CHAPTER FORTY EIGHT

SWASH ON STEEP AND SHALLOW BEACHES

R. T. Guza¹, E. B. Thornton (M. ASCE)², R. A. Holman³

Abstract

Extensive field observations of swash on natural beaches are used to relate the magnitudes of swash oscillations to incident wave conditions and the beach slope. Swash fluctuations at wind wave frequencies (defined here as $f > 0.05$ Hz) appear to be "saturated." As in laboratory experiments with monochromatic waves, wave breaking prevents the magnitudes of swash oscillations at incident wave frequencies from increasing past a certain level which depends on the beach slope. All data sets considered support this conclusion. In contrast, the magnitude of swash oscillations at surf beat frequencies (defined as $f < 0.05$ Hz) varies between data sets. Possible reasons for the discrepancy are discussed. Despite their differences, all data sets show that motions at surf beat frequencies dominate the swash spectrum on dissipative beaches. As in previous studies, the frequencies of spectral hills and valleys in the spectra of surf zone sensors suggest that a significant fraction of the surf beat energy is contained in motions which are standing in the cross-shore direction. Preliminary analysis indicates that shoreward propagating surf beat is coupled to incident wave groups.

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INTRODUCTION

The location of shoreline water level (run-up) is important in coastal dynamics. Run-up is composed of a super elevation of mean water level (set-up) and of fluctuations about the set-up level (swash). The present work concerns swash oscillations on natural beaches. The objective is to relate the amounts of swash energy in low (i.e. surf beat) and high (i.e. incident wave) frequency bands to incident wave conditions and the beach slope. Previously nonreported field data is supplemented by the extensive field observations of swash reported in Guza and Thornton [1982; in press] and Holman and Sallenger [in press], hereafter referred to as GT and HS. Taken together, these observations span a wide range of incident wave conditions (significant wave heights 20-400 cm, most energetic spectral period 6-20 sec) and beach morphologies (foreshore slopes .025-.125).

The GT swash data were collected on the California coast with a resistance wire gauge. HS used time lapse photography of run-up during a month long experiment at Duck, North Carolina. In all experiments, incident wave heights were calculated from pressure sensor data collected directly offshore of the run-up measurements. Each HS run was 35 minutes long, while GT runs varied between 35 and 256 minutes. Roughly 150 hours of run-up data are considered here.

Huntley et al., [1977] suggested that naturally occurring swash consists of "saturated" high frequency and "unsaturated" lower frequency components, corresponding roughly to the incident wave and surf beat frequency bands. Swash motions at wind wave frequencies are discussed first. Laboratory experiments and theories for monochromatic incident waves are briefly reviewed because they suggest nondimensional parameters useful in discussing this frequency band. As suggested by Huntley et al., [1977], the magnitudes of wind wave swash oscillations in field data are saturated, qualitatively similar to monochromatic laboratory wave results. Surf beat frequencies are considered next. Apparent discrepancies, between data sets, in the magnitude of surf beat swash oscillations are discussed. Finally, some preliminary results concerning the relationship between surf beat and incident wave groups are presented.

WIND WAVE FREQUENCY BAND

Monochromatic results

Miche [1951] hypothesized that the amplitude of swash oscillations due to monochromatic incident waves is proportional to the amount of shoreline reflection and thus to the standing wave amplitude. Furthermore, the standing wave amplitude at the shoreline with incident wave breaking was assumed equal to the maximum value which occurs without wave breaking. Thus, a maximum swash oscillation supposedly occurs with incident waves just large enough to break. Further increases in incident wave height were hypothesized to increase the amplitude of the progressive component (which is dissipated by breaking and has zero shoreline amplitude), while the standing component and swash amplitudes remain constant (i.e., saturated). Carrier and Greenspan [1958] used the fully nonlinear, inviscid, shallow water
equations to study the maximum possible size a standing wave can attain on an impermeable sloping beach. A review of their work, and of the general problem of waves on a sloping beach is given by Meyer and Taylor [1972]. Carrier and Greenspan found that a standing wave solution is possible if

$$e_s = \frac{a_s^2 \sigma^2}{g \tan^2 \beta} \leq 1 \tag{1}$$

where \( \beta \) is the slope of a plane beach, \( \sigma \) is the radian frequency, \( 2a_s \) the vertical swash excursion, and \( e_s \) a nondimensional swash parameter. According to inviscid, linear theory, the standing wave amplitude at the shoreline is amplified, relative to the standing wave amplitude in deep water \( (a_o^s) \) by [Stoker, 1947; Meyer and Taylor, 1972].

$$a_s = a_o \left[ \frac{\pi}{2 \tan \beta} \right]^{1/2} \tag{2}$$

The deep water condition for a standing wave which will not break at the shoreline is given by, using (1) and (2),

$$\frac{a_o^2 \sigma^2}{g} \left[ \frac{\pi}{2} \right]^{1/2} \tan^5 \beta \leq 1 \tag{3}$$

In terms of the deep water progressive wave amplitude \( a_o \), the criterion for total reflection of incident waves is [Meyer and Taylor, 1972]

$$\varepsilon_i = \frac{a_o^2}{\sigma^2} (2\pi)^{1/2} \tan^{-5/2} \beta \leq 1 \tag{4}$$

Combining the Miche saturation hypothesis with inviscid linear theory for the maximum amplitude standing wave yields

$$\varepsilon_s = \varepsilon_i \leq 1 \tag{5}$$

$$e_s = 1, a_i > 1.$$

According to this model, if \( \varepsilon_i \) is small, then increasing the incident wave height (i.e. \( e_i \)) results in an increased swash excursion \( (e_s) \) and the swash is "unsaturated." For large \( \varepsilon_i \), increasing the incident wave height results in a larger breaker height and steady set-up, but the swash oscillations \( (e_s) \) do not increase. The swash is "saturated."
Several laboratory experiments with monochromatic incident waves have confirmed the basic saturated swash hypothesis. There are, however, some differences in the observed maximum values of \( e_i \) \( \sim 1.25 \), Battjes, 1974; \( \sim 2.0 \), Van Dorn, 1978; \( \sim 3.0 \), Guza and Bowen, 1976] and in the proper nondimensional form for the incident waves (\( e_i \) in eq. 5).

Typical laboratory data are shown in Figure 1 based on the data of Guza and Bowen [1976]. For \( e_i < 1.0 \), there was no visible wave breaking and \( e_i = e_i \) as predicted by eq. 5. For \( 1.0 < e_i < 9.0 \) the swash motion (\( e_i \)) increases slowly with increasing \( e_i \) until reaching a saturated value of \( \sim 3.0 \) at \( e_i \sim 9.0 \). Further increases in \( e_i \) do not increase \( e_i \). A modification of the Miche hypothesis (eq. 5) which better fits this data (Figure 1) is

\[ e = \begin{cases} e_i ; & e_i < 1.0, \\ \frac{1}{2} ; & 1 < e_i < 9.0, \\ 3 ; & e_i > 9.0. \end{cases} \]

The \( e_i^{1/2} \) dependence occurs in a transition region between complete reflection and spilling wave conditions. The \( e_i^{1/2} \) functional form does not correspond to any theory and is only a convenient and simple fit to the data. For comparisons with other results it is useful to recast eq. 6 in terms of the Irribarren, or surf similarity parameter [Battjes, 1974]

\[ \frac{H}{L}^{1/2} = |\frac{1}{\tan \beta}|^{1/4} \]

with \( L \) and \( H \) the deep water wavelength and height. The ratio of the vertical swash excursion (\( R_V = 2a \)) to \( H \) is then

\[ \frac{R_V}{H} = \left( \frac{\pi}{2\beta} \right)^{-1/4} ; \frac{\xi}{3} < \xi < \xi_0 \]

where \( \xi = \frac{\pi}{2\beta}^{1/4} \) is the minimum \( \xi \) value for complete reflection (corresponding to \( e_i = 1.0 \) in eq. 7) and the small slope assumption has been made (\( \beta \sim \tan \beta \)). Note that large waves correspond to large \( e_i \) (eq. 6c) and small \( \xi \) (eq. 8a).
Figure 1. Nondimensional swash ($\varepsilon_k$, eq. 1) versus nondimensional incident wave height ($\varepsilon_0$, eq. 4) for monochromatic lab data [Guza and Bowen, 1976]. Solid lines correspond to a modified Miche hypothesis (eq. 6).

Figure 2. Swash/incident wave height ratio ($R^*/H_0$) versus surf similarity parameter ($\xi_m$). --- Eq. 8 for indicated values of $\beta$; ---- eq. 9.
As shown in Figure 2, eq. 8 is qualitatively similar to the result of Battjes [1974] based on laboratory experiments with breaking waves on relatively steep slopes

\[ \frac{R^V}{H_\infty} = 1.25 \frac{\xi_\infty^2}{\pi} \quad .3 < \xi_\infty < 1.9 \]  

(9)

In fact, in the saturated range eq. 9 has the same functional form as the modified Miche model (eq. 8a). The difference in the constants corresponds to the different observed saturated values of \( \xi \) (1.25 and 3.0 in eq 9 and 8a, respectively). The important point here is that eqs. 8 and 9 describe a large amount of monochromatic lab data. Although run-up studies with random waves exist, the data are generally not analyzed in a form suitable for the present application.

Field Data: magnitudes

Figure 3 shows the field data superimposed on eqs. 8 (with \( \beta = 6^\circ \)) and 9. The "significant" swash and incident wave heights (\( R^V_{\text{inc}} \) and \( H_\infty \)) are defined as four times the observed variance above \( R_{0.05} \) and \( L_\infty \) (which appears in \( \xi_\infty \)) is based on the incident wave frequency with the maximum power. Because run-up heights can have non-Rayleigh distributions, the significant heights in the present context are simply characteristic heights defined in terms of the variance. Figure 3 also shows the best fit straight line given by HS for that data only. Note that a linear dependent \( \frac{R^V_{\text{inc}}}{H_\infty} \) on \( \xi_\infty \) does not correspond to the \( \xi_\infty \) dependence of the fully saturated Miche (eq. 8a) or Battjes (eq. 9) models, but is consistent with the transition range suggested by the Guza and Bowen [1976] laboratory data (Figure 1, eq. 8b). However, the field data is clearly too scattered to define a particular functional dependence on \( \xi_\infty \).

Some of the scatter in Figure 3 is due to the subjectivity of digitizing the HS films and to nonconstant elevations above the bed of the GT resistance wires [Holman and Guza, 1984]. In addition to these instrumental errors, there are more fundamental problems associated with the definitions of \( \xi_\infty \) and \( R^V_{\text{inc}} \). The \( L_\infty \) term in \( \xi_\infty \) (eq. 7) should probably be defined using the entire incident wave spectrum rather than only the most energetic spectral component. The frequency range for \( R^V_{\text{inc}} \) (here \( f > .05 \) Hz) might be more reasonably selected as the range of saturated frequencies, or as having a particular relationship to a characteristic incident wave frequency. The present choice of \( .05 \) Hz as the low frequency cut-off corresponds very roughly to a lowest frequency between .25 and .9 times the frequency of the most energetic incident wave band. There are considerable experimental and conceptual shortcomings in the present work. Nevertheless, the clear decrease in \( \frac{R^V_{\text{inc}}}{H_\infty} \) with decreasing \( \xi_\infty \) (Figure 3) further confirms the idea that saturation is a relevant concept for swash on natural beaches.
Figure 3. Ratio of observed significant swash height in the incident wave band \( R_{s, inc}^v \) to significant incident wave height \( H_{s, inc} \) versus \( \xi_{mo} \).
- o, Holman and Sallenger [in press]
- x, Guza and Thornton [1982] and new data
- *, Holman and Bowen [1984]

Dashed lines are eq. 7 for \( \beta = 60^\circ \) and eq. 8 (labeled B). Solid line is best fit line given by Holman and Sallenger.

Figure 4. Significant swash height in the surf beat (infragravity) frequency band \( R_{s, inf}^v \) versus \( H_{s, inf} \). Data is from Guza and Thornton [in press].
SURF BEAT FREQUENCIES

Field Data: magnitudes

In contrast to swash at wind wave frequencies, there are no comprehensive laboratory experiments which provide suggestions about the nondimensional parameters controlling the magnitude of swash oscillations at surf beat frequencies. Laboratory experiments have been hampered by both the generation of spurious free long waves (Bowers, 1977) and multiple reflections between the beach and wave generator [Flick et al., 1981]. Thus, although laboratory measurements with non-monochromatic incident waves do exist, the swash motions at surf beat frequencies are contaminated to an unknown degree. Work presented at the 19th ICCE (Kostense and Vis) describes the first variable depth experiments apparently free of both paddle generated free long waves and long waves re-reflected from the wavemaker. Such experiments, particularly when extended from two incident wave frequencies to a spectrum, will hopefully provide important insights into naturally occurring surf beat. There are no theories which claim to predict surf beat swash energy levels for a spectrum of incident waves. Bounded long wave theories [Longuet-Higgins and Stewart, 1962, 1964] are not valid in very shallow water. Symonds et al., [1982] model the generation of long waves in the surf zone, but the necessary extension of the model from a two frequency deterministic incident wave field to a random wave spectrum has not been done.

While theoretical work provides little guidance, field studies have indicated several general trends. The first is an apparent linear dependence between incident wave and surf beat energy levels [Tucker, 1980; Holman, 1981; Gana and Thornton, 1982; in press]. Figure 4 shows the observed linear relationship between $R_v^s$, $s_{IG}$ (the significant vertical swash excursion at infragravity frequencies) and $S_{m,m}$ for the GT data. Figure 5 shows the same plot for the HS data. While there may be an indication of some dependence, the HS data are scattered. (Note that the GT data do fall within the general scatter of the HS data).

One reason for the great variability in the HS data lies in the longshore variability of the beach face slope. During the month the HS data were collected, the beach morphology was occasionally rhythmic with longshore length scales of several hundred meters. While these slope variations are small on an incident wave length scale (and the incident band data are correspondingly well behaved), they are large on the length scales associated with infragravity waves. The longshore variation of $R_v^s$, $s_{IG}$ in the same data run, appears in Figure 5 as a wide range of $R_v^s$, $s_{IG}$ values for the same $S_{m,m}$.

The second general trend that has been previously noted in the literature is that the presence of infragravity energy is in some way linked to the degree to which a beach is "dissipative" [Sasaki et al., 1976; and others]. Since $s_{IG}$ and $\xi_m$ have been linked to the dissipative characteristics of a beach, HS plotted the non-dimensional infragravity band swash height, $r_{IG} = s_{IG}/S_{m,m}$ against $\xi_m$. Figure 6 shows this plot, together with the best-fit linear slope to the HS data. This parameterization does appear to reduce the scatter of the HS data. However, it also shows that the HS and GT data are systematically
Figure 5. Same as Figure 4, but data is from Holman and Sallenger [in press, reprinted with permission of AGU].

Figure 6. $\frac{R_s \times G}{H_s,\infty}$ versus $\xi$.
- $\infty$, Holman and Sallenger [in press]
- $x$, Guza and Thornton [1982; in press]
- *, Holman and Bowen [1984]

Solid line is best fit line to HS data.
different in this parameter space. While the HS data show a clear
trend, the GT data show no significant slope when $r_{IG}$ is regressed
against $\zeta_{w}$. Note that the linear dependence between $r_{IG}$ and $\zeta_{w}$ in the
HS data implies that $R_{s,IG}/H_{s,w}$ (with the significant horizontal swash
excursion $R_{s,IG} = R_{s,IG}(\beta)$) is independent of local $\beta$.

Perhaps the most important difference between the data sets are the
inferred low Irribarren number (large waves) limiting values of $r_{IG}$.
Based on linear regressions of $r_{IG}$ against $\zeta_{w}$, the limits are of the
order of 0.1 and 1.0 for the HS and GT data sets respectively. Separate
evidence from two highly dissipative beaches ($\zeta = 0.25$) tends to
support the GT limit, with observed values of $r_{IG}$ of at least 0.6
[Wright et al., 1982; Holman and Bowen, 1984].

A potentially simple explanation for the apparent discrepancy
between the data sets lies in the rather arbitrary definition of the
infragravity band. A cutoff frequency of 0.05 Hz may be generally
appropriate for west coast swell, but may be too low for the higher
frequency east coast waves. For Great Lakes data this cutoff would be
ridiculous. It can be easily seen that variability in incident wave
period could induce an artificial trend in a plot such as Figure 6, for
a truly constant $r_{IG}$. For similar incident wave heights, shorter
incident periods will be associated with smaller $\zeta_{w}$, and will also have
a smaller apparent infragravity energy since the fixed cutoff of .05 Hz
will encompass a smaller portion of what may properly be considered true
infragravity energy. Longer incident periods are associated with larger
$\zeta_{w}$ and a proportionally larger $r_{IG}$ since the .05 Hz cutoff encompasses
more of the "true" infragravity energy. Thus the differences between
the HS and GT data sets in Figure 6 may only represent the differences
in incident wave frequencies encompassed by the data.

Summarizing, there are at least two potential factors contributing
to the differences in the surf beat data sets. These are effects
associated with three dimensional topography, and the arbitrariness of
the present cut-off frequency separating the surf beat and wind wave
bonds. Note that altering the cut-off frequency will also alter the
amount of wind wave energy, and improved agreement between the surf beat
data sets may unfortunately be accompanied by increased differences in
the wind wave band (Figure 3). Further research on this problem is
clearly needed.

Field data: generation mechanisms

The idea that surf beat is a forced oscillation associated with
incident wave groups originated with Munk [1949] and Tucker [1950].
They interpreted their low frequency observations, taken several hundred
meters offshore, as being due to mass transport shorewards under high
incident wave groups, with the release of low frequency free waves at
the break point where the groups are destroyed by breaking. The long
waves then reflect off the heech face and propagate offshore. Tucker
[1950] found that high wave groups were correlated with troughs in the
low frequency waves. The time lag of maximum correlation approximately
equaled the sum of the travel times for incident wave groups to
propagate from the observation point to the break point, and seaward going long waves to return from the break point. Longuet-Higgins and Stewart [1964] subsequently showed that Tucker’s observation that high wave groups were correlated with troughs in the low frequency waves agree with the predictions of second-order theory for forced waves if it is assumed that the long waves reflect at the beach. Munk’s results were similar to Tucker’s, except that with a similar time lag he found crests of long waves correlated with high wave groups, implying a 180° phase shift for the reflected long wave. Both Munk [1949] and Tucker [1950] imply that there is a small nonlinear forced long wave correction under shoreward propagating wave groups, and a larger seaward propagating low frequency wave released at the break point or beach face. In contradiction, Hasselman et al., [1962] presented evidence that the shoreward propagating nonlinearly forced motion is larger than any seaward propagating component. More recent observations suggest that incoming and outgoing waves are of roughly equal magnitude, forming a quasi-standing wave [Suhayda, 1974; and many others]. An example from the GT data set is shown in Figure 7 where measured surf beat run-up spectra are coupled with numerical integrations of the long wave equations to predict the energy spectrum at offshore sensors, and the phase between offshore sensors and run-up meter. As in previous studies, valleys in the observed surf beat energy spectra at offshore sensors, and jumps in the relative phase between sensors, occur at the nodal frequencies of simple standing wave (either leaky or high mode edge wave) models.

The question of whether there are long waves associated with groups of incoming waves is addressed by calculating correlations between the two. The data considered here is from a 68 minute run at Torrey Pines on 21 November 1978. The envelope of the high frequency wind waves was obtained by squaring the wind wave time series, and then low pass filtering this signal. A similar approach has been independently taken by Kim and Huntley, and their results are also presented in this volume. Table 1 shows the maximum correlation, and the associated time lag, between the envelope of the deepest sensor (P4) and the envelope at other locations. The correlations are high for sensors outside the breaker region, seawards of W29 (Table 1). This indicates that well defined groups of waves propagate across the nearshore until shoaling and/or wave breaking radically alters the group structure. Theoretical travel times are approximated by using a group velocity equal to \((gh)^{1/2}\). These times are nearly equal to the observed times of maximum correlation except in very shallow water where bottom slope effects are not negligible, and the \((gh)^{1/2}\) assumption breaks down.

Correlations between the low frequency motion and envelope at each sensor are also given in Table 1. At time lag 0, the correlation \(C_T(\tau = 0)\) at the 5 deepest stations are all negative, as would be found with the bound long wave solutions of Longuet-Higgins and Stewart [1962, 1964]. Most of these correlations are barely significantly different than zero with 95% confidence. They are, however, comparable to the maximum correlations observed \(C_{\text{max}}\) in Table 1. At the shallowest three stations, \(C_T(\tau = 0)\) has substantially higher values.
Table 1. $C_1$ is the correlation between the wind wave envelopes at P4 and other sensors, and $\tau_{max}$ the time lag of maximum correlation, both observed and calculated. $C_2$ values are correlations between the envelope and low frequency motion at the same sensor. $C_2^{max}$ is the maximum correlation (at lag $\tau_2$), and $C_2(\tau=0)$ the correlation at lag 0.

<table>
<thead>
<tr>
<th>SENSOR</th>
<th>P4</th>
<th>P7</th>
<th>P7A</th>
<th>P10</th>
<th>P16</th>
<th>W29</th>
<th>P30</th>
<th>W38</th>
<th>W41</th>
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<tr>
<td>Offshore Location(m)</td>
<td>456</td>
<td>360</td>
<td>303</td>
<td>233</td>
<td>159</td>
<td>103</td>
<td>73</td>
<td>47</td>
<td>17</td>
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<tr>
<td>Depth(cm)</td>
<td>1006</td>
<td>736</td>
<td>669</td>
<td>553</td>
<td>381</td>
<td>173</td>
<td>130</td>
<td>85</td>
<td>47</td>
</tr>
<tr>
<td>$C_1^{max}$</td>
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<td>.93</td>
<td>.92</td>
<td>.90</td>
<td>.87</td>
<td>.58</td>
<td>.50</td>
<td>.43</td>
<td>.43</td>
</tr>
<tr>
<td>$\tau_{max}^{(sec)}$ observed</td>
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<td>11</td>
<td>19</td>
<td>28</td>
<td>40</td>
<td>49</td>
<td>50</td>
<td>53</td>
<td>148</td>
</tr>
<tr>
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<td>10</td>
<td>17</td>
<td>26</td>
<td>37</td>
<td>48</td>
<td>56</td>
<td>64</td>
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<tr>
<td>$C_2^{max}$</td>
<td>.16</td>
<td>-.20</td>
<td>-.14</td>
<td>-.18</td>
<td>-.30</td>
<td>-.17</td>
<td>.32</td>
<td>.51</td>
<td>.45</td>
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<tr>
<td>$\tau_2^{(sec)}$</td>
<td>-225</td>
<td>170</td>
<td>28</td>
<td>6</td>
<td>4</td>
<td>-91</td>
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<td>4</td>
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<tr>
<td>$C_2(\tau=0)$</td>
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<td>-.13</td>
<td>-.11</td>
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<td>.00</td>
<td>.32</td>
<td>.46</td>
<td>.43</td>
</tr>
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</table>
than at the deeper stations. The maximum correlations at the shallow stations occur at lags $\tau_{\text{max}}$ very close to zero (a positive value of $\tau_{\text{max}}$ means the envelope leads the long wave). Curiously, $C_2(\tau = 0)$ changes sign between deep and shallow water. The consistent pattern of correlations near zero lag suggests that there is a component of surf beat associated with local wave groups. However, the correlations are disturbingly low and there is no obvious indication of the outgoing long wave energy which contributes to the ubiquitous quasi-standing wave patterns observed by many investigators, and in this data set in particular (Figure 7).

Additional insights are obtained by using colocated pressure and current meters to decompose the long wave into seaward and shoreward propagating components. With $\eta(t)$ and $n(t)$ the long wave sea surface elevation and cross-shore velocity time series, plus and minus characteristic ($PC(t)$, $MC(t)$) time series are defined as

$$PC(t) = \frac{1}{2} \left[ \eta + \left( \frac{h}{g} \right)^{1/2} u \right]. \quad (10a)$$

$$MC(t) = \frac{1}{2} \left[ \eta - \left( \frac{h}{g} \right)^{1/2} u \right]. \quad (10b)$$

If $\eta$ and $n$ are normally incident shallow water waves following the flat bottom dispersion equation, then $PC(t)$ and $MC(t)$ are the time series of shoreward and seaward propagating waves respectively. Figure 8 shows the time lags for maximum correlation between the envelope of sensor P10 (distance = 233 m) and $PC$ and $MC$ for the six available colocated pressure/current meters. The numbers on the figure are the values of the maximum positive and negative correlations. Correlation values between the P10 envelope and seawards propagating long wave characteristics are circled, while those between the envelope and the shoreward propagating wave are not circled.

In three cases ($x = 233, 259, 47$ m) the time lag for one of the maximum correlations of the incoming characteristics was not between $\pm150$ sec., and these values are not shown. The solid lines on Figure 8 are the calculated travel times for groups of long waves to propagate from P10 to various locations, assuming reflection occurs at the shoreline and the phase speeds equal to $(gh)^{1/2}$. Incoming and outgoing long waves are both significantly correlated with the envelope at P10 ($x = 233$ m). In fact, the maximum correlations of the outgoing long waves with the P10 envelope are comparable to those between the incoming long waves and the P10 envelope. Without the decomposition into incoming and outgoing long waves, the maximum correlations ($C_2^{\text{max}}$, Table 1) are generally reduced because the envelope is correlated to both components, but with different time lags. Note the comparable magnitudes of the maximum positive and negative correlations between the seawards propagating long wave and the P10 envelope (circled values in Figure 8) at each position. Given their similar values, and the inaccuracies in the theoretical travel times in very shallow water, it is not possible to tell whether or not the outgoing long wave is phase shifted by $180^\circ$. 


Figure 7. Upper panels compare measured surf beat elevation (A, ----) and cross-shore velocity (B, ----) energy spectra with predictions (......) based on measured run-up spectra (A, ---) and hypothesis of standing long waves. Lower panels compare predicted (...) and measured (%) phase difference between run-up and the offshore sensors (depth = 85 cm, x = 47 cm, 21Nov78, Torrey Pines Beach).

Figure 8. Time lags for maximum correlation between the wind wave envelope at a sensor 233 m offshore, and the seaward and shoreward propagating long waves at various offshore locations.
or not. It is clear, however, that both seaward and shoreward propagating components are correlated with the wind wave envelope. The variances of $PC(t)$ and $MC(t)$, at any particular location, differed by a maximum of 28%, with the shoreward propagating component larger at all positions. The average variance difference was 17%, or roughly an 8% difference in incoming and outgoing long wave amplitudes. This result is very preliminary, but the small differences in incoming and outgoing long wave amplitudes leads us to speculate that the outgoing long wave is simply the reflection of the incoming long wave. However, substantial improvements in several important aspects of the analysis, and consideration of a wider range of data sets are required before any firm conclusions can be reached. The present discussion demonstrates the potential value of decomposing the long wave into incoming and outgoing components and separately correlating these with the wind wave envelope.

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