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SEDIMENT RESUSPENSION AND CROSS-SHORE CYCLING IN NEARSHORE ENVIRONMENTS

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Abstract: A series of field experiments were conducted to investigate sediment re-suspension and cross-shore cycling in nearshore environments with special emphasis on different frequency components (wind waves, swell, infra-gravity waves etc.). Measurements included simultaneous records of surface elevation, cross-shore current velocities, and suspended sediment concentrations both inside and outside of the breaker zone. Measurement locations were selected to cover a range of hydrodynamic and sedimentological conditions. The results indicated that wave groups appeared to be more capable of re-suspending sediments than incident waves. Results of co-spectral analysis indicated that the direction of cross-shore (suspended) sediment flux on the frequency domain was different for each location under different conditions. This leads to the hypothesis that there are additional factors such as the local wave climate, grain size, beach slope, bed forms, etc., governing the pattern of cross-shore suspended sediment transport flux in the frequency domain.

INTRODUCTION

With the rapidly increasing population density along coastal stretches globally, coastal erosion has become a prime concern, needing immediate attention. Accurate prediction of sediment transport in nearshore environments, however, is one of the most important and complex challenges presently faced by coastal researchers. Although nearshore sediment transport occurs mainly in the longshore direction, the generally smaller cross-shore transport plays a dominant role in determining seasonal shoreline evolution, beach morphology, etc. Further, it has been noticed that longshore transport is predominantly due to steady motions, whereas the cross-shore transport is driven by a range of mean (tides, undertow, etc.) and oscillatory components (wind waves, swell, wave groups, infra-gravity waves, etc.). These different frequency components appear to influence the cross-shore sediment transport differently both in direction and magnitude. Therefore, an improved understanding of the processes of sediment suspension and cycling within this highly dynamic region is essential to accurately predict cross-shore sediment transport, and thus coastal stability.

Wave groups

With any combination of waves a point will occur where all frequencies interact and the resulting wave has minimal amplitude. A set, or group of waves between two of these points is called a wave group (Figure 1). It also follows that maximum wave heights occur through a positive interference between the waves (Figure 1).

Group bound long wave

Longuet-Higgins and Stewart (1962 and 1964) developed the theory of radiation stress and explained the presence of low frequency oscillations in nearshore environments under non-breaking waves; as a wave group passes a particular point, waves that are larger than mean of the wave group depress the mean water surface, thereby forcing a long wave, which is defined as a group bound long wave. Therefore, wave groups are always associated with a 'group bound long wave' (Figure 1).

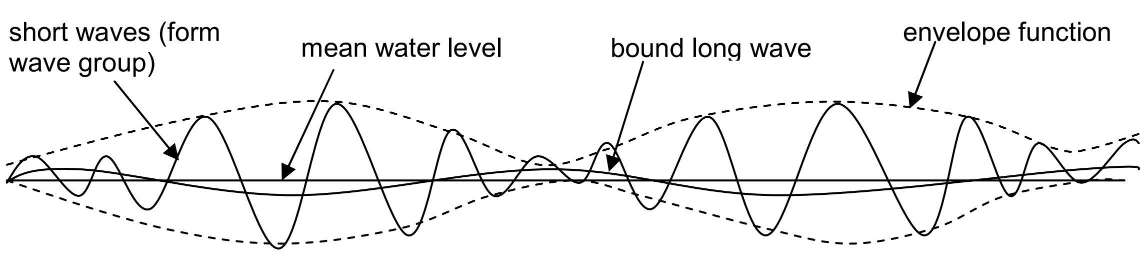

Figure. 1. Wave groups and group bound long wave.

BACKGROUND

Majority of previous studies in nearshore regions have revealed that the suspension of sand, and hence, the cross-shore sediment flux in the nearshore region, occurs in an event-like manner over a range of time scales ranging from seconds (wind waves, swell) to minutes (wave groups or infragravity waves) (Brenninkmeyer 1976; Hanes and Huntley 1986; Osborne and Greenwood 1993; Masselink and Pattiaratchi 2000). These studies also indicated that suspension events that occurred at low frequencies were much more pronounced than those at incident frequencies (Hanes and Huntley 1986; Huntley and Hanes 1987; Davidson et al. 1993; Osborne and Greenwood 1993; Masselink and Pattiaratchi 2000). This enhances the assumption that wave groups are more capable of stirring sediment particles from the seabed than incident waves. Vincent et al. (1991) presented a possible explanation for the pronounced suspension events under low frequency oscillations (wave groups) aided by variation in ripple geometry. However, this phenomenon of higher suspension events at wave group frequencies was not just experienced over rippled beds. Clarke et al. (1982) suggested that these higher suspension events occurred as a result of bursts of intense turbulence caused by the largest waves within the group. Osborne and Greenwood (1993) further elucidated this with the aid of turbulence transfer.

Observations made under different conditions, covering various parts of the globe, however, appeared to be inconsistent, especially with respect to the direction of sediment flux (onshore/offshore) under different frequency components. Past investigations have suggested that shoaling waves outside the breaker zone at lower frequencies (wave groups, infragravity waves), the cross-shore sediment flux was in the offshore direction and reversed to onshore direction under higher frequencies (wind waves, swell) (Huntley and Hanes 1987; Hanes 1988). The shoreward sediment flux under incident waves was due to the increasing wave asymmetry as waves shoaled, and the mechanism for seaward flux under low frequencies (wave groups) was explained by higher waves of the wave groups causing higher suspension events, which in turn coincided with the offshore phase of the group bound long wave forcing sediment shoreward (Larsen 1982; Shi and Larsen 1984).

Contradictory results have also been found in the literature, where offshore fluxes were evident at incident frequencies and vice-versa (Davidson et al. 1993; Aagaard and Greenwood 1995; Masselink and Pattiaratchi 2000), leading to the assumption that there were additional factors influencing the cross-shore sediment transport in nearshore environments. Thus, a better understanding of the factors governing the direction of cross-shore sediment flux (cycling) on frequency domain is required.

This paper reports results obtained through a series of field measurements (water surface elevation, horizontal current velocities, and suspended sediment concentration) undertaken in nearshore environments (outside the breaker line) at different locations covering various conditions such as differing wave climate, grain size, beach slope, bed forms, etc. These results were then utilized to explore the consistency in cross-shore sediment flux on frequency domain under different conditions.

FIELD EXPERIMENTATION

Field sites

The field measurements that provided the basis for the present study were undertaken at several locations—Mullaloo Beach, Floreat Beach, and Broome (Western Australia) and Chilaw (Sri Lanka)—covering a range of conditions. The selected sites had long straight exposed beaches, where waves were not distorted, and an absence of offshore bars. The beach slopes at Floreat, Mullaloo, and Chilaw were approximately 1:20, whereas in Broome the slope was around 1:50. The selected sites also contained a wide range of grain sizes. At Mullaloo Beach the mean grain size was 0.28 mm, which was relatively coarse. The mean grain size was 0.15 mm at Chilaw, 0.11 mm (very fine) at Broome, and 0.20 mm at Floreat. Grain sizes at all the sites showed little variation in the cross-shore direction.

Instrumentation

The data on surface waves, currents, and suspended sand concentrations were collected with the 'S' probe - an instrument package developed at the Centre for Water Research, University of Western Australia. The 'S' probe consists of a Paroscientific Digiquartz pressure sensor and Neil Brown ACM2 acoustic current meter together with three optical backscatter (OBS) turbidity sensors (four additional OBS's were coupled with the S probe in the Broome measurements). The pressure sensor was located 0.35 m above the seabed. The two-dimensional horizontal velocity at 0.20 m above the seabed was recorded by the current meter. The OBS sensors recorded the concentration profile at three levels at City Beach: 0.050, 0.125, and 0.275 m above the seabed. At Broome the OBS's were installed at 0.050, 0.075, 0.11, 0.165, 0.245, 0.37, 0.55, and 0.82 m from the seabed.

Similar to Huntley and Hanes (1987), the cross-shore current velocity was measured only at one point, as we assumed that the velocities under oscillatory flow in shallow water remained constant over the depth except within the narrow bottom boundary layer. This was confirmed by the measurements recorded with a 2MHz ADCP, Aquadopp Profiler at Floreat beach, where the vertical variation of the cross-shore current velocity was observed to be constant.

The majority of measurements were conducted just offshore of the breaker zone, where the presence of wave groups was visually observed. In Chilaw, however, the instrument station was moved across the breaker line, and measurements were obtained both inside and outside the breaker line. In Broome, where the tidal range is large (~ 10 m), the breaker line at the location of the instrument location varied with time. All measurements from Broome presented in this paper were obtained around high tide (morning and early afternoon) before the onset of the sea breeze.

Visual observations of the bottom geometry near the instrument station at half hourly intervals were undertaken in Broome using a snorkel and mask, which contributed to understanding the presence of ripples, or flat bed (sheet flow conditions).

Most of the measurements were obtained during calm sea conditions (i.e., in the morning before the inception of the sea breeze) dominated by swell, which is ideal for pronounced wave groupiness. The aim was to obtain data sets that covered all possible frequency components (incident waves, infra-gravity periods, etc.).

Beach profiles were surveyed using a total station (Theodolite), while sediment samples collected at the field sites were used to determine the median grain size and to calibrate the OBS's. The sand samples obtained at the field sites were calibrated following the method described by Ludwig and Hanes (1990). Additional details of the field measurements can be found in Masselink and Pattiaratchi (2000) and Pattiaratchi et al. (1997).

DATA ANALYSIS AND RESULTS

Sediment re-suspension

The role of wave groupiness on sediment re-suspension was investigated by comparing time series records of the wave groupiness envelope, cross-shore current velocity, and suspended sediment concentration. The groupiness envelope was computed by low-pass filtering the modulus of the cross-shore current record at 0.01 Hz (List 1991). Figure 2 presents the time series records of cross-shore current velocity and suspended sediment concentration obtained from Mullaloo, Western Australia during calm sea conditions dominated by swell. The re-suspension events appear to be closely associated with the passage of wave groups.

Cross-shore sediment cycling

Cross-correlation and co-spectral analyses were performed to quantify the different aspects involved in sediment re-suspension and cross-shore cycling. The results obtained for the cross-shore current velocity and suspended sediment concentration data records (presented in Figure 2) are shown in Figure 3 (Mullaloo, Western Australia). The data set included 8192 points with a frequency of 5 Hz. The instrument station was maintained just outside the breaker zone, and the seabed was found to be flat (sheet flow).

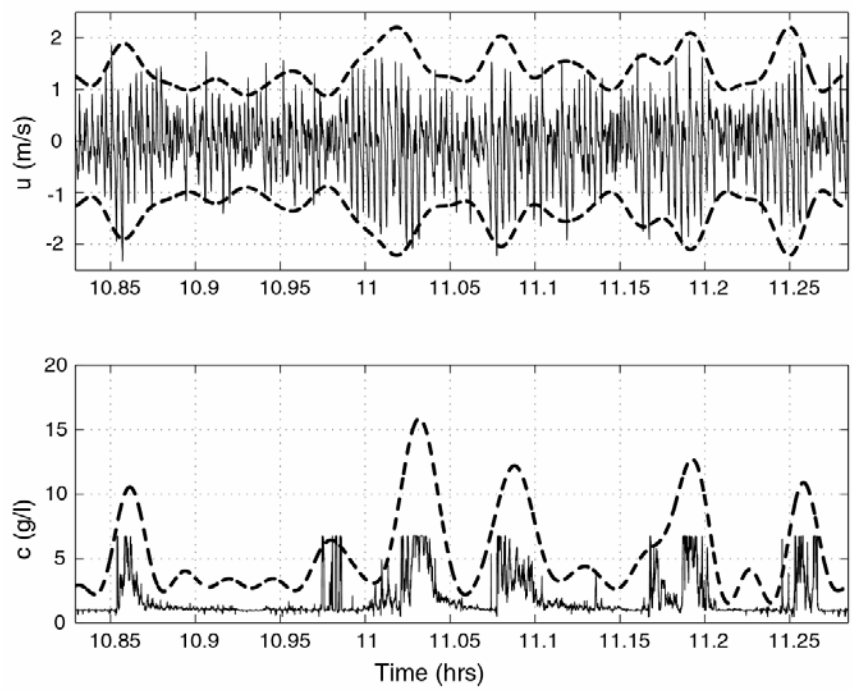

Fig. 2. Time series of: (a) cross-shore current velocity u (solid line) and envelope function of u (thick dashed lines); and, (b) suspended sediment concentration c 0.125 m from the bed (solid line) and low-pass filtered c (thick dashed line).

The normalised auto-spectra of the cross-shore current and suspended sediment concentration (Figure 3a) were used to identify the dominant frequencies (two curves were not in the same scale as scales were adjusted to make spectral peaks distinct). Figure 3b presents cross-correlation between the groupiness envelope and the low-pass filtered cross-shore current. Groupiness envelope highlighted the presence of wave groups, while the low-pass filtered cross-shore current signal underlined the presence of low frequency oscillations. Figure 3c shows the most important aspect of the present study: the co-spectrum between the time series of cross-shore current and sediment concentration, which portrays the directional variation in cross-shore sediment flux on the frequency domain. Finally, the cross-correlation between the groupiness envelope of cross-shore current velocity and low-pass filtered sediment concentration (Figure 3d) elucidates the relationship between the two time series.

Figure 3a shows that the dominant peak for the cross-shore current was approximately 0.075 Hz, which corresponded to swell (~ 13 s), and the secondary peak was approximately 0.15 Hz (~ 7 s), due to first harmonic. The auto-spectra for sediment concentration, however, showed a low secondary peak at swell frequency (~ 0.075 Hz) and a distinct dominant peak at a very low frequency of 0.01 Hz (100 s), which corresponded to wave groups, indicating that more sediment was stirred at low

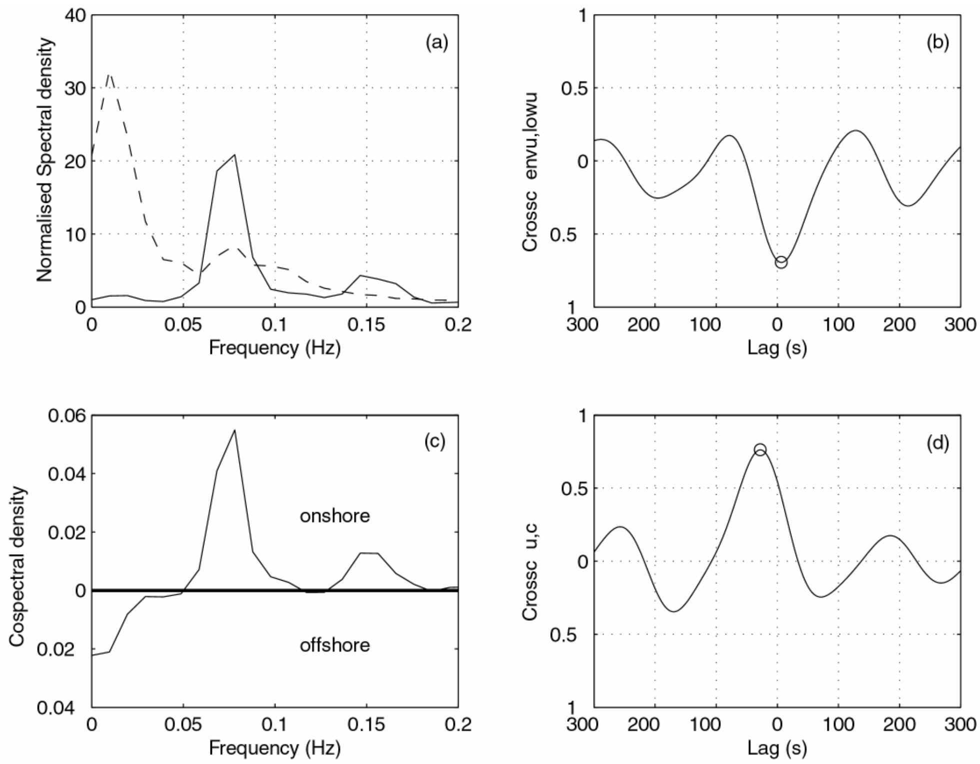

Fig. 3. (a) the normalised auto-spectra of cross-shore currents (u—solid line) and nearbed suspended sediment concentration (c—dashed line); (b) cross-correlation between an envelope function of *u* and low-pass filtered *u*; (c) the co-spectrum between u and c (units of the co-spectral density are $(gl^{-1})(ms^{-1})Hz^{-1}$); and, (d) cross-correlation between the envelope function of *u* and the low-pass filtered c

frequencies (wave groups). This has already been observed in Figure 2 and previously explained by several researchers.

A strong negative relationship with a time lags close to zero between the groupiness envelope and the low-pass filtered cross-shore current velocity is evident from Figure 3b. This strong negative correlation was an indication of the presence of a group bound long wave in association with the wave groups (Longuet-Higgins and Stewart 1964). The co-spectrum between the cross-shore current velocity and the suspended sediment concentration demonstrates the original finding for shoaling waves outside the breaker zone (Huntley and Hanes 1987): the cross-shore sediment flux was onshore at high frequencies (swell and wind waves) and offshore at low frequencies (wave groups). These measurements were obtained just outside the surf zone, where shoaling waves were associated with increased velocity (wave) asymmetry and skewness towards the onshore direction, forcing onshore transport under incident wave frequency. This indicates that the shoaling waves with increasing wave asymmetry in the onshore direction resulted in onshore sediment flux under incident wave frequencies. Moreover, it was apparent that high waves in groups stirred more sediment, which in turn coincided with the trough of the group bound long wave forcing the sediment offshore at low frequencies (Larsen 1982; Shi and Larsen 1984; Hanes 1991; Osborne and Greenwood 1992b).

Figure 3d confirms that the cross-shore current velocity and the sediment concentration had a strong positive correlation with a time lag of 27.8 s. This indicated that the suspended sediment concentration lagged the maximum offshore velocity of the bound long wave by the same time difference, which may result in a reduction in offshore sediment flux under low frequencies. Similar analysis with the sediment concentration revealed it measured higher in the water column, showing that this lag increased with the height. Hence, the cross-shore sediment flux for this set of data from Mullaloo Beach, Western Australia was in agreement with the original explanation for non-breaking waves outside the surf zone.

The same analysis approach was applied to a similar set of data collected from Broome, Western Australia. Data collection commenced during the rising tide (approximately 09:30 hrs), and was completed before the onset of the sea breeze (approximately 13:30 hrs). Figure 4 presents the results of the co-spectral analysis undertaken for a data set that commenced at approximately 11:30 hrs (around high tide), and of 16384 data points with the sampling frequency of 5 Hz. The instrument station was positioned a reasonable distance (~ 100 m) outside the breaker zone, since it was at high tide. Mean water depth (h) during this data set was approximately 2.7 m with a significant wave height (H_s) of 0.37 m (H_s/h was quite low - approximately 0.15). Cross-shore current velocity was measured at 0.25 m above the bottom, and the suspended sediment concentration was measured from 0.075 m above. Visual observations of the bottom topography were undertaken at half-hourly intervals. During this data set, two-dimensional ripples of approximate length (λ) 0.06–0.08 m and height (η) ~0.005 m were observed at the bottom. Hence, the corresponding ripple steepness ($\eta/\lambda < 0.1$) was less than 0.1, indicating the ripples are post-vortex. However, when the tide level was lower where the instrument station was positioned, either within or just outside the breaker zone, the ripples appeared to have eroded, leading to sheet flow conditions.

Similar to Figure 3a, Figure 4a shows a dominant peak of cross-shore current velocity of approximately 0.06 Hz (~17 s), which corresponded to swell waves, and the suspended sediment concentration peaked at a much lower frequency of 0.005 Hz (200 s), which showed the passing of wave groups. Here, the co-spectrum between the cross-shore current velocity record and the suspended sediment concentration (Figure 4b) indicated that at both swell (incident wave) and wave group frequencies the cross-shore sediment flux was directed offshore in contrast with the findings of Hanes and Huntley (1987).

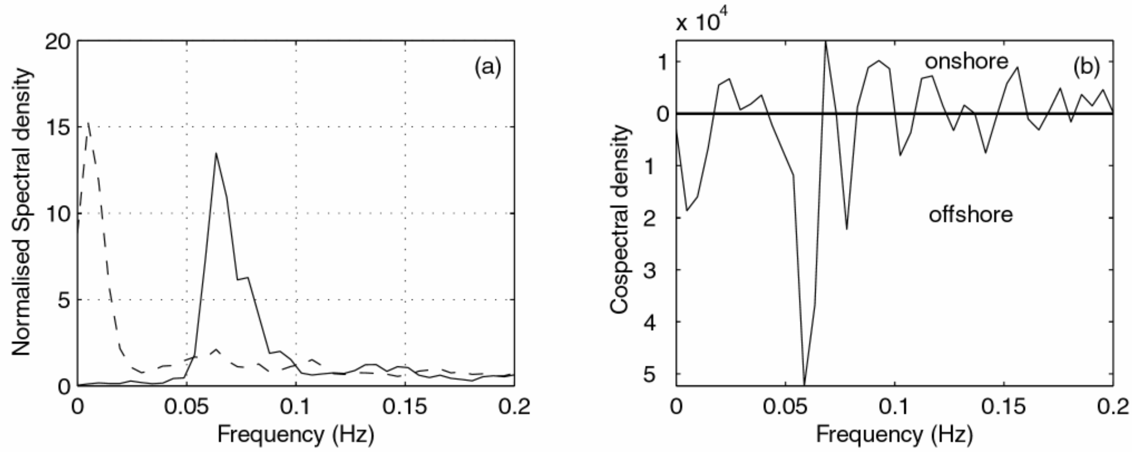

Fig. 4. (a) the normalised auto-spectra of cross-shore currents (u—solid line) and nearbed suspended sediment concentration (c—dashed line); (b) the co-spectrum between u and c (units of the co-spectral density are $(gl^{-1})(ms^{-1})Hz^{-1}$).

During this particular set of measurements, the instrument station was placed far outside the surf zone, where the normalised velocity skewness ($\langle u^3\rangle / \langle u^2\rangle^{3/2}$) calculated according to Russell and Huntley (1999) was found to be very low (~ 0.18) compared to the values obtained when the instrument station was close to the surf zone (~ 0.9). The normalised velocity skewness values (incident waves) calculated for the entire series of data sets, as the instrument station was first close to the breaker line, further offshore, and back in the surf zone with the tidal cycle, is presented in Figure 5.

The same pattern displayed in Figure 4b (variation of cross-shore sediment flux on frequency domain) could be observed throughout the rising tide and around high tide. It changed slowly with the falling tide, however, as the cross-shore sediment flux at incident wave (swell) frequency reversed to the onshore direction, the low frequency component (wave groups) remained in an offshore direction (Figure 6). This set of measurements (Figure 6) was collected at approximately 13:00 hrs, and therefore it was not surprising that sediment flux was onshore under swell frequency, given the instrument station was positioned just outside the surf zone. This confirmed that as waves shoal closer to the shoreline, they became more skewed in the direction of wave propagation, resulting in increasing onshore sediment flux under incident wave (swell) frequencies.

At this stage, the ripples were eroded leading to sheet flow conditions, as the instrument station was once again back in the surf zone towards the end of this set of measurements (approximately 13:30 hrs).