Wave Energy and Direction Observed near a Pier

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Abstract: Alongshore gradients in wave energy and propagation direction were observed near a pier that extends 500 m from the Duck, N.C., shoreline to about 6-m water depth. When incident waves approached the beach obliquely, wave energy observed near the shoreline 200 m downwave of the pier was as much as 50% lower than observed 400 m downwave, and waves close to the pier were more normally incident than those farther downwave. Alongshore gradients were much smaller 400 m offshore of the shoreline, upwave of the pier, and with nearly normally incident waves, confirming that the gradients are associated with wave propagation under the pier. A spectral refraction model for waves propagating over the measured bathymetry, which includes a depression under the pier, accurately predicts the observations 400 m downwave of the pier, but overpredicts energy near the pier. Refraction model predictions that include partial absorption of wave energy by the pier pilings reproduce the observed alongshore gradients, suggesting that piling-induced dissipation may be important.

INTRODUCTION

Alongshore gradients in wave energy and direction were observed downwave of a pier. The observed alongshore gradients in wave properties could result from refraction over the larger-scale bathymetry (especially the depression under the pier, Fig. 1) and from dissipation and scattering by the two rows (separated 5 m in the alongshore) of 47 1-m-diameter steel pier pilings (separated 12.2 m in the cross shore). Many formulas for wave transmission through pile-type breakwaters (Hayashi and Kano 1966; Truitt and Herbich 1986; Kriebel 1992) do not apply to the relatively wide gaps between the pier pilings, although it has been suggested that rows (Dalrymple and Fowler 1982; Dalrymple et al. 1988; Herbich and Douglas 1988) and arrays (Ball et al. 1996) of piles lead to reduced transmission. Here, a linear spectral refraction wave model (Longuet-Higgins 1957; Le Méhauté and Wang 1982) is used to investigate bathymetric refraction and piling dissipation effects. Spectral refraction over the observed bathymetry accurately models the waves observed 400 m downwave of the pier, but overpredicts wave energy and propagation angle close to the pier. A crude extension of the refraction model to include energy dissipation by the pier pilings is more accurate.

FIELD OBSERVATIONS OF ALONGSHORE GRADIENTS

Waves, currents, and bathymetry were observed nearly continuously between 1 Aug and 3 Dec 1997 with a two-dimensional array of instruments extending 400 m from the shoreline to approximately 5-m water depth, and spanning 200 m in the alongshore direction (Fig. 1). The southern end of the array was located 200 m north of the U.S. Army Field Research Facility pier near Duck, N.C. Water depths under the pier are as much as 1.5 m greater than the depths 50 m to either side of the pier (Fig. 1).

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The seafloor elevation at each instrumented location was estimated every 3 h with sonar altimeters, and the larger-scale bathymetry (e.g., Fig. 1) was surveyed approximately every 2 weeks with an amphibious vehicle (Lee and Birkemeier 1993). To eliminate cases where alongshore inhomogeneity in the observed wave field is affected by alongshore depth variations within the array, a 3-h record was excluded if the standard deviation of depths (measured with sonar altimeters) along any instrumented alongshore line was greater than 20 cm or if the depth at the altimeter closest to the pier differed from the mean alongshore depth by more than 20 cm. To prevent bias from waves in the inner surf zone where energy levels may be saturated, and thus depend primarily on the local depth, only cases with incident (5-m water depth) significant wave heights $H_s < 125$ cm were included. Approximately 660 3-h runs were retained.

Spectra from 3-h-long time series of observed bottom pressure were converted to sea-surface elevation using linear finite depth theory. Total energy and significant wave height were calculated from sea-surface elevation spectra integrated between 0.05 and 0.20 Hz. Data from each pair of colocated bidirectional current meters and pressure gauges (Fig. 1) were used to estimate the mean wave propagation direction θ and directional spread σ_θ (Kuik et al. 1988) both as a function of frequency and averaged over the 0.05–0.20 Hz frequency band.

Incident wave properties were estimated with data from the colocated pressure and current meter at cross-shore coordinate $x = 500$, longshore coordinate $y = 828$ m (Fig. 1), located in 5-m depth where observed alongshore energy gradients were weak. When low energy ($H_s = 25$ cm) waves arrived at the pier area from oblique southerly angles ($\theta = -26°$, $\sigma_\theta = 20°$), alongshore gradients in wave energy were observed near the shoreline [Fig. 2(a)]. In contrast, observed alongshore energy gradients were small when the array was not downwave of the pier (i.e., for northerly or normally incident waves). For example, alongshore gradients in wave energy were small for low energy, nearly normally incident swell [Fig. 2(b), $H_s = 42$ cm, $\theta = -5°$, $\sigma_\theta = 17°$]. In both cases shown in Fig. 2 breaking within the array was insignificant and shoaling increases the wave energy near the shoreline.

Alongshore gradients in wave energy are larger for waves with more southerly propagation angles. For example, the southerly waves [e.g., Fig. 2(a)] consisted of swell with frequency $f = 0.1$ Hz and mean direction (in 5-m depth) $\theta = -15°$, and higher frequency ($0.14 < f < 0.17$ Hz) seas with more oblique ($-35° < \theta < -45°$) propagation angles [Figs. 3(a and b)]. The alongshore gradient in wave energy near the shoreline is more pronounced (e.g., the relative change is greater) for the more oblique seas [compare the spectra from $x = 209$ m in Fig. 3(a)]. An alongshore gradient in wave di-

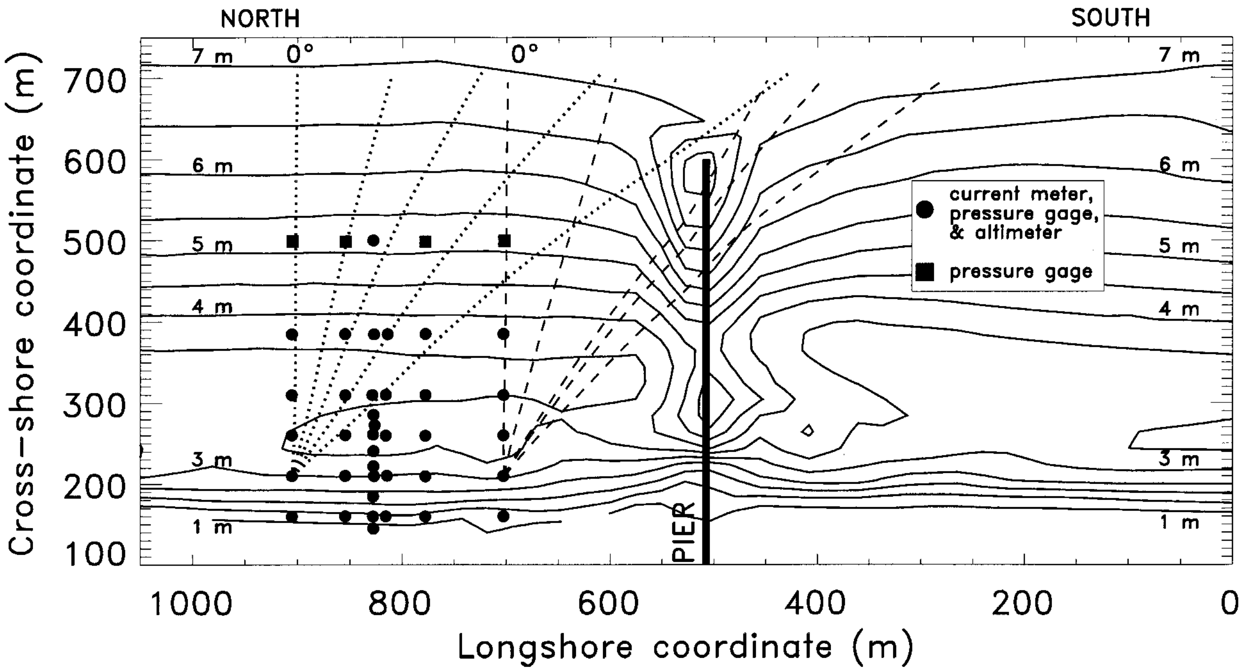

FIG. 1. Sensor Array (Symbols) and Nearshore Bathymetry (Depth Contours Relative to Mean Sea Level in 0.5 m Steps). Broken Curves Are Approximate Ray Paths (Using Snell's Law) for Shoreward Propagating $f = 0.15$ Hz Waves with Incident Angles (in 5-m Depth) from 0° to −40° in Steps of −10°. Rays for $f = 0.10$ Hz Waves Are Similar

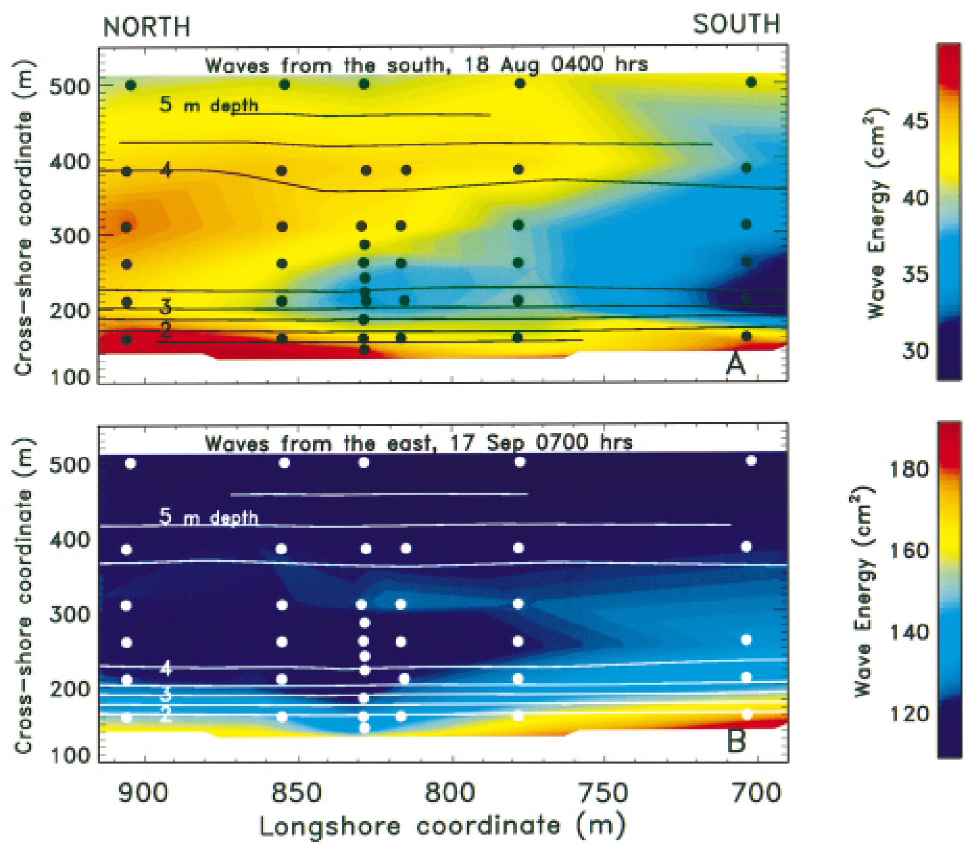

FIG. 2. Contours of Total (0.05–0.20 Hz) Wave Energy (Color Scales on Right Side). Symbols Are Sensor Locations and Curves Are Water Depth Contours for Each 3-h Period. Waves Arrived from: (a) South; and (b) East (Nearly Normal Incidence)

rection also is observed near the shoreline [Fig. 3(b)], especially for the highly oblique seas, which are about 10° closer to normal incidence near the pier ($y = 703$ m) than in the same water depth 200 m to the north ($y = 905$ m). These observations are consistent with partial blocking of waves by the pier pilings. Mean angles closer to normal incidence are expected if wave components with the most southerly directions are blocked by the pier, while more normally incident components in the same frequency band arrive at the measurement location without propagating under the pier (see the rays in Fig. 1).

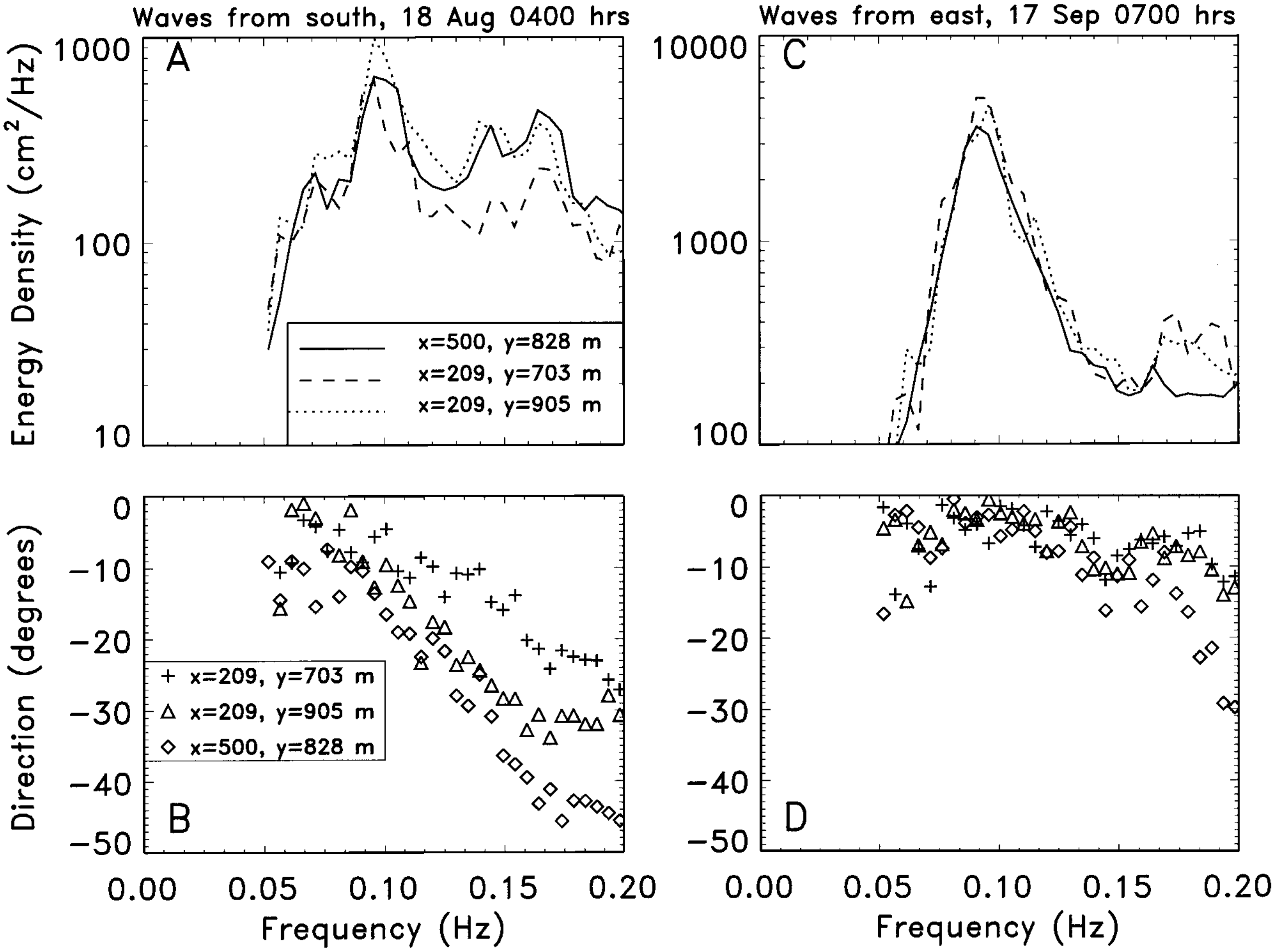

FIG. 3. Energy Density [Note Different Ordinate Scales in (a) and (c)] and Propagation Direction [(b) and (d), Negative Directions Are Waves from South] versus Frequency

With normally incident waves [Fig. 2(b)] alongshore gradients in energy and direction are small at all frequencies [Figs. 3(c and d)].

Alongshore gradients in wave energy and direction depend on the incident wave propagation angle (Figs. 4 and 5, respectively). For each 3-h observation, the ratio of the (frequency-integrated) wave energy observed near the pier (y = 703 m) to that observed in the same water depth, but farther from the pier (averaged over 775 $\leq y \leq$ 905 m) was calculated, and sorted into 2.5°-wide directional bins. All bins have more than four points, and the results do not change significantly for different directional bin widths. Alongshore energy gradients were weak in 5-m depth for all incident wave directions and increased shoreward (top to bottom in Fig. 4) and with increasing southerly angle of incidence. The difference between the frequency-averaged wave directions observed near the pier (y = 703 m) and (in the same water depth) farther from the pier (775 $\leq y \leq$ 905 m) also increased shoreward and with increasing southerly angle of incidence (Fig. 5). Alongshore variations in wave energy and direction between 775 and 905 m were not significant, except for a few cases with the most southerly incident waves [e.g., Fig. 2(a)].

SPECTRAL REFRACTION MODEL PREDICTIONS

The wave field downwave of the pier was modeled using linear spectral refraction (Longuet-Higgins 1957; Le Méhauté and Wang 1982) based on Snell's Law (e.g., seaward ray tracing, Fig. 1) and spectral energy conservation. Piling effects were simulated by reducing the amount of energy propagating along ray paths passing under the pier. The model was initialized in 6.5-m water depth, offshore of the pier and neighboring bathymetry. Frequency-directional spectra in 6.5-m depth were assumed alongshore homogeneous over 500-m length scales, and were obtained by back refracting frequency-directional spectra estimated using observations from the alongshore array of pressure sensors in about 5-m water depth (x = 500 m, Fig. 1) and a maximum likelihood estimator (Pawka et al. 1983). Model bathymetry was constructed from nearshore surveys performed 5 days prior to the observations shown in Figs. 2(a), 3(a), 6, and 7. Sonar altimeter estimates show little change of the seafloor location during the intervening 5 days. Cubic spline interpolation was used to create a regular bathymetric grid with 6-m spacing. Grid depths were adjusted to account for the mean tidal level during each 3-h time period.

Spectral refraction with no pier blocking (e.g., 100% transmission) accurately predicts the heights of small nonbreaking waves observed along a cross-shore transect 400 m downwave of the pier [y = 905 m, Fig. 6(a)], but overpredicts wave heights closer to the pier [y = 703 m, Fig. 6(a)]. Neglected diffraction effects may contribute to model errors. The severity of these errors depends on the complexity of the local bathymetry and the width, in both frequency and direction, of the incident wave field (O'Reilly and Guza 1991). The errors are small when estimating integral properties of a spectrum (e.g., significant wave height) over natural bathymetries. In addition, diffraction reduces spatial gradients by propagating energy away from areas of energy convergence and into areas of energy divergence (Pierson et al. 1953). Therefore, diffraction would increase slightly the modeled wave heights in the region

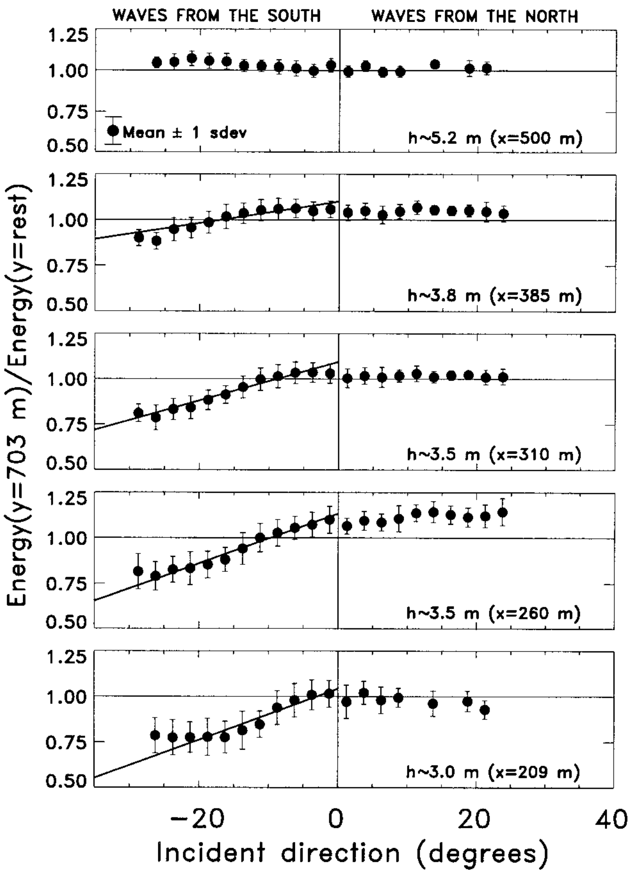

FIG. 4. Ratio of Wave Energy Observed Nearest the Pier (*y* = 703 m) to Energy Averaged over the Rest of the Array at the Same Depth (775 ≤ *y* ≤ 905 m) versus Frequency-Averaged Direction of Incident Waves. Solid Lines Are Least Squares Fits to Unbinned Data with Directions Less Than 0° (Waves from South)

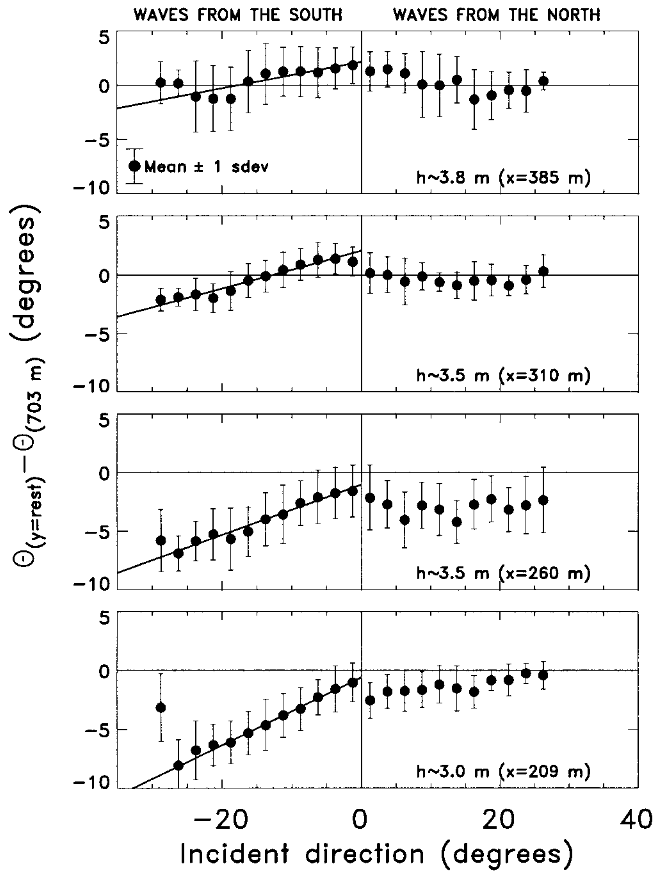

FIG. 5. Difference between Mean Wave Propagation Angles Observed Nearest the Pier (*y* = 703 m) and Averaged over the Rest of the Array at the Same Depth (775 ≤ *y* ≤ 905 m) versus Mean Direction of Incident Waves. Solid Lines Are Least Squares Fits to Unbinned Data with Directions Less Than 0° (Waves from South)

of wave energy divergence north of the pier (e.g., $y = 703$ m), and thus further increase discrepancies with the observations.

The observed alongshore gradients in wave height are predicted accurately if 45% energy blocking by the pier pilings is included [Fig. 6(b)]. Model predictions far from the pier ($y = 905$ m) are insensitive to blocking [cf. Figs. 6(a and b)] because only a small fraction of the energy reaching these locations passes under the pier (Fig. 1). In contrast, blocking reduces predicted wave heights in the pier shadow ($y = 703$ m), in agreement with the observations [Fig. 6(b)]. Nearly all the highly oblique ($-35° < \theta < -45°$, $\sigma_\theta \approx 10^3$ in 5-m depth) $0.14 < f < 0.17$ Hz waves reaching the most heavily shadowed location ($x = 209$, $y = 703$ m) pass under the pier, and energy levels in this frequency range are predicted to be almost 45% lower with 45% blocking than with no blocking [Fig. 7(a)]. The corresponding reduction in the predicted energy level of the lower frequency ($f = 0.1$ Hz) more normally incident ($\theta = -15°$, $\sigma_\theta = 15°$) swell is less than 20%, because a smaller fraction (approximately half) of the 0.1 Hz energy reaching this location passes under the pier (Fig. 1). Blocking also improves predictions of propagation direction in the pier shadow [Fig. 7(b)].

The 30–50% blocking required to reproduce the observations is higher than implied by theories (Hayashi and Kano 1966; Truitt and Herbich 1986; Kriebel 1992) for energy dissipation by the relatively widely spaced piles. Energy transmission may be reduced further by enhanced dissipation associated with the rough, barnacle-encrusted piles, and by reflection and scattering (Dalrymple and Fowler 1982; Dalrymple et al. 1984, 1988). Diffraction and reflection of energy

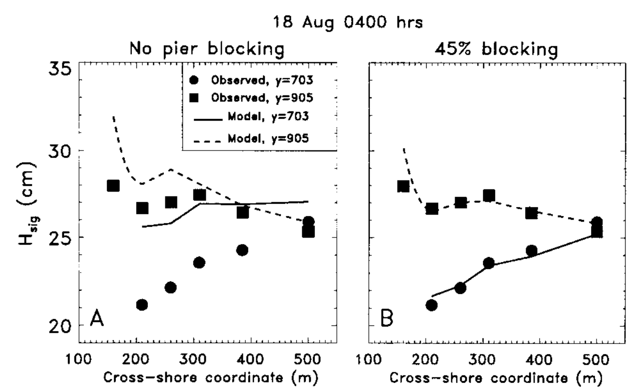

FIG. 6. Observed (Symbols) and Modeled (Curves) Significant Wave Height versus Cross-Shore Coordinate for Data Shown in Figs. 2(a), 3(a), and 3(b): (a) Model with No Blocking; and (b) Model with 45% Blocking

by the bathymetric trench under the pier (Kirby and Dalrymple 1983; Williams 1990; McDougal et al. 1996) (not included in the spectral refraction model) causes less than 5% additional alongshore energy variation. Model errors also could result from inaccurate surveys of the steep bathymetry under the pier, and from the effects of currents, which were not measured near the pier and thus were neglected. Although a detailed study of piling effects therefore is not possible, the model-data comparisons (Figs. 6 and 7) suggest piling-induced dissipation is important.

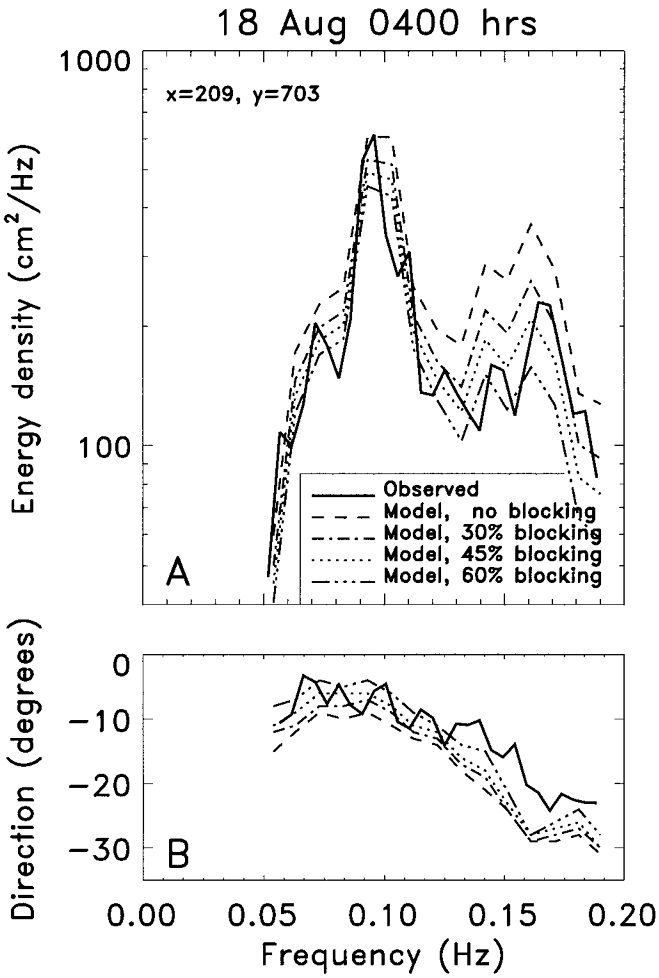

FIG. 7. (a) Energy Density; and (b) Mean Propagation Direction versus Frequency at *x* = 209, *y* = 703 m (Solid Curves Are Observations and Broken Curves Are Model Predictions)

CONCLUSIONS

Significant alongshore variations of wave energy levels and propagation directions were observed downwave of a pier and an associated bathymetric depression. Energy levels observed relatively far downwave of the pier are reproduced by a linear and dissipationless model that accounts for refraction over the observed bathymetry, and is initialized with the observed offshore wave frequency-directional spectrum. Model predictions of wave energy levels and propagation directions closer to the pier are improved by including dissipation by the pier pilings.

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