COMPARISON OF MODEL AND OBSERVED NEARSHORE CIRCULATION

by

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ABSTRACT

Results from a two-dimensional numerical model for nearshore circulation induced by waves and wind are compared with observations made during two storms at a beach on Lake Michigan. Model-input data include bathymetry, offshore wave characteristics, wind histories, and local water-level changes. The predicted locations of the breaker zone are in rough accord with those observed during the storms. Data for comparison with model results consist of wave and current observations across the surf zone, especially those acquired by using a towed, instrumented sled. The comparisons show that the model often predicts peak currents near the breaker zone quite well, but underestimates the decay of wave height and the strength of longshore currents across the surf zone. Wave breaking on the bar-trough beach structure prevalent in this study apparently is not well represented by the model. An improved breaking criterion, treatment of breaking waves as traveling bores, and inclusion of horizontal mixing of momentum might add to better simulation of surf-zone currents.

1. INTRODUCTION

Numerous efforts to observe nearshore circulation have been undertaken and reported, and recently, numerical models to simulate nearshore circulation have been developed and described. Seldom, however, have attempts been made to evaluate model simulations against observational data. Two major field studies at a beach on Lake Michigan were planned to provide data for the assessment of the simulative capabilities of a two-dimensional numerical model for nearshore circulation induced by wind and waves. The first field study was scheduled to take place during a fall storm, while the second study was scheduled for a spring storm. The second study was planned to provide an independent data set and to allow for changes in observational techniques suggested by analysis of the data from the first study and application of a model to those conditions.

The numerical model considered in this study was developed by Birkemeier and Dalrymple (1975). It is based on a finite-difference solution of the vertically-averaged equations of motion which are averaged in time over a wave period producing radiation stress terms. Given bottom topography, deep-water wave characteristics, and wind, the model simulates in two dimensions (on a relatively fine horizontal grid), the

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nearshore circulation field, the wave field, and mean water surface elevations. Wave heights and directions in the computational grid are determined by the refraction procedure of Noda et al. (1974), that includes wave-current interaction. The merits and failings of the model are discussed in terms of extensive comparisons with the wave and current data acquired in this study.

2. MODEL DESCRIPTION

The numerical model used in this study was described in detail by Birkemeier and Dalrymple (1975). The salient features of the model and the modifications made to it for the present application are noted here.

An explicit finite-difference scheme was used to solve the vertically-integrated equations of motion including radiation stresses. The wave refraction part of the model includes wave-current interaction and was described by Noda et al. (1974). No-flow conditions were imposed at the beach and at the last offshore row of the computational domain. Periodic boundary conditions for all variables were imposed at two remaining boundaries, thus defining a periodic length of beach.

Quadratic bottom friction was represented as the product of water density, a friction coefficient, the magnitude of the velocity vector, and the velocity vector itself. This friction formulation was modified to include numerical integration over a wave period of the total velocity vector (orbital wave motion and mean current). This modification resulted in more realistic values of bottom friction for large incident wave angles and for mean currents that were the same order of magnitude as the orbital velocities (Liu and Dalrymple, 1978). The friction coefficient is the only free parameter in the model. Its value was 0.01 for most cases. A dissipation term was added in the equation for wave height as the time average of the product of bottom shear stress and orbital wave velocity. This dissipation term was made zero wherever breaking was predicted by the model. The breaking criterion was a modified Miche formula in which breaking wave height was proportional to the hyperbolic tangent of water depth divided by wavelength at breaking (Noda et al. 1974). The model also allowed for flooding of dry beach to occur as a result of set-up and changes in lake level.

In summary, the model formulation included wave refraction, wave-current interaction, anisotropic bottom friction, wave set-up, wind effects, and coastal flooding. An improved representation for bottom friction was used and wave height dissipation outside of breaking areas was added. Finally, the model was applied to a much more complex nearshore environment than in the developmental study of Birkemeier and Dalrymple (1975).

Model application requires site-specific input data. These include deep-water wave characteristics, viz., wave height, period, and direction, detailed bathmetry for the given study area, local still-water-level changes during the study period, and wind data. The simulated variables (nearshore circulation, wave field, and mean-water-level changes) require other data for model evaluation. These include primarily wave and current measurements in the surf zone. The methods for acquiring all of these data and specific examples of processed information are discussed in the next section.

3. FIELD PROGRAM

The study site covers 0.5 km of sand beach near Zion, Illinois, along the western shore of Lake Michigan. Inland of the beach are low marshlands and dunes that rise about 3 m above lake level. The lake bottom immediately offshore is composed mainly of sands and silty sands. Portions of the sandy beach contain coarse pebbles that are often exposed near the waterline. The shoreline is almost straight in the study area. Longshore sand bars lead to surf zone widths of 40-60 m, typically, and outer bars often result in another breaker zone about 150 m offshore.

The first major field study was conducted during a storm in November, 1977. This study was designed specifically to obtain the required model-input data and to gather data on waves and on currents in the surf zone for comparison with model results. Figure 1 shows a plan view of the nearshore study area, which extends about 0.3 km lakeward. Offshore wave information for the model was obtained from a Wave-Rider buoy moored in 20 m of water about 4 km offshore. Wave data at a transitional depth were obtained from a bottom-mounted pressure cell fixed in 4.4 m of water at the outer extent of the nearshore study area. The cell also was equipped with an integrated output to allow measurement of local still-water-level changes throughout the storm.

Detailed bathymetric surveys were conducted before and after the storm to provide depth data for the model and to assess net changes in bottom topography. Bottom soundings were made on a 20 x 20 m grid using digital, position/depth recording equipment aboard an Argonne survey boat. Standard surveying techniques were used to collect beach topographic data on a 5 m (offshore) x 20 m (alongshore) grid in the region from the storm berm to about 60 m lakeward of the still water line.

Waves across the surf zone were measured with four helically-wound, resistance-wire wavestaffs. The staffs were placed on a line perpendicular to shore in 0.5, 0.75, 1.5, and 2.5 m of water with 1.2 m of their 2-m active element above the still water level. The outermost staff was about 70 m offshore. Longshore-current profiles were measured by using a towed sea sled similar to the one developed by Teleki et al. (1975). As shown in Fig. 1, the sled traversed the surf zone on a cable-winching system. The sled was equipped with two Bendix B-10, ducted-impeller current meters, placed at 0.5 and 1.0 m above the bottom of the sled and oriented approximately shore-parallel. The signals from the current meters were electronically averaged over several wave periods. A 4-m wavestaff also was mounted on the sled to provide additional data on waves across the surf zone. In addition, a 10-m meteorological tower was erected on the beach to measure wind speed and direction, and air temperature; steel reinforcing bars (rebars) were jetted

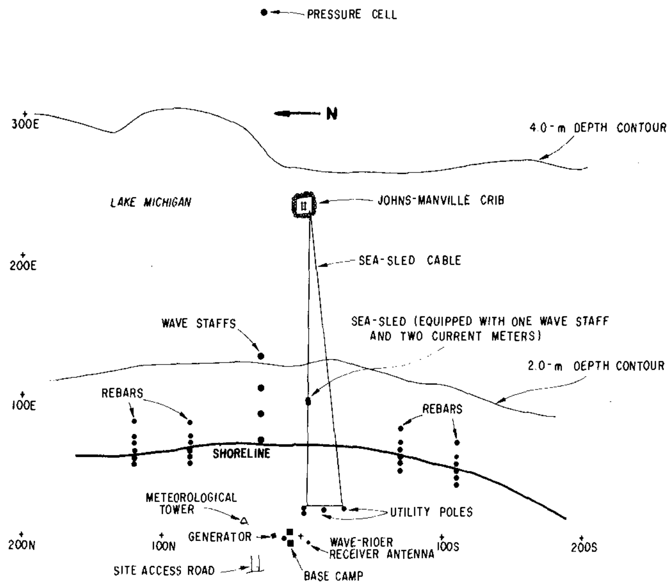

Fig. 1. Plan View of Experiment Site and Horizontal Coordinate System.

into the beach face along four separate transects to allow depth profiling during the storm; dye tracking in the surf zone was used to provide additional information on currents; and aerial photography was conducted during the daylight hours of the storm to provide estimates of wave direction.

Sets of observational data were gathered every three hours over the 27-hr storm period. Each set of data contained: 5-min records taken at each of six locations across the surf zone with the sled-mounted current meters and wavestaff, 5-min records taken with the fixed wavestaffs and the pressure cell when the sled was at the beginning and end of its traverse; and ancillary data taken using the other equipment described above. All wave and current data were recorded on strip charts and subsequently digitized to allow computer analysis. Hourly-averaged wind speeds ranged from 9-15 m/s during the storm. Offshore significant wave heights and periods varied from about 0.5-2.5 m and 3.8-6.5 s, respectively. Significant breaker heights varied from 0.5-1.5 m, incident breaker angles were 20-30° off normal (ESE), and both spilling and plunging breakers were present. Longshore currents near the breaker line varied from about 0.6-1.5 m/s. The spatial distributions of longshore current across the surf zone was highly variable. Significant bar movement occurred as a result of the storm, and depth changes as great as 0.8 m were found in the extreme nearshore area.

The second major field study was conducted in April, 1978. It provided an independent data set and allowed for improved observational techniques. The experimental set-up and procedures were similar to those in the first study with the following notable exceptions. The fixed wave staffs were placed outside the breaker zone in a directional array, although only minimal information was acquired due to damage incurred early in the storm. Additional rebar transects were installed. A multi-channel digital data logger was used to record all of the instrument data on magnetic tape at 0.1-s intervals, thus eliminating the need for strip chart recorders. Most data records were still of 5 min duration, but some 17-min wave records were acquired at 3-hour intervals during the storm. For most of the experiment the sled-mounted current meters were oriented perpendicular to each other, thus allowing measurement of the current vector during the sled's transits of the surf zone. Finally, the sled was equipped with a dye-dispensing system to allow the introduction of patches of dye into the surf zone.

Figure 2 shows the pre-storm bathymetry inferred from shipboard soundings and from standard surveying techniques. The beach is characterized by a steep face, a persistent longshore trough, and a somewhat disorganized bar structure that repeats itself on the order of several hundreds of meters. Depth contours beyond 2.0 m are highly convoluted, although a pattern of outer bars exists about 150 m offshore. Depth contours greater than 4.0 m tend to be much more regular.

Observational data during the storm again were gathered at approximately 3-hr intervals over a 24-hr period. Hourly-averaged wind speeds ranged from 7-16 m/s. A summary of offshore (Wave-Rider buoy) and transitional-depth (pressure cell) wave data is given in Fig. 3. Signigicant wave heights and periods measured by the Wave-Rider buoy (4 km offshore) varied from about 1.25-2.25 m and 4.5-6.3 s, respectively. Significant wave heights as measured by the pressure cell at the outer extent of the nearshore study area (0.35 km offshore) varied from about 0.60-1.25 m before that instrument failed due to storm damage. Wave approach was very oblique (70° off normal incidence, NNE) with breaking angles as large as 45° off normal. Figure 4 summarizes current-meter data acquired by the towed sled during nine different transits of the surf zone. The following specific points should be noted: 1) peak currents near the breaker line ranged from 1.0-1.8 m/s; 2) on/offshore flow was small; 3) the differences between currents measured at 0.5 and 1.0 m above the bottom were small (cycles 1-3); and 4) a relatively strong flow was observed across the entire surf zone in most cases, probably as a result of the bar-trough structure of the beach (note inset showing depth profiles along sled path). Most of the data to be discussed below are taken from this second study, although they are generally representative of the first study, too.

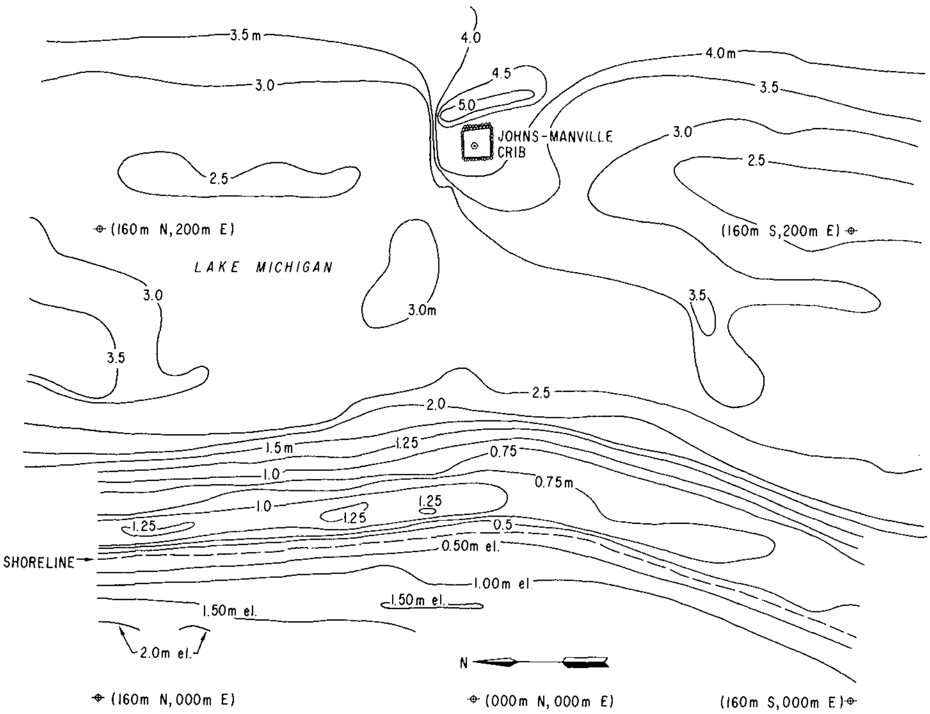

Fig. 2. Pre-storm Bathymetry of Nearshore Study Area, April, 1978.

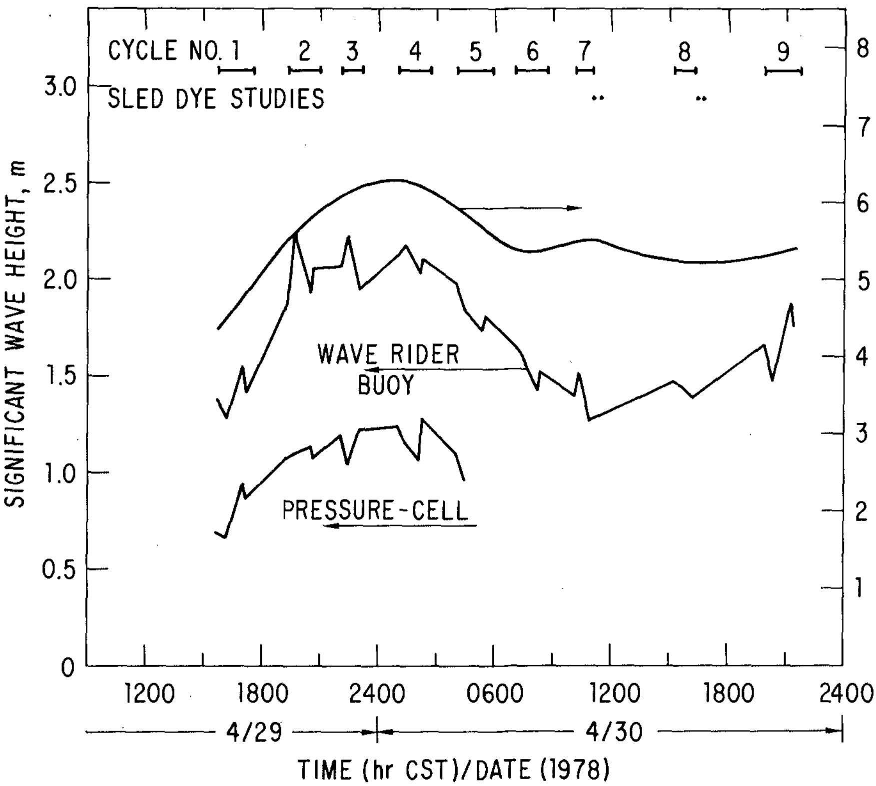

Fig. 3. Offshore (Wave-Rider buoy) and Transitional-Depth (pressure cell) Wave Data, Second Field Study. Data Acquisition Periods (Cycles No. 1-9) are Indicated.

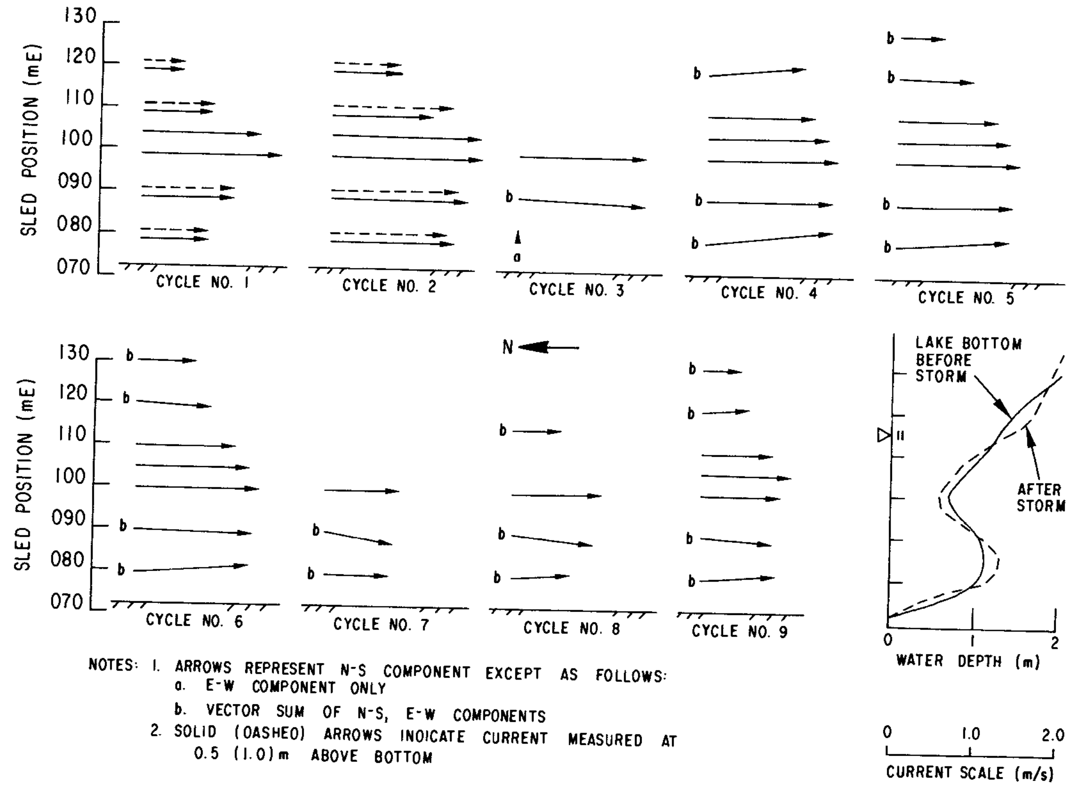

Fig. 4. Current-Meter Data Across Surf Zone Acquired with Towed Sled, and Water Depth Along the Sled Path, April 1978 Study.

4. MODEL APPLICATION

a. Adaptation to Study Site

Model-input data gathered during the fall and spring field efforts were used to make a site-specific application of the numerical circulation model. The alongshore grid spacing was chosen to be 10 m, while a 5-m spacing was used in the offshore direction to provide the necessary resolution of typical depth profiles. Still-water depths from the bathymetric survey were specified for this grid and were adjusted for calculations made during the storm with local lake-level data from the pressure cell. A conservative time step of 0.5 s was selected based on the linear stability criterion, and a quasi-steady model solution was found for given wind and wave conditions by integrating for 1000 time steps. Root-mean-square (rms) wave heights inferred from the Wave-Rider data were used to drive the model. The incident wave field was increased linearly from zero to full strength over the first 100 iterations to minimize water-level oscillations at the natural frequency of the basin defined by the model topography. The total energy and water-level fluctuations were monitored for as many as 2000 iterations in some numerical experiments before 1000 steps was chosen as a good compromise between a quasi-steady solution and computational expediency. The offshore extent of the model was about 200 m, which was far enough to include the outer bars. The effect of model alongshore extent (and the imposed periodicity) on the model currents near the center of the grid is shown in Fig. 5. The sensitivity of the model currents to alongshore extents greater than about 200 m was found to be small compared to changes produced by uncertainties in other model parameters. An extent of 260 m was chosen for most numerical experiments.

Deep-water wave angle was found to be an important parameter that was difficult to estimate accurately based on the observed data. The model, as formulated, used Snell's law and the given deep-water wave characteristics to estimate incident wave height and direction at the offshore extent of the model grid. The following procedure was adopted to find consistent estimates of offshore wave angle: depth contours were assumed parallel from deep water to transitional depth (5 m); standard refraction and shoaling calculations were used to find the deep-water wave angle that would transform the measured deep-water wave height into the wave height measured at transitional depth. The deep-water wave angles calculated by this procedure were found to bear no simple relation to the contemporary wind directions. However, the resulting wave angles at transitional depth did agree with those inferred from the limited aerial photography conducted during the studies, within the errors inherent in these measurements.

Various numerical experiments were performed to test the sensitivity of the model results to small changes in wave height, wave angle, still water level, and friction coefficient. Discussion of these tests and selected comparisons with observed waves and currents are given in the next subsection.

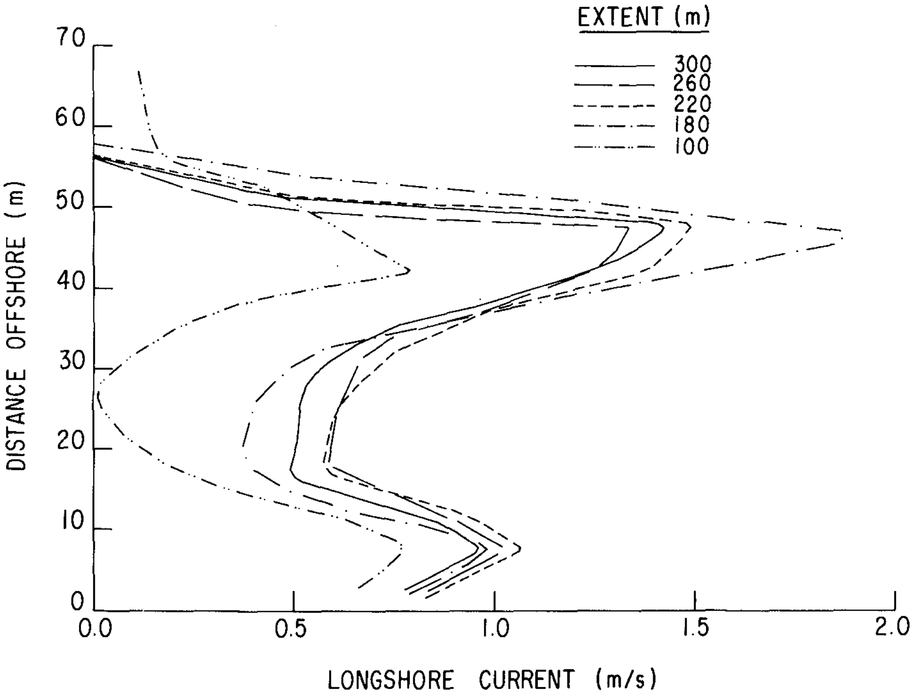

Fig. 5. Effect of Variation of the Model Alongshore Extent on Model Current Profiles (along computation row corresponding to 000 N).

b. Comparisons with Observed Data

Two-dimensional simulations of waves and currents were generated for many of the different wind and deep-water wave conditions observed during the field program. As stated previously, rms wave heights were used to drive the model. Figure 6 is a representative plot of the velocity field predicted by the model, subject to a 1.44-m wave field (5.3 s period) approaching from 73° off normal incidence. A wind of 15 m/s at 80° off normal also was acting, and local still-water level had risen about 0.2 m above the level assumed for the depths given in Fig. 2. The offshore distance in Fig. 6 represents about one-third of the total model extent. The strongest currents are predicted just inside the breaker zone (40 m offshore) and in the trough region (10 m offshore). The overall pattern is highly two-dimensional and the effects of the inner bars are quite apparent (Fig. 2).

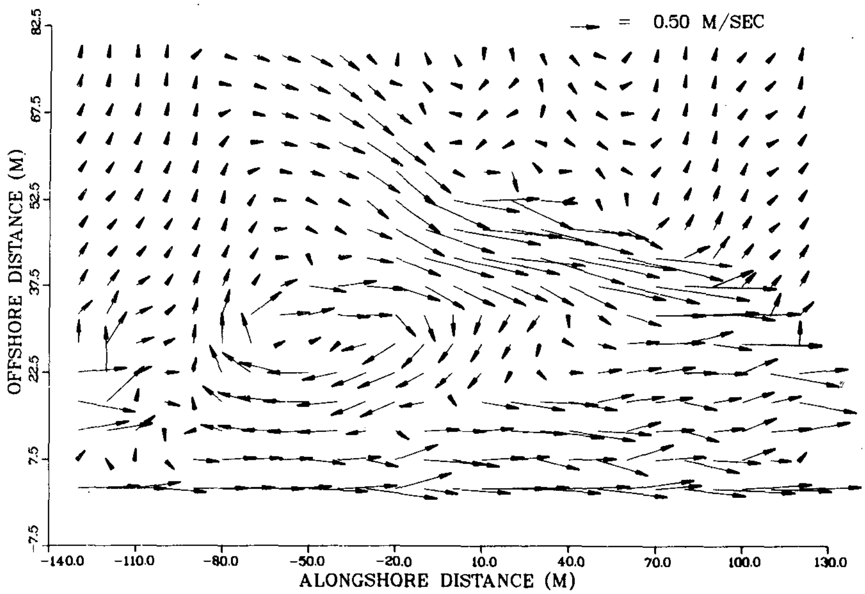

Fig. 6. Model Velocity Field for Second Storm Bathemetry, 1.44 m and 5.3 s Deep-Water Waves from 73° Off Normal and 15 m/s Winds from 80° Off Normal (NNE). (Offshore coordinate stretched for clarity.)

Comparisons of model and observed variables are presented in Figs. 7-11, for observational data acquired during six different transits of the surf zone with the towed sled. Profiles of the alongshore component of model currents at two adjacent rows in the grid are shown in Fig. 7a along with current-meter data acquired from the sled (along 000 N). The model results do not show high variability between adjacent rows. Observed current speeds outside the breaker zone (60-70 m) are much stronger than those in the model. However, other contemporary current studies in the lake, outside the surf zone, showed average lake currents of 0.2-0.3 m/s. It is unlikely that the model boundaries represent a periodic segment of the lake itself, and thus, it is expected that inclusion of lake currents in the model would improve comparisons outside the breakers without significantly changing computed results inside the breakers. Figure 7b shows model and observed wave heights, indicating that the height near breaking is in close agreement for this case, although the heights inside of the breaker zone are somewhat over estimated.

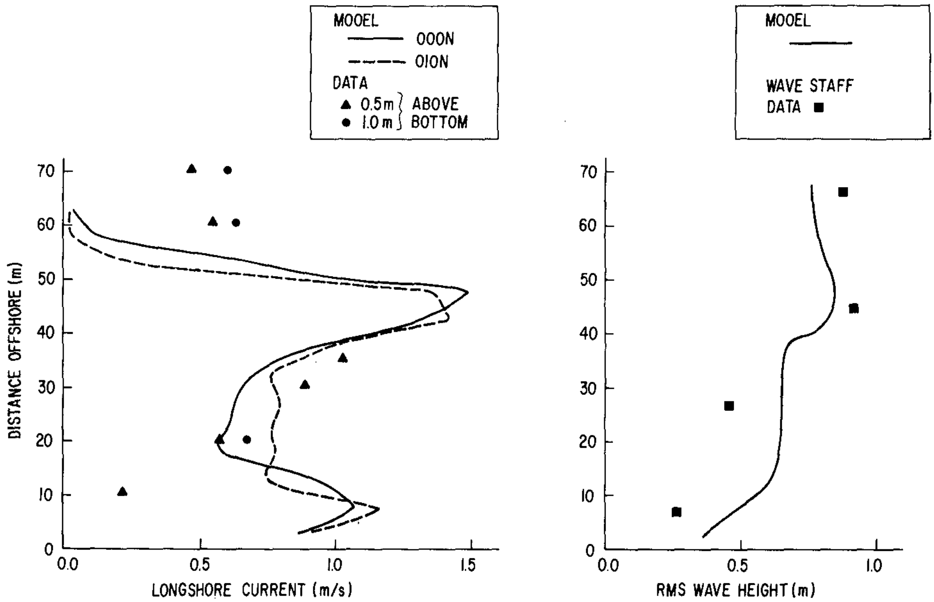

Fig. 7. Comparison of Model and Observed Current Profiles (a) and Wave Heights (b). Model Results for Adjacent Computational Rows are Shown in (a).

Changes in wave climate during the time required for the sled to traverse the surf zone (30-45 min) lead to significant changes in the location of the breaker zone predicted by the model. Figure 8a shows the measured currents for a particular sled transit and the model longshore current profile resulting from the observed wave conditions at the beginning (Case A) and end (Case B) of that transit. The location of the breaker zone in the model shifts about 10 m between these two cases, although model currents inside of the breaker zone are essentially unchanged.

Smaller uncertainties in model-input data result in better agreement with observations for some occasions during the study. Figure 8b gives comparative results for an occasion when wave angle is known with more certainty due to the availability of aerial photos, model topography (based on post-storm surveys) is more likely representative because these current data were acquired near the end of the storm, and the wave climate is less severe with little or no breaking over the trough region. The combination of these conditions appears to result in better agreement between model and observations inshore of the breaker zone than in other comparative cases.

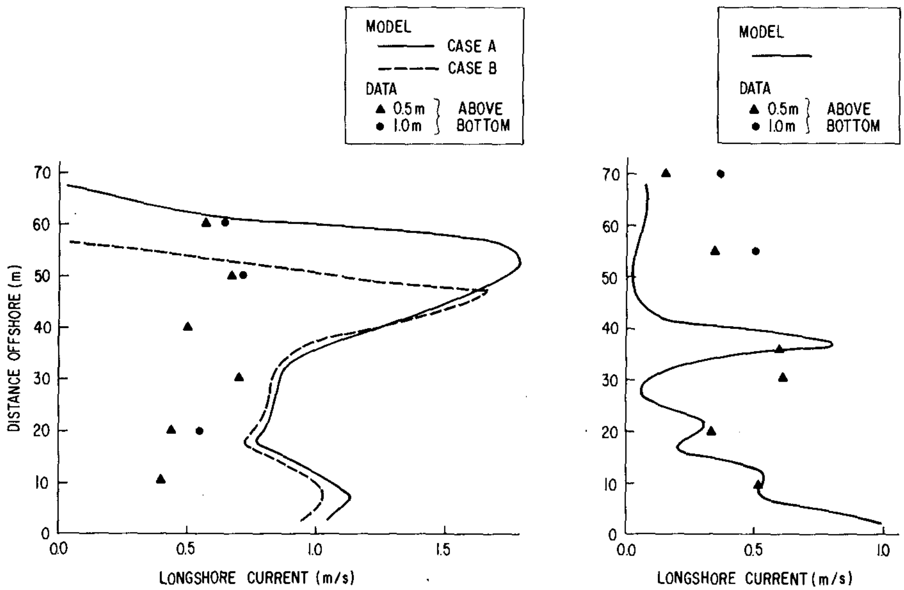

Fig. 8. Comparison of Model and Observed Current Profiles for Different Wave Climates at the Beginning (Case A) and End (Case B) of a Sled Transit (a) and for a Less Severe Wave Climate (b).

The model seems to underestimate the *difference* between wave heights near breaking and heights inshore of the breaker zone as evidenced in Fig. 9b. These wave height discrepancies contribute in part to a model current profile that is more sharply peaked than the observed data profile (Fig. 9a). Several numerical experiments were tried in this case and in others to alleviate these discrepancies. Small changes in incident wave angle (10-15°) led to 30% or greater changes in calculated wave heights near shore (for large incident angles), but current profile shapes were essentially unchanged. Model lake current profiles also were largely unaffected by moderate changes in lake level (0.3 m) and changes in the model friction coefficient. Model friction might be adjusted to effect agreement between observed and model peak currents. However, discrepancies between observed and model peak currents could also be accounted for by the discrepancies between observed and model wave heights near breaking. Therefore, fine adjustments in the value of the friction coefficient appear unjustified.

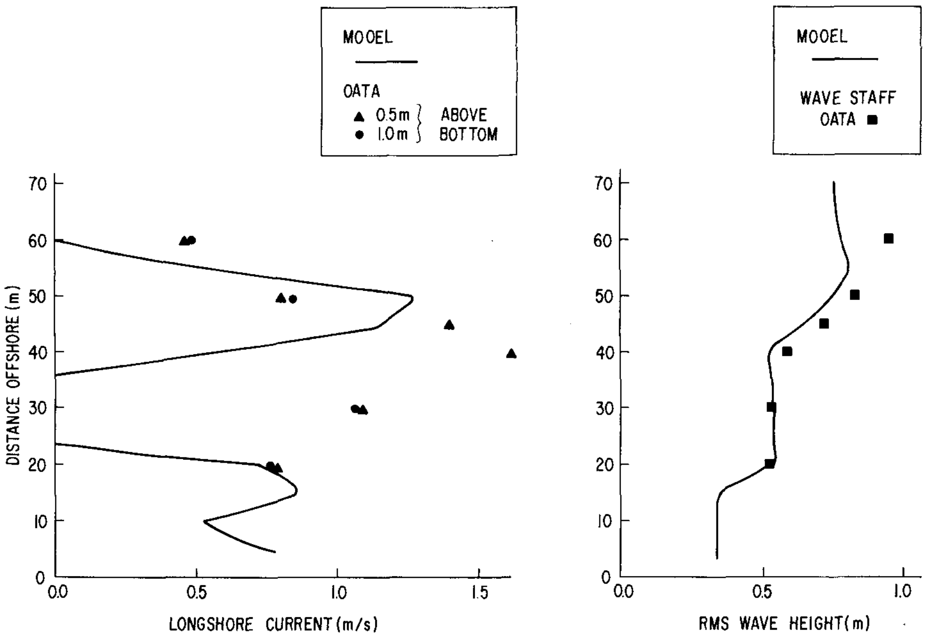

Fig. 9. Comparison of Model and Observed Current Profiles (a) and Wave Heights (b). Model Underestimates Differences between Wave Heights Near Breaking and Heights Inshore of Breaker Zone (b) Resulting in Sharply Peaked Model Current Profiles (a).

A further example of the underestimate of wave height decay in the surf zone model is shown in Fig. 10b. For this case, the observations indicate about a 50% reduction in wave height across the surf zone, whereas model heights decay only about 25%. Again model current profiles (Fig. 10a) deviate significantly from observations, although peak currents agree quite well. The proportionality constant in the model breaking criterion was varied over wide limits in an attempt to better imitate the main features of the observations. In effect, the ratio of breaking wave height to mean-water depth at breaking was varied from 0.65 to 0.95. Results were quite different, of course, but were no more or less in agreement with observations than the results shown here.

In Fig. 11 a final comparison of waves and currents reaffirms the previous statements. Observed currents are relatively strong across the surf zone in contrast to the model results (Fig. 11a). This is due in part to the fact that the model does not predict the observed breaking over the trough region (20-30 m offshore) along the sled path. Observed wave heights suggest that considerably more energy is extracted from the wave field in this region than predicted by the model.

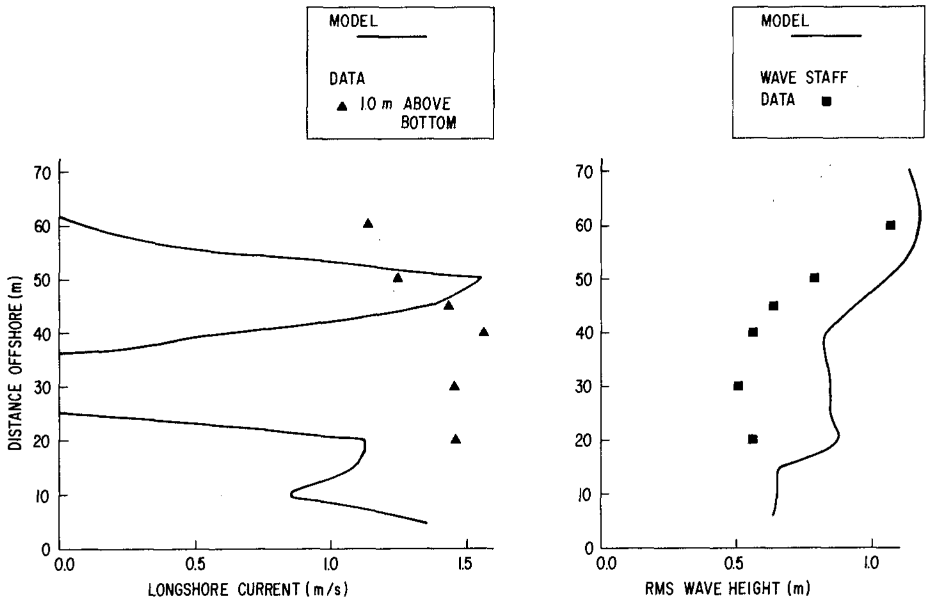

Fig. 10. Sharply Peaked Model Current Profiles (a) Result From Underestimation of Wave Height Decay (b) Across the Surf Zone.

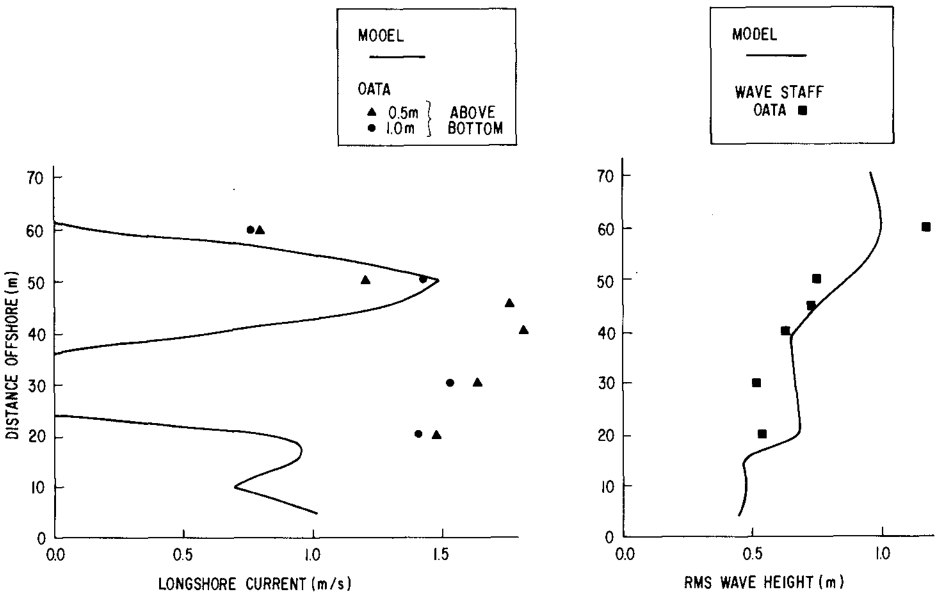

Fig. 11. Additional Comparisons of Model and Observed Current Profiles (a) and Wave Heights (b) Suggest That More Energy is Extracted from the Wave Field Inshore of the Breaker Zone Than the Model Predicts.

5. SUMMARY

New data on waves and currents in the surf zone during two storms were collected. Extensive comparisons were made between these data and results from a state-of-the-art, two-dimensional, numerical model for near-shore circulation. Model current fields showed a highly two-dimensional pattern for all cases that were studied. The tracking of dye packets and relatively large dye clouds in the surf zone also revealed a two-dimensional structure with some regions of stagnant flow and others with strong on/offshore flow. Significant variations in model results were caused by uncertainties in model-input data, such as wave angle, topography, and still-water level. These inherent variations preclude the quantification of the extent to which the model results match the observations. Comparisons do show, however, that the model often predicts peak currents quite well, but underestimates the decay of wave height and also the strength of longshore currents inside of the breaker zone. That is, predicted wave heights lakeward of the breaker zone are often in fair agreement with observed heights. The predicted location of the breaker zone is in rough accord with the location inferred from aerial photos and other visual observations. Thus peak current predictions are quite good. Within the surf zone, however, more energy is extracted from the actual wave field than is predicted in the model. As a result, the distribution of longshore momentum across the model surf zone does not agree well with observations. Apparently, model simulation of waves does not adequately represent the behavior of waves in a region of barred topography. An improved breaking criterion that includes reflection off the bar, or the treatment of a breaking wave as a traveling bore, as suggested by Battjes and Janssen (1978), might improve model results. The present model formulation does not include a specific representation for horizontal mixing of momentum, and provision for such mixing might lead to better simulation of the observed currents within the surf zone.

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