CHAPTER 56

WAVE GROUP FORCED NEARSHORE CIRCULATION

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Abstract

Forcing of the nearshore circulation system by incident wave groups is examined. Attention is focused on the generation of migrating rip currents and development of low frequency motion. Analysis of experimental results categorises the migrating rip currents as very low frequency motion in the FIG energy band. It is suggested that migrating rip currents, in addition to shear waves, are a valid generation mechanism for very low frequency motion in the nearshore region.

Introduction

The primary currents in the nearshore area are longshore currents, cross–shore currents (or undertow), and rip currents. Longshore currents, generated by incident waves with an oblique approach to the shoreline, flow parallel to the beach carrying sediments downwave. Cross–shore currents develop to maintain the mass flux balance in the surf zone. They can transport sediments offshore, although they can not carry sediments far beyond the breaker line. Rip currents are more powerful surface currents and are a major mechanism for water exchange across the breaker line. They can transport large amounts of sediment a considerable distance beyond the surf zone. Numerous theories exist for the presence of rip currents as discussed by Dalrymple (1978). All these features of the nearshore circulation system are generally considered stationary processes.

Underlying the nearshore currents is a low frequency motion which is typically unsteady and periodic in nature. This motion includes surf beat, edge waves, and far-infragravity motions. Much attention has been given to the characterization of these wave motions, but as yet, their generation mechanisms are not totally understood.

The fundamental aim of the research work described in this paper was to study the nearshore circulation system and evaluate its response to forcing by offshore wave groups. In particular, we examined the generation of slowly migrating rip currents by the offshore wave groups, and the corresponding development of low frequency motions in the surf zone.

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Wave Groups and Low Frequency Motion in the Nearshore Region

Initial discoveries of low frequency motion (frequencies < incident wave frequency, periods 30–300s) in the nearshore region are attributed to Munk (1949) and Tucker (1950). They observed oscillations in the water surface elevation which had periods of several minutes. Munk named these long, low frequency waves 'surf beat'. Tucker found the best evidence of surf beat during periods of long, regular groups of incident waves, and noted that the long waves were out of phase with the wave groups.

Longuet–Higgins and Stewart (1962, 1964) demonstrated theoretically, using radiation stresses, that a small second–order undulation accompanies a first–order wave group, leading to the development of a set–down wave, a long, forced wave in the nearshore region. It was shown that the forced wave has the same wave length and period as the incident wave group and is 180° out of phase with the group, as observed by Tucker. They suggested that the surf beats seen by Munk and Tucker were seaward propagating free waves formed by the release of the forced, set–down waves as they are reflected near the coastline.

Following these initial surf beat studies, the majority of research on the interaction of wave groups and the nearshore circulation system has focused on edge waves. Gallagher (1971) showed that non–linear interactions between wind waves, leading to an inter–frequency energy transfer, can initiate forced edge waves in the surf zone which can grow resonantly. In a laboratory study, Bowen and Guza (1978) considered both resonant and non–resonant interactions between incoming wave trains and confirmed that, when the frequency and longshore wave number of incident wave groups satisfy the edge wave dispersion relationship, theoretically predicted edge wave motions can be generated and maintained.

Huntley, Guza and Thornton (1981) summarised that there are three different generation mechanisms for nearshore low frequency motion: progressive edge waves, standing edge waves (caused by an obstruction or topographic form), and forced second–order waves under incident wave groups. From their analyses of data from the National Sediment Transport Study field experiment at Torrey Pines Beach, California, they found the most important of these generation mechanisms to be progressive edge waves. They observed long–wave motion in the surf zone with frequencies and wave lengths that corresponded to those predicted by the edge wave dispersion relationship. However, they also found that other generation mechanisms were important, primarily forced motion due to standing edge waves.

Tang and Dalrymple (1989) also worked with the NSTS data set, but concentrated on nearshore motions at much lower frequencies than those in the edge wave band. Figure 1 shows the edge wave energy identified by Huntley, Guza and Thornton, but there is also a significant pocket of energy in the lowest frequency band. Tang and Dalrymple demonstrated, through various statistical analysis methods, that offshore wave groups were significantly correlated with the measured, very low frequency motion (< 0.0015 Hz, periods > 660 sec.). During the field experiment, observations were made of slowly migrating rip current cells in the surf zone which had the same wave length as the very low frequency motion. Tang and Dalrymple hypothesised that the incident wave groups forced a response in the surf zone in the form of migrating rip currents, which, in turn, had a very low frequency motion signature in wave number–frequency space.

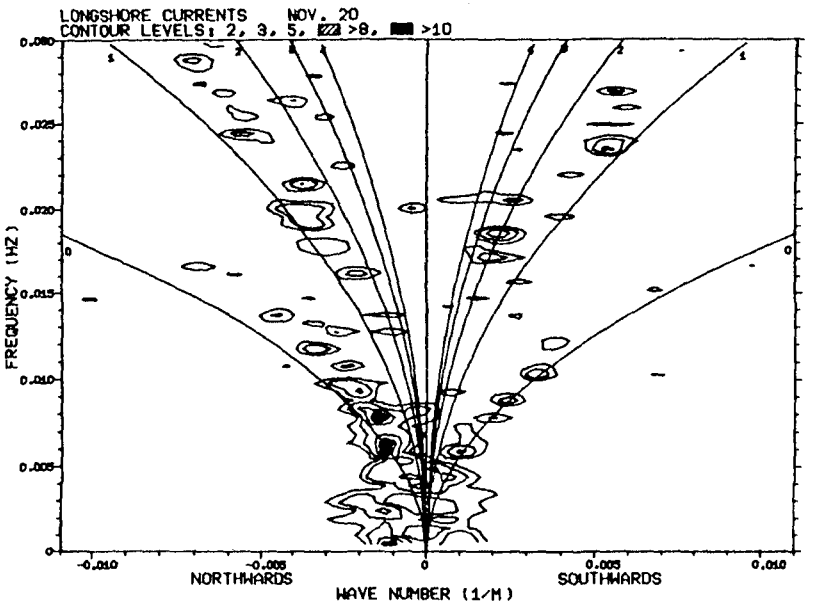

Figure 1: Wave number–frequency spectrum derived from cross-shore current measurements at an offshore location. Torrey Pines Beach, California, USA. (Fig. 10B–5 of Tang and Dalrymple, 1989)

Data from the SUPERDUCK field experiment (see Crowson *et al.* (1988)) conducted at Duck, North Carolina, were analysed by Oltman–Shay, Howd and Birkemeier (1989) and produced solid evidence of high energy motion at very low frequencies. These low frequency oscillations can be clearly seen in the velocity records (fig. 2), particularly in the longshore velocity records. Oltman–Shay *et al.* also analysed their data in wave number–frequency space and clearly demonstrated that the high energy, low frequency motion is distinct from edge wave motion (fig. 3). An approximately linear relationship between wave number and frequency was also revealed, implying that the low frequency motion is non-dispersive. This very low frequency motion was observed only in the presence of a mean longshore current, and changed speed and direction with that mean current. Oltman–Shay *et al.* named this kinematically distinct, low frequency band of energy the 'far infra–gravity (FIG) band' and, in a companion paper by Bowen and Holman (1989), it was suggested that the observed motions were generated by instabilities in the mean longshore current. These instabilities lead to the formation of a longshore–progressive shear wave, which has the restoring force of vorticity rather than gravity.

Theoretical Considerations

Since incident wave groups appear to be important to the dynamics of the nearshore circulation system, we examine their simplest form. Consider the summation of two sinusoidal incident wave trains, as described by linear theory. The

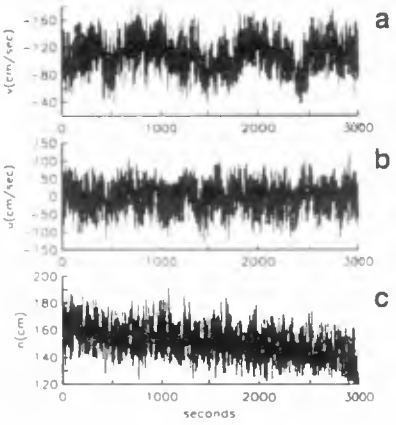

Figure 2: Time series measurements of (a) longshore (v), (b) cross-shore (u) velocity, and (c) surface displacement (η) colocated in the surf zone. Duck, North Carolina, USA. (Fig. 2 of Oltman-Shay *et al.* , 1989)

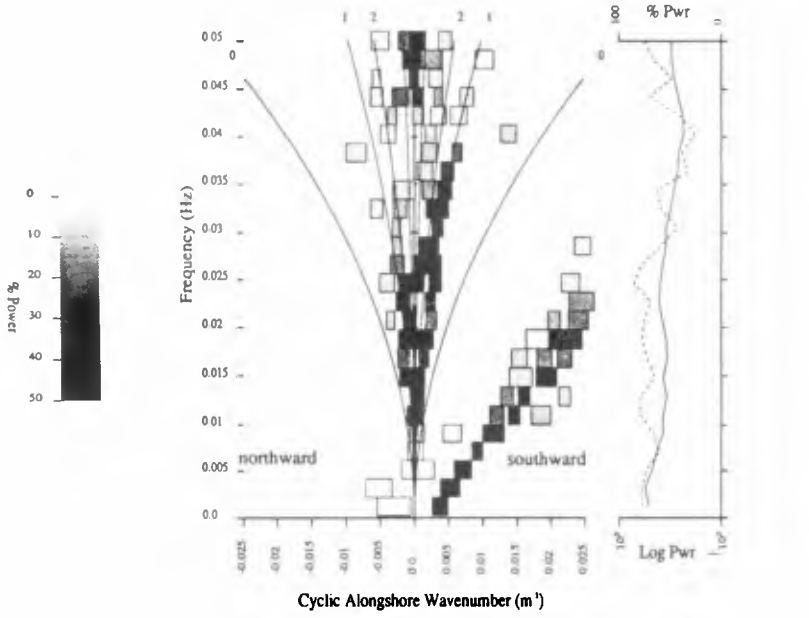

Figure 3: Wave number-frequency spectrum derived from cross-shore velocity measurements in the surf zone. Duck, North Carolina, USA. (Fig. 6b of Oltman-Shay *et al.* , 1989)

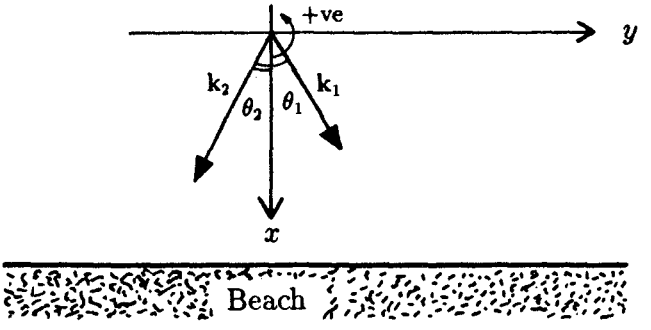

Figure 4: Coordinate system.

velocity potential and water surface elevation are given by:

$$\phi(\mathbf{x},z,t) = \frac{ga_1}{\omega_1}\frac{\cosh k_1(h+z)}{\cosh k_1 h}\cos\psi_1 + \frac{ga_2}{\omega_2}\frac{\cosh k_2(h+z)}{\cosh k_2 h}\cos\psi_2 \qquad (1)$$

$$\eta_t(\mathbf{x},t) = \frac{1}{g}\frac{\partial\phi}{\partial t}\bigg|_{z=0} = a_1\sin\psi_1 + a_2\sin\psi_2 \qquad (2)$$

where
$\psi_i = (\mathbf{k_i}\cdot\mathbf{x} - \omega_i t)$, phase function of wave train, $i = 1,2$
$\mathbf{k}_i = |\mathbf{k}_i|\cos\theta_i = k_i\cos\theta_i$, wave number of wave train, $i = 1,2$
ω_i = frequency of wave train, $i = 1,2$
a_i = amplitude of wave train, $i = 1,2$
g = acceleration due to gravity
h = water depth
$\mathbf{x} = (x,y)$

The wave numbers, $\mathbf{k_i}$, are related to the angular frequencies of the waves by the linear dispersion relationship. Note from figure 4 that the x axis is positive onshore.

Through the use of various trigonometric identities, the total water surface elevation can be rewritten and expressed as the sum of a modulated sine wave and a plane wave train:

$$\eta_t(\mathbf{x},t) = 2a_1\sin\left(\frac{\psi_1+\psi_2}{2}\right)\cos\left(\frac{\psi_1-\psi_2}{2}\right) + (a_2-a_1)\sin\psi_2 \qquad (3)$$

By introducing the definitions:

$$\left.\begin{array}{rcl}\omega_1 &=& \omega - \frac{\Delta\omega}{2}\\ \omega_2 &=& \omega + \frac{\Delta\omega}{2}\end{array}\right\}\quad \begin{array}{rcl}\omega &=& \frac{\omega_1+\omega_2}{2}\\ \Delta\omega &=& \omega_2-\omega_1\end{array} \qquad \left.\begin{array}{rcl}\mathbf{k}_1 &=& \mathbf{k} - \frac{\Delta\mathbf{k}}{2}\\ \mathbf{k}_2 &=& \mathbf{k} + \frac{\Delta\mathbf{k}}{2}\end{array}\right\}\quad \begin{array}{rcl}\mathbf{k} &=& \frac{\mathbf{k}_1+\mathbf{k}_2}{2}\\ \Delta\mathbf{k} &=& \mathbf{k}_2-\mathbf{k}_1\end{array}$$

we develop η_t in terms of the average frequency, ω, the average wave number

vector, $\mathbf{k}$, and their difference terms, $\Delta\omega$ and $\Delta\mathbf{k}$:

$$\eta_t(\mathbf{x},t) = 2a \underbrace{\sin(\mathbf{k}\cdot\mathbf{x}-\omega t)}_{\text{carrier wave}} \underbrace{\cos\left(\frac{1}{2}(\Delta\mathbf{k}\cdot\mathbf{x}-\Delta\omega t)\right)}_{\text{wave envelope}} + (a_2-a_1)\sin\left(\underbrace{(\mathbf{k}\cdot\mathbf{x}-\omega t)-\left(\frac{1}{2}(\Delta\mathbf{k}\cdot\mathbf{x}-\Delta\omega t)\right)}_{\psi_2}\right) \quad (4)$$

For $a_1 = a_2$, the second term is eliminated. The total water surface elevation now consists of a carrier wave, propagating in the $(\mathbf{k}_1+\mathbf{k}_2)/2$ direction, at speed $(\omega_1+\omega_2)/|\mathbf{k}_1+\mathbf{k}_2|$, modulated by a wave envelope, which propagates at speed

$$Cg = \frac{\omega_1-\omega_2}{|\mathbf{k}_1-\mathbf{k}_2|} \quad (5)$$

in the $\mathbf{k}_1-\mathbf{k}_2/2$ direction. The longshore component of the speed of propagation of the wave envelope, Cg_y, is easily obtained from equation 5.

From the velocity potential (eq 2), expressions can also be developed for the longshore and cross-shore velocities:

$$u = -\frac{\partial\phi_t}{\partial x} = g\mathbf{k}f(\mathbf{k})(a_1\cos\theta_1\sin\psi_1 + a_2\cos\theta_2\sin\psi_2) + O(\Delta\mathbf{k},\Delta\omega) \quad (6)$$

$$v = -\frac{\partial\phi_t}{\partial y} = g\mathbf{k}f(\mathbf{k})(a_1\sin\theta_1\sin\psi_1 + a_2\sin\theta_2\sin\psi_2) + O(\Delta\mathbf{k},\Delta\omega) \quad (7)$$

where

$$f(\mathbf{k}) = \frac{\cosh k(h+z)}{\cosh kh}$$

From these expressions it can be noted that the cross-shore velocity and the water surface elevation (eq 2), are in phase at both the incident wave frequency and the group frequency. However, the longshore velocity moves in and out of phase at the incident wave frequency and is 180° out of phase at the wave group frequency. Similar phase differences at the group frequency were observed in the field by Kim and Huntley (1986).

As the incident wave trains propagate towards the shore they alternatively reinforce and cancel each other out, creating periodic, longshore variations in wave height. Lines of cancellation, or nodal lines, can be seen in the wave field. For the special case where the intersecting wave trains are of the same frequency $Cg = 0$, and the wave groups do not propagate. At the intersection of the nodal lines with the beach, rip currents develop, as demonstrated by Dalrymple (1975). The longshore spacing of the nodal lines, and hence the rip currents, can be predicted by:

$$Lg_y = \frac{2\pi}{k_2\sin\theta_2 - k_1\sin\theta_1} \quad (8)$$

In general, for two incident wave trains with slightly different frequencies, $\omega_1 \neq$

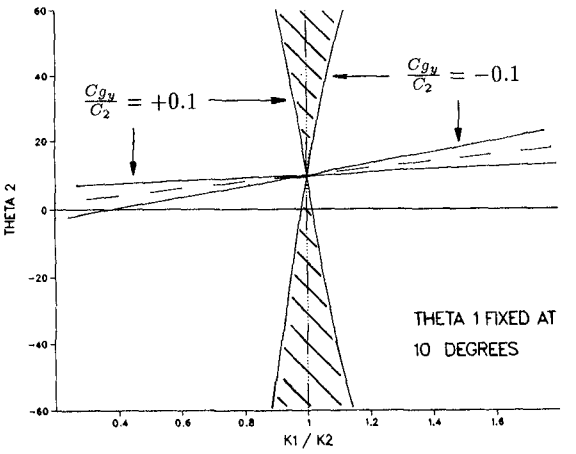

Figure 5: Graphical representation of the incident wave conditions suitable for the development of migrating rip currents.

ω_2, the speed of propagation of the wave envelope is no longer zero. Therefore, the nodal lines in the wave field are no longer stationary. Since we know that rip currents can develop in the surf zone for $Cg_y = 0$, we now suggest that for $Cg_y \approx 0$ rip currents can be generated and will migrate slowly along the beach with the nodal lines. To facilitate prediction of suitable conditions for migrating rip currents, a dimensionless expression is developed from equation 5:

$$\frac{Cg_y}{C_2} = \frac{(k_r - 1)(k_r \sin\theta_1 - \sin\theta_2)}{k_r^2 + 1 - 2k_r \cos(\theta_1 - \theta_2)} \tag{9}$$

using the shallow water assumption, $\omega_1/\omega_2 = k_1/k_2$, and where $k_r = k_1/k_2$, the ratio of the wave numbers of the two wave trains, and C_2 is the celerity of the second wave train. This expression must be $\ll 1.0$ to enable rip currents to develop. Equation 9 is represented graphically in figure 5 which is for the case where θ_1 is fixed at $+10°$.

The lines represent contours of Cg_y/C_2. The dashed line represents the conditions for stationary rip currents. The graph shows two families of solutions. The horizontally oriented lines represent conditions when the nodal lines are propagating in the on/offshore direction, at large angles to the beach normal. These conditions do not lead to the development of rip currents on the beach, but instead create a surf beat effect. The vertically oriented family of solutions represent conditions which do lead to the development of rip currents. Values of $Cg_y/C_2 = \pm 0.1$ were arbitrarily selected as limits for the development of migrating rip currents, and several test cases were selected within these limits for the experimental work. Care was taken to avoid incident wave conditions that would initiate edge waves.

Experimental Facilities and Procedures

The migrating rip currents were simulated in the directional wave basin at the University of Delaware. The basin measures $20m$ x $20m$ x $1.1m$. Along

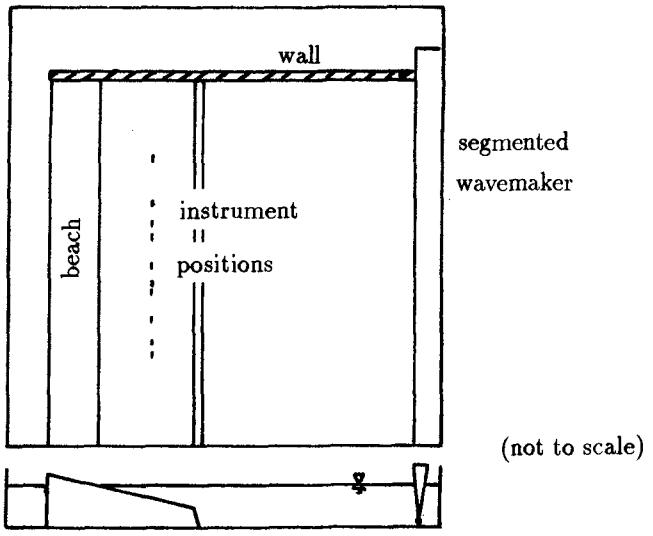

Figure 6: Plan and elevation of the directional wave basin at the University of Delaware, showing the experimental set–up.

one wall there is a segmented wavemaker composed of thirty individually actuated paddles (fig. 6). A wooden beach, $14.65m$ in length, was installed in the basin providing an idealised, planar slope of 1:10. A closed basin condition was maintained as required for wave generation using the 'designer waves' technique, Dalrymple (1989). The water depth was maintained at $81cm$ for the duration of the experiments.

Cross–shore and longshore currents were measured at ten locations along the beach using Marsh–McBirney electromagnetic current meters. The instrument locations were in the form of a ten–point, linear array, $1.52m$ seaward from the still water line, outside the surf zone. The data sampling frequency was set at $10Hz$ and record lengths containing 4096 data points were obtained.

Four experimental cases were run and are summarised in figure 7. The first two cases, RTEST and PTEST, are identical except for their wave heights. The fourth experimental case, STEST, is of note since the rip currents propagate along the beach in a direction opposite to that of the incident waves. Further details of the laboratory experiments are presented in Fowler (1990).

Results

Cross–shore and longshore velocity records were obtained for each experimental case at all ten locations in the linear array. Typical velocity records from one location are presented in figure 8. The cross–shore record clearly shows the wave groups arriving in the nearshore region. The two records are seen to be out of phase as suggested by the theory, although quantitative evaluation of this has not been performed. The longshore velocities have about half the magnitude of

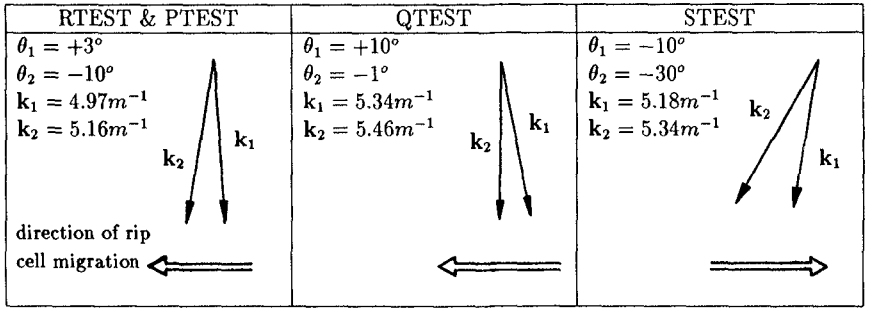

Figure 7: Summary of the four experimental cases.

the cross–shore velocities, but the low frequency modulation is very prominent. This low frequency modulation can be very clearly seen in the frequency spectrum (fig. 9). The incident waves are easily identifiable, but the spectrum is dominated by a low frequency peak due to the rip currents migrating along the beach. This conclusion is confirmed by visual observations of the period of the rip cells in the laboratory.

With the exception of the RTEST data, for each experimental case the cross–shore velocity records from all ten instrument locations were combined and analysed using either a direct Fourier transform method (DFT), or a maximum likelihood method (MLM), to create a wave number–frequency spectrum. Frequency is represented on the vertical axis, and alongshore wave number, here defined as $2\pi/L$, where L = wave length, is along the horizontal axis. Within this framework, contour lines of energy are plotted. The curved lines represent the theoretical edge wave dispersion relationship for modes 0, 1 and 2. For the RTEST experimental case, data from three locations were considered unreliable and discarded. A wave number–frequency spectrum was produced from the remaining seven velocity records.

The low frequency portion of the wave number–frequency spectra for each of the four experimental cases are presented in figures 10 through 13. In each graph the occurence of low frequency motion is clearly represented and cannot be due to edge wave motion as it is not coincident with any of the edge wave dispersion relationship curves. The frequency of the energy in each case corresponds to visual observations in the laboratory of the period of the migrating rip cells passing a fixed point.

Compared to QTEST and STEST, the PTEST and RTEST experimental cases produced stronger rip currents, which flowed further offshore before dissipating. Consequently, the current meters were further from the head of each passing rip current and the offshore velocities due to the rip were more pronounced. The rip current signature in the cross–shore velocity records is sharper for these cases. When their experimental results were analysed in wave number–frequency space, a second pocket of energy appeared at twice the frequency and half the wave length of the primary feature, a harmonic of the fundamental mo-

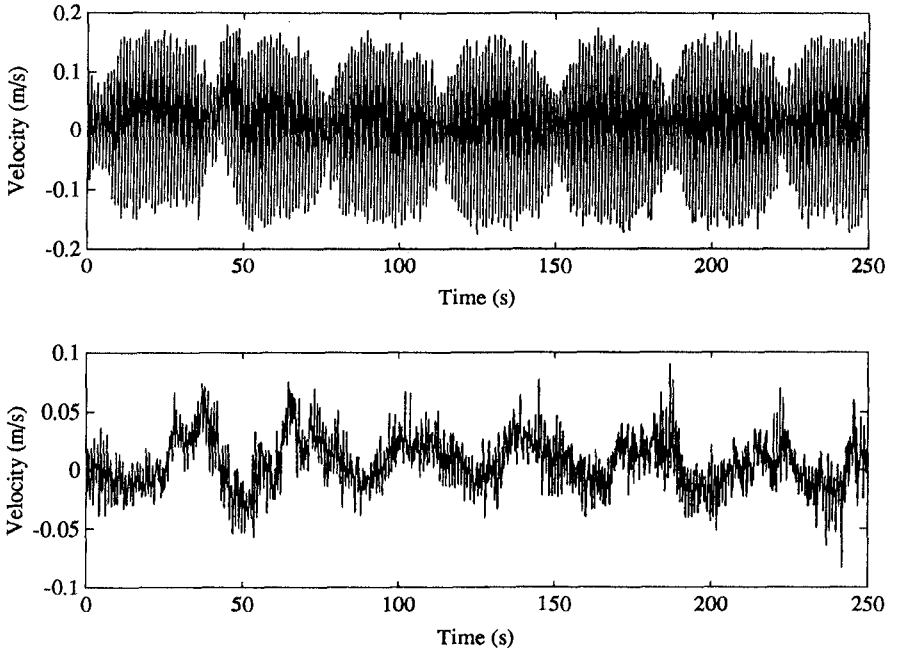

Figure 8: Typical cross–shore (top) and longshore (bottom) velocity records from one location in the instrument array.

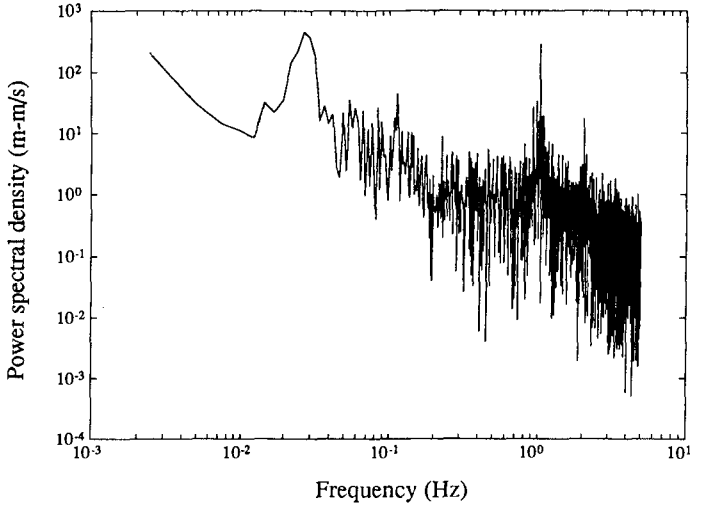

Figure 9: Typical frequency spectrum from one longshore velocity record.

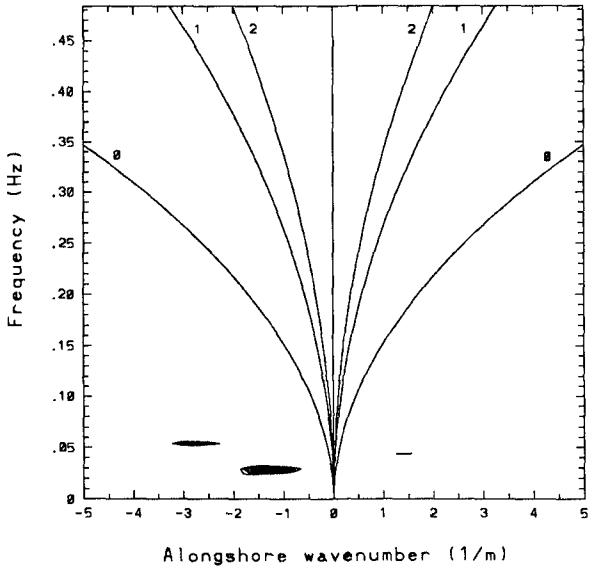

Figure 10: Wave number–frequency spectrum derived from cross-shore velocity records for the RTEST experimental case.

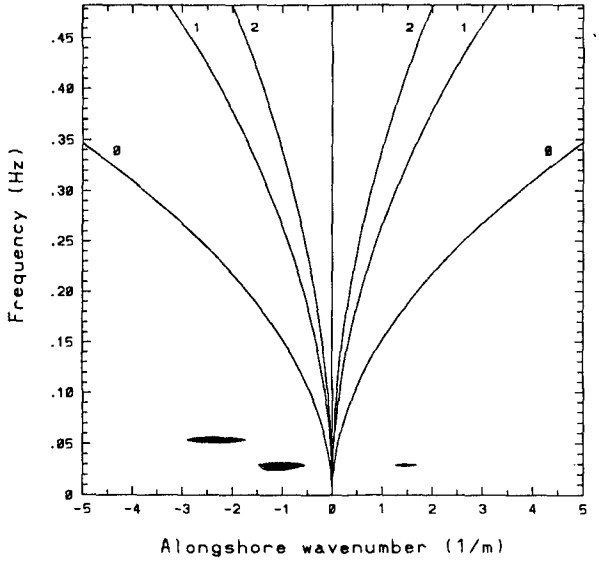

Figure 11: Wave number–frequency spectrum derived from cross-shore velocity records for the PTEST experimental case.

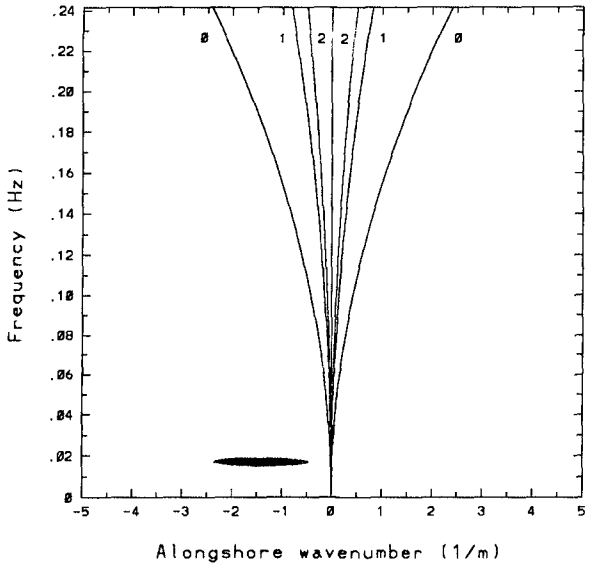

Figure 12: Wave number–frequency spectrum derived from cross–shore velocity records for the QTEST experimental case.

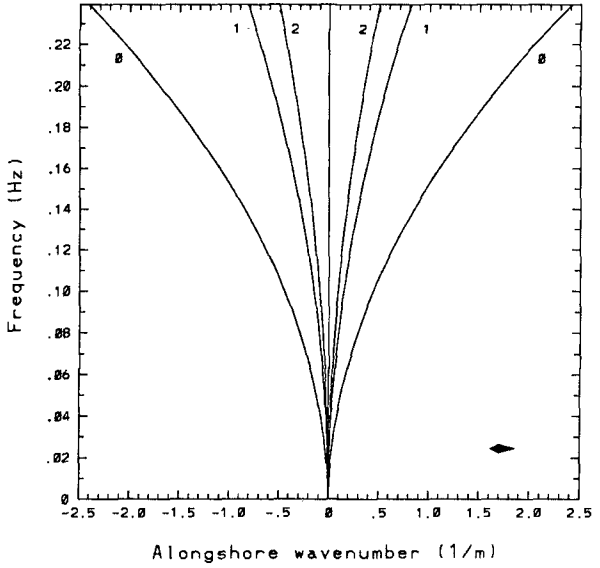

Figure 13: Wave number–frequency spectrum derived from cross–shore velocity records for the STEST experimental case.

tion. This is seen in figures 10 and 11.

The first three experimental cases, RTEST, PTEST, and QTEST, were analysed using the DFT method. Peak splitting due to large directional spread ruled out the use of an MLM for these cases. The DFT method tended to spread the energy over several wave number bins, but the central wave number is still in fairly good agreement with the observed wave lengths. The theoretically calculated wave numbers are over-predicted compared to the wave number-frequency spectra results. However, it must be remembered that equation 8 is based on linear wave theory and includes a shallow water assumption.

MLM analysis was successful on the STEST results producing a better definition of the low frequency motion in the wave number-frequency spectrum. The pocket of low frequency energy is located in the positive wave number region, unlike the previous cases, simply because the rip currents were migrating in the opposite direction.

Conclusions

Incident wave groups have been shown to be important to the dynamics of the nearshore circulation system. Simple linear theory, based on two incident wave trains with $\omega_1 \approx \omega_2$, provided a generation mechanism for slowly migrating rip currents. This suggested mechanism was verified in a laboratory wave basin. Rip currents developed in the surf zone where nodal lines in the offshore wave field intersected the beach. The rip currents propagated along the beach at the same speed as the nodal lines propagated through the wave field.

The longshore spacing of the rip currents can be predicted with some limitations. All the rip spacings were somewhat over predicted and this is thought to be due to the use of linear theory and the shallow water assumption.

The theory predicted the cross-shore and longshore velocities to be out of phase by 180°, a phenomenon previously observed in the field and qualitatively seen in the laboratory results.

Offshore, incident wave groups have been shown to force a response of the nearshore circulation system in the form of migrating rip currents. In turn, these migrating rip currents have a signature in wave number-frequency space that classifies them as very low frequency motion in the nearshore region, in the previously named 'FIG' energy band. It is therefore proposed that migrating rip currents are an alternative to shear waves as a generation mechanism for very low frequency motion in the nearshore region. Future research should include consideration of how to uniquely identify these two mechanisms in the field.

Acknowledgement

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References

Bowen, A.J. and Guza, R.T. (1978). "Edge waves and surf beat", *J. Geophys. Research*, 83, C4, 1913-1920.

Bowen, A.J. and Holman, R.A. (1989). "Shear instabilities of the mean longshore current; 1. Theory", *J. Geophys. Research*, 94, C12, 18023–18030.

Crowson, R.A., Birkemeier, W.A., Klein, H.M., and Miller, H.C. (1988). "SUPERDUCK nearshore processes experiment: Summary of studies CERC Field Research Facility", *Tech. Rep. CERC–88–12*, Coastal Eng. Res. Cent. Vicksburg, Mississippi.

Dalrymple, R.A. (1975). "A mechanism for rip current generation on the open coast", *J. Geophys. Research*, 50, 24, 3485–3487

Dalrymple, R.A. (1978). "Rip currents and their causes", *Proc. 16th Intl. Coastal Engineering Conf.*, ASCE, Hamburg, 2, 1414–1427.

Dalrymple, R.A. (1989). "Directional wavemaker theory with sidewall reflection", *J. Hydraulic Research*, 27, 1, 23–33.

Fowler, R.E. (1990). "Wave group forced nearshore circulation: a generation mechanism for migrating rip currents and low frequency motion", Thesis to be presented to the University of Delaware, Newark, Delaware, in 1990, in partial fulfillment of the requirements for the degree of Master of Civil Engineering.

Gallagher, B. (1971). "Generation of surf beat by nonlinear wave interactions", *J. Fluid Mechanics*, 49, 1–20.

Huntley, D.A., Guza, R.T., and Thornton, E.B. (1981). "Field observations of surf beats; 1. Progressive edge waves", *J. Geophys. Research*, 86, C7, 6451–6466.

Kim, C.S., and Huntley, D.A. (1986). "On time delays in the nearshore zone between onshore and longshore currents at incident wave frequencies", *J. Geophys. Research*, 91, C3, 3967–3978.

Longuet–Higgins, M.S., and Stewart, R.W. (1962). "Raditaion stress and mass transport in gravity waves, with application to 'surf beats' ", *J. Fluid Mechanics*, 13, 481–504.

Longuet–Higgins, M.S., and Stewart, R.W. (1964). "Raditaion stress in water waves; a physical discussion, with applications", *Deep Sea Res.* , 11, 529–562.

Munk, W.H. (1949) "Surf beats", *Trans. Am. Geophys. Union*, 30, 849–854.

Oltman-Shay, J., Howd, P.A., and Birkemeier, W.A. (1989). "Shear instabilities of the mean longshore current; 2. Field observations", *J. Geophys. Research*, 94, C12, 18031-18042.

Tang, E.C.-S., and Dalrymple, R.A. (1989). "Nearshore circulation: Rip currents and wave groups", in *Nearshore sediment transport*, R.J. Seymour, ed., Plenum Press.

Tucker, M.J. (1950) "Surf beats: sea waves of 1 to 5 min. period", *Proc. Royal Soc.*, A202, 565–573.