BOUNDARY ROUGHNESS AND BEDFORMS IN THE SURF ZONE

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ABSTRACT


Hydrodynamical models of the nearshore system frequently assume that a single friction coefficient is sufficient to represent flow conditions at a point in the surf zone. Furthermore, models attempting to relate bed configuration to surf zone flows have relied primarily upon the wave orbital velocity as an indicator of potential bedforms, and thus as the control on boundary roughness. The data presented here point out potential errors arising from either of these approaches. The results of a field experiment conducted at Wendake Beach, Ontario, show that at a single location in an active surf zone, the Darcy-Weisbach friction coefficient, $f$, varied by approximately 250% (in this case between 0.016 and 0.041).

It is also shown that existing bedform models, based upon primary wave motions alone, do not accurately predict conditions at this study site. For a relatively constant wave orbital velocity and velocity asymmetry, it is found that changes in bed roughness, as a result of bedform development, are reflected mainly in the vertical profile of the longshore current velocity. A sequence of bedforms, from oscillatory ripples through flat bed, is inferred from the data, and found to be supported by diver observations and preserved primary sedimentary structures.

INTRODUCTION

Considerable time and effort has been expended on research into the nature of the complex interactions at the fluid—sediment interface, especially concerning the development of bedforms. These interactions are important to both the accurate modeling of modern prototype fluid systems, and the analysis of bedding genesis and interpretation of sedimentary environments. However, in nearshore systems dominated by wave-generated oscillatory flows and wave-induced, quasi-steady currents, our knowledge of fluid—

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sediment interaction remains rudimentary. According to Allen (1982, Vol. I, p.444), "Little attempt has been made to define the existence fields of bedforms in oscillatory flows", and about wave-current ripples he goes on to say (1982, Vol. I, p.448), "These forms are less well known and understood than their more symmetrical relatives".

To a large extent, this lack of understanding can be attributed to the paucity of prototype data describing these bedforms. Although considerable advances have been made in the last decade or so in formulating conceptual models of bedform sequences in oscillatory flows (e.g., Clifton, 1976; Davidson-Arnott and Greenwood, 1974, 1976; Allen, 1982; Clifton and Dingler, 1984) there is still relatively little empirical evidence to support these models (see, for example, Clifton et al., 1971; Davidson-Arnott and Greenwood, 1976; or Dabrio and Polo, 1981, for some prototype results). Thus, a primary motivation for this research was to improve the data base, attempt to determine the sequential development of bedforms through a storm, and recognize the key fluid—sediment relationships. Toward this end, a field experiment was conducted at Wendake Beach, Ontario, in May and June, 1980.

STUDY SITE AND EXPERIMENTAL DESIGN

The Wendake Beach study site was located on the southeastern shore of Nottawasaga Bay, in Lake Huron (Fig.1). The nearshore slope is gentle (≈0.015), with three low-amplitude, nearshore bars. The mean sediment diameter by weight frequency distribution, D, is 0.21 mm. Additional details of this site are presented in Randall (1982), Sherman (1982) and Greenwood and Sherman (1983, and 1984, this volume). For this field experiment, six bi-directional, fast-response electromagnetic water current meters (Marsh-McBirney models 511 and 512) were deployed in two vertical arrays (of three current meters each) along the edges of the outer nearshore trough. In vertical array 1 (VA1), about 50 m from the still water line, the current meter elevations were 0.10, 0.60, and 1.00 m above the bed, and in vertical array 2 (VA2), about 105 m offshore, the installation elevations were 0.10, 1.00, and 1.45 m (Fig.2). Water depths at the two arrays were 1.60 and 1.70 m, respectively. The purpose of the vertical arrays was to measure an assumed logarithmic velocity profile in the longshore current. It has long been recognized that the structure of these vertical profiles should reflect the magnitude of boundary roughness (e.g., Nikuradse, 1933; Wooding et al., 1973), although in the nearshore there are complications arising primarily from the presence of the wave boundary layer (Grant and Madsen, 1979) and near-bed sediment transport (Smith and McLean, 1977; Grant and Madsen, 1982). Stratification due to temperature or suspended sediments was not considered to be a factor at this site. There was occasional direct observation of bed configuration during the storm by divers, and indirect monitoring through post-storm box core samples taken at the vertical arrays. The evidence from these measurements and observations allow at least a qualitative description of the nearshore flow regime.
Nine sets of measurements were obtained from the current meters during a storm that occurred on June 8, 1980, with specific record lengths of either nine or eighteen minutes, and with sampling at approximately 0.5 s intervals, or less. Thus each file for each current meter comprises about either 1000 or 3000 samples.

FLOW STRUCTURE AND BOUNDARY ROUGHNESS

Mean flow conditions through the storm were determined in the first stage of data analysis. From each of the vertical arrays, all of the longshore current velocity measurements from the set of three current meters were averaged to obtain a depth-integrated, mean velocity at that location. The velocities at each elevation were then averaged and compared to the depth-integrated mean. These results are illustrated in Fig.3. The forms of these profiles indicate the presence of the type of near bed deformation expected, although the anomalous surface decrease in velocity is not readily explainable. Also note that the relatively small amount of vertical variability (plus or minus
CURRENT METER LOCATIONS: LINE 0
WENDAKE BEACH: 1980:06:08

Fig. 2. Current meter locations in the vertical arrays, 1980:06:08. SWL is still water level.

RELATIVE VELOCITY PROFILES WENDAKE BEACH 1980:06:08

Fig. 3. Relative longshore current profiles through a storm, 1980:06:08. Vertical dashed lines at VA1 and VA2 represent depth integrated mean current velocities. Points are mean velocities relative to the array mean at different elevations above the bed and the associated numbers are the ratios of point velocities to the depth-integrated average.

about 10% of the overall average) supports the general longshore current modeling assumption of velocity homogeneity through the water column (see discussion in Basco, 1982). Nevertheless, the two bottom current meters in VA2 consistently produced results that were consistent with the presence of a logarithmic boundary layer. The data from VA1 do not fit the logarithmic model because the velocity gradient between the two elevations is too
steep to yield physically plausible boundary roughness lengths. This is be-
lieved to reflect, in part, the relative insensitivities of the two lower current
meters in VA1 (model 511). These instruments have a calibration precision
of only 3 cm s$^{-1}$, whereas the other four current meters (model 512) cali-
brate at ±0.3 cm s$^{-1}$. These terms do not include the ±10% measurement
errors of the instruments. Thus these data are suspect and not considered
further.

Using the 0.10 and 1.00 m current meters (CM6 and CM4, respectively) in
VA2, the apparent roughness length $z_o$, as felt by the longshore current, may
be derived using analytic geometry:

$$\ln z_o = \frac{(V_b \cdot \ln z_a) - (V_a \cdot \ln z_b)}{V_b - V_a}$$

(1)

where $V$ and $z$ refer to the longshore current velocity and elevation above
the bed, respectively, and the subscripts $a$ and $b$ refer to values for the lower
and upper current meters, respectively.

The first analytic complication arises in the determination of the elevation
for the current meter sensors. Although they were originally installed at 0.10
and 1.00 m above the bed, it is known, through data obtained from locally
emplaced, depth-of-disturbance rods (Greenwood et al., 1980; Greenwood
and Hale, 1980) and box core data, that the bed elevation decreased a maxi-
mum of 0.16 m through the storm. Thus, at some stage of the storm, pre-
sumably at its peak, the elevations of the lower current meters, CM6 and
CM4, were 0.26 and 1.26 m above the bed, respectively. These changes in
the values of $z$ have important effects in the derivation of $z_o$. For example,
the natural log of 10 cm is 2.30, whereas ln 26 cm is 3.26. This change in
ln $z$ can result in apparent changes in the roughness length of several orders of
magnitude. It was therefore decided to attempt to model bed elevation change
through the storm based upon several assumptions.

First it must be assumed that the maximum amount of bed depression is
coincident with the largest longshore current velocities. For the June 8
storm, this velocity was 0.55 m s$^{-1}$ at 1130 h (Eastern Daylight Saving
Time). Thus, at this time it is assumed that the elevation of CM4 is 1.26 m
above the bed. It is also, somewhat arbitrarily, assumed that bed depression
begins when the longshore current velocity exceeds 0.10 m s$^{-1}$. Thus, when
the current velocity is less than 0.10 m s$^{-1}$ the bed elevation is a constant.
Above 0.10 m s$^{-1}$, the bed elevation is assumed to vary as a function of the
square of the velocity. This assumption is based upon bed shear stress in-
creasing solely with $V^2$ and ignoring potential changes associated with wave
effects.

Given the above qualifications, changes in the value for $z$ for each instru-
m ent were calculated through the storm. These changes are shown in Fig.4.
Of the ten values shown, three are measured; the two end points and the
maximum depression. The result of the predictions for the other values is
a reasonable sequence of elevations through the storm. Thus values for both
the mean longshore current velocities (averaged over a record length) and the
projected height above the bed are available for each of the current meters. These values are substituted, in turn, into eq.1 to calculate the apparent roughness lengths at VA2 through the storm.

An independent estimate of the minimum physical roughness of the bed may be obtained by using grain size information to calculate the Nikuradse (1933) equivalent sand grain roughness, \( k_s \), and thus derive a value for \( z_o \) for plane bed conditions. It is assumed here that \( k_s = 2D_{50} \), where \( D_{50} \) is the mean grain size by weight (0.21 mm at Wendake Beach), and the constant of proportionality represents the effect of an uneven surface packing of the sediment on an otherwise plane bed (Yalin, 1972). Further assuming that:

\[
k_s = 30 \ z_o
\]

(Schlichting, 1968), the minimum value of \( z_o \) for the Wendake Beach surf zone should be about 0.014 mm (minimum \( k_s \) = 0.42 mm).

Table I presents a summary of the VA2 data used in these calculations and the results. Note that the difference between the \( k_s \) estimates of \( 6.73 \times 10^{-2} \) m at 0910 and \( 5.26 \times 10^{-2} \) m at 0935 may not be significant because the measurements used for these calculations are at or near the limits of the current meter accuracy. For example, the only difference in velocities for the file pair WAV20 and VERT5 is the 0.005 m s\(^{-1}\) velocity at CM6. Because of the instrument calibration, however, the smallest increment of velocity that can be measured is 0.003 m s\(^{-1}\). Thus these values may be virtually identical. Note that even this small difference in velocity results in a change of about 25% in the estimate of \( k_s \). Therefore all values of \( k_s \) presented here must be considered as approximations only. Figure 5 illustrates the velocity profiles and the resulting estimates of \( z_o \), including the minimum estimate based upon the grain size procedure. Note also the dashed lines labeled 10 and 100 cm. These indicate the unadjusted instrument elevations. It can be seen that the failure to account for bed elevation changes could greatly reduce the derived estimates of \( z_o \). Indeed, most estimates would then fall below the minimum physical limit set by \( 2D_{50}/30 \).
TABLE I

Summary of data used for the derivation of bed roughness estimates, Wendake Beach surf zone, 1980:06:08. The velocities from CM6 and CM4 are denoted by subscripts a and b, respectively. The predicted changes in bed elevation are $\Delta z$. VERT files are of 18 min duration, WAV files are 9 min long.

<table>
<thead>
<tr>
<th>File name</th>
<th>Time (h)</th>
<th>$v_a$ (m s$^{-1}$)</th>
<th>$v_b$ (m s$^{-1}$)</th>
<th>$\Delta z$ (m)</th>
<th>$z_o$ (m $\times 10^{-3}$)</th>
<th>$k_s$ (m $\times 10^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VERT2</td>
<td>0420</td>
<td>0.137</td>
<td>0.180</td>
<td>-0.01</td>
<td>0.09</td>
<td>0.28</td>
</tr>
<tr>
<td>WAV19</td>
<td>0530</td>
<td>0.313</td>
<td>0.405</td>
<td>-0.07</td>
<td>0.33</td>
<td>0.98</td>
</tr>
<tr>
<td>VERT3</td>
<td>0600</td>
<td>0.359</td>
<td>0.450</td>
<td>-0.10</td>
<td>0.24</td>
<td>0.72</td>
</tr>
<tr>
<td>WAV20</td>
<td>0910</td>
<td>0.381</td>
<td>0.512</td>
<td>-0.13</td>
<td>2.24</td>
<td>6.73</td>
</tr>
<tr>
<td>VERT5</td>
<td>0935</td>
<td>0.386</td>
<td>0.512</td>
<td>-0.13</td>
<td>1.75</td>
<td>5.26</td>
</tr>
<tr>
<td>WAV21</td>
<td>1130</td>
<td>0.460</td>
<td>0.551</td>
<td>-0.16</td>
<td>0.14</td>
<td>0.42</td>
</tr>
<tr>
<td>WAV22</td>
<td>1400</td>
<td>0.267</td>
<td>0.346</td>
<td>-0.09</td>
<td>0.52</td>
<td>1.56</td>
</tr>
<tr>
<td>VERT8</td>
<td>1515</td>
<td>0.136</td>
<td>0.181</td>
<td>-0.07</td>
<td>0.65</td>
<td>1.96</td>
</tr>
<tr>
<td>WAV24</td>
<td>1900</td>
<td>0.199</td>
<td>0.288</td>
<td>-0.08</td>
<td>3.28</td>
<td>9.83</td>
</tr>
</tbody>
</table>

Fig. 5. 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, representing record lengths of 18 and 9 min, respectively. $2D_{so}/30$ is a sand grain roughness estimate of the minimum physical roughness length.
The values of $z_0$ shown here range from 0.09 to 3.28 mm. Using the already mentioned relationship between $z_0$ and $k_s$, the range of equivalent sand grain roughness is thus from 2.8 to 98 mm. These values of $k_s$ can be used to obtain graphic estimates of the Darcy-Weisbach $f$ from the familiar Moody diagram, where specific values of $f$ are found as a function of the Reynolds number and relative roughness. Plotting the Wendake Beach data against this relationship, we obtain the results shown in Fig.6. The arrows and numbers are to indicate the sequence of findings. The data show a minimum $f$ of 0.016 and a maximum estimate of 0.041, representing a variability of about 250%. Most previous attempts at quantifying bed friction in the surf zone have assumed either a constant value for the entire nearshore or constant friction coefficient at a given location with spatial variability according to changes in local slope and relative roughnesses (e.g., Wright et al., 1982). This is clearly not the case here, where a large variability is found at a point. These changes may arise from several sources: a change in the turbulent structure of the flow; a change in the wave boundary layer thickness; a change in the thickness of the near bed sediment transport layer, changes in bed configuration; or combinations of the above. It is believed that changes in bed configuration are primarily responsible for the range of $f$ found in these data, for the reasons presented below.

RESULTS AND DISCUSSION

For the Wendake Beach data, most values of the Reynolds number are shown to be near or beyond the limit for fully developed turbulent flow (this limit is indicated by the dashed line curving from upper left to lower right in Fig.6). For fully rough flow, the Darcy-Weisbach friction factor depends solely upon the relative roughness (e.g., Vennard, 1961). Therefore it is not likely that the variability in $f$ is attributable to changes in Reynolds number.

Grant and Madsen (1979) have theoretically proposed that the presence of the wave boundary layer within the current boundary layer will result in an increase in apparent boundary roughness (that felt by the current) from the physical boundary roughness and enhanced stress. Thus changes in the thickness of the wave boundary layer would be reflected in changes in the apparent bottom roughness length. According to Grant and Madsen (1979), the thickness of the wave boundary layer ($\delta$) may be approximated by:

$$\delta = 2\kappa |u_{*cw}|/\omega$$

(3)

where $\kappa$ is the Von Karman constant (0.4), $\omega$ is the radian frequency, $2\pi/T$, and $|u_{*cw}|$ is the shear velocity due to wave and current interaction:

$$|u_{*cw}| = \left(\frac{1}{2} f_{cw} \alpha \right)^{1/2} u_m$$

(4)
where $f_{cw}$ is the combined wave and current friction coefficient, and for trans-directional flow:

$$
\alpha = 1 + \left(\frac{v}{u_m}\right)^2
$$

(5)

where $v$ is the steady current velocity and $u_m$ is the wave orbital velocity:

$$
u_m = \gamma (gh)^{1/2}
$$

(6)

where $g$ is the gravitational constant, $h$ is water depth, and $\gamma$ is the wave (amplitude) breaking criterion (0.4). Grant and Madsen (1979) also propose that $f_{cw}$ is a function of $v/u_m$ and $k_s/A_b$, where $A_b$ is the horizontal orbital amplitude, $A_b = u_m/\omega$. From these relationships it can be seen that, for a constant water depth and bottom roughness, $\delta$ will depend only upon $T$ and $v$.

Changes in $v$ affect the ratio of the steady current to the oscillating current, $v/u_m$. This ratio is one control on $f_{cw}$ (Grant and Madsen, 1979). However, for trans-directional flow, relatively large changes in $v/u_m$ change $f_{cw}$ only slightly. For the range of $v/u_m$ measured at Wendake Beach (Table II), estimates of $f_{cw}$ change by only about 10% and the ratio is almost constant through the peak of the storm. It is therefore presumed that for these results, the wave boundary layer thickness is dependent primarily upon wave period. As wave period increases, so should the boundary layer thickness. For the Wendake Beach data, through the storm, the peak wave period varied from a minimum of 2.3 s to a maximum of 6.4 s, a variability of about 69%. However, through the middle of the storm, when there were large changes in apparent roughness, the mean period varied only about 17%,

Fig.6. Wendake Beach storm data plotted on a Moody Diagram. Arrows and numbers indicate the sequence of $f$. Values of $f$ range from about 0.016 to about 0.041.
TABLE II

Predicted and measured orbital velocities and relative velocities at VA2, 1980:06:08, Wendake Beach

<table>
<thead>
<tr>
<th>File</th>
<th>$U_{\text{max}}$</th>
<th>$U_{\text{rms}}$</th>
<th>$V_{\alpha}/U_{\text{rms}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>VERT2</td>
<td>1.24 (m s$^{-1}$)</td>
<td>1.09 (m s$^{-1}$)</td>
<td>0.13</td>
</tr>
<tr>
<td>WAV19</td>
<td>1.03</td>
<td>1.08</td>
<td>0.29</td>
</tr>
<tr>
<td>VERT3</td>
<td>1.53</td>
<td>1.12</td>
<td>0.32</td>
</tr>
<tr>
<td>WAV20</td>
<td>1.26</td>
<td>1.07</td>
<td>0.34</td>
</tr>
<tr>
<td>VERT5</td>
<td>1.40</td>
<td>1.12</td>
<td>0.35</td>
</tr>
<tr>
<td>WAV21</td>
<td>1.37</td>
<td>1.18</td>
<td>0.39</td>
</tr>
<tr>
<td>WAV22</td>
<td>1.37</td>
<td>1.12</td>
<td>0.24</td>
</tr>
<tr>
<td>VERT8</td>
<td>1.15</td>
<td>0.96</td>
<td>0.15</td>
</tr>
<tr>
<td>WAV24</td>
<td>1.18</td>
<td>1.05</td>
<td>0.19</td>
</tr>
</tbody>
</table>

*For $d = 2.00$ m, $U_m$ (predicted) = 1.73.

between 5.3 s and 6.4 s. Further, $T$ increased from 5.3 s at 0910 to 6.4 s at 1130 while $k_s$ dropped from 6.73 to 0.42 cm. Thus, while there is no doubt that the presence of the wave boundary layer is reflected in the measurements leading to the derivation of $z_o$ (or $k_s$), it alone cannot account for either the direction or magnitude of variability in the boundary roughness.

Smith and McLean (1977), and Grant and Madsen (1982), have shown how apparent roughness is also affected by the thickness of the near-bed sediment transport layer. According to Grant and Madsen (1982) the thickness of this layer, as reflected in its contribution to the total roughness, is approximated by:

$$k_{bs} = 160 (s + C_m)D\psi_c [(\psi'/\psi_c)^{1/2} - 0.7]^2$$  \hspace{1cm} (7)

where $k_{bs}$ is the sediment transport induced roughness, $s = \rho_s/\rho$, where $\rho_s$ is the density of the sediment and $\rho$ is the fluid density, $C_m$ is an added mass coefficient (taken as 1/2 for spheres), $\psi_c$ is the critical value of the Shields parameter for the initiation of motion and $\psi'$ is the maximum value. Grant and Madsen (1982, p.471) define:

$$\psi' = \tau'_{bm}/\rho(s - 1)gD$$  \hspace{1cm} (8)

where $\tau'_{bm}$ is the maximum value of the skin friction under the wave:

$$\tau'_{bm} = \frac{1}{2} \rho f_w' u_m^2$$  \hspace{1cm} (9)

where $f_w'$ is based upon $k_s$ and $T$. Therefore, for constant sediment characteristics, and with an otherwise unchanging bed roughness, the thickness of the near bed sediment transport layer depends upon $u_m$ and $T$ only, and as noted above (eq.4), $u_m$ is a function of water depth in the surf zone, and $T$ is relatively stable through the storm. Thus, in an otherwise constant
environment, changes in $k_s$ or $z_o$ cannot be solely accounted for by changes in $k_{bs}$.

It should be noted that even under optimum conditions, i.e., with several high-resolution current meters in an array and the bottom precisely defined, large errors in $z_o$ (hence $k_s$) are to be expected. Grant et al. (1983) working on the continental shelf, used four acoustic current meters to measure water velocities and an echo sounder to sense the bottom. Regression lines fit to the data with $R^2 > 0.99$ showed estimates of $z_o$ to vary on the order of ±100% at the 95% confidence level. Uncertainty as to the bed elevation at Wendake Beach, and the overall precision of measurement required to accurately locate $z_o$, imply that values of bed roughness reported here be used only as indicators, not absolutes. However, the order of magnitude variability in roughness estimates (Table I) is much greater than the potential error terms alone can account for. Therefore, although specific values of $k_s$ (or $z_o$) may be inaccurate, the temporal variability is real.

As expected, attention may therefore be focused upon changes in the surf zone bed configuration as being the primary agent affecting measurements of $z_o$. It is assumed that the major influence on bed deformation is the wave orbital velocity, with the current adding a secondary, but important contribution to the total stress. Indeed most attempts to formulate models of bed form development due to periodic waves (Clifton, 1976; Davidson-Arnott and Greenwood, 1976; Allen, 1982; Clifton and Dingler, 1983) rely, at least in part, on the use of orbital velocity and mean grain diameter as the main variables. Using Clifton's (1976) model, the bed form thresholds are found to be functions of $u_m$, $D$, and, in some cases, $T$. For the threshold of sheet flow and flat bed, Clifton has used Dingler's (1974) data to set this limit based upon grain size. The critical orbital velocity for transition to sheet flow is given by Clifton's (1976) model, the bed configuration throughout the storm is predicted as flat, and therefore could not account for the measured variability in $z_o$.

\[
U_{mc} = (3.88D \times 10^5)^{1/2}
\]

where $U_{mc}$ is the threshold velocity. Using this relationship and the Wendake Beach mean grain diameter of 0.021 mm, the critical orbital velocity for plane bed configuration is about 0.90 m s\(^{-1}\).

Estimates of the Wendake Beach orbital velocities are obtained from linear wave theory, using eq.4, and from the current meter data that provide a maximum measured velocity ($u_{max}$) and a predicted velocity, $u_{rms} = 2.8$ s, where $s$ is the standard deviation of the current meter record and 2.8 is an $H_{rms}$ analogy (after C.E.R.C., 1977, pp.3-12). This yields a conservative estimate for the orbital velocity. From eq.4, the predicted value of $u_m$ is 1.73 m s\(^{-1}\). The results obtained from the current meter record through the storm are presented in Table II. For all data records summarized in Table II, the values of $u_m$ exceed the threshold velocity given by eq.8. Thus, according to Clifton's (1976) model, the bed configuration throughout the storm is predicted as flat, and therefore could not account for the measured variability in $z_o$.

Clifton's (1976) model also attempts to define the effects of wave orbital
asymmetry, $\Delta u_m$, on bedform development. His work suggests that for a given wave period and sediment grain diameter, the nature of bed deformation is a function of the relationship between $u_m$ and $\Delta u_m$. Again, however, the current meter data indicate that there was little variability in $\Delta u_m$ through the storm. Indeed this factor was almost constant when changes in $z_o$ were greatest, near the peak of the storm.

Of the surf zone velocities measured, only the longshore current showed a substantial variation through the monitoring period. Figure 7 illustrates the measurements of $V$, $u_{rms}$, and $\Delta u_m$ ($\Delta u_m$ is plotted as the mean flow asymmetry, after Dingler, 1974) through the storm. Given the relative uniformity of the latter two variables, they are considered constants against which changes associated with current can be evaluated.

Diver observations and box core data, taken across the surf zone, clearly indicate that plane bed conditions were not present at all times throughout the storm. There was instead a sequential development of bedforms, and this sequence seems to qualitatively correspond with changes in longshore current velocities (implicitly superimposed on a constant $u_m$). Figure 8

![Figure 7. Sequence of surf zone velocity measurements through the storm, 1980:06:08.](image-url)
shows the concurrent changes in the current velocity, $V$, and $\ln z_o$, through the storm. There is a general, coincident increase in $V$ and $\ln z_o$ up to about 50 cm s$^{-1}$. Then the incremental increase in velocity (at 1130 h) is accompanied by a large decrease in the apparent roughness length. Thereafter, the lower velocities are associated with increasing roughness. These changes in bed roughness are primarily attributed to changes in bed configuration, a finding in contradiction with nearshore bedform development models employing $U_m$ only.

A tentative means of identifying the bedforms is offered in Fig.9. Here, the natural log of the equivalent sand grain roughness is plotted through the storm. The upper pair of lines represent predicted roughness values obtained using relationships between ripple height and $k_s$. From a limited data set obtained by direct measurement and from box core data, a typical ripple height, $\eta$, for Wendake Beach varied between 1.5 and 2.5 cm. According to Stefanick (as cited in Jonsson, 1980) a reasonable approximation of the bedform induced boundary roughness is $k_s = 2.5 \eta$. This relationship is plotted for the pair of estimated $\eta$. Working backwards, these lines, therefore, serve as indicators of the expected bed configurations, given a measured estimate of $k_s$. There are pairs of points at the beginning and end of the series to represent the variability in $k_s$ that arises from a 2 cm error in the estimate of $z$ used to obtain $z_o$. These represent maximum errors for the
series because the relative change in $\ln z$ is greatest for the smaller values of $z$. The value of 2 cm was selected as being approximately the potential ripple height migration effect on bed elevation.

The information presented in Fig. 9 suggests that for most observations ripples were present. This is not surprising, as the ripples occur at the beginning and end of the storm sequence. The lower and upper end points of the first and last values of $k_z$, respectively, are considered errors based upon physical considerations of what was occurring at those times. A larger than rippled bed is present at 0910 h, with a large decrease in roughness at 1130 h. This drop in roughness, associated with increased velocities, is assumed to indicate a change to a flat bed configuration. The difference between this roughness derived from the velocity profiles and the grain roughness (4.2 and 0.42 mm, respectively) is attributed to nearbed sediment transport. These results ignore any possible effects of bedform orientation (relative to the flow) on boundary roughness.

Based upon this analysis, and field observations, inferred bed form types are plotted with shear stress, $\tau_0$ ($\tau_0 = 1/2 \rho fV^2$; with $f$ found from Fig. 6) and $V$ (Fig. 10). The numbers at each point are to identify the sequence of the data. This figure shows two clusters of supposed ripples, two megaripple predictions and one value at plane bed. The change of position between the

Fig. 9. Equivalent sand grain roughness estimates and roughness values attributed to specific bedforms. The upper dashed lines are ripple values.
SHEAR STRESS, CURRENT VELOCITY
AND INFERRED BED FORMS

Fig.10. Boundary shear stress, longshore current velocity and inferred bedforms. Numbers indicate the sequence of data.

ripple clusters is attributed to changes in the thickness of the near-bed sediment transport layer due to changing bed roughness and velocity. Note also that among the six ripple observations, there is a distinct segregation between points from the waxing and waning limbs of the storm (as indicated by the point numbers). Points 1, 2 and 3 lie almost in a straight line, and points 7, 8 and 9 are all above that line. This corresponds well with what is found in studies of river flow regime, where the rating loop effect is well documented (Allen, 1982). This effect is a function of the response time of the bed to changes in flow. With decreasing current velocities, the bedforms change more slowly, response time is increased, and thus relict roughnesses may be present during velocity measurements. The rating loop effect also seems to be indicated in the Fig.8 data.

Figure 11 is Southard's (from Middleton and Southard, 1977) conceptual model of the relationships between bed form, velocity \( U \), and boundary shear stress \( \tau_0 \). In this model it is shown that a given current velocity is associated with a unique bedform. For increases in velocity within a specific bedform class, there is a relatively uniform change in bed shear stress [e.g., increasing in the ranges of ripples (R) and sand dunes (SD)]. There are also relatively abrupt changes in \( \tau_0 \) associated with small changes in \( U \) in the transition between bedform regimes. Of particular interest is the rapid decrease in \( \tau_0 \), despite an increase in \( U \), with the change from dunes to flat bed (F). Note that in general, the data shown in Fig.10 follow a similar form of curve. Figure 12 is the Wendake Beach data plotted in a manner
Fig. 11. Southard's (Middleton and Southard, 1977) conceptual model of the relationship between mean flow velocity, boundary shear stress and bedforms. R is ripple, SD is sand dunes, F is flat bed, and A is antidunes.

Fig. 12. Predicted bedform transitions through a storm sequence, as interpreted from the Wendake Beach data and Southard's conceptual model (Fig.11). All gradients and cut-off points are estimates.

corresponding with that used by Southard. These data show changes in $\tau_0$ with changes in $V$ that are gradual within bedform groups and with steep gradients between the inferred groups. The cross-bars indicate the estimated breaks between groups. This analysis is speculative, of course, because of the
small size of the data set and the uncertainties with some of the measurements. Nevertheless, the concurrence of this progression with that suggested by Southard indicates that these findings are not unreasonable.

More concrete evidence of the propriety of the relationship suggested in Fig. 12 is obtained from analysis of an epoxy relief peel of a box core taken at VA2 after the storm. This peel (Fig. 13) clearly shows a quasi-planar structure at −0.16 m. This is at the maximum depth of disturbance, as indicated above. The presence of the plane lamination at −0.16 m (equivalent to a flat bed configuration) reinforces the validity of the method used for measuring bed roughness, as this is the configuration predicted from the data. Further, if bedforms produced during the falling limb of the storm at least partially reflect the rising limit sequence, the supposition of the sequential development of ripples through flat bed is also supported. Although the presence of megaripples is not clearly indicated in the peel (see Davidson-Arnott and Greenwood, 1976, figs. 7e and 8b for some examples), some form of large-scale, rhythmic roughness is apparent. Allen (1981) describes similar structures, undulatory laminations, that he attributes to the existence of low-amplitude, rolling grain ripples, occurring subsequent to flat bedding and before vortex ripples appear (in a waning sequence). This was perhaps the case at Wendake Beach. Small scale ripple cross-lamination is present in the upper 3 or 4 cm of the peel. These last forms are the product of oscillatory ripple formation toward the end of the storm.

CONCLUSIONS

Although wave orbital velocity is the primary agent responsible for generating the shear stress that causes bed deformation in most wave-dominated nearshore zones, the magnitude and variability in wave parameters are not sufficient to correlate directly with changing bedforms. Indeed, as Grant and Madsen (1979) suggest, wave-current interaction can substantially enhance the stress over that predicted for waves alone. However, present models relating nearshore bedforms to flow conditions consider only the direct wave effects. For example, Clifton and Dingler (1984, this volume) note that their model is designed to operate only in the absence of secondary, unidirectional flows, and is thus inappropriate for the description of conditions in nearshore zones where such currents are present. The formulation of a comprehensive wave and current model may be possible using a format similar to that shown in Figs. 11 and 12 where a total contribution to τ₀ and V by the waves and current can be determined. This is, however, not attempted here, because it is beyond the intent of the present study. Where wave and current characteristics are unknown, approximations using existing theories will have to be employed, but they must also predict the magnitude of the longshore current. Further, a great deal of additional field data is required to accurately fix the relationships and limits shown in Fig. 12 (indeed, to see if they are real). Finally, it has been shown that apparent bed roughness, as reflected by the Darcy-Weisbach friction coefficient, can vary at least 250% at a given
Fig. 13. Epoxy peel from box core taken at VA2 after the 1980:06:08 storm. Near-plane bed configuration is present at maximum depth of disturbance as predicted from data. Large-scale undulatory laminations may be associated with post-vortex, rolling grain ripples (Allen, 1981). Small-scale ripple cross-stratification is present near the top of the peel. Slight landward slope at $-0.16$ m is due to core position on landward slope of the outer bar. Some distortion due to sampling appears along the edges of the peel. Area shown is approximately $35 \times 25$ cm.
location in the surf zone (at Wendake Beach, values ranged from 0.016 to 0.041 in 2 m of water). This result implies that care must be taken in applying models that assume a uniform friction coefficient to the solution of surf zone flow problems. Ideally, future models will not consider this parameter to be a constant.

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