Enhancement of Cross-Shore Profile Evolution Models for Sustainable Coastal Design

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ABSTRACT

Results obtained from the validation of a cross-shore profile evolution model, Uniform Beach Sediment Transport-Time-Averaged Cross-Shore (UNIBEST-TC), were examined and further analyzed to reveal the reasons for the discrepancy between the model predictions of the field data at the surf zone of the Duck Beach in North Carolina, USA. The UNIBEST model was developed to predict the main cross shore parameters of wave height, direction, cross shore and long shore currents. However, the results of the model predictions are generally satisfactory for wave height and direction but not satisfactory for the remaining parameters.

This research is focused on exploring the discrepancy between the model predictions and the field data of the Duck site, and conducting further analyses to recommend model refinements. The discrepancy is partially attributed due to the fact that the measured values, were taken close to the seabed, while the predicted values are the depth-averaged velocity. Further examination indicated that UNIBEST-TC model runs consider the RMS of the wave height spectrum with a constant gamma-value from the offshore wave spectrum at 8.0m depth. To confirm this argument, a Wavelet Analysis was applied to the time series of wave height and longshore current velocity parameters at the Duck site. The significant wave height ranged between 0.6m and 4.0m while the frequencies ranged between 0.08 to 0.2Hz at 8.0m water depth. Four cases corresponding to events of both high water level and low water level at Duck site were considered in this study. The results show that linear and non-linear interaction between wave height and long-shore current occur over the range of frequencies embracing; the low frequency band of infragravity (0.001- 0.02Hz) waves band and short incident wave band (0.05-0.10Hz). The current results highlight the necessity of incorporating interaction terms between wave - wave and wave- current in the development of cross shore and longshore model formulations.

INTRODUCTION

Understanding nearshore processes is increasingly important because the majority of the world's coastlines are eroding. The increased threat of global warming and the resulting rise in sea level may accelerate erosion problems. Coastal processes are characterized by complex, nonlinear phenomena as described by Thornton et al. (2000); they also involve patterns covering a wide range of spatial and temporal scales (Figs. 1-a, 1-b).

Many efforts have been underway to develop realistic coupled wave-current-morphologic evolution models. However wave – current interaction not only modifies wave properties but also modifies velocity gradients (Figs.1-c, 1-d) of the longshore and cross shore currents as demonstrated previously by the second author Ismail (1983), (1984) and (2007). Significant progress has been made during the past decade, and the prospects for major advances in the next 10 years are exciting. Even though substantial progress has been achieved in the investigation of physical mechanisms driving coastal morphodynamic processes, present knowledge remains insufficient to correctly understand, model, and forecast the behavior of many coastal systems.

The objective of the current research work is to provide model developers with useful information that can be used for further improvements of the model in areas of poor model performance by applying new theories and expanding the limitation of applicability. Among the available deterministic and probabilistic profile models that have been compared with hydrodynamic and morpho dynamic data of field experiments on the time scale of storms are:

- UNIBEST-TC of Delft Hydraulics (DH);
- COSMOS of HR Wallingford (HR);
- CROSMOR2000 of University of Utrecht (UU);
- BEACH1/3D of University of Liverpool (UL);
- CIIRC of University of Catalunya (UC).

The validation of the above programs was based on the use of hydrodynamic and morpho dynamic data on the LIP experiments in 2D large-scale wave flume of Delft Hydraulics; COAST3D-Storm Experiment at 3D field site of Egmond (The Netherlands) during period of 18 Oct. to 12 Nov. 1998. The general outcome of validation process was as reported by Leo van Rijn et al (2003) and is outlined below.

Profile models can quite accurately (errors smaller than 10%) represent the significant wave height distribution along the surf zone, if the wave breaking model is properly calibrated; the wave breaking coefficient should be a function of local wave steepness and bottom slope for most accurate results. The models can simulate the longshore and cross shore currents in 3D field conditions only in a reasonable way with relative accuracies of 30% to 50%.

Profile models which yield good results for hydrodynamics do not automatically yield good results for morphodynamics; often additional calibration using measured bed profile changes is required to obtain good morpho dynamic results; the calibration coefficients involved are not proven to be site-independent.

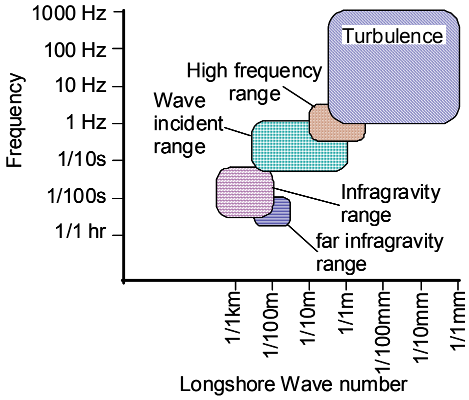

Figure 1-a. Spatial -Time Scales of Waves in the Nearshore

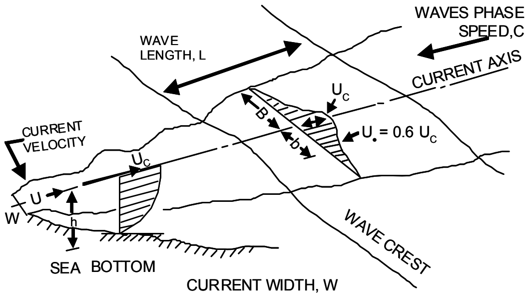

Figure 1-b. Velocity and Length Scales of Waves and Currents (after Ismail & Wiegel, 1983)

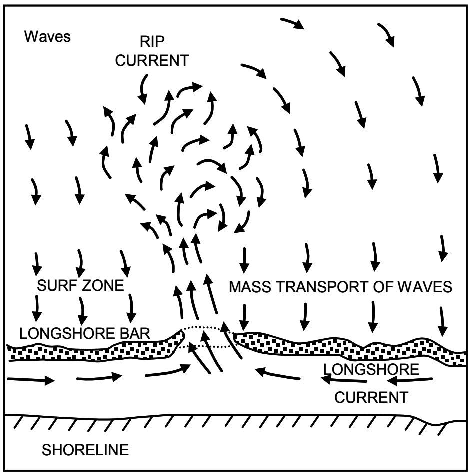

Figure 1-c. Schematic of Nearshore Processes

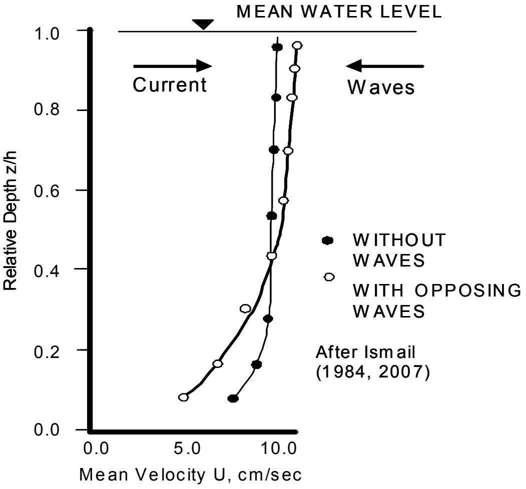

Figure 1-d. Modifications of Current Velocity Profiles

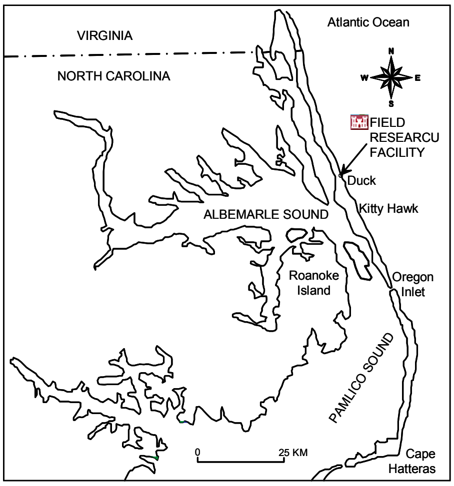

Figure 2-a. Field Research Facilities , US Army Corps, of Engineers, Duck, N.C.

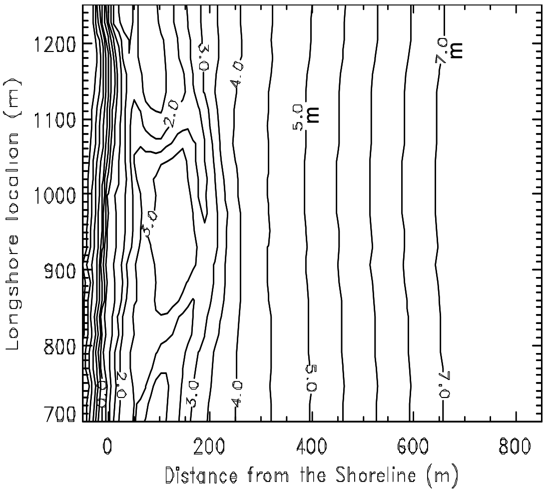

Figure 2-b. Plan View of the Beach Bathymetry at Duck, N.C. (Elsayed, 2006)

Validation of UNIBEST-TC at Duck Coastal Site, NC, USA

The first author of this paper (Elsayed, 2006) has investigated the validity of profile model UNIBEST-TC against the field data of the surf zone of the Duck Beach in North Carolina, USA (Fig.2) for the periods from 22 to 27 September and from 10 to 20 October, 1998. He also tested the model validity at the tidal surf zone of Egmond beach (The Netherlands) for events during the period of April to May1998 (Egmond-Main campaign) within the European COAST3D. The results for the validation were inline with previous results referenced above for the Egmond site in the Netherlands. However, the model prediction for the Duck site in USA is again generally acceptable for wave height and direction but not satisfactory for the longshore and cross current parameters. Further analyses were conducted (Fig. 3) and four cases corresponding to events of both high water level and low water level are considered in this study and listed in Table 1.

Table 1. Wave Conditions for Model Validation Runs at Duck, NC

Case	Water Level	$H_{significant}$	H_{rms}
1	HWL	2.5 m	1.8m
2	LWL	0.6 m	0.4m
3	HWL	0.75m	0.55m
4	LWL	0.67m	0.5m

Motivation for Current Research and Analysis of Coastal Data at Duck Site

The UNISET-TC model has proved to be capable in general of predicting wave height and wave direction for both coastal sites. However the predictions of long-shore current and cross shore currents remain unsatisfactory for the Duck site as well as at Egmond site. The difference between the measured and the predicted values for long-shore current and cross-shore current was attributed partly due to the location of measurements, which are at a certain water depth, and the predicted values which are the depth-averaged velocity. Beside that, the turbulence in the breaker zone leads to errors in the measurements, which could be another factor.

Examination of UNIBEST-TC model indicated that the input to the model was the RMS of the wave height and a constant gamma-value derived from the offshore wave spectrum. Accordingly the model predictions will not take into effect the various wave components within the spectrum (Phillips, 1958). As highlighted by Thornton et al (2000) field observations and models suggest that alongshore currents induced by breaking of wind-waves are often unstable (Longuett-Higgins, 1970). The growing instabilities, called shear waves, have periods of 1-10 minutes. Accordingly, results from fully nonlinear models suggest that shear instabilities might both alter significantly the cross-shore structure of the mean alongshore current and produce energetic eddies. Therefore, it appears that there is a need to examine the wave envelope for short waves and bound long waves and thereby pave the way to improve model predictive capability.

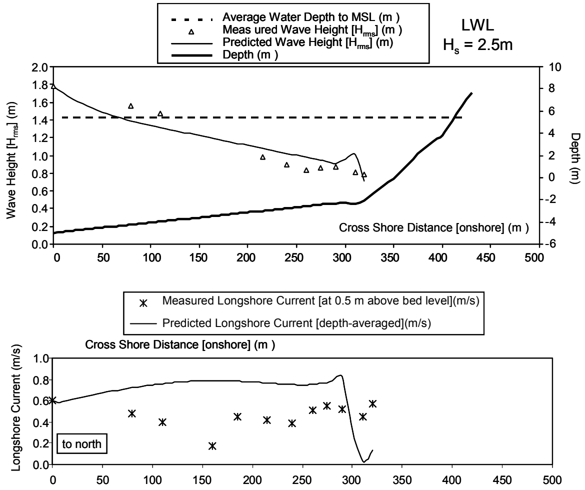

Figure 3-a. Measured and predicted values of wave height and longshore current velocity (case 1)

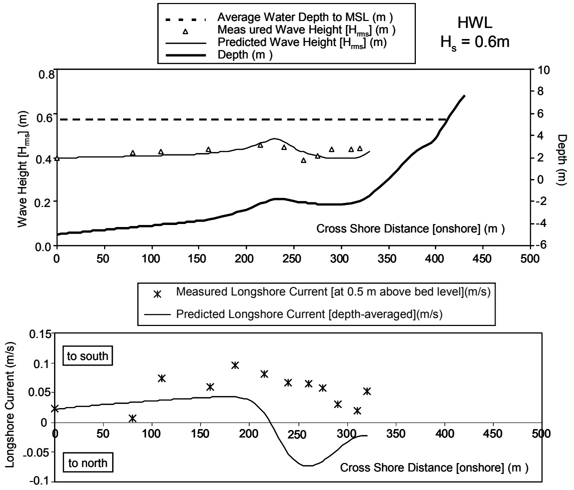

Figure 3-b. Measured and predicted values of wave height and longshore current velocity (case 2)

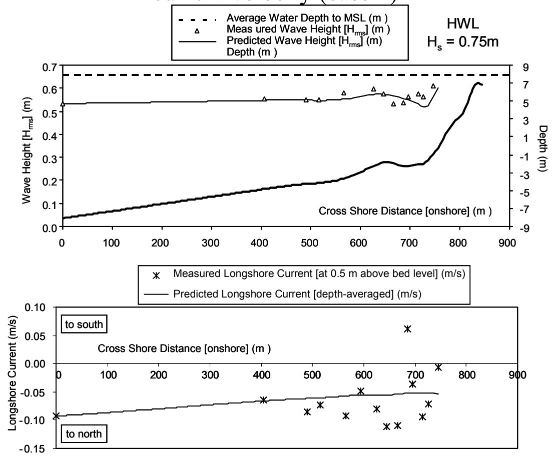

Figure 3-c. Measured and predicted values of wave height and longshore current velocity (case 3)

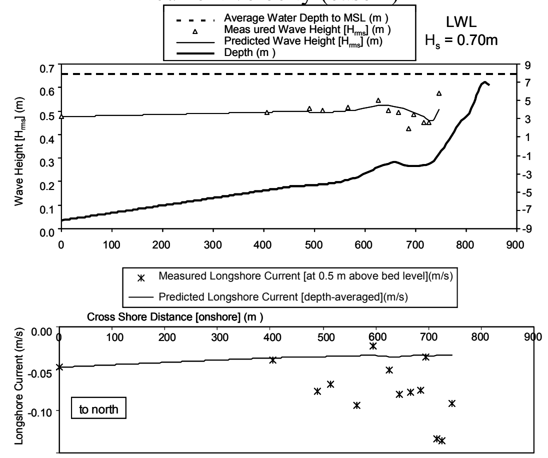

Figure 3-d. Measured and predicted values of wave height and longshore current velocity (case 4)

Duck Coastal Site: Many studies have been carried out in order to interpret the behavior of the bar system in the surf zone of Duck beach in the US. The objective was to study the bar system (consisting of one or two shore-parallel bars) in the surf zone of Duck beach, North Carolina, U.S.A, over long-term periods. As described by Elsayed (2006) the beach and foreshore are rather steep (1:12) and consist of a mixture of medium/coarse sand with median diameters between 0.5 and 1 mm and carbonate shell debris up to 20%. Offshore, the bottom slope approaches to about 1 to 160 at the 8.0m contour, and the median grain size decreases to 0.1 mm. The surf zone at Duck coastal site is characterized by a persistent, very dynamic inner bar, approximately 30 to 120 m offshore of the shoreline with the bar crest between 1.0 and 3.0 m (bar height of 1-2 m) and by a low-amplitude outer bar approximately 300 to 400 m offshore.

Wave Observations: The environmental conditions at the Duck site were described by Fedderson et al (1996) and Elsayed (2006). In 8m water depth, the significant wave height ranged between 0.2 m to 4 m and the mean wave angle between ± 50 degrees. The mean wave frequency ranged from about 0.08 to 0.2 Hz. Maximum mean longshore currents ranged from 0.1 to 1.4m/s. Fluctuations in mean water level were about 1 m at spring tide. Tidal currents in depths less than 8 m are less than 0.03 m/s.

Longshore Current Observations: During the Super Duck field experiment, low frequency alongshore propagating motions were observed by Oltman-Shay et al. *(*1989) that had similar frequencies (0.01 to 0.001 Hz) to but much shorter wave lengths of the order 100m than edge waves. These waves were related to the magnitude and direction of the mean longshore current, and have been related to a shear instability of the longshore current, and thus named shear waves. These waves are vorticity waves, and unlike incident and edge waves are not irrotational. Therefore, to confirm the presence of such spectral variations in wave conditions in 1998 at Duck coastal site its, spectral analysis was conducted to the time series of wave height at 8.0m water depth and the velocities of the long-shore current at the mid point of its profile. These results are shown in Fig. (4-a) through Fig. (4-d) for the four design cases considered in this study at Duck site. The results show patterns of low, medium, and high wave frequency bands.

Fourier and Wavelet Transform: The spectral analysis at a single point by its nature does not show whether if linear or nonlinear interaction does exist. Therefore, Wavelet analysis which is becoming a common tool for analyzing localized variations of power within time series is considered for use. The Wavelet's theory is a powerful alternative to the Fourier analysis and gives more flexible engineering for signal processing particularly for analysis of time series. However this circumstance makes the Fourier transform a poor method for a research of functions with the changeability's characteristics in the time. For example the Fourier transform does not distinguish a signal representing the sum of two sine waves from a signal consisting of the same sine waves but joining sequentially. Accordingly, a Wavelet Analysis was conducted to the obtained time series of wave height and long shore current shown in Fig. (4-a) through Fig.(4-d).

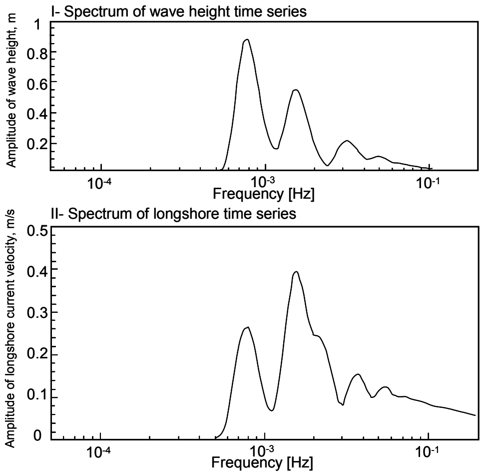

Figure 4-a. (I) Spectrum of the incident wave height
(II) Spectrum of the longshore current (case 1)

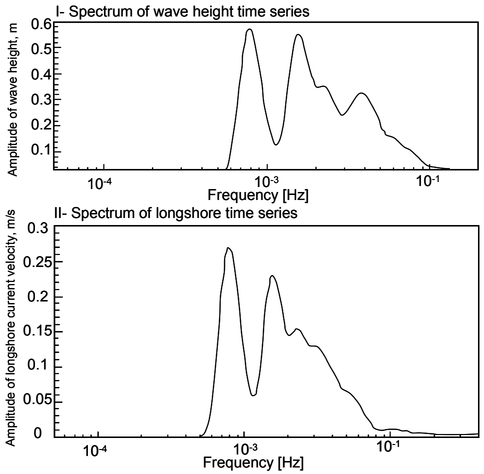

Figure 4-b. (I) Spectrum of the incident wave height
(II) Spectrum of the longshore current (case 2)

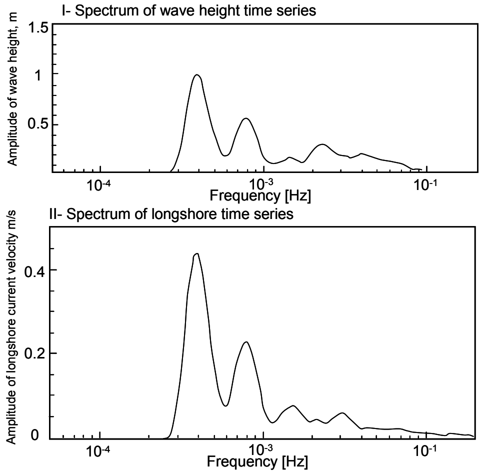

Figure 4-c. (I) Spectrum for the incident wave height
(II) Spectrum of the longshore current (case 3)

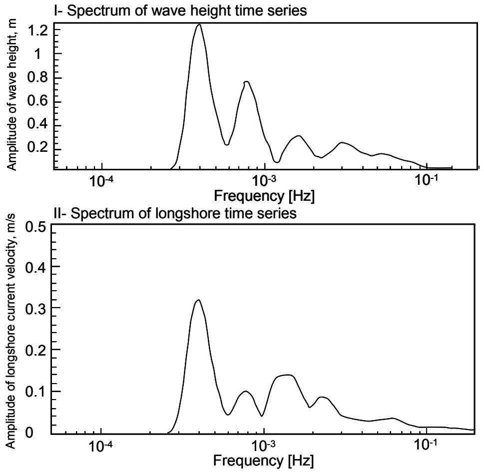

Figure 4-d. (I) Spectrum of the incident wave height
(II) Spectrum of the longshore current (case 4)

In the next section we will give a brief description of wavelet analysis which was applied previously by Elsayed (2008) on the interaction between winds and the induced wind-waves.

Application of Wavelet Analysis to UNISET-TC Predictions

The continuous wavelet transform $W(a,\tau)$ of a function h (t), is defined as:

$$W(a,\tau) = \int_{-\infty}^{+\infty} h(t)\psi^{*}{}_{a,\tau}(t)dt \tag{1}$$

where a and τ are scale and time variables respectively, and $\psi_{a,\tau}$ represents the wavelet family generated by continuous translations and dilations of the mother wavelet $\psi(t)$.

These translations and dilations are obtained by

$$\psi_{a,\tau} = \frac{1}{\sqrt{a}}\psi\left(\frac{t-\tau}{a}\right) \tag{2}$$

Following Torrence and Compo (1998) and Addison (2002), the complex Morlet wavelet (Morlet, 1981) to be implemented in this study is defined as:

$$\psi(t) = \Pi^{-1/4} e^{iw_o t} e^{\frac{-t^2}{2}} \tag{3}$$

In this definition, w_o is chosen to be 6.0 to approximately satisfy the wavelet admissibility condition (Farge, 1992).

Torrence and Compo (1998) developed a code for computing the continuous wavelet transform of the time series of the signal. In this work the code was modified to compute the cross–bispectrum and the wavelet cross-bicoherence.

In order to have a statistical stability the wavelet power spectrum is integrated over a finite time interval (Milligen et al., 1995, 1997). Therefore, the wavelet power spectrum becomes:

$$P_{xx} = \int_T W_x^*(a,\tau) W_x(a,\tau) d\tau \tag{4}$$

$W_x(a,\tau)$ wavelet transform of the time series

$W_x^*(a,\tau)$: the complex conjugate of wavelet transform of the time series

T: a finite time interval

The wavelet cross-spectrum is defined as follows:

$$P_{xy} = \int_T W_x^*(a,\tau) W_y(a,\tau) d\tau \tag{5}$$

$W_x^*(a,\tau)$: the complex conjugate of wavelet transform of the first time series

$W_y(a,\tau)$: the wavelet transform of the second time series

It should be noted that the results of the cross-spectrum depend heavily on the fluctuations of the individual signals because if one of the signals is fluctuated less than the other the effect of the more fluctuating signal will dominate in the resultant cross-spectrum (Hajj et al. 1998).

The normalized wavelet cross-spectrum (to have values between 0 and 1) gives the linear coherence as follows:

$$Coh_{xy}(a) = \frac{\left|P_{xy}(a)\right|^2}{P_{xx}(a)P_{yy}(a)} \tag{6}$$

$Coh_{xy}(a)$: linear coherence between two time series

$P_{xx}(a)$: power spectrum of first time series

$P_{yy}(a)$: power spectrum of second time series

$P_{xy}(a)$: cross-spectrum of the first and the second time series

The wavelet cross-bispectrum is defined as follows:

$$B_{yxx}(a1,a2) = \int_T W_y^*(a,\tau)W_x(a1,\tau)W_x(a2,\tau)d\tau \tag{7}$$

where $\frac{1}{a} = \frac{1}{a1} + \frac{1}{a2}$ (frequency sum rule).

The wavelet cross-bispectrum measures the amount of phase coupling in the time interval T that occurs between wavelet components of scale lengths a1 and a2 of x(t) and wavelet component a of y(t) such that the sum rule is satisfied (Milligen et al., 1995).

The normalized squared wavelet cross-bicoherence is defined as

$$[b_{yxx}(a1,a2)]^2 = \frac{|B_{yxx}(a1,a2)|^2}{[\int_T |W_x(a1,\tau)W_x(a2,\tau)|^2\, d\tau][\int_T |W_y(a,\tau)|^2\, d\tau]} \tag{8}$$

The wavelet bicoherence is a measure of phase coupling that occurs in a signal or between two signals. Phase coupling is defined to occur when two wave frequencies, f1, f2, are simultaneously present in the signal(s) along with their sum (or difference) frequencies, and the sum of the phases of these frequency components remains constant. The bicoherence measures this quantity and is a function of two frequencies f1 and f2 which is close to 1. When the signal contains three frequencies f1, f2, f that satisfy the relation f=f1±f2, bicoherence does exist. If this relation is not satisfied, then bicoherence is close to zero (Milligen et al., 1995).

The computed linear coherence and quadratic bicoherence represented by Equations (6) and (8) are given in Fig.(5-a) through Fig. (5-d) for the four cases.

SUMMARY OF RESULTS AND DISCUSSION

The results of UNISET-TC model verifications were given in Fig. (3-a) through Fig. (3-d) which illustrate the measured and predicted values for wave height and longshore current. Fig. (3-b) and Fig. (3-d) correspond to the two cases of high water level while Fig. (3-a) and Fig.(3-c) correspond to low water level. Since the field measurements at Duck site do not provide continuous time series required to conduct wavelet analysis, UNISET-TC model was used to obtain the time series of longshore current velocities and wave height.

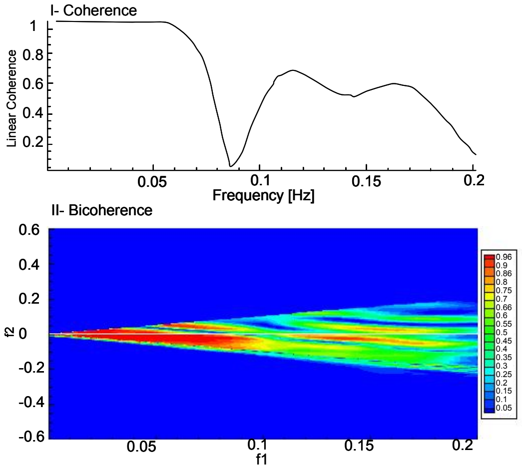

Figure 5-a. (I) Wavelet Coherence (wave height & longshore current) (II) Wavelet bicoherence (wave height f1 & wave height f2 & longshore current f) (case 1)

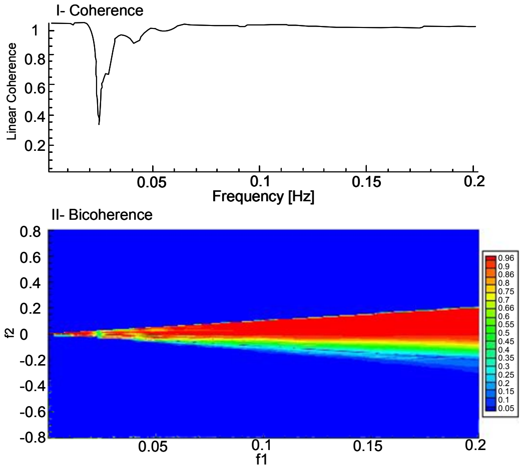

Figure 5-b. (I) Wavelet Coherence (wave height & longshore current) (II) Wavelet bicoherence (wave height f1 & wave height f2 & longshore current f) (case 2)

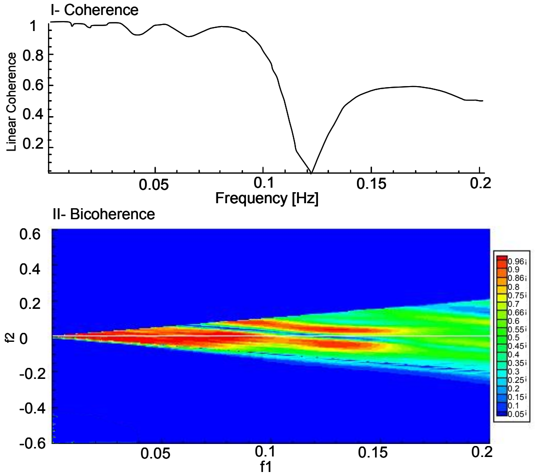

Figure 5-c. (I) Wavelet Coherence (wave height & longshore current) (II) Wavelet bicoherence (wave height f1 & wave height f2 & longshore current f) (case 3)

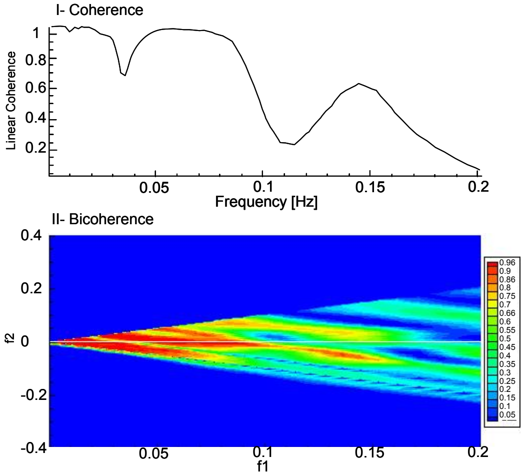

Figure 5-d. (I) Wavelet Coherence (wave height & longshore current) (II) Wavelet bicoherence (wave height f1 & wave height f2 & longshore current f) (case 4)

These time series were shown in Fig. (4-a) through Fig.(4-d) for the four cases of water level. The data in these figures highlight that there are three dominant frequency bands: 0.001-0.01 Hz, 0.01—0.04 Hz and 0.05-0.10 Hz. The first band represents the so-called "shear" which co-exit with bound edge waves and the primary incident waves.

The computed linear coherence and quadratic bicoherence (Equations 6 and 8) which were given in Fig.(5-a) through Fig.(5-d) show that there is both linear and nonlinear interaction between wave height and longshore current for the frequencies that are around or less than 0.1 Hz. The drop in the value of linear coherence at 0.1 and 0.2 is associated with a drop in bicoherence level at the same range of frequencies.

A close inspection of Fig. 5 reveals that there is nearly complete bicoherence for frequencies less than 0.05-0.08 Hz. Such coupled interaction, due to low frequency components, account for the deviations between the model and the prototype. Model deviations, around the offshore bar, are more apparent for the conditions of low water level (Cases 2 and 4). In addition, the presence of the opposing rip currents is more likely to reduce the predicted velocities of longshore currents.

Long Waves (infragravity waves) and Beach Profile Evolutions:

Smith (1998) reports on the observance of these low frequency waves using two "Phased-Array Doppler Sonars" (PADS), which were deployed at Duck, NC, as part of a major near-shore experiment in 1997. Additionally field observations by Senechal, et al (2002) on the French Atlantic coastline showed the presence of a low energy narrow band and long swell but also in the presence of high secondary wave generation due to nonlinear triad interactions. Their work demonstrated the effect of low frequency waves on the beach profile evolution.

The generation of such long period waves can be explained by two different mechanisms. On one hand the breaking is thought to release bound long waves due to wave grouping (Longuett-Higgins, 1970). On the other hand wave grouping produces a break point and set-up oscillation that acts as a piston at the wave group period. In both cases these incident long period waves reflect on the beach face, interfering with the incident waves to produce long period standing waves known as surf-beats (Thornton, 2000). The strong correspondence in field experiments between long wave and morphological features length scales, has suggested that long waves may generate off-shore bars. While strongly depending on the incident wave conditions, these infragravity waves also play an important role on the swash process.

Conclusions

The deviation between the predicted and measured values of long shore currents using UNISET-TC model has been confirmed at Duck coastal site. On the other hand the model prediction is better in cases of high water level compared to the cases of low water level and high amplitude waves. These deviations are due to potential effects of strong rip currents and subsequent interaction, while high finite amplitude waves give rise to linear and nonlinear interaction.

The current results confirm previous field observations of nearshore processes that waves in the infragravity range, shear and edge waves, play an important role on near shore hydrodynamics and beach morphology.

The results of spectral and wavelet analyses at Duck coastal site highlight the existence of infragravity waves along single or multiple bars and the importance of incorporating the interaction of low frequency waves (less than 0.05 Hz) with the incident wave components (0.08-0.15Hz).

Although many studies using wavelet analysis have suffered from an apparent lack of precise quantitative results, such advanced technique proved to be capable of extracting patterns characteristic of low-, medium- and high-frequency wave bands. The results of wavelet analysis indicate that the linear and non-linear interaction between wave height and longshore current does exist in all cases in the low frequency range which is less than 0.08 Hz.

The main conclusion of this research work is that the UNIBEST- TC and similar models need to take into effect the interaction between waves and longshore currents. Furthermore the models should consider the effects of long waves within the spectrum as well as the generated edge waves. Nevertheless, modeling of this wide range of processes on real beaches needs extensive field data of high spatial and temporal resolutions. Such challenging goal remains to be pursued to enhance state of art prediction of the cross-shore evolution profiles.

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