SHORE-PARALLEL FLOWS IN A BARRED NEARSHORE

By

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ABSTRACT

A field experiment to measure the horizontal and vertical structure of shore-parallel, nearshore currents was conducted at Wendake Beach, Georgian Bay, Canada, in 1980. Waves and currents were measured with continuous resistance wire wave staffs and bi-directional, electromagnetic current meters, respectively. Substantial variations from theoretical horizontal velocity profiles were found as an influence of small amplitude nearshore bars. Data smoothing resulted in a Longuet-Higgins type mixing parameter estimate of $P \approx 0.18$. Vertical velocity profiles analysis suggests that an estimate of mean, surf zone roughness length is of the order of 1×10^{-3}m.

INTRODUCTION

Since the seminal work of Longuet-Higgins and Stewart (1962) on the concept of radiation stress, a strong body of theory has emerged for the prediction of depth-integrated, mean, shore-parallel flows generated by non-normally incident progressive gravity waves breaking across a planar beach slope (Longuet-Higgins, 1970a b; Ostendorf and Madsen, 1979). However, intrinsic to the modelling of fluid motion using momentum flux across the surf zone are indices describing lateral mixing and bed shear. Unfortunately, prototype experiments of a sophistication necessary to test existing theory and also provide data for determining the coefficients involved in a stress balance model of longshore currents are limited. This limitation is extreme where topographic effects-nearshore bars- introduce a potentially important modifying effect on current generation. Sonu (1972) provided a qualitative description of a spatially variable nearshore current in the presence of a bar but only very recently have more quantitative studies been undertaken (Meadows, 1977, 1978; Symonds and Huntley, 1980; Allender et al., 1979; Allender and Ditmars, 1981). This paper presents

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the results of a field experiment designed specifically to examine the horizontal and vertical structure of the shore-parallel flow field across a non-tidal, barred nearshore under a wide range of incident wave conditions and to provide a dataset suitable for determining parameters describing the nearshore mixing and bed friction.

Location of Study Site

The experimental site was located at Wendake Beach, Ontario (Fig. 1): the area is a non-tidal, low-energy, storm-wave dominated coastal system with a maximum fetch of 84 km to the WNW but extremely restricted in width. Short period, steep waves that may exceed 2 m significant height with 5 to 6 second peak periods are generated during the passage of cyclonic disturbances. Wave approach angles frequently change even within a single storm in response to wind shifts in this fetch limited environment, and waves are subject to continuous forcing within the nearshore zone throughout most of the storm period.

The nearshore slope is gentle (approximately 0.015) and characterized by 3 bar-trough systems (Fig. 2); the outermost bar is highest (0.40 m) and essentially straight with a crest some 110 m offshore, while the inner two bars at distances of 65 m and 10 m from the shoreline have heights of only 0.15 m to 0.20 m and are sinuous to crescentic. The surf zone width is clearly constrained by these bars under many conditions but the general nearshore gradient is so low that breaking waves occur lakeward of the outermost bar, with a fully developed surf zone landwards, during much of the period of storm wave activity.

Experimental Design

Two types of instruments were used to monitor the fluid motions. Water surface elevation changes associated with waves were measured by surface piercing, continuous resistance wave staffs. Two or three meter long, helically wound steel wires (0.35 mm diameter) set in 18.8 mm PVC pipe (groove 0.75 mm, pitch 18.8 mm) were mounted by insulated brackets on 37.5 mm galvanized steel pipe. The latter was mounted on a two meter long base with fin to prevent rotation, and was jetted into the bed. The staffs were field calibrated individually to specific oscillator-detector circuits and were linear except for the lowermost 0.25 m. RG58A/U coaxial cable provide the shore-link. The oscillator circuit provides a 5 kHz square wave output and a simple half-wave rectifier and R-C Filter acts as a detector.

Shore-normal and shore-parallel flows were monitored using biaxial, electromagnetic flow meters designed by Marsh-McBirney, Inc. (Model OEM 512). Based on the Faraday Principle of electromagnetic induction, they use a time constant of 0.2 s and measure flow up to 3 ms^{-1}. Considerable work on the accuracy of these meters has been undertaken (Cunningham et al., 1979; White, 1979; Huntley, 1979 etc.)

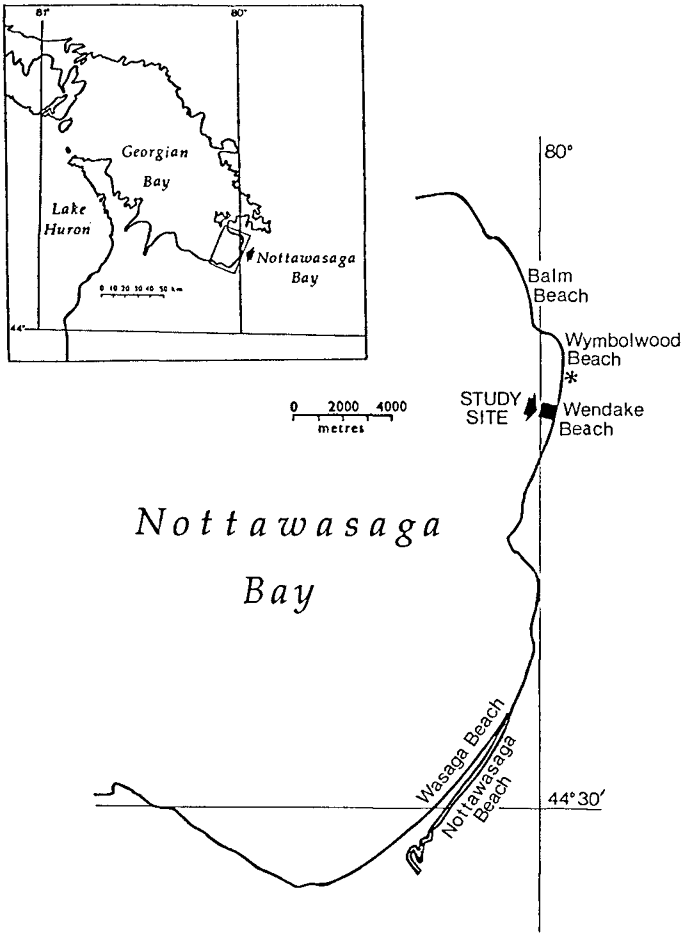

Figure 1: Location map of the study site, Wendake Beach, Ontario, Canada.

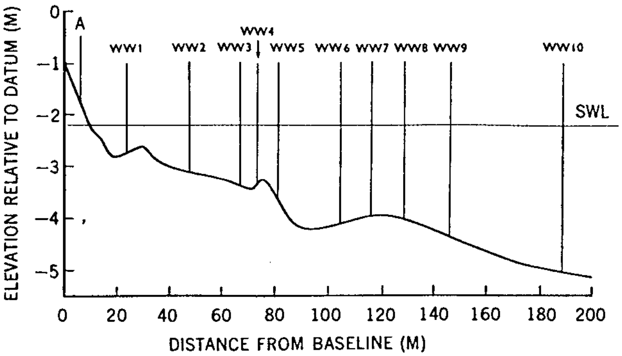

Figure 2a: Locations of instruments along the central profile, 1980:05:12 to 1980:06:05.

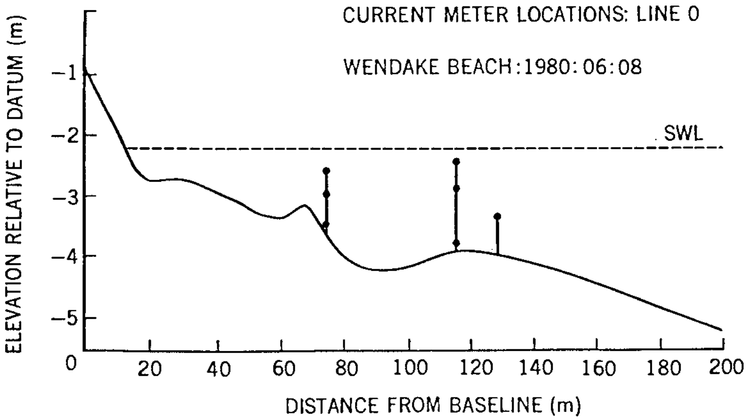

Figure 2b: Locations of current meters, 1980:06:06 to 1980:06:12.

and while some problems still exist the level of accuracy is better than 10%. The meters were mounted on a specially designed bracket (to allow rotation in both the vertical and horizontal planes), which itself was mounted on a stainless steel support. A galvanized steel pipe with fin to prevent rotation provide the base support and this again was jetted into the bed. The locations of the instruments are shown in Figures 2 and 3.

All sensors were hardwired to shore where a computer-controlled, data acquisition system (Fig. 4) provided instrument power, signal conditioning and detection, and data storage. A Hewlett-Packard 9835B mini computer with 125 K bytes of memory and real time clock controlled a high speed scanner-multiplexer (HP3495A) and digital voltmeter (HP3437A) allowing high density sampling of the current and wave sensors. Up to 40 channels could be monitored simultaneously. Record lengths varied between nine and twenty-five minutes with sampling at 2 Hz. Digital storage was on magnetic tape cartridges or flexible disc (HP9895).

Two specific plans were adopted for instrument deployment: a shore-normal array of ten wave staffs and seven flowmeters (Fig. 2a) allowed examination of the horizontal flow structure, while two sets of 3 flowmeters mounted vertically at the locations of wave wires 5 and 7 gave information on the vertical flow structure (Fig. 2b). At regular intervals during the experiments the system was activated to provide synchronous records of waves and currents at different positions across the surf zone thus giving a time series for evaluating the spatial and temporal variability of shore-parallel flows under a wide range of incident wave conditions. Specifically the datasets were used to evaluate: (i) the spectral characteristics of the incident waves; (ii) the spatial and temporal variability of shore-parallel flows; (iii) the parameters necessary to determine lateral mixing and eddy viscosity across the surf zone; (iv) the coefficients necessary to describe bed friction; (v) the influence of the non-planar slope on the above mentioned properties. Two storm events on May 30 - June 1, and June 8, 1980, will be described in this paper, with emphasis on lateral mixing and bed friction effects.

Nearshore Slope

An estimate of nearshore slope was obtained by fitting a least-squares regression line to measured profile data. R^2 values of better than 0.99 were obtained for a slope of 0.013 that intercepted the axis ($x = 0$) at -0.40 m. For a given value of water depth at the breaker line, h_b, the slope and intercept approximations were used to predict the width of the surf zone. Then an estimate of the actual slope was obtained using $s = h_b/x_b$. The process may be summarized:

$$s = 0.013\ h_b/(h_b - 0.40) \tag{1}$$

The resulting values of s ranged from 0.017 to 0.014.

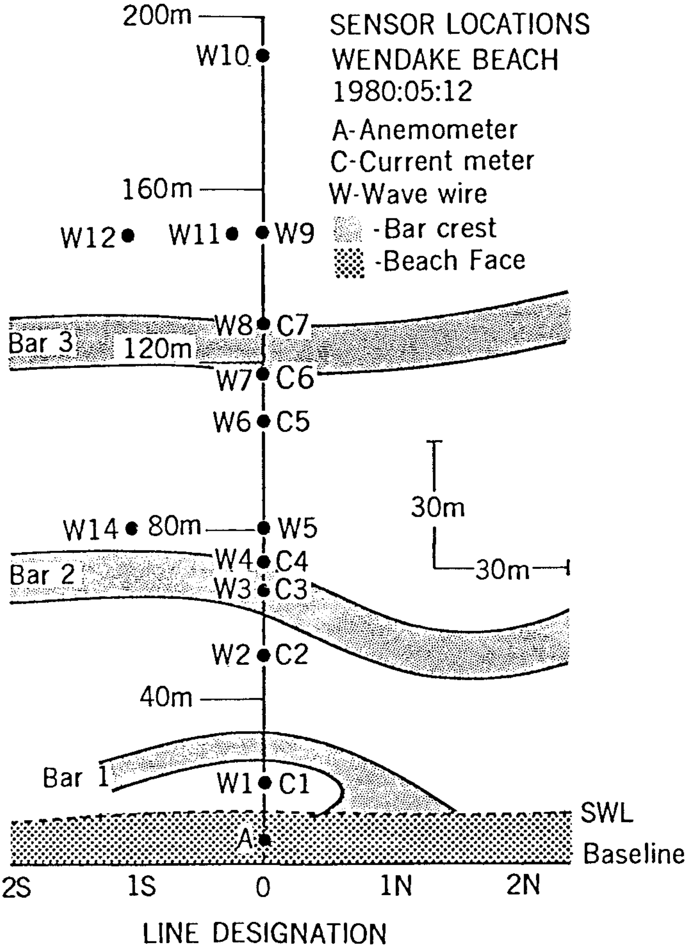

Figure 3: Map view of instrumentation locations utilized for monitoring the first storm: W indicates a wave staff, C, a current meter, and A, an anemometer and wind vane.

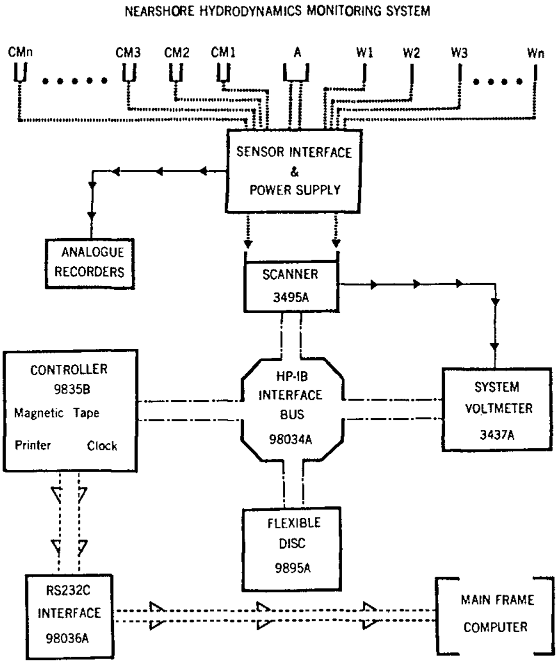

Figure 4: Schematic of the nearshore hydrodynamics monitoring system.

Storm Wave Characteristics

During the passage of depressions, waves in excess of 1.3 m mean amplitude and 5 s peak period provide the major local forcing for shore-parallel flows. Figures 5a and 5b illustrates the characteristic wave energy spectra incident to the surf zone during storms. A number of features are noteworthy:

(i) wave spectra in this continuous forcing environment exhibit large energy values over a wide range of frequencies below the peak frequency, which itself is marked by a very sharp truncation at the lower frequency end in all cases.

(ii) as expected, spectral growth (Fig. 5a) is accompanied by a consistent shift in the spectral peak to lower frequencies while there is an equally rapid increase in frequency during the decay phase (Fig. 5b). There is some evidence, however, for a dispersive effect during the decay period since at 0620 h the peak period (4.9 s) is greater than during the storm peak (4.6 s) and a broader peak at these longer periods is present.

(iii) during the most intense part of the storm, wave breaking produces a marked bimodal spectrum with the secondary peak at the frequency of the first harmonic.

(iv) in general there is very little evidence for structure in the spectra at frequencies lower than that of the incident spectrum. Some evidence is seen for a subharmonic during the early part of the storm (Fig. 5a & b) and for an oscillation at a frequency 1/4 times that of the incident wave; such structure is however, within the 95 percent confidence band for the spectra. The lack of low-frequency energy probably reflects the distance offshore of the wave staff, since under highly dissipative conditions many workers have noted the dominance of low frequency components (Huntley, 1976; Holman, 1981; Wright et al., 1982, etc.). Certainly storm conditions at Wendake Beach produce highly dissipative conditions, with the surf scaling parameter (Guza and Inman, 1975) ranging up to 192 x 10^2 (Greenwood and Sherman, 1983). Examination of the wave spectra nearer to the shoreline does indeed reveal an increase in this low frequency component.

Shore-Parallel Flows

HORIZONTAL STRUCTURE

During the storm event 1980:05:31 to 1980:06:01 fourteen records of the horizontal variability of longshore currents were obtained and Figure 6 illustrates six discrete records, from the periods of wave growth (Fig. 6a), the storm peak (Fig. 6b) and wave decay (Fig. 6c).

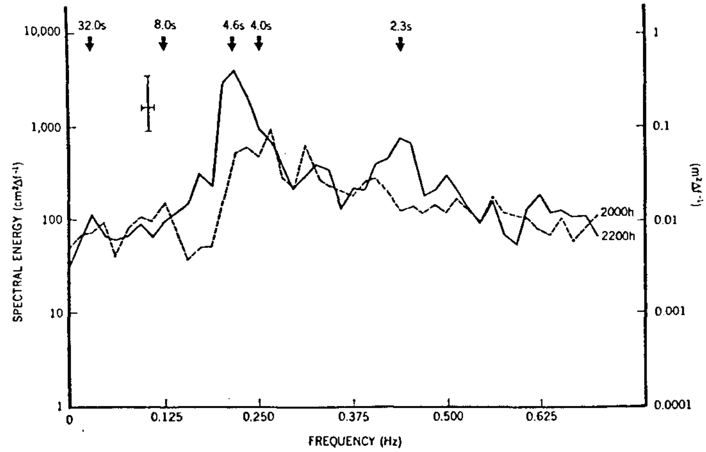

Figure 5a: Wave spectra from waxing limb of storm, WW9, 1980:05:30, 32 degrees of freedom. Vertical and horizontal crossbars indicate 95% confidence bar and unit bandwidth (0.016 Hz), respectively.

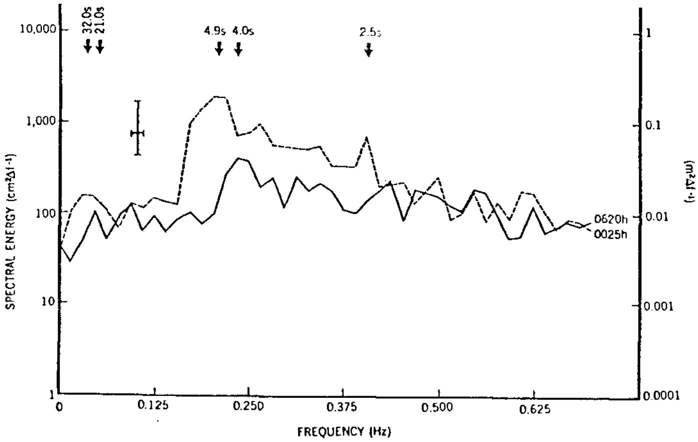

Figure 5b: Wave spectra from waning limb of storm, WW9, 1980:06:01, 32 degrees of freedom. Vertical and horizontal crossbars indicate 95% confidence bar and unit bandwidth (0.016 Hz), respectively.

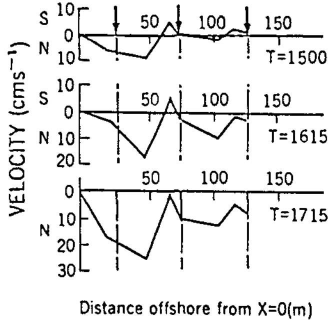

Figure 6a: Beginning of storm

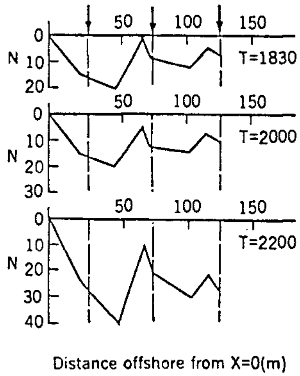

Figure 6b: Peak of storm

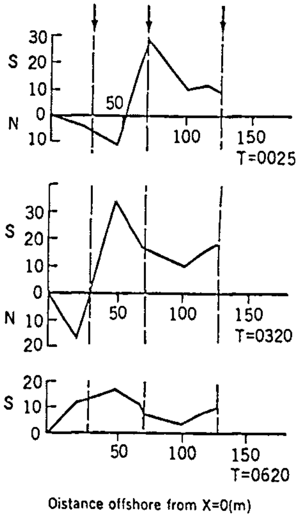

Figure 6c: End of storm

Figure 6: Time series of mean shore-parallel flows across a barred surf zone. Note the bars are located 20 m, 75 m, and 120 m, from the zero baseline.

As the storm grows flows accelerate with the increased wave driving and become more coherent up to the storm peak at 2200 h. At this time velocities reached a maximum of 40 cms^{-1}, with a maximum mean wave amplitude of 1.3 m at this time and peak period of 4.6 s.

Although bar heights are low and beach slope extremely flat in the nearshore, the topography exerts a marked influence on the horizontal structure of the flow field. Two distinct compartments of flow are associated with the outermost two bars. A marked reduction in velocity immediately landward of the bar crest should be noted with maximum flows in the trough on the landward side where water depth begins to decrease. Considerable variability in velocity is evident: excluding the zero velocity at the beach face a four-fold variation is present during the peak of the storm (2200 h). This contrasts markedly with the relative uniformity of surf zone flows across a bar-trough system claimed by Allender and Ditmars (1981). High velocities in the trough have been noted previously by Teleki et al., (1976) and ascribed to a longshore pressure gradient forcing due to wind setup.

A reversal in wind and wave direction around 2300 h produced a rapid response of the shore-parallel flows within the surf zone (Fig. 6c) in this fetch limited environment. However, an interesting feature of surf zone structure at this time was a horizontal stratification of flow reflecting a bi-directional disequilibrium response to the local wave forcing. This reversal persisted for more than 3 hours and may relate to the existence of a longshore pressure gradient (Komar, 1976, p. 196; Symonds and Huntley, 1980). However, it is important to note that between 2330 h and 0025 h the bulk of the surf zone flow was reversed and accelerated to a speed of 30 cms^{-1} in association with the change in direction of wave approach, thus implying dominance of the local forcing.

LATERAL MIXING

It is clear that a strong shore-normal variability in the average shore-parallel component of flow is evident on barred topography with the maximum velocities displaced landward of the initial break point which would occur on the bar crests. Such a pattern has long been recognized (Bowen, 1969; Longuet-Higgins, 1970 a & b) and although the shifting position of the breaker zone has been suggested as a significant control in a random wave field (Thornton, 1978) the primary control on a planar beach has been thought to be the lateral mixing associated with the horizontal Reynolds'stresses present under breaking waves. The latter tend to diffuse the local momentum flux and provide a smearing effect on the theoretical monotonic decay of currents across the surf zone (Longuet-Higgins, 1970 a & b). In an effort to compare the observations on a barred nearshore with the theory for a planar slope developed by Longuet-Higgins, estimates of his lateral mixing parameter, P, were attempted.

Dimensionless Velocity Profiles

Relative velocity values across the surf zone were calculated following Longuet-Higgins (1970b) by determining: (a) surf zone width based upon incident wave amplitudes, solitary wave breaking criterion and mean beach slope; (b) computed maximum velocity at breaking in the absence of lateral mixing, which involved a wave angle measure derived from a weighted orbital vector derived from the coherence between the surface elevation fluctuations and the measured orbital velocities; (c) a drag coefficient of the Darcy-Weisbach form assuming fully turbulent flow, a smooth boundary, and an equivalent grain roughness (following the experiments by Nikuradse).

Thus the longshore current at the breaker line, V_o (assuming no lateral mixing), is obtained from

$$V_o = \frac{5\pi}{8} \frac{\alpha S}{C} \sqrt{gh_b} \sin\theta_b \tag{2}$$

where α is a breaking criterion (α = 0.39), C is the drag coefficient, and θ the angle of wave approach at the breaker line. Figure 7 illustrates the typical form of these profiles. Note praticularly the drop in velocity in the troughs immediately landward of the bars, and the increase to a maximum velocity in the mid trough. This shift in maximum velocities landward from the break point reflects the lateral mixing while the velocity differential from bar crest to the trough immediately landward reflects both differences in energy dissipation as a result of increasing water depths and differences in mass also as a result of increasing water depths.

Mixing Parameter P

Estimates of the Longuet-Higgins mixing parameter, P, were attempted by averaging and smoothing the relative velocities and then fitting the observed distribution to theoretical distributions based on differing mixing values (Fig. 8). The extreme values associated with non-coherent flow reversals and the local perturbations associated with the second bar have been eliminated in Figure 8 and the dimensionless velocity profiles have been averaged over the storm period and over a given interval of offshore relative distance (0.2X). It should be noted that in all cases at least six points were averaged in each interval, except for the lakeward most unit, represented by one value. The upward deflection of the curve at this location is thus less powerful an indicator of the nearshore flow.

Initial examination of the average velocity profile reveals a pattern for the whole surf zone which is very similar in its general shape to the predicted curves. The distribution is however, skewed landwards to a significant degree. To effect a best fit comparison with the Longuet-Higgins' curve the empirical-average, relative velocities were purposefully adjusted so that the measured maximum was

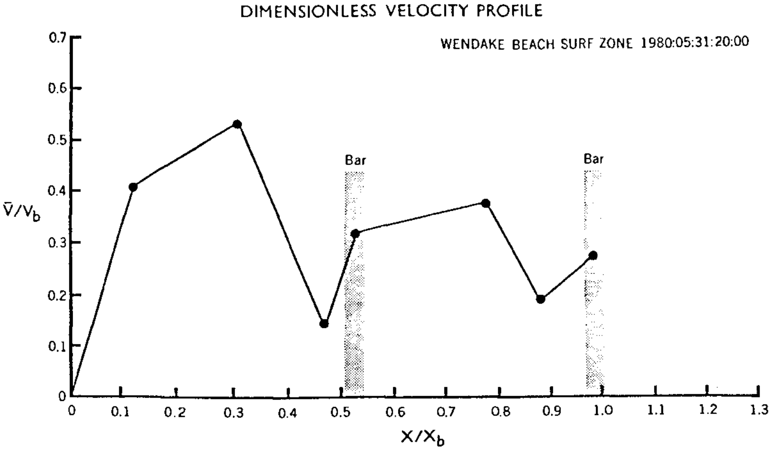

Figure 7: Dimensionless velocity profile during period of surf zone extension to outer bar.

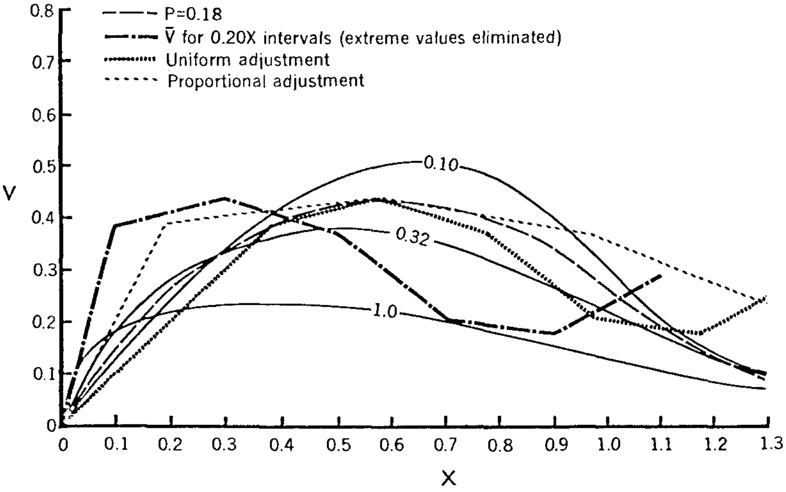

Figure 8: Theoretical and Empirical velocity profiles across the Wendake Beach surf zone.

coincident in position with the theoretical maximum. Both an absolute uniform adjustment and a proportional adjustment was applied to each value. In the former case each relative velocity is translated the same absolute distance as the maximum while in the latter case each velocity is translated a distance in the same proportion as the maximum velocity. Given the constraints of this adjustment, the best fit curve suggests a mixing parameter value of about 0.18, similar to other estimates that have been made (Longuet-Higgins, 1970b; Komar, 1975; Horikawa and Isobe, 1980; Symonds and Huntley, 1980).

VERTICAL STRUCTURE

Two sets of three current meters were used to measure the vertical structure of the longshore current (Fig. 2b). A depth-averaged, mean longshore current velocity was obtained for the storm of 1980:06:08, comprising a set of 27 observations. Mean values for specific elevations above the bed were also computed. The respective values are plotted with the overall mean as illustrated in Figure 10. For vertical arrays 1 and 2 (Fig. 9), the depth-averaged, mean velocities were 21 cms^{-1} and 28 cms^{-1}, respectively. The numbers associated with the current meter locations indicate the ratio of mean currents at that elevation to the overall mean. Note that the maximum mean variability is only about 10% of the depth-averaged flow. These findings are consistent with those of Meadows (1977), and the data suggests that the common practice of modeling longshore currents as depth-average or integrated values is not inappropriate.

Nevertheless, the form of these profiles also shows a consistent deformation of the velocity field strongly suggestive of the influence of bed friction. Assuming a logarithmic boundary layer velocity profile, and examining data from the lower two current meters in the lakeward array (VA2), estimates of boundary roughness may be obtained from

$$\ln Z_o = \frac{(V_b \cdot \ln Z_a) - (V_a \cdot \ln Z_b)}{V_b - V_a} \qquad (3)$$

where Z_o is the boundary roughness length, V is the longshore current velocity, Z is the elevation above the bed, and the subscripts $_a$ and $_b$ refer to values of the upper and lower current meters, respectively. Velocity measurements are obtained directly from the current records. Because the sand bed is moveable, however, estimates of instrument elevation must be made.

From direct measurement, the bed elevation before and after the storm is known. The maximum bed depression is also known from depth of activity rod and box core data (Greenwood <u>et al.</u>, 1980). Other values for bed elevation are then interpolated between these three points by assuming that the magnitude of bed elevation change is directly proportional to V^2 and the total elevation changes through the storm. These estimates then provide the basis for solutions to

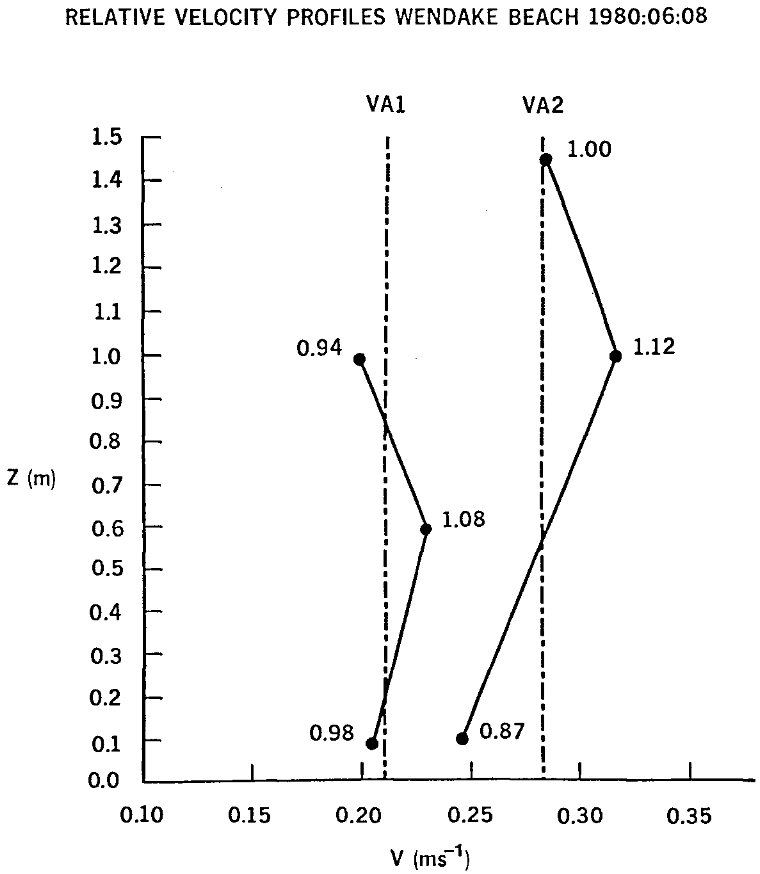

Figure 9: Mean velocity profiles from vertical current meter arrays, 1980:06:08.

equation (3). By plotting V_Z and lnZ, estimates of Z_0 may also be obtained graphically as the intercept of the line representing a logarithmic profile. Figure 10 illustrates these profiles. The dashed lines at ln 10 cm and 100 cm illustrate the values of Z that would have been used without the attempt at modeling bed elevation change. The lower dashed line represents a practical lower limit on expected values of Z_0, as determined from considerations of minimum roughness associated with skin friction on a plane bed. This relationship assumes that a Nikuradse equivalent sand grain roughness K_s, is approximated by $2D_{50}$, where D_{50} is mean grain size by weight-frequency distribution, and further, that $K_s/30 = Z_0$. It is reassuring that all of the estimates of Z_0 from the velocity profiles lie near or above this limit. This partially justifies the use of two points to determine the logarithmic profile. In terms of absolute values, the estimate of $2D_{50}/30$ obtained for the Wendake Beach data is about 0.013 mm, whereas the measured values range between about .01 mm and 3.28 mm. This variability in bed roughness over two orders of magnitude is believed to be mainly a reflection of changes in bedforms associated with wave orbital velocities, although the velocity profile measurements will also reflect changes in the wave boundary layer and internal stratification due to sediment transport. Further details concerning this analysis are presented in Sherman and Greenwood (1983).

For estimates of bed roughness effects on the deformation of the velocity field, a value for the friction (shear) velocity may be obtained from:

$$V_Z = \frac{V_*}{\kappa} \ln (Z/Z_0) \qquad (4)$$

where V_* is the friction velocity and κ is Von Karman's constant (0.40). Values of V_* may further lead to estimates of boundary shear stress due to the mean current through solving

$$\tau_0 = \rho V_*^2 \qquad (5)$$

where τ_0 is the boundary shear stress.

CONCLUSIONS

The data obtained during the Wendake Beach experiments allows a numerical approximation of key parameters controlling nearshore hydrodynamics. Qualitatively, the strong influences of minor nearshore relief upon the horizontal velocity structure have been demonstrated. Quantitatively, values for a lateral mixing parameter and a wave-current friction factor have been obtained for use in further modeling of the longshore flow. Specific conclusions may be summarized as follows:

1) On a "statistically" planar nearshore slope, bars of low amplitude (less than 0.4 m) exert strong control on longshore current development, particularly the horizontal structure .

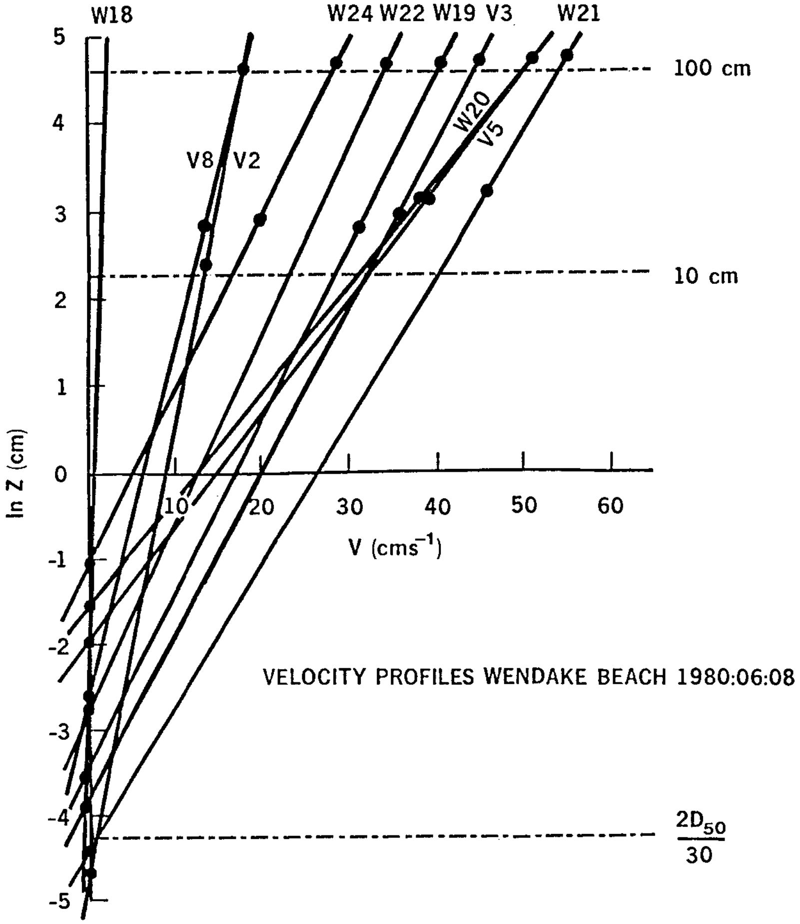

Figure 10: Graphical estimation of boundary roughness length from measurements of average longshore current velocity and estimated elevations above the bed. V and W are file designators here. V files are of 18-20 min. duration and W files of 9 minute length.

2) By discounting localized topographic effects, averaging methods yield an empirically derived, horizontal current structure in good agreement with the theoretical predictions of Longuet-Higgins (1970 b).

3) An estimate of the lateral mixing parameter, P, was found to be approximately 0.18 for the Wendake Beach nearshore.

4) Based upon assumptions of a logarithmic vertical velocity profile an average boundary roughness length of $Z_0 \approx 1$ mm is obtained from this data set.

5) Estimates of Z_0 vary over two orders of magnitude, presumably reflecting changes in bedform configuration and sediment transport.

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Richards Bay South breakwater

PART III
COASTAL STRUCTURES AND RELATED PROBLEMS

Waves breaking over Gans Bay breakwater