Nearshore Water Level Surges in the Surf Zone

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and

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Abstract

Field data of wave setup and wave height measured at the Field Research Facility in Duck, NC are compared with a one-dimensional time-averaged numerical model. The results are used to determine the effective placement of a limited number of measurement instruments available for the study.

Introduction

A series of pressure gauges, deployed on the pier at the Field Research Facility in Duck, NC, is part of the larger study that includes the detailed measurement of the the bathymetry, wave characteristics and currents.

Three Paroscientific pressure gauges are located near the bottom and along the pier as shown in Fig. 1. The pier extends approximately 500 meters from the shoreline and is nearly shore normal. An additional gauge is located approximately 300 meters north of the pier and 350 meters seaward of the end of the pier. Table 1 indicates the along-shore and cross-shore position of the four pressure gauges that are referenced in this report. These positions are given relative to the coordinate system set up at the Field Research Facility. Also, the deployment depth and the position of the bottom on January 12, 1998 are given relative to NGVD.

SandyDuck Storm Data from January 28, 1998

Data samples are available for the 24 hour period of January 28, 1998. The cases of largest and smallest water depth occurring at 7:00 and 13:34, respectively on January 28, 1998, are analyzed in some detail in the following section.

The data samples are 40 windows of time equally spaced throughout the day, each 2048 seconds in length. With the data sampled at 2 Hz, the time series for each gauge is comprised of 4096 sample points. Time averaging is indicated by an overbar in the following.

The available raw data, p_*, is the pressure head in the form of a pressure time series normalized by the weight of water and measured relative to NGVD.

$$p_* = \frac{p}{\rho g} = p' + (d + \bar{\eta}_{NGVD}) \tag{1}$$

where

Table 1: Locations of Four Gauges Deployed During SandyDuck Experiment.

Gauge	Cross-shore (m)	Longshore (m)	Deployment Position below NGVD (m)	Bottom Position below NGVD (m)
651	182.9	513.6	1.01	1.46
641	239.11	516.64	1.64	1.96
1861	566.9	516.6	8.17	8.57
111			7.49	7.9

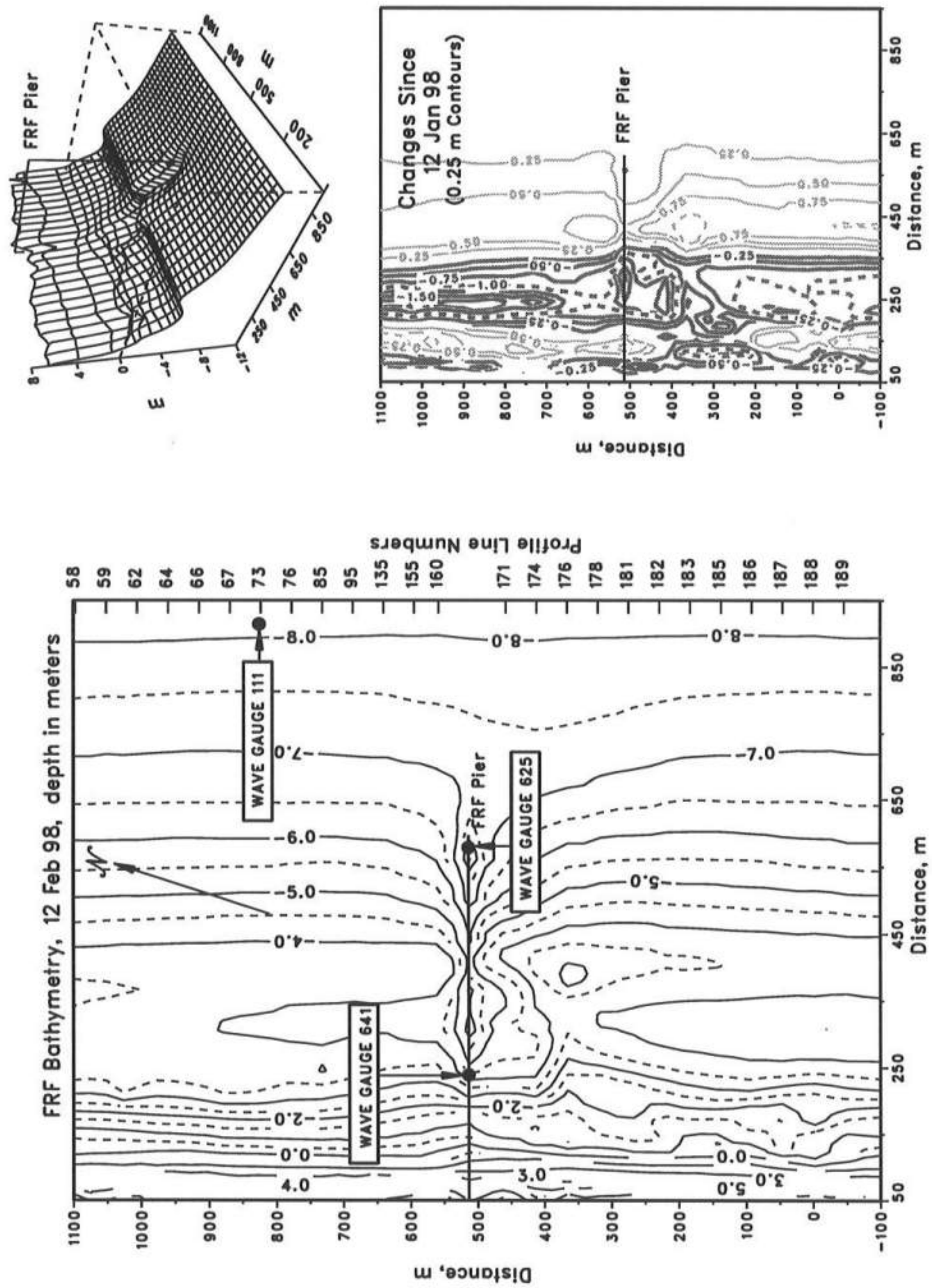

Figure 1: Bathymetry of the Area Surrounding the Pier.

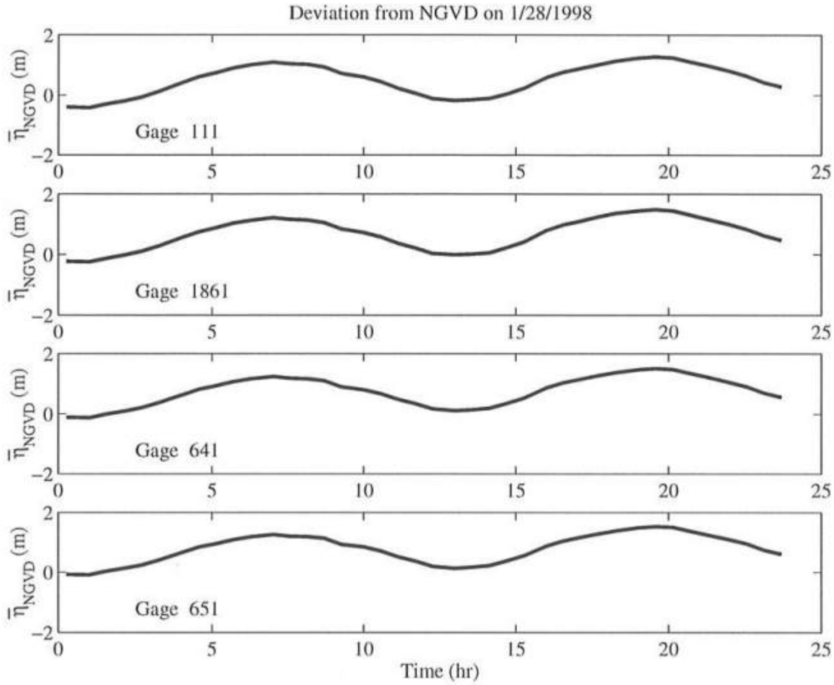

Figure 2: Recorded Deviation in Mean Water Level , $\bar{\eta}_{NGVD}$, from NGVD.

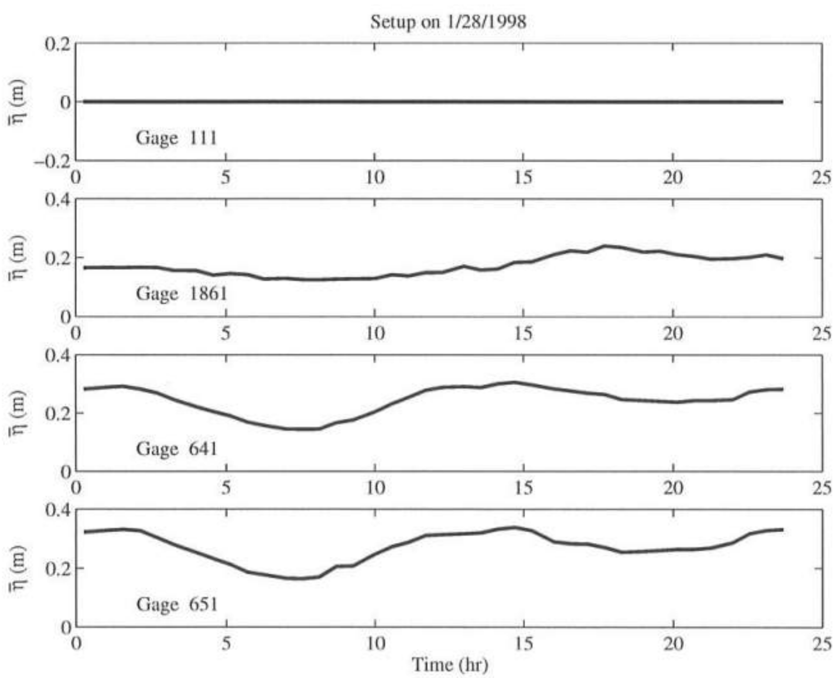

Figure 3: Recorded Setup where the Deviation in Mean Water Level at Gauge 111 is Assumed to be Due to Tides and Storm Surge only, with Zero Wave Setup.

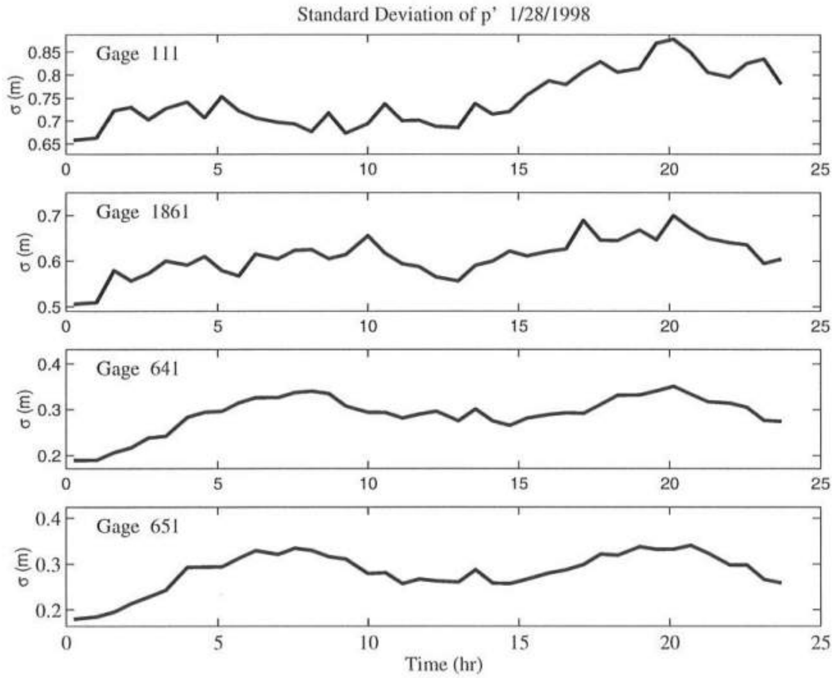

Figure 4: Standard Deviation σ of the pressure head p' for 24 Hours of 1/28/1998.

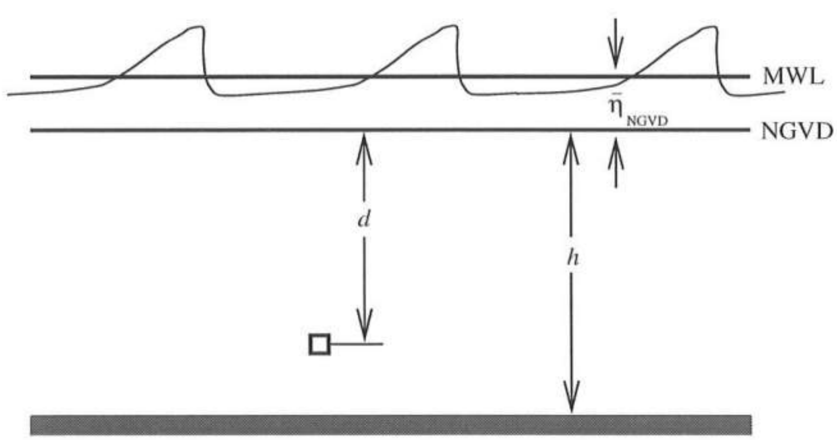

Figure 5: Definition Sketch.

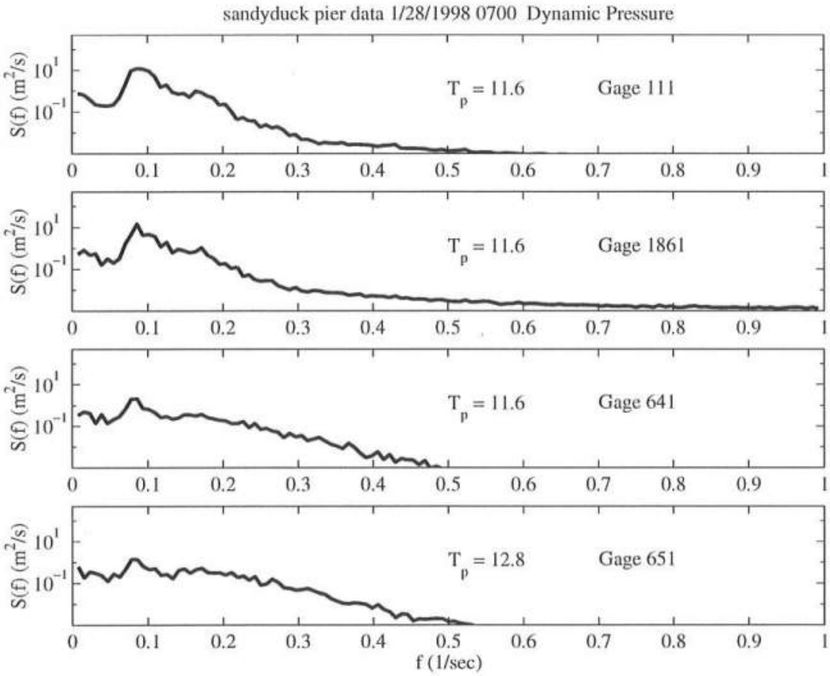

Figure 6: Smoothed Frequency Spectrum of p' for High Tide.

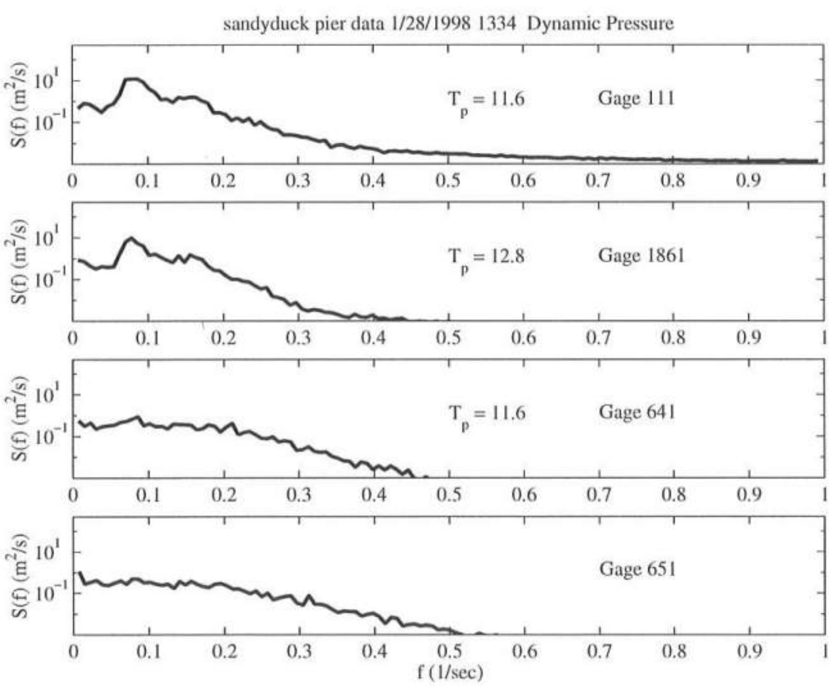

Figure 7: Smoothed Frequency Spectrum of p' for Low Tide.

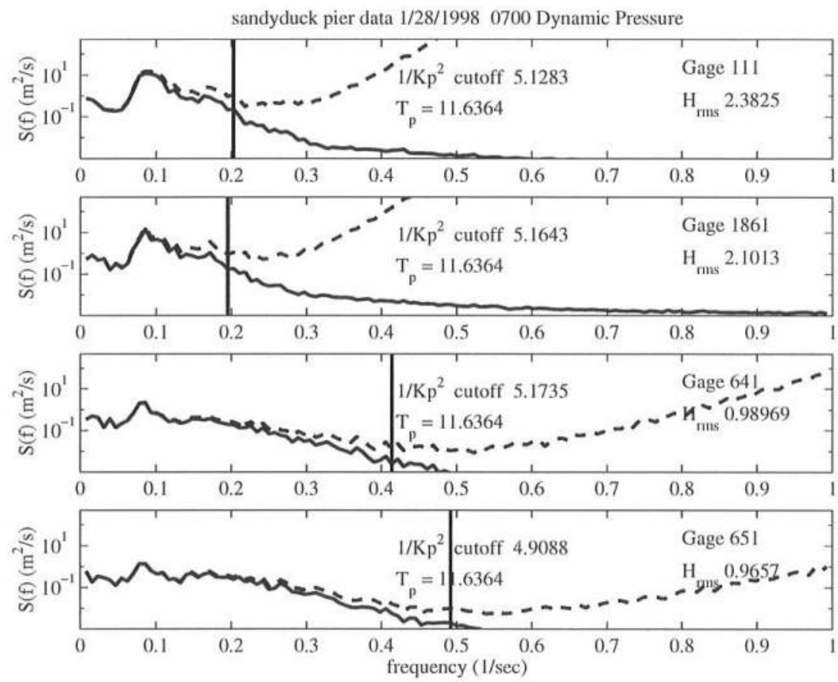

Figure 8: Smoothed Frequency Spectrum, High Tide: $--\ \eta'$, $\ —\ p'$.

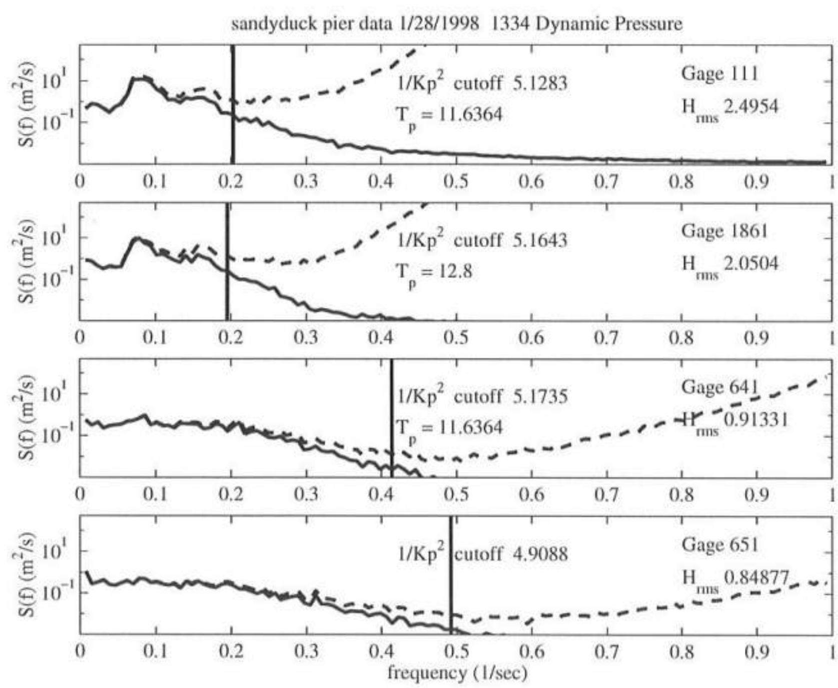

Figure 9: Smoothed Frequency Spectrum, Low Tide: $--\ \eta'$, $\ —\ p'$.

$p =$ pressure
$\rho g =$ unit weight of water
$p' = [p_* - (d + \bar{\eta}_{NGVD})] =$ pressure head with $\bar{p'} = 0$
$d =$ deployment depth listed in Table 1 and shown in Fig. 5
$\bar{\eta}_{NGVD} =$ time averaged deviation from NGVD shown in Fig. 5

All 40 time windows were analyzed for each of the four gauges. The deviation of the time averaged free surface $\bar{\eta}_{NGVD}$ is shown for the 24 hour period of 1/28/98 in Fig. 2. Clearly, the deviation is dominated by semi-diurnal tidal forcing with high tide occurring at 7:00 and low tide occurring at 13:34. Fig. 3 shows the setup at the four gauges where wave induced setup is assumed to be zero at the most seaward gauge, 111.

The magnitude of the pressure variation is parameterized by σ, the standard deviation of the pressure head p'. The variation of σ with time is given for each gauge is shown in Fig. 4. The standard deviation of the pressure time series is an indicator of wave height, and Fig. 4 shows that the wave height decreases landward due to wave breaking.

Figs. 6 and 7 show the frequency spectrum of the pressure head p'. The results provided have been Bartlett averaged by splitting the 4096 points into 16 windows each with a length of 256 points. The peak period, calculated as the reciprocal of the frequency with the maximum energy, is given in each panel. The peak period is practically constant in the cross-shore direction for each case except for the most shoreward gauge at low tide. At gauge 651, as seen in Fig. 7, the frequency spectrum is essentially flat over the wind wave and low frequency ranges and the peak period is not reported for gauge 651.

To obtain the the root-mean-square wave height and setup of the free surface from the pressure record, a linear wave theory is normally employed locally (e.g., Guza and Thorton 1980). Expressing the free surface and pressure head as the sum of Fourier components with the angular frequency, ω_n

$$\eta' = \sum_{n=1}^{N} F_\eta(\omega_n) \quad ; \quad p' = \sum_{n=1}^{N} F_p(\omega_n) \tag{2}$$

where $\eta' =$ the free surface elevation relative to the mean water level (MWL) with $\bar{\eta'} = 0$. Following linear theory (e.g., Dean and Dalrymple 1984), the pressure Fourier components can be expressed as

$$F_p(\omega_n)e^{i\omega_n t} = F_\eta(\omega_n)e^{i\omega_n t}\, K_p(\omega_n) \tag{3}$$

where $K_p(\omega_n)$ is the pressure response factor given by

$$K_p(\omega_n) = \frac{cosh\,[k_n(h-d)]}{cosh\,[k_n(h+\bar{\eta}_{NGVD})]} \tag{4}$$

with

$$\omega_n^2 = k_n g\; tanh\,[k_n(h+\bar{\eta}_{NGVD})]$$

Table 2: Calculated Values for $H_{rms}(m)$ for High Tide.

Gauge	Based on Spectral Estimate of σ_s with Linear Pressure Response	Based on Spectral Estimate of σ with $K_p = 1$	Based on Estimate of σ from Time Series with $K_p = 1$	Based on Upcrossing Analysis with $K_p = 1$
651	0.98	0.90	0.91	0.83
641	1.00	0.92	0.92	0.90
1861	2.21	1.71	1.71	1.68
111	2.44	1.97	1.97	1.93

where

k_n = wave number

g = gravitational acceleration

$(h + \bar{\eta}_{NGVD})$ = local water depth below MWL

$(h - d)$ = vertical distance of the pressure gauge above the bottom

The free surface component $F_\eta(\omega_n)$ can be calculated after solving for the component of the pressure head time series $F_p(\omega_n)$ along with the linear dispersion relation for the wave number k_n as

$$F_\eta(\omega_n) = \frac{F_p(\omega_n)}{K_p(\omega_n)} \tag{5}$$

Likewise, the relation between the Fourier components of the frequency spectra for η' and p' (e.g., Goda 1985)

$$S_\eta(\omega_n) = \frac{S_p(\omega_n)}{[K_p(\omega_n)]^2} \tag{6}$$

However, difficultly arises in the short wave limit as $K_p(\omega_n)$ grows small. Therefore, a frequency cutoff is used to avoid artificially magnifying the free surface components at the higher frequencies. In this analysis, the frequency cutoff, f' corresponds to $(1/K_p^2) \simeq 5$.

Given the truncated spectrum, an estimate of the root-mean-square wave height is given by

$$H_{rms} = \sqrt{8}\sigma_s \tag{7}$$

where σ_s is the spectral estimate of the standard deviation given by

$$\sigma_s = \left(\int_0^{f'} S_\eta \, df \right)^{\frac{1}{2}} \tag{8}$$

where f' = cutoff frequency based on $(1/K_p^2) \simeq 5$. The calculated frequency spectrum of the free surface as well as the frequency spectrum of the measured pressure head time series are shown in Figs. 8 and 9. The vertical line shows the position of the cutoff frequency, f', given at each gauge. The spectral estimates for H_{rms} are given in Tables 2 and 3 for high and low tide.

Table 3: Calculated Values for $H_{rms}(m)$ for Low Tide.

Gauge	Based on Spectral Estimate of σ_s with Linear Pressure Response	Based on Spectral Estimate of σ with $K_p = 1$	Based on Estimate of σ from Time Series with $K_p = 1$	Based on Upcrossing Analysis with K_p
651	0.86	0.80	0.81	0.73
641	0.92	0.84	0.85	0.77
1861	2.17	1.67	1.67	1.63
111	2.65	2.08	2.08	2.07

Alternatively, the pressure attenuation associated with $K_p(n) > 1$ can be be neglected if pressure is assumed hydrostatic below the instantaneous free surface elevation. Using this assumption, known as the long wave approximation, H_{rms} can be calculated several ways. The spectral estimate for the standard deviation with $K_p = 1$ is given by

$$\sigma = \left(\int_0^{f_{nyq}} S_p \, df \right)^{\frac{1}{2}} \tag{9}$$

where f_{nyq} is the Nyquist frequency of 1 Hz for the case of 2 Hz sampling frequency. The estimates for $H_{rms} = \sqrt{8}\sigma$ based on σ with $K_p = 1$ are given in Tables 2 and 3

The standard deviation σ can also be calculated directly from the measured time series p'_j with $j = 1, 2, ..., N_p$ as

$$\sigma = \left(\frac{1}{N_p} \sum_{J=1}^{N_p} p_j'^2 \right)^{\frac{1}{2}} \tag{10}$$

where N_p is the number of points in the time series. The estimates for $H_{rms} = \sqrt{8}\sigma$ based on the direct estimate of σ from the time series are given in Tables 2 and 3.

Finally, H_{rms} is also calculated with a zero upcrossing method of the measured time series p' as a final check where the long wave approximation is again used. The root-mean-square wave heights based on the upcrossing analysis are presented in Tables 2 and 3.

Comparison of Data to Numerical Model, CSHORE

In the analysis that follows, the one-dimensional time-averaged model CSHORE, is compared to the data from the storm on Jan. 28, 1998. The model predicts the cross-shore variations of the mean and standard deviation of the free surface elevation from outside the surf zone to the lower swash zone on beaches. Nonlinear correction terms are included in the cross-shore radiation stress and energy flux that become important in very shallow water. The model is initiated at the end of the pier, at gauge 1861; the root-mean-square wave height and wave induced setup are then calculated from the seaward boundary to the lower region of the swash zone.

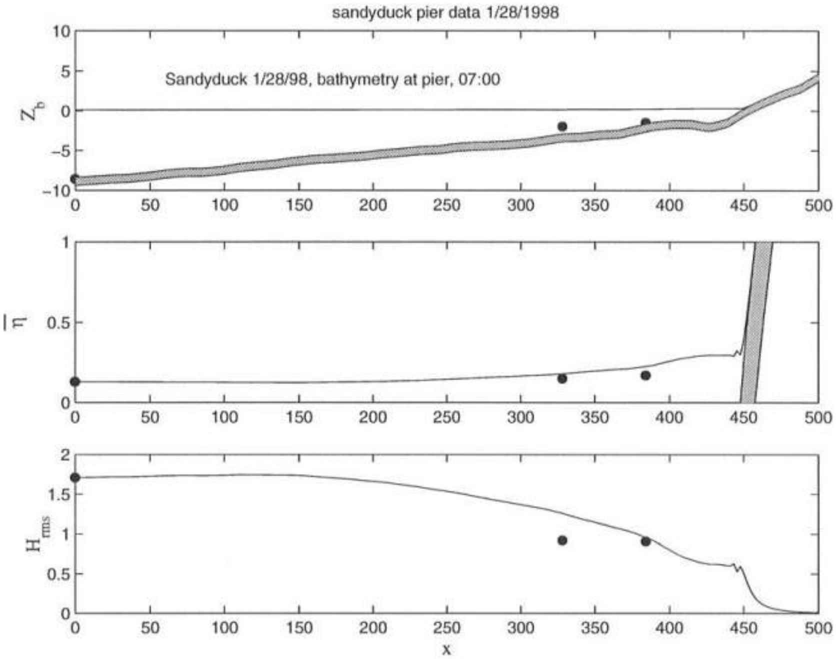

Figure 10: Bathymetry and Comparison of Calculated and Measured Setup and Root-mean-square Wave Height for High Tide with Zero Setup at Gauge 111.

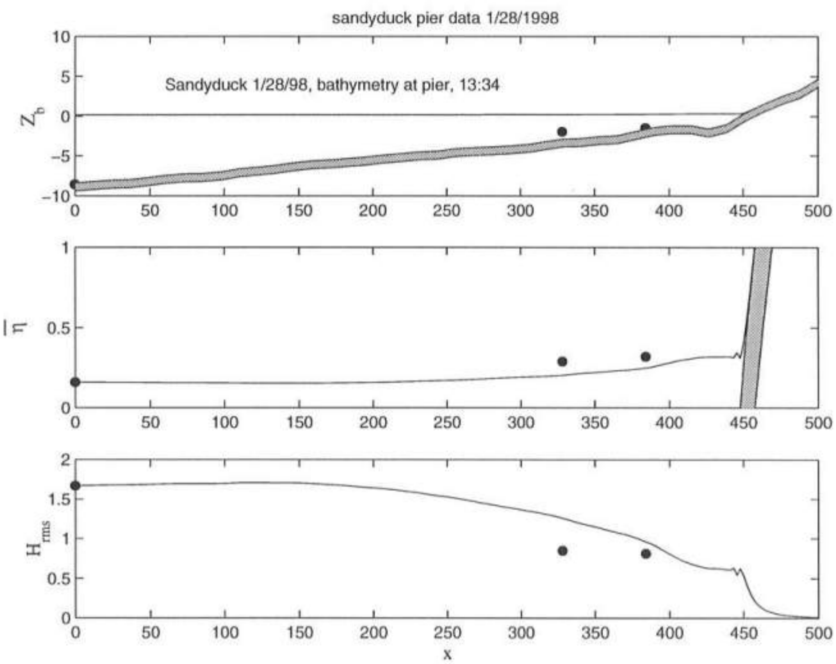

Figure 11: Bathymetry and Comparison of Calculated and Measured Setup and Root-mean-square Wave Height for Low Tide with Zero Setup at Gauge 111.

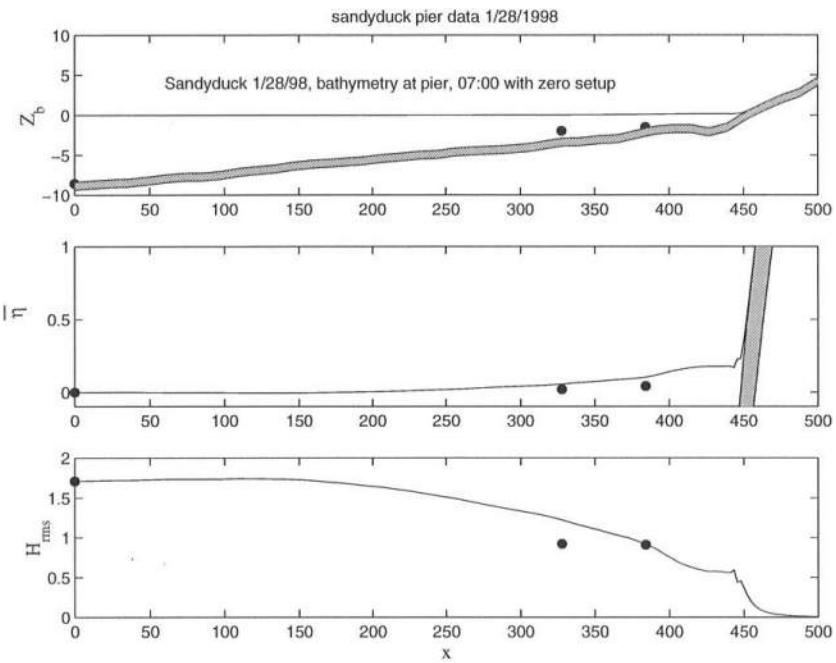

Figure 12: Bathymetry and Comparison of Calculated and Measured Setup and Root-mean-square Wave Height for High Tide with Zero Setup at Gauge 1861.

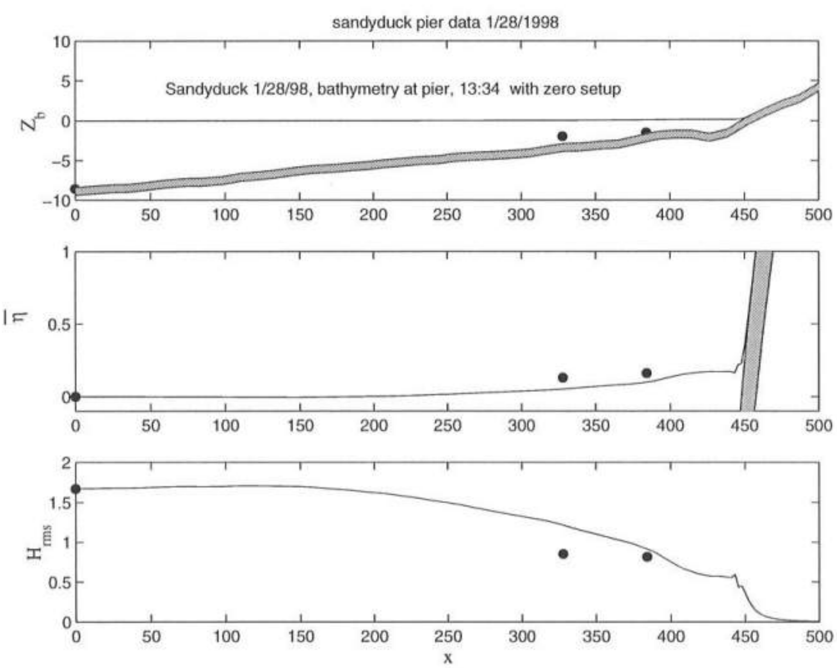

Figure 13: Bathymetry and Comparison of Calculated and Measured Setup and Root-mean-square Wave Height for Low Tide with Zero Setup at Gauge 1861.

Table 4: Comparison of Wave Height and Setup for High Tide with Zero Setup at Gauge 111.

	Wave Setup (m)		$H_{rms}(m)$	
Gauge	Measured	Predicted	Measured	Predicted
1861	0.13	0.13	1.71	1.71
641	0.15	0.18	0.92	1.26
651	0.17	0.23	0.90	0.96

Table 5: Comparison of Wave Height and Setup for Low Tide with Zero Setup at Gauge 111.

	Wave Setup (m)		H_{rms} (m)	
Gauge	Measured	Predicted	Measured	Predicted
1861	0.16	0.16	1.67	1.67
641	0.29	0.20	0.85	1.26
651	0.32	0.25	0.81	0.96

The free surface setup is assumed to be zero at the most seaward gauge, 111. Any deviation in the mean water level at this gauge is presumably due to the tide and storm surge. Therefore the setup at the seaward boundary is taken as the difference in the mean water level from gauge 111 and gauge 1861. Likewise, the setup at the two interior gauges, 641 and 651, is calculated from the data as the difference in the mean water level at the gauge and the mean water level at gauge 111.

It is evident from Tables 2 and 3 that the various methods used to calculate H_{rms} yield values that are similar. In the model to data comparisons that follow, the H_{rms} based on the standard deviation of the time series p', based on $K_p = 1$, is utilized in order to be consistent with the derivation of the model CSHORE. The empirical parameters of CSHORE are those given by Johnson and Kobayashi(1998) and are not adjusted in the present comparisons.

Fig. 10 shows the model to data comparison for the data taken at 7:00 on 1/28/1998. This comparison corresponds to the time of greatest water depth or high tide with zero setup at gauge 111. The bathymetry shown in Fig. 10 and used for the numerical computation was recorded with soundings along the pier on January 7,

Table 6: Comparison of Wave Height and Setup for High Tide with Zero Setup at Gauge 1861.

	Wave Setup (m)		$H_{rms}(m)$	
Gauge	Measured	Predicted	Measured	Predicted
1861	0.00	0.00	1.71	1.71
641	0.02	0.05	0.92	1.22
651	0.04	0.10	0.90	0.92

Table 7: Comparison of Wave Height and Setup for Low Tide with Zero Setup at Gauge 1861.

	Wave Setup (m)		H_{rms} (m)	
Gauge	Measured	Predicted	Measured	Predicted
1861	0.00	0.00	1.67	1.67
641	0.13	0.05	0.85	1.22
651	0.16	0.10	0.81	0.91

1998. The dots in the first panel show the position of the bottom at the time that the pressure time series was recorded. The slight mismatch in the position of the bottom is due to changes in bathymetry that occurred between the time that the soundings were taken and the time that the pressure data was taken. Predicted and measured values for the setup and wave height at high tide are tabulated in Table 4. The wave height is overpredicted by the one-dimensional model in the region of the two available data points. Fig. 11 shows the comparison for the time corresponding to the lowest mean water level, or low tide. Predicted and measured values for the setup and wave height at low tide are tabulated in Table 5. Again, the wave height is overpredicted by the one-dimensional model in the region of the two available data points.

In order to check the sensitivity of the computed results to variations in the setup at the seaward boundary, additional computations are included. In previous computations the setup at the seaward boundary was specified as the difference between the mean water levels at gauge 111 and 1861. However, the difference may be due to measurement datum errors rather than actual wave induced setup. Figs. 12 and 13 show the comparisons of cross-shore variation of the setup and H_{rms} if zero setup is specified at the seaward boundary, gauge 1861. Tables 6 and 7 give the corresponding predicted and measured values for the setup and wave height.

This mismatch in the predicted and measured wave heights is due in part to the application of a one-dimensional model when the assumption of normally incident waves on a long straight coast of alongshore uniformity is questionable. Scour in the vicinity of the pier due to the effect of the piles is clearly evident in Fig. 1. The depth of the scour is approximately 1 m; that is to say that the level of the bottom is approximately 1 m below the bathymetry far from the pier. The scour hole may reduce the wave height through refraction. The bathymetry in the vicinity of the pier causes incoming wave energy to refract out and reduces the wave height at the positions where the pressure is measured.

The numerical model predicts the time averaged free surface elevation, $\bar{\eta}$ reasonably well. The setup is slightly overpredicted at 7:00, or high tide, while the model underpredicted the setup at 13:34, or low tide.

Suggested Placement Improvements

Given the limited number of gauges in this project, different deployment positions may yield a better representation of the cross-shore variation of the wave setup and root-mean-square wave height across the surf zone. It is suggested that gauge 641 be placed approximately 60 m farther offshore. Additionally, moving gauge 651 inland a distance of 100 meters will permit the measurement of the larger setup closer to the shoreline.

Acknowledgments

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