CHAPTER 168

NEARSHORE SEDIMENT FLUX AND BOTTOM BOUNDARY DYNAMICS THE CANADIAN COASTAL SEDIMENT TRANSPORT PROGRAMME (C-COAST)

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ABSTRACT
The Canadian Coastal Sediment Transport Programme (C-COAST) is designed to increase our knowledge of the dynamics of non-cohesive shorefaces through field measurement of sediment transport and the response of the bottom boundary under combined waves and currents. Suspended sediment concentrations are measured using Optical Backscatterance Suspended Solids Sensors (OBS-1P - D & A Associates) and a new multi-frequency, Remote Acoustic Sediment Transport system (RASTRAN). Near-bed velocities are measured using electromagnetic and electroacoustic flowmeters; cross-products of velocity and concentration provide estimates of sediment flux. The bottom boundary response is determined at the roughness (bedform) scale using a High Resolution Remote Tracking Sonar (HRRTS II) and at the shoreface scale using Depth-of-Activity rods and standard survey. Suspended sediment flux is extremely episodic, responding to individual waves, wave groups and low frequency motions, including mean flows. A significant time-dependent transport is revealed in the vertical structure. Net transport includes contributions from wind waves, low frequency waves and mean flows. A sediment transport balance controlling local slopes can therefore be achieved by spatial and/or temporal divergence of these components. Reservations must exist with respect to transport models which use depth and/or time averaged terms and which fail to recognize the distinct components of fluid motion contributing to the total sediment transport.

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INTRODUCTION

Perhaps the most intransigent problem restricting our understanding of coastal behaviour is the relationship between local sediment flux rates, sediment flux divergence and the response of the bottom boundary. Laboratory experimentation has been extensive and a number of parameterizations of the system have been proposed; however, they fail when applied to the prototype (see Seymour and Castel, 1989). Existing physically-based theory (e.g. Bowen, 1980a, Bailard, 1981) provide useful qualitative predictions, but include time and depth-averaged terms which remain questionable (Bowen, 1980b; Bailard, 1987). Few field data exist which have the necessary temporal and spatial resolution for evaluating either existing sediment transport theory or the underlying assumptions. A requirement in the testing of existing models and in the generation of new models is adequate field measurement of sediment transport and bottom boundary response. The Canadian Coastal Sediment Transport Programme (C-COAST) is a joint University venture, which has evolved from the Canadian Coastal Sediment Study (C^2S^2 - Willis, 1987), and is designed specifically to measure sediment transport and the concurrent response of the bottom boundary under combined waves and currents on the shoreface. The overall objectives are to: (i) investigate the spatial and temporal behaviour of near-bed suspended sediment concentrations; (ii) compute suspended sediment fluxes and relate them to both the forcing agents and to the bottom boundary responses; (iii) investigate the mechanisms controlling the directions and rates of suspended sediment flux; (iv) understand the nature of cross-shore and alongshore sediment fluxes on barred and non-barred shorefaces. In this paper we summarize the methodologies adopted, focus on mechanisms for cross-shore suspended sediment flux and suggest implications for existing models of sediment transport and beach equilibrium.

EXPERIMENTAL DESIGN

In Phase I of the programme, four field experiments have been completed at: (i) Bluewater Beach, a single barred (1987) or double barred (1988) shoreface with a slope of 0.014 in medium-to-fine sands in Nottawasaga Bay, in the Canadian Great Lakes. (ii) Queensland Beach, Nova Scotia, a non-barred shoreface in medium sands, with a slope of 0.03-0.10 and a spring tide range of 2 m on the Eastern Seabord of Canada. (iii) Stanhope Lane Beach, Prince Edward Island, a triple barred shoreface in medium-to-fine sands, with a micro-tidal regime in the Southern Gulf of St. Lawrence, Canada.

SEDIMENT FLUX DETERMINATION

Direct measurement of sediment flux in the field is still difficult and a wide range of techniques have been tried (for reviews of philosophy and methodology see Greenwood et al., 1979; Huntley, 1982; Horikawa, 1988; Basinski, 1989; Seymour, 1989). No reliable bedload sensor exists; however, development of reliable, high frequency response, optical and acoustic sediment concentration sensors provide, together with reliable velocity sensors, measurements of suspended sediment flux. The cross-product of velocity and sediment concentration vectors determined from "collocated" sensors is an approximation of the "instantaneous" sediment transport rate, assuming that the sediment moves at the same speed as the fluid. Time-averaging this product gives the "net" sediment transport rate. Assuming also that values of velocity and concentration are both composed of a steady ($\bar{u},\bar{c}$) and an unsteady (u',c') part, then the "net" transport is:

$$\begin{aligned}\langle uc \rangle &= \langle (u + u')(c + c') \rangle \\ &= \bar{u}\bar{c} + \langle \bar{u}c' \rangle + \langle u'\bar{c} \rangle + \langle u'c' \rangle\end{aligned}$$

Since $\langle \bar{u}c' \rangle$ and $\langle u'\bar{c} \rangle$ must tend to zero then:

$$\langle uc \rangle = \bar{u}\bar{c} + \langle u'c' \rangle$$

where $\bar{u}\bar{c}$ is the "mean" transport and $\langle u'c' \rangle$ is the "flux coupling" induced by correlations between velocity and concentration (Jaffe et al., 1985). The latter can most conveniently be computed from the co-spectrum (Huntley and Hanes, 1987), which also reveals the relative importance of differing frequencies to the rate and direction of this "oscillatory" transport. Integration of the cospectrum (or part thereof) gives the "net oscillatory" (or part thereof) transport.

Such computations, however, depend upon accurate high resolution (temporal and spatial) measurements of the velocity and concentration vectors. Figure 1 illustrates a typical monitoring station used in the C-COAST programme. It consists of "collocated" vertical arrays of current and concentration sensors, together with a wave sensor, either a pressure sensor or a continuous resistance staff (see Greenwood et al., 1990 for details) and an underwater digitization and transmission system (UDATS; Hazen et al., 1988).

The structure of the local suspended sediment profile has been determined most usually from point measurements using Optical Backscatterance Suspended Solids Sensors (OBS-1P - see Downing et al., 1981; D & A, 1989). Quasi-

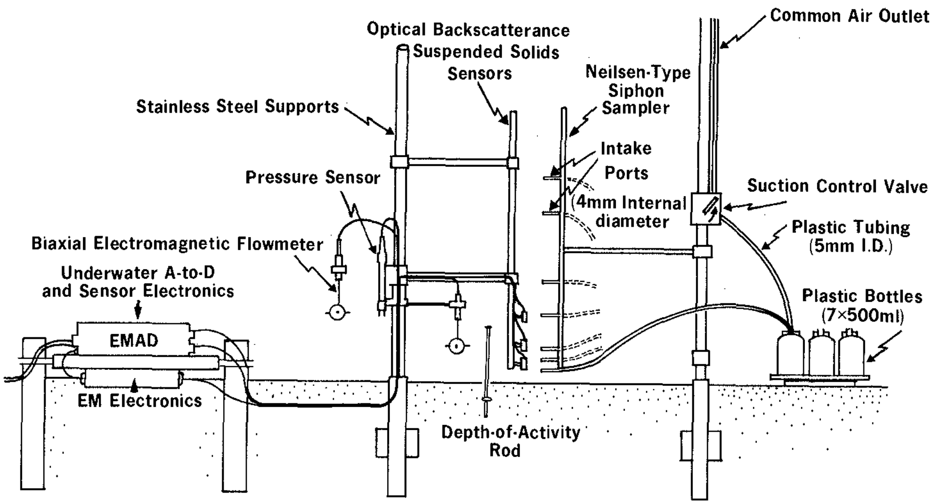


Figure 1. Typical sensor deployment configuration; note that neither RASTRAN nor HRRTS II are depicted.

continuous concentration profiles (2 cm resolution) is also possible using a new multifrequency (1, 2.5, 5 MHz) Remote Acoustic Sediment Transport system (RASTRAN, Hay et al., 1988). Direct multiple point measurements of sediment concentration are obtained using a modified Neilsen-type hydraulic sampler (Neilsen, 1984). Extensive calibrations of the optical and acoustic suspended sediment sensors have been undertaken and cross-calibrations between the two have been made in the laboratory and in the field (Figure 2 - see Greenwood et al., 1990 for details).

BOTTOM BOUNDARY DYNAMICS

The response of the bottom boundary to sediment transport has traditionally been determined at large scales using standard Survey Techniques and Depth-of-Activity Rods measured by SCUBA divers (Greenwood and Hale, 1980; Greenwood, 1987). Such techniques are restricted by environmental constraints to pre- and post-storm measurements; spatial and temporal resolution is, therefore, limited to time-averaged values and gross morphological shifts. In the C-COAST experiments, bed elevation changes have been monitored locally on a continuing basis using acoustic imaging. RASTRAN is capable of determining bottom elevations continuously to within a few centimeters, while a new High Resolution Remote Tracking Sonar (HRRTS II - see Greenwood et al.,

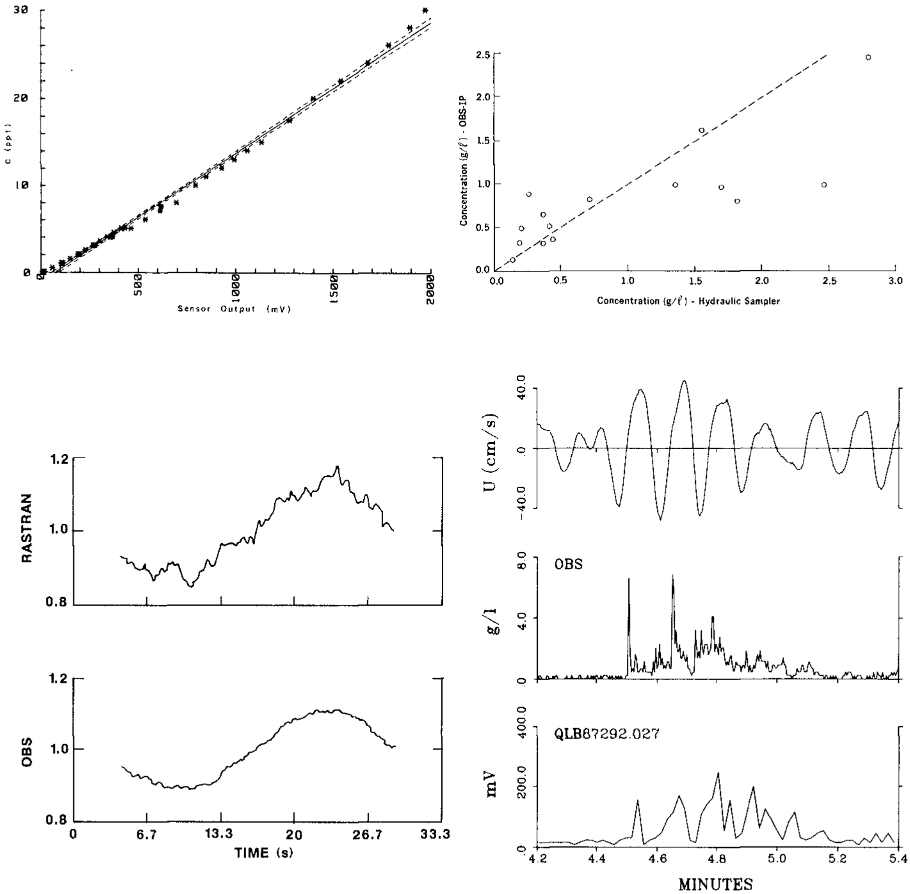


Figure 2 Optical and acoustic measurements of concentration: (a) calibration curve for the OBS-1P including the 95 % confidence band; (b) comparison between time-averaged concentrations using the OBS-1P and a Neilsen-type sampler; the 1:1 line is shown; (c) optical and acoustic signals from the same sediment concentrations generated in a suspended sediment jet - signals have been normalized with respect to the means; (d) field response of the OBS-1P (middle) and RASTRAN (bottom) to the same re-suspension event and the near-bed velocity field (top). Note: the uncalibrated RASTRAN signal was sampled at 0.8 Hz, whereas the OBS and velocity data were acquired at 4 Hz.

1985; Greenwood and Richards, 1991) can resolve bed elevations on a continuous basis to the order of less than one centimeter. Also the local bottom roughness (bedforms - Figure 3) can be measured over several meters with HRRTS II which uses a 5 MHz transducer, with a beam width of 0.72 degrees (nominal), a 30 s pulse length, a repetition rate of 20 Hz and , and which is driven mechanically along a track mounted on the bed.

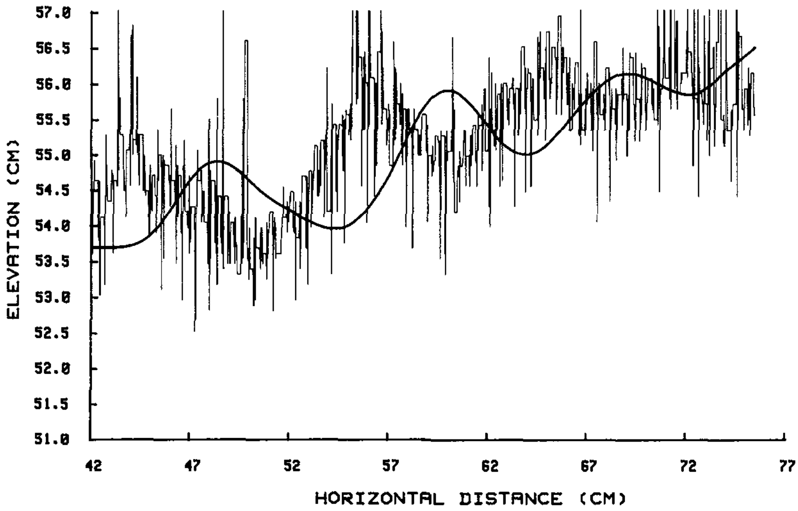


FIGURE 3 Acoustic signature of the bottom boundary using HRRTS II: shown are an unfiltered signal sampled at 8 Hz and a filtered spatial series; note the phase shift associated with the six pole recursive digital filter. Asymmetric ripples with heights of 0.5-1.5 cm and spacings of 9-11 cm existed at this time; considerable sediment re-suspension creates much of the noise.

SEDIMENT RE-SUSPENSION

Sediment re-suspension is an extremely episodic process even under breaking waves; however, contrary to expectations, the suspended sediment concentrations do not exhibit strong spectral signatures typical of the major forcing function (near-bed velocity (stress) - Figure 4). Spectral peaks at the frequency of the primary wave and the first harmonic may be seen under shoaling waves and indicate a dependency upon stresses generated during both onshore and offshore half-wave cycles; this pattern disappears with increasing elevation. A large low frequency peak is present in this example. Under breaking waves, the high frequency peaks disappear and spectral density increases rapidly with decreasing frequency.

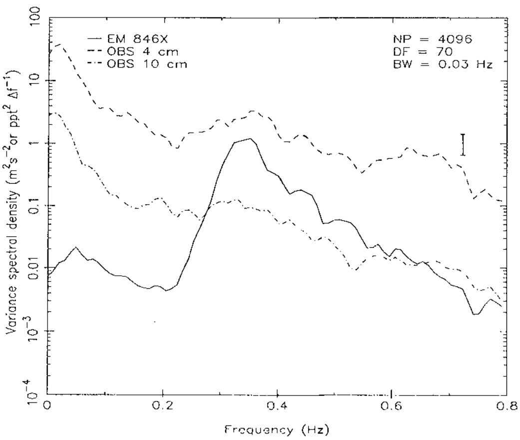


FIGURE 4 Spectra of cross-shore velocity (EM846X) and sediment concentration (OBS) at 4 and 10 cm elevation; the vertical bar indicates the 95% confidence limits, NP = sample size, DF = degrees of freedom BW = bandwidth.

A more appropriate expression of the dynamics of sediment suspension is achieved with time series (Figure 5):

(i) sediment concentrations respond to both individual wave cycles and, more importantly, to wave groups. As a group of large waves pass re-suspension occurs as a cumulative increase and then decrease in concentration lasting for several tens of seconds; fluctuations associated with individual wave cycles are superimposed. Spatially coherent re-suspension events can be identified as wave groups propagate across the nearshore, and even within surf zones dominated by spilling breakers. Since wave groupiness is ubiquitous in both wind forced wave fields (e.g. Great Lakes) and swell (e.g. East Coast) it plays an extremely important role in sediment transport.
(ii) small asymmetries in the near-bed velocity field associated with non-linear wind waves can induce significantly larger asymmetries in transport. Figure 5 illustrates the larger landward transports induced by wind waves shoaling over the lakeward slope of a bar.
(iii) concentrations decrease rapidly away from the bed in general (Figure 6), with maxima measured at 0.04 m elevation only rarely exceeeding 10-15 g/l, even under spilling breakers. While time-averaged values decay exponentially with height (Osborne, 1990), this is not a good reflection of the transport process. Concentration gradients over the lowest 0.20 m vary within wave cycles

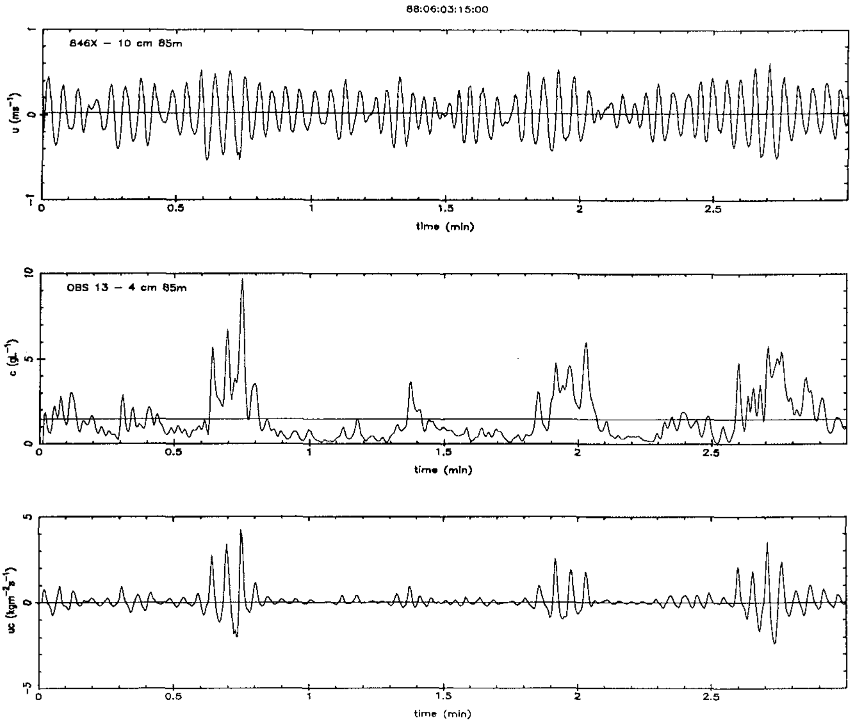


FIGURE 5 Time series of cross-shore velocity (u), sediment concentration (c) and sediment flux (uc) at one elevation, 85 m offshore in 1.8 m of water.

from large decay rates (6C), to near-uniformity (6N) and occasionally inversions with height (6 F). This variation results from both the varying intensity of turbulence from one half wave cycle to the next as a wave group passes and the vertical propagation of separation vortices shed from rippled beds. The latter are common even in the surf zone, under flow conditions well above the threshold established by laboratory experiments for flat bed (Ollerhead and Greenwood, 1990).

(iv) phase lags between the near-bed maximum velocity and maximum sediment concentration are common and increase with increasing elevation above the bed. The lag does decrease with increasing velocity, as might be expected (Osborne, 1990).

(v) complex interactions involved in natural sediment re-suspension prevent identification of simple thresholds (velocity or acceleration) for the initiation of suspension . No simple functional relationships can be established between concentration increases and increases in the forcing function, even allowing for phase lags.

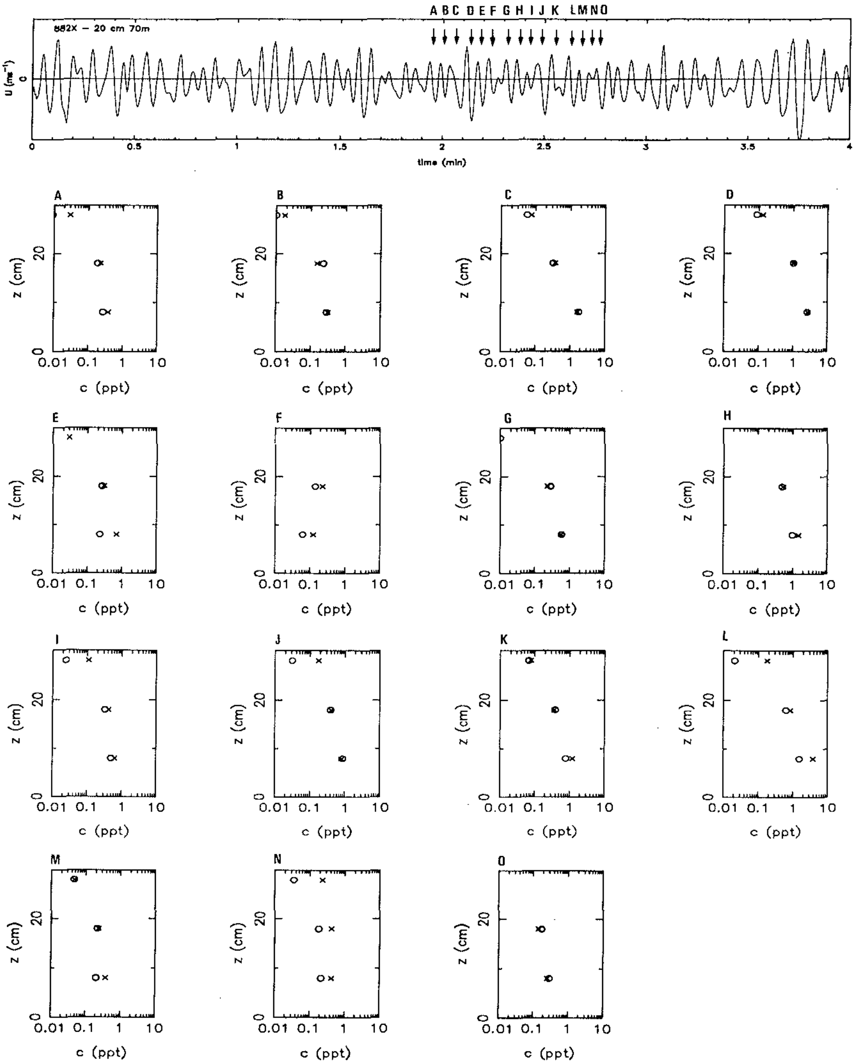


FIGURE 6 Time series of suspended sediment concentrations averaged over each half-wave cycle and at several elevations; crosses indicate the onshore phase of motion, the circles the offshore phase. The arrows indicate the fifteen wave cycles analysed.

The episodic, time-dependent nature of sediment re-suspension clearly influences both the directions and rates of transport at any particular elevation above the bed (Figure 5). Phase lags may cause actual reversals of net transport within a short distance of the bed. Furthermore, the direction and rates of sediment transport reflect contributions from both oscillatory components of fluid motion and mean flows. Estimates of the oscillatory components can be determined from the co-spectrum (Figure 7). Note in this example: (a) large onshore transports at wind wave frequencies (all elevations); (b) at low frequencies transport is offshore near the bed and onshore higher in the water colum. Contributions to the net transports from both "oscillatory" and "mean" components have been computed for a range of wave, current and bedform conditions (Osborne, 1990; Osborne et al., 1990) and it is clear that these contributions vary both with time and over space (with respect to distance above the bed and distance offshore). Figure 8 illustrates an example of the variations across shore in the transport contributions with respect to height above the bed for both non-breaking and occasionally spilling conditions on a non-barred marine beach. Under non-breaking waves, only a small amount of net transport was occurring; this was close to the bed and landward under wind wave asymmetries. Net oscillatory transport is generally landward under near-breaking waves while the mean transport is offshore at all levels. It is clear that the "oscillatory" and "mean" transport components can operate in different directions and at similar rates, such that large volumes of sediment may be transported but the net transport may be close to zero. This suggests the possibility of a locally balanced sediment transport system producing steady state slopes, even under high waves and large suspended loads.

DISCUSSION AND CONCLUSIONS

Both the OBS-1P and RASTRAN give coherent signals from sands suspended by waves and currents. Laboratory cross-calibrations and field comparisons of the time-averaged OBS-1P signals and hydraulic sampling of sediment concentrations supports the contention that both optical and acoustic sensors record sediment concentrations accurately. The acoustic system has the added capability of recording "continuous" vertical profiles and the advantage of being non-intrusive.

Suspended sediment transport is neither continuous nor a simple diffusive process under the combined flows (oscillatory and quasi-steady) of the shoreface. Rather it is extremely episodic and not always coherently related to single incident waves cycles, even under wave breaking. A strong association exists with the velocity structure (and stresses) induced by wave groups. The latter is true for environments with local wind-waves as

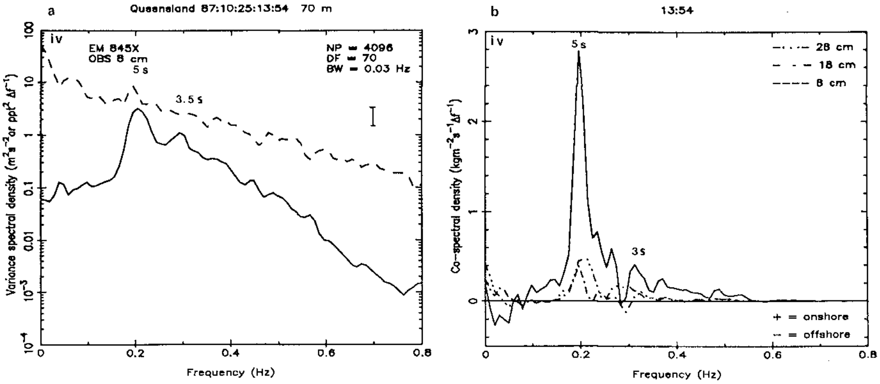
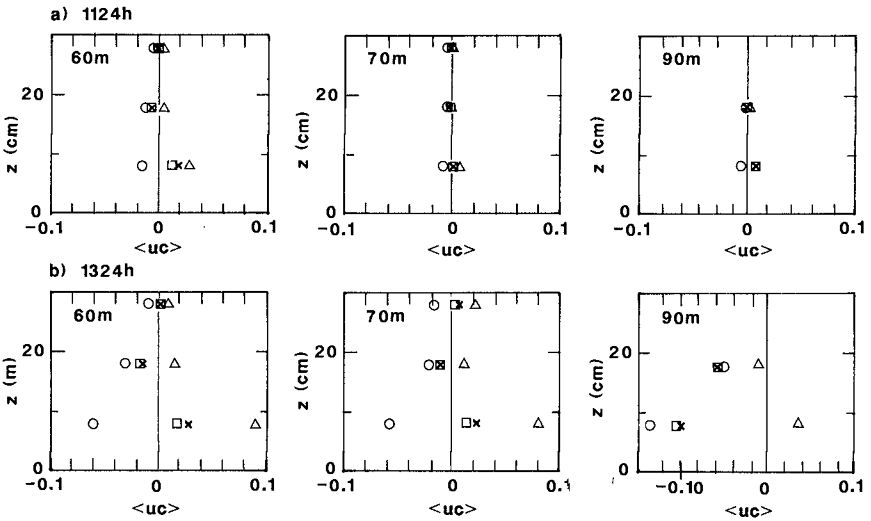


Figure 7 Velocity and concentration spectra (a) and associated cospectra (b) for transport 70 m offshore on a planar beach under near-breaking and spilling breakers. Note: the spectral estimates use 4096 values (17 minutes) with 70 degrees of freedom and a bandwidth of 0.03 Hz; the 95% confidence band for the spectral estimates is shown by the vertical bar.



□ $\langle uc \rangle_{total} = 1/n \; \Sigma \; uc$ ○ $\langle uc \rangle_{mean} = 1/n \; \Sigma u * 1/n \; \Sigma c$

× $\langle uc \rangle_{total} = \langle uc \rangle_{mean} + \langle uc \rangle_{osc}$ △ $\langle uc \rangle_{osc} = \Delta f/f_c \; \Sigma \; C_{uc}(f)$

Figure 8 Vertical structure of net suspended sediment transport across shore on a non-barred shoreface, Queensland Beach: (a) shoaling waves; (b) near-breaking (90, 70 m) and occasionally spilling waves (60 m).

Sediment re-suspension also exhibits a strong time-dependency; significant phase lags exist between near-bed velocity (stress) and sediment concentration at any given elevation. Furthermore, vertical gradients in sediment concentration are variable at the wave cycle scale. Although time-averaged profiles of sediment concentration can be described by an exponential decay function, "instantaneous" profiles may show extremely large gradients or near uniformity in the near-bed water column during suspension events; "concentration inversions" are not uncommon. This temporal dependency with elevation clearly controls both sediment transport rates and directions at any specific elevation.

The bed geometry (bedforms) has a large influence on the vertical gradients in the sediment concentration. Sediment re-suspension is characterized by the vertical propagation of coherent turbulent vortices resulting from flow separation over rippled beds, which persist even under spilling breakers.

Present predictive models for cross-shore sediment transport fail to incorporate the effects of wave groupiness or the vortex-shedding effects of bed forms and inadequately model the depth and time dependant character of the system. Furthermore, the strong frequency dependence of suspension transport and the relative contributions to the total transport from wind waves, low frequency waves and mean flows have still to be effectively addressed.

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