to translate the intensity of the backscattered signal into suspended sand concentrations, was carried out in a recirculating tank at Southampton University (UK). Since the backscattered signal is a function of grain size, the OBSs were calibrated with surficial sediment from the deployment site

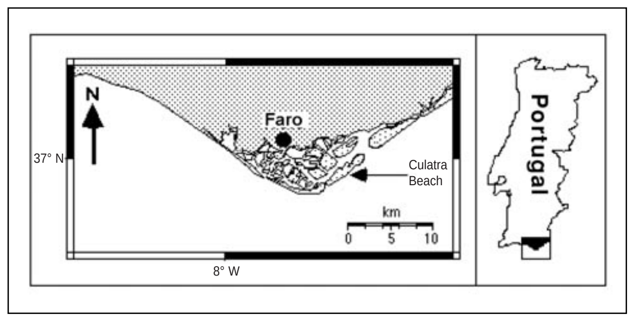


Figure 1. Location of Culatra beach, Algarve, Portugal

(mean grain size 0.26 mm). Measurements of suspended sediment transport were also made using sediment traps and total transport using fluorescent sand tracers. Details on the deployment site and EMCM and PT calibration procedure are given in Ciavola *et al.* (1997a). Data from sensors were only available when the equipment was submerged, which happened for about 2-3 h during high tide.

Time-series of cross-shore and longshore velocity (u, v) and sediment concentration (c) were plotted to check data quality. The lowest OBS records came from the second and third datasets, which most of the time contained saturation values, possibly due to being buried, were discarded. The lower current-meter record from the second dataset was also discarded, due to instrument failure. Univariate statistical descriptions of velocity and sediment concentrations (mean and standard deviation), wave characteristics, and cross-spectral characteristics of velocities and sediment concentrations were determined using the MATLAB™ environment.

Wave characteristics were computed using the moments of the pressure transducer spectra after correction for depth attenuation (Davidson, 1992). The boundary between the gravity and infragravity bands was defined at 30 s, and chosen after examining spectral minima. Significant wave heights (H_s) in the incident (gravity) and infragravity bands were estimated from the cumulative variance by summing spectral estimates across the frequency bins using $H_s = 4\sigma_n$, where σ_n is the square root of the variance of surface elevation time-series.

Suspended sediment transport

The net flux of sediment (q_s) can be determined by averaging the instantaneous flux measurements:

$$q_s = \overline{u \cdot c} = \frac{1}{n} \sum u \cdot c \qquad [1]$$

where u and c are, respectively, the instantaneous velocity and the suspended sediment concentrations, and n is the number of data points in the sample. This flux can be partitioned into steady, oscillatory and random components, respectively (Jaffe, Sternberg and Sallenger, 1984):

$$q_s = \overline{u \cdot c} = \overline{u} \cdot \overline{c} + \overline{\tilde{u} \cdot \tilde{c}} + \overline{u' \cdot c'} \qquad [2]$$

where the bar denotes time averaging. The oscillatory modes can be deconstructed further into fluxes due to gravity waves (incident or short-period waves, subscript g) and infragravity waves (long-period waves, subscript i). Knowing that the last term of equation [2] is generally expected to be small (Nielsen, 1992), the total suspended sediment load can be expressed as:

$$q_s = \overline{u} \cdot \overline{c} + \overline{\tilde{u}_i \cdot \tilde{c}_i} + \overline{\tilde{u}_g \cdot \tilde{c}_g} \qquad [3]$$

The local mean sediment transport rate, $\overline{u} \cdot \overline{c}$, is computed as the product between the time-averaged velocity and the time-averaged concentration. A convenient way of computing the oscillatory components is through cross-spectral analysis (Huntley and Hanes, 1987). The co-spectrum yields the cross-product of velocity and concentration as a function of frequency, and reveals the relative contribution of the different frequency bands –gravity and infragravity– to both the direction and the rate of suspended sediment transport.

Suspended sediment transport modes were calculated based on the upper current-meter and optical backscatter sensor (≈ 43 cm from bed), since they were the only ones that worked without any error during the three tidal semi-cycles.

RESULTS

Waves and currents

The total surface elevation was clearly dominated by the gravity band in the three datasets (figure 2). Wave-height conditions did not change significantly among the three tidal datasets, being approximately 0.4 m. Zero-up-crossing periods were approximately 5 s, and also showed a small variation during the observation period. Wave height in the infragravity band showed a slight variation from 0.20 m during the first tide to 0.12 m during the last one. Since the diurnal high tide of 7 October 1993 (afternoon) was approximately 20 cm lower than the first (7 October 1993, morning) and third high tide (8 October 1993, morning), the rig was always in the breaker zone, and no data was collected in the shoaling zone.

The two components of the steady currents (cross-shore $\overline{u}$ and longshore $\overline{v}$) were calculated for each burst of data and for each current-meter (figure 3). Positive values of cross-shore velocity indicate onshore flow, whilst positive values on longshore

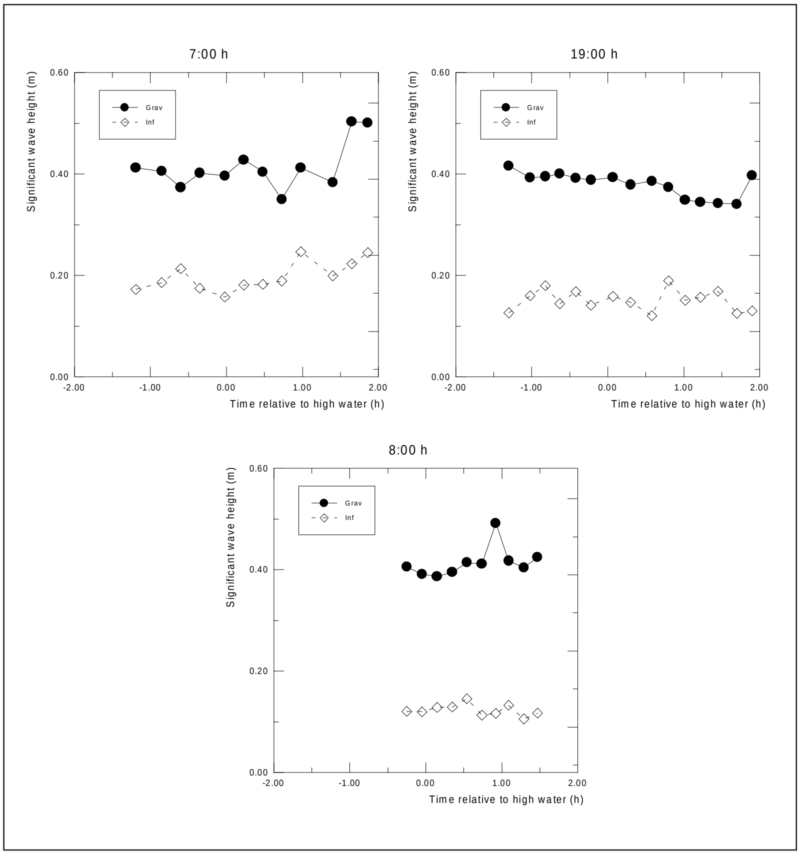


Figure 2. Significant wave-height data against time relative to high water for the three datasets

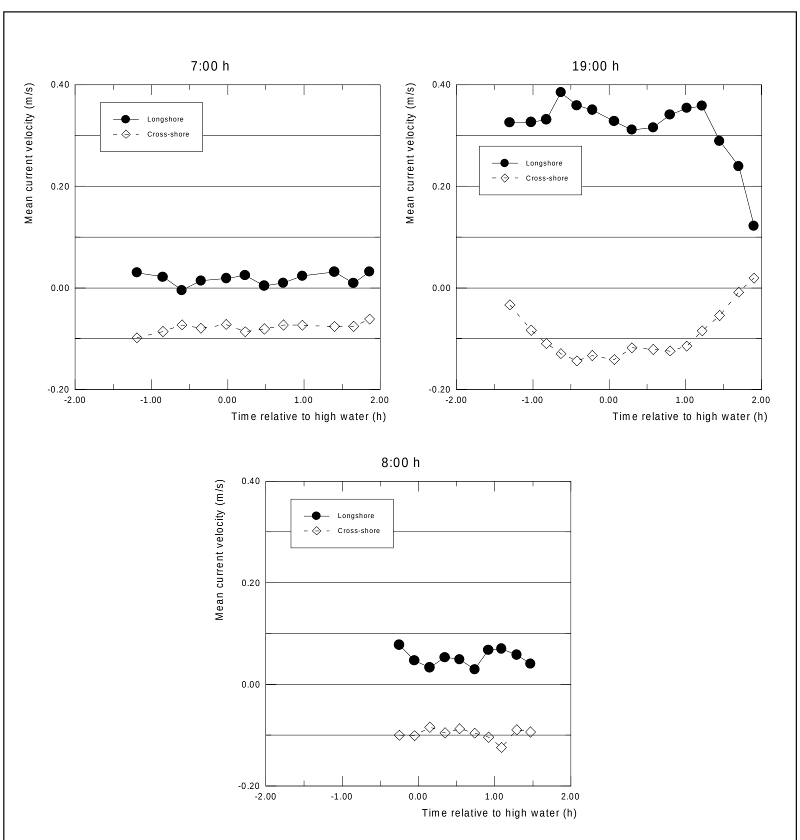


Figure 3. Mean longshore and cross-shore current velocities against time to high water for the three datasets

current indicate eastward flow. Mean longshore current velocities reached a maximum in the second dataset (between 0.3-0.4 m/s) while they were one order of magnitude smaller during the first (0-0.03 m/s) and third tides (0.03-0.07 m/s).

This increase in current speed is attributed to a moderate wind that was blowing alongshore during the second tide (Ciavola *et al.*, 1997a). Mean cross-shore current velocities were always directed offshore, with very similar magnitude for all tides (≈ 0.1 m/s).

Suspended sediment

Figure 4 presents a 10 min data record from the first tide, showing water depth, cross-shore and longshore velocities at 0.45 m above the bed, and suspended sediment concentration at three elevations from the bed.

This time-series shows that suspension occurred during intermittent events at time-scales near those

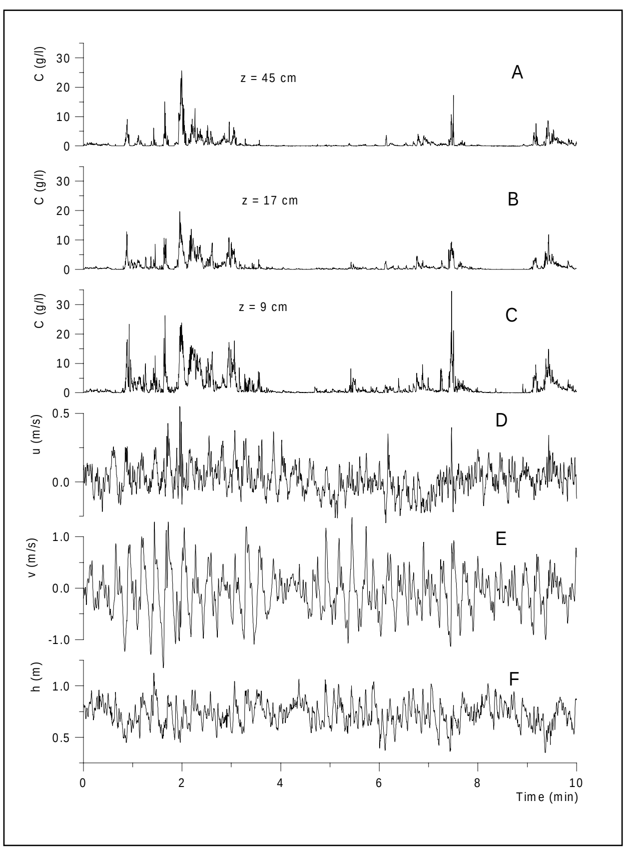


Figure 4. Time series (9th run of the first tide) of sediment concentration at three levels from the bed (A, B, C), longshore velocity (D), cross-shore velocity (E) and surface elevation (F)

of the incident wave period, as well as the presence of a large low-frequency modulation. Although the suspension of sediment occurred intermittently, the burst average concentration profiles are smooth, decreasing monotonically with elevation, and showing a coherent variation throughout the tidal cycle (figure 5).

For the first tide, mean sediment concentration was relatively low, and exhibited a strong cross-shore variation in concentration level. Outside the surf zone, time average concentrations were approximately 0.5 g/l at OBS2. Around the plunge point, the average concentration level increased to a maximum of about 1.5 g/l, at the same height above the bed. Following the pattern of current measurements, mean concentration values were much higher during the recording of the second dataset, attaining mean values of up to 14 g/l at OBS2 and 7 g/l at OBS3 (the lowest OBS was probably buried). In this set of measurements, an increased occurrence of suspension events on the ebb tide is visible. Around the third high tide, mean concentration decreased again, with values around 2-3 g/l outside the surf zone, while concentrations of up to 5 g/l were detected in the surf zone by OBS2.

Cross-shore sediment transport modes

The local net cross-shore suspended sediment transport was highly variable (figure 6). Outside the surf zone, cross-shore transport was weaker and generally directed offshore due to the presence of an offshore steady current, whereas in the breaker zone the fluxes driven by the incident waves were usually dominant. This last flux had opposite directions in the three datasets, being directed onshore in the second dataset and offshore in the other two. Cross-shore transport due to infragravity motions had a maximum, directed offshore, in the breaker zone, but with a magnitude that was almost negligible.

Longshore sediment transport modes

The total mean gravity and infragravity modes of longshore transport, at approximately 43 cm from the bed, are shown in figure 7. Total longshore suspended sediment transport followed the same pat-

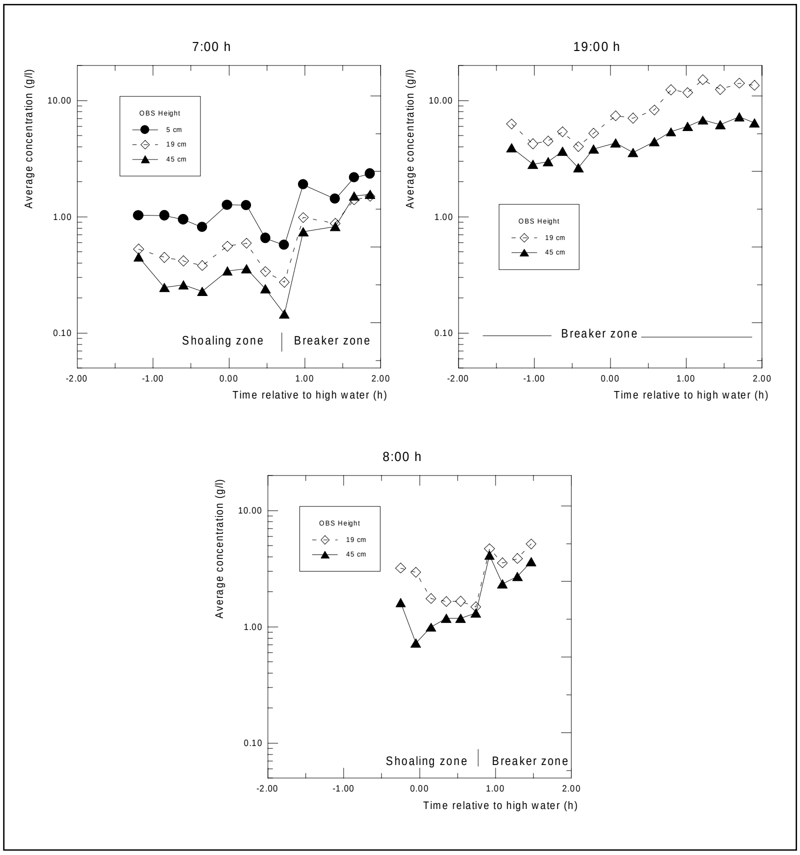


Figure 5. Time-averaged sediment concentrations

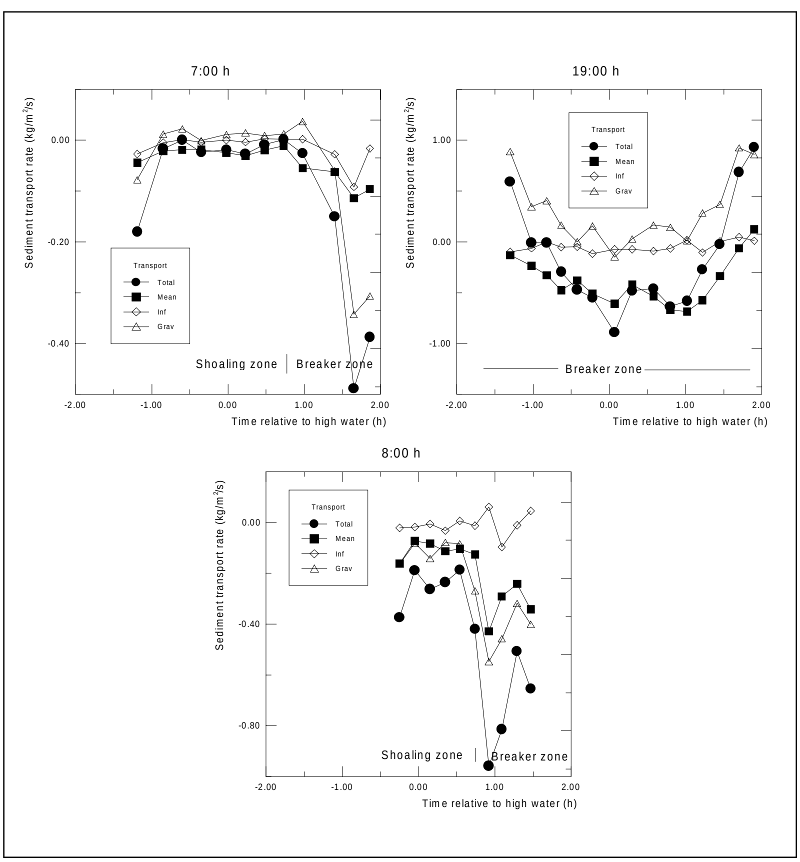
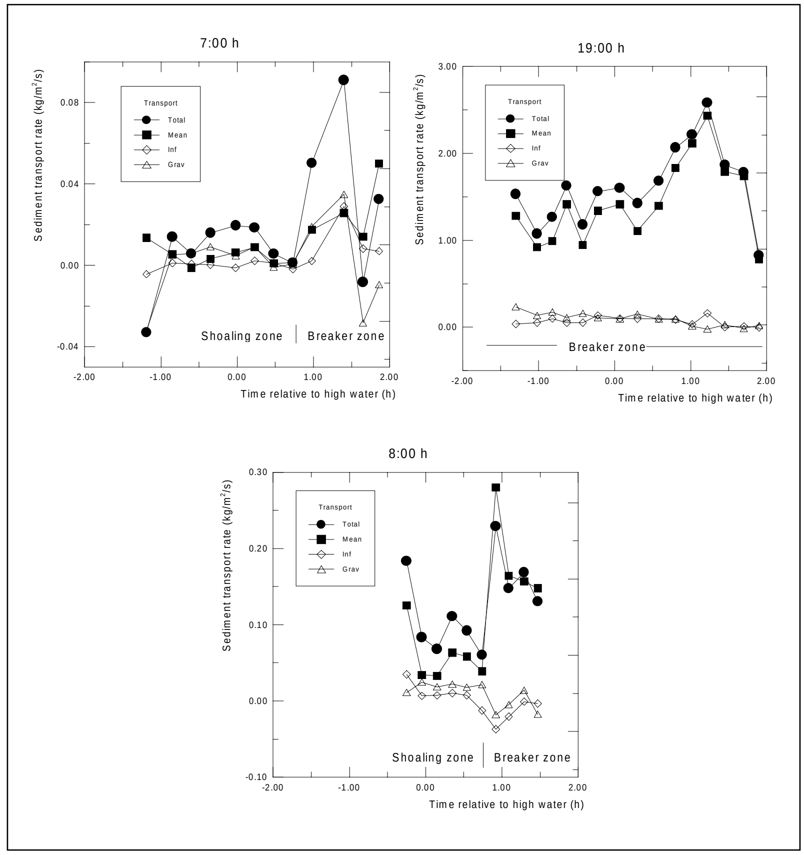


Figure 6. Cross-shore transport modes (note different scales for the three tides)

Figure 7. Longshore transport modes (note different scales for the three tides)



tern as the mean longshore current, reaching its maximum during the second tide and minimum during the first one. As expected, the current-related steady components accounted for most of the transport, being the oscillatory contribution, incident and infragravity, generally very small, attaining only some significance during the first tide, when total transport was very small. During this tide, the oscillatory component even induced a reversal in longshore transport direction.

Total longshore sediment transport

The time-average flux q(x,z) of sediment alongshore is a function of both distance offshore (x) and elevation from the bottom (z), and can be calculated from:

$$q(x, z) = q_0\ (x)\ p(x, z) \qquad [4]$$

where q_0 (x) is the flux at the bottom and p(x,z) is the profile function. As observed in sediment traps deployed during the experiment and during comparable field studies (e.g. Kraus and Dean, 1987; Rosati *et al.*, 1991; Levoy *et al.*, 1994) the flux profile can be described by a simple exponential curve whose shape is independent of the measurement location in the surf zone:

$$p(x, z) = p(z) = e^{-az} \qquad [5]$$

where *a* is the decay parameter of the flux profile. Therefore, the total longshore transport, between the shore (x = 0) and the breaker line ($x = x_b$), can be computed from:

$$Q_s = \int_0^{x_b} \int_0^{h(x)} q_0\ (x) e^{-a.z}\ dz\ dx \qquad [6]$$

where h(x) is the water depth.

In order to solve equation [6], it is necessary to know the cross-shore distribution of the longshore sediment flux at the bed q_0(x). This problem, expressed in slightly different forms, has been addressed by several authors (see Komar, 1990, for a discussion), although no definitive solution has been found to date. Therefore, the distribution was inferred from the collected data, using the approach described in the following section.

Cross-shore distribution of longshore sand transport

Since no measurements of sediment transport were made at the bed, values had to be deduced from the observed ones, measured at elevation z from the bed. The bed flux can be calculated from the knowledge of the flux at height z from the bed, assuming an exponential profile, by:

$$q_{0b} = q_{zb}e^{az} \quad [7]$$

If parameter a is constant, then this equation shows that the bed concentration is linearly related to a flux measured at height z from the bed, so the shape of the cross shore suspended sediment concentration curve is equal at all heights. Since during the present experiment, the only pair of EMCM and OBS that ran without any errors was the one located approximately 0.43 m from the bed, it was decided to use those values for estimating this relationship (figure 7).

Taking into account the tidal variation, and assuming that on a non-barred shoreface the observed temporal variations represent, approximately, spatial variations (i.e. $x/x_b = (h_b - h)/\text{slope}$), it was possible to calculate the cross-shore suspended transport distribution [q(x)] normalised by the measured maximum transport (q_{max}). The obtained results for the datasets are in figure 8.

Despite some expected scatter (due to tidal asymmetry, uncertainties in breaker position, etc.),

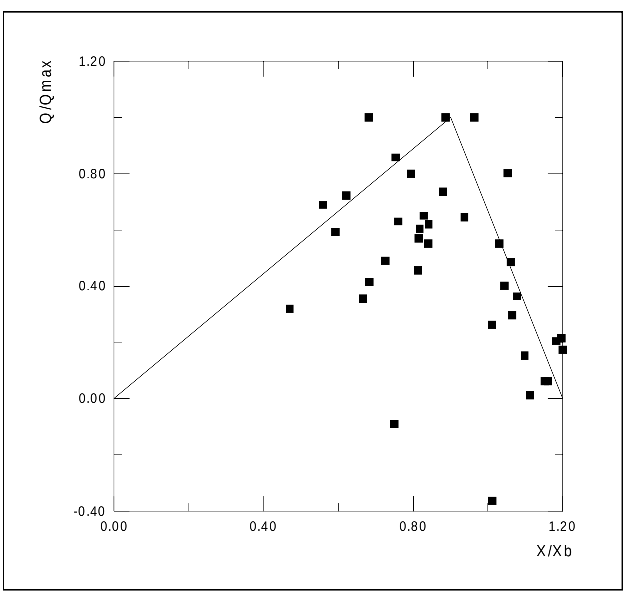


Figure 8. Local relative transport rate of suspended sediment transport *vs* relative position in the surf zone

these data show a well-defined peak near the breaker line ($0.7 < x/x_b < 0.9$), decreasing both seawards and shorewards. Because of the irregular distribution of cross-shore measurements, a simple linear model was adjusted.

The fitted model is similar to the ones presented by Sternberg, Shi and Downing (1989), Komar (1990) and Bodge and Dean (1987), and represent a reasonable fit to the data. Since there where no measurements in the swash zone, it was assumed that the transport rate was zero at the shoreline, increasing linearly up to $x/x_b = 0.9$ and then decreasing again to zero up to $x/x_b = 1.2$:

$$\frac{q_0}{q_{0max}} = \begin{cases} \dfrac{x}{0.9x_b} & \text{for } 0 < x \leq 0.9\,x_b \\ \dfrac{1.2x_b - x}{0.3x_b} & \text{for } 0.9x_b < x \leq 1.2x_b \end{cases} \quad [8]$$

This distribution does not take into account the swash zone, because no data were collected there. After having determined cross-shore variations in longshore transport, the only missing link to solve equation [6] is knowledge of the decay parameter.

Decay parameter estimation

To determine the decay parameter, the vertical variation within the water column of alongshore sediment transport must be known. Unfortunately, this was not feasible for the present experiment, because for most of the time, only one pair of EMCM and OBS was working at the same height. However, the parameter can also be estimated using analyses of concentration profiles.

The relationship between concentration and sediment flux is given by:

$$q(z) = c(z)\,u(z) \quad [9]$$

If $u(z)$ is constant, then the flux and concentration profiles have exactly the same shape, so if the flux profile is exponential, the concentration profile is also exponential, with the same decay parameter:

$$c(z) = c_0e^{-az} \quad [10]$$

Although this is not exactly true, because it has been observed that the mean longshore velocity profile has a logarithmic profile, the differences are only significant near the bottom. Therefore, if the values used for estimating the decay parameter are not taken too close to the bottom, the differences are negligible.

In the present study, the decay parameter was estimated by least-square fitting of the available concentration profiles obtained from the OBS arrays. Since the number of points available for the analysis was very low (the concentration was determined at three heights for the first dataset, and at only two for the other two datasets), it was expected that the values would exhibit considerable variations.

The calculated values ranged between 0.5 and 7, being most of them between 1 and 4, with a mean value of 2.5 (figure 9). It can also be seen that the data did not reveal any evident trend, supporting the idea of a concentration profile shape independent of surf-zone location, with the scatter due only to the lack of experimental data. However, it must be stressed that calculations were performed using a very limited dataset, so the values presented here can be regarded as merely indicative.

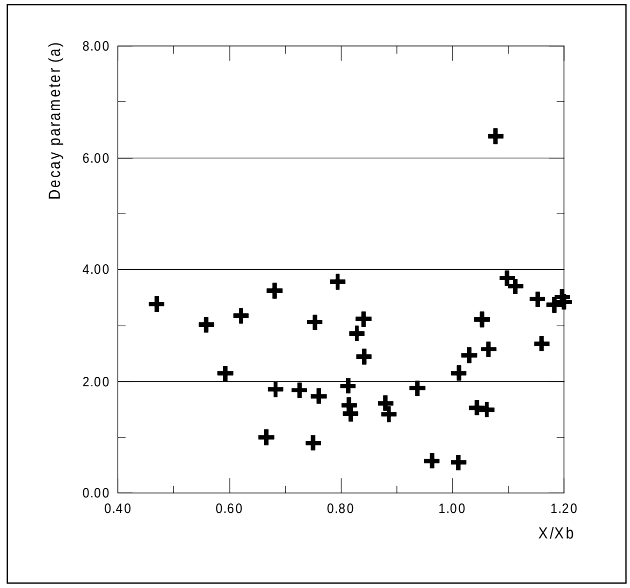


Figure 9. Cross-shore variation of decay parameter

Total transport computations

Assuming a linear variation of the water depth from the shoreline to the breaker line, and that flux at the bed follows eq. [8], total longshore transport can be rewritten as:

$$Q_s = \int_0^{0.9\,x_b} \int_0^{h_b x/x_b} q_{0max} \frac{x}{0.9x_b} e^{-az}\, dz\, dx +$$

$$+ \int_{0.9xb}^{1.2x_b} \int_0^{h_b x/x_b} q_{0max} \frac{1.2x_b - x}{0.3x_b} e^{-az}\, dz\, dx \qquad [11]$$

not taking into account longshore transport in the swash zone ($x/x_b < 0$). [11] can be rewritten as:

$$Q_s = q_{0max}\, x_b \left(\frac{0.6}{a} - \frac{1.111}{a^3\, h_b^2} - \frac{3.333}{a^3 e^{1.2a\, h_b}\, h_b^2} + \right.$$
$$\left. - \frac{4.444}{a^3 e^{0.9a\, h_b}\, h_b^2} \right) \qquad [12]$$

After substituting x_b and h_b for the observed values (x_b = 7 m, h_b = 0.7 m):

$$Q_s = q_{0max} \left(\frac{4.2}{a} - \frac{15.873}{a^3} - \frac{47.619}{a^3 e^{0.84a}} + \right.$$
$$\left. + \frac{63.492}{a^3 e^{0.63a}} \right) = q_{0max} f_1(a) \qquad [13]$$

Using equation [7], it is possible to rearrange equation [13] in order to calculate total flux as a function of the measured flux at 43 cm from the bed:

$$Q_s = q_{0.43max}\, e^{0.43a}\, f_1(a) = q_{0.43max}\, f_2(a) \qquad [14]$$

Using equation [14] and a decay parameter value equal to the observed mean (2.5), it was possible to estimate the total longshore transport for the three datasets, which are shown in table I.

Table I. Total longshore transport (Q) for the three tides, estimated from OBS sensors

Tide	q_{max} (m/s)	Q - OBS (m^3/s)
7:00 h	3.40E – 05	1.13E – 04
19:00 h	9.77E – 04	3.24E – 03
8:00 h	8.68E – 05	2.88E – 04

In order to determine the influence of the uncertainties associated with the decay parameter estimate on total transport, a graph of the $f_2(a)$ function was made (figure 10). For the observed range of decay parameter estimates (1-4), the corresponding values of calculated sediment transport varied by a factor of two, which is within the accuracy expected for sediment transport calculations.

DISCUSSION

Recent field studies of suspended sediment transport on beaches focused essentially on dissi-

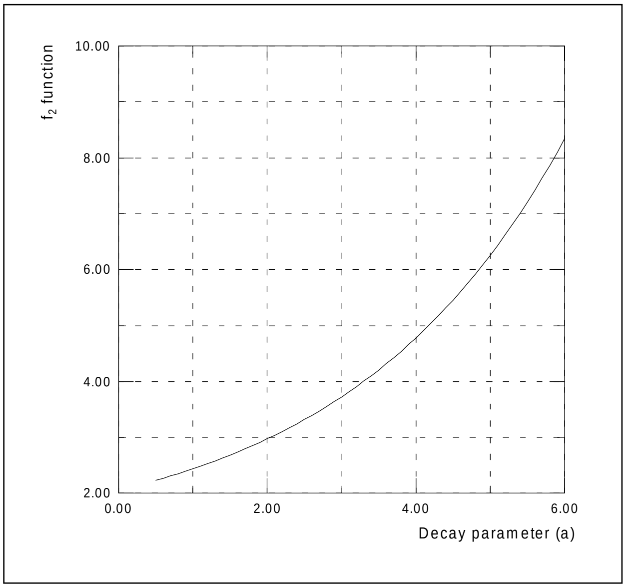


Figure 10. Variation of f_2 function with decay parameter (see text for explanation)

pative and intermediate beaches (Beach and Sternberg, 1988; Davidson *et al.*, 1993; Aagaard and Greenwood, 1995; Beach and Sternberg, 1996; Osborne and Vincent, 1996). The present field measurements offer an opportunity to increase the understanding of the short- term dynamics of steep beaches with plunging breakers.

In the breaker zone, time-averaged concentrations were usually greater than 1 g/l, reaching values of 5 g/l at 45 cm away from the bed, despite the quite moderate wave conditions (Hs $\approx$ 0.4 m). These high concentration values are probably associated with the presence of plunging breakers. As pointed out by several authors (Kana, 1978; Van Rijn, 1989; Beach and Sternberg, 1996) breaker type is a dominant factor in wave-related sediment suspensions. Spilling breakers are less effective than plunging breakers, which is probably because of the relatively small scale of the eddies that are generated. Although fluid motion within breakers is still poorly understood, Miller (1976) examined the generation of turbulent vortices. In spilling breakers, vortex generation is weak and confined to the near-surface region, but in plunging waves a jet is impelled into the preceding trough, often penetrating as far as the bed, generating large sediment concentrations. This mechanism can explain the large suspended sediment concentrations found and account for the large sand-mixing depth observed (Ciavola *et al.*, 1997b) and for the high transport rates measured (Ciavola *et al.*, 1997a). The dependency of longshore sand transport on breaker type was first proposed by Kana (1978) and subsequently confirmed by other authors (e.g. Levoy *et al.*, 1994; Beach and Sternberg, 1996). For example, Levoy *et al.* (1994) presented two different empirical coefficients for global longshore transport rate, which depend on breaker/beach type. When the beach is reflective with plunging waves, these authors proposed a coefficient that is 10 times greater than the one when the beach is dissipative with spilling waves.

The asymmetry of suspended sediment concentration observed, especially in the second tidal cycle, agrees with the findings of Davison *et al.* (1993) and Russel (1993). These authors measured higher SSCs during the ebb than during the flood tide on macro-tidal dissipative and intermediate beaches. According to their results, the increased occurrence of suspension events on the ebb-tide may be caused by variations in the level of the beach water-table (more likely to be important on a high gradient slope like the present one), or be caused by bedform alterations between the flood and the ebb tide. As no bedforms were measured during the present experiment, it is not possible, at the moment, to give a definitive answer to this problem.

We found that longshore sand transport was generally dominated by current-related fluxes. This is especially true during conditions of high longshore sediment transport rates. This observation, which opposes the ideas of Hanes (1988), is particularly interesting because it indicates that longshore velocity and concentration oscillatory terms (equation [6]) are usually not correlated, and makes it possible to calculate longshore computations using time-averaged quantities.

Outside the surf zone, cross-shore sediment transport was also dominated, although to a lesser extend, by current-related transport, whereas in the surf zone incident wave-related fluxes were dominant. Contrary to much previous research carried out on dissipative and intermediate beaches (Beach and Sternberg, 1988; Davison *et al.*, 1993; Beach and Sternberg, 1996; Osborne and Vincent, 1996), infragravity motions were always found to be very weak. Although it is known that these motions increase near the shoreline, where we took no measurements, looking at trends in our collected data, it does not seem probable that they dominate the transport process, at least under moderate wave conditions.

In order to test the reliability of optical sensors for determining longshore sand transport, they were compared with tracer results obtained by Ciavola *et al.* (1997a). However, before any comparison can be made, the differences in the type of measurements obtained with the methodologies must be pointed out. OBSs measurements were obtained around high tide, when the beach state was more reflective, whereas tracer results give an integrated estimation covering the entire tidal cycle, accounting for the effects of tidal fluctuations on beach state and sediment transport processes. Although at the time of the experiment, these phenomena were probably not very pronounced, due to the limited tidal excursion, they should be taken into account. The results obtained using the two methods are shown in table II.

Table II. Comparison of total longshore transport from OBS sensors and sand tracers

Tide	Q - OBS (m^3/s)	Q - Tracers (m^3/s)	Q - Tracers/ Q - OBS
7:00 h	1.13E – 04	2.30E – 03	20.3
19:00 h	3.25E – 03	1.38E – 02	4.3
8:00 h	2.88E – 04	2.30E – 03	8.0

The results for the second and third tides agree reasonably well, especially if it is taken into account that several assumptions were made: an over-simplification of suspended sediment concentration patterns in the surf zone (including the extrapolation down to the bed, which may not be a valid representation of real bed load); errors in determining peak sediment transport; transport in the swash zone that was not accounted for. The fact that swash-zone transport was excluded can probably explain a large part of the observed differences. In fact, in the few papers where swash zone-transport was determined, it accounted for a large portion of the total longshore transport. Using a multicolor tracer experiment on Orai beach, Kraus, Farinato and Horikawa (1981) found that the transport rate was greatest for the tracer injected in the swash zone. In the series of experiments described by those authors, maximum transport occurred near the shoreline, the breaker line or both. Bodge and Dean (1987), using a short-term sediment impoundment scheme, consisting of the rapid deployment of a low-profile barrier, concluded that swash zone transport can represent from 5 % to more than 60 % of the total drift. Levoy *et al.* (1994), in the analysis of cross-shore sediment transport, obtained using sediment traps, found that, during wind-wave conditions acting on steep beaches, the swash zone transport sometimes exceeded 3 to 4 times the mean longshore transport integrated over the width of the breaker zone.

If the differences for the last two datasets seem reasonable, for the first one the observed disagreement appears too large to be explained by these factors only. Moreover, for the first and last datasets, tracer results gave the same estimate of longshore drift, even though mean current velocity was much lower during the first tide. As already observed in other sand-tracer experiments performed by the DISEPLA Group (unpublished) and by other authors (e.g. Kraus, Farinato and Horikawa, 1981), the velocity of the tracer centroid appears to be large during the first few hours after release, and then it slows down. For example, in the successive sampling performed by Kraus, Farinato and Horikawa (1981), there was a tendency for the tracer to move rapidly during the first hour after injection and then to slow down a great deal, with tracer advection speeds presenting a variation of a factor of four, as a function of the elapsed time after injection. One of the basic assumptions underlying the use of tracers for the determination of longshore sand transport rates is that tracer material is in equilibrium with the transport system. However, since tracers are generally released on the beach, or in the first few centimetres of the bed, initially they travel at a much higher speed, requiring a few hours to be completely mixed within the moving bed. This invalidates the use of the 'river of sand model' (Komar and Inman, 1970), at least,for the first few hours after release. This might explain the difference in estimates obtained with the use of tracers and optical techniques for the first tide. A promising alternative model for interpreting sand tracer distribution is the 'waiting time theory' proposed by Galvin (1987, originally developed in 1964). According to this theory, tracer movement must balance erosion and deposition around a mean bed elevation. This model predicts well the delay in release from the tracer source, slowing down the advection velocity. However, we are not aware of any tracer data interpretation based on this theory.

CONCLUSIONS

Data obtained during our experiment on Culatra Island confirmed that field measurements of longshore sand transport are still subjected to various kinds of errors and to a large degree of uncertainty. Many of the differences in results produced by various previous studies are intrinsic to the sampling techniques employed, and only with independent methods is it possible to determine their underlying errors. In the present paper, the results from fluorescent tracers and optical techniques were found to give similar results, once their major limitations were considered. For sand tracers, a major shortcoming appears to be the requirement of sufficient time for complete mixing to take place, while for OBSs it seems to be their inability to measure swash-zone transport.

This experiment has also confirmed that the sedimentary behaviour of steep reflective beaches with plunging breakers is very different from that of gentle-gradient beaches with spilling breakers. In fact, for this type of beach, suspended sediment concentration and longshore sand transport are much larger, supporting the idea that one of the major limitations of longshore sediment transport models is their lack of dependence on breaker/beach type. Further research must be carried out in order to better describe physical processes and to develop a reliable quantitative framework.

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