(3) Data requirements for RCPWAVE.

(a) Primary input to the RCPWAVE model includes the following: parameters describing the domain to be modeled, such as the number of computational grid cells in each direction and the cell dimensions; definition of the water depth at each cell; and definition of the incident wave height, period, and direction along the offshore domain boundary for each wave condition to be simulated. Model output includes wave height, period, and direction at each cell of the computational domain, and an indication of whether or not the wave is calculated to be a broken wave.

(b) Typically the first step in the model application process is to discretize the model domain into a rectangular mesh. The grid mesh that is created can be overlaid on a bathymetric chart, assuming the grid and chart are plotted to the same horizontal scale, and depths at each cell can be digitized for use as model input. A constant correction to the depths, representing a datum change or a specific water level change, can be included in the input data set. An arbitrary number of wave conditions, each defined by a unique combination of height, period and direction, can be simulated. Wave conditions to be simulated are usually defined after a statistical analysis of the wave climate in the region being studied. Bathymetry specification and incident wave conditions comprise the bulk of the effort to create the input data set.

c. REFDIF.

(1) Introduction. The model REF/DIF 1, which has been developed for practical application, is based on the mild-slope, wave-current model equation developed by Kirby (1984), which may be written as

$$\frac{D^2\varphi}{Dt^2} + \nabla \cdot U \frac{D\varphi}{Dt} - \nabla \cdot (CC_g \nabla\varphi) + (\sigma^2 - k^2 CC_g)\,\varphi = 0 \tag{II-3-27}$$

where φ is the velocity potential at the free surface, and where

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + U \cdot \nabla \tag{II-3-28}$$

$$\nabla = \left(\frac{\partial}{\partial x} \;,\; \frac{\partial}{\partial y} \right) \tag{II-3-29}$$

$$U = (U(x,y) \;,\; V(x,y)) = \text{ambient current vector} \tag{II-3-30}$$

$$\sigma = \omega - k \cdot U \tag{II-3-31}$$

$$C = \frac{\sigma}{k} \tag{II-3-32}$$

$$C_g = \frac{\partial\sigma}{\partial k} \tag{II-3-33}$$

$$\sigma^2 = gk \tanh(kh) \tag{II-3-34}$$

Several additional features are included in the model in order to increase its range of application and accuracy.

(2) Wave breaking. The model tests whether the local wave height has exceeded a fixed threshold, which is set at $h/d = 0.78$. For local wave heights exceeding this value, a breaking wave energy flux decay model is started in order to remove energy from the wave train. The model used is described in Dally, Dean, and Dalrymple (1985). The reader is referred to Kirby and Dalrymple (1986a) for further details.

(3) Wave damping mechanisms.

(a) In addition to the strong wave breaking mechanism described above, REF/DIF 1 also provides the user with three selectable bottom damping mechanisms. These are: laminar bottom boundary layer damping, sand-bed percolation damping, and turbulent bottom boundary layer damping.

(b) At present, no laboratory or field data sets clearly point to the need for including bottom damping effects in model simulations. Laboratory experiments usually include too short a propagation distance for damping effects to accumulate significantly. In the field, damping due to bottom effects may be balanced or overshadowed by wave growth resulting from wind-wave interaction, and so one should not be considered in the absence of the other. At present, it is recommended that these user-selectable damping mechanisms not be included in model simulations.

(4) Wave nonlinearity.

(a) Wave nonlinearity has a strong effect on the phase speed of waves and thus can significantly modify both refraction and diffraction effects. For example, waves shoaling on a plane beach refract more slowly than predicted by linear theory, since the increase in wave height with decreasing water depth speeds up the waves, in opposition to the direct, linear-theory effect decreasing depth, which slows them. Diffraction effects are typically enhanced. Phase speed is greater in a high-amplitude, illuminated area than in a low-amplitude, shadowed area; this causes refractive bending of waves into the shadow area, causing an increase in wave height in the shadow zone relative to the predictions of linear theory.

(b) REF/DIF 1, designed to predict the propagation of a monochromatic wave in intermediate water depth, includes the effects of nonlinearity as predicted by third-order Stokes wave theory (Kirby and Dalrymple 1983). Since the model is often used to predict wave-height distributions into the surf zone and up to dry land boundaries, the model must also be corrected to avoid the singularities arising from the invalidity of Stokes theory in shallow water. In order to provide a smooth correction to the model results in the shallow-water limit, Kirby and Dalrymple (1986b) provided an algorithm that gives a smooth patch between Stokes theory and an empirical modification to linear theory developed by Hedges (1976). The approximate theory does not cause any degradation in solution accuracy in comparison to the Stokes theory alone for intermediate depth experiments; see Kirby and Dalrymple (1986b) for relevant documentation.

(5) Numerical noise filter. Higher-order forms of the parabolic approximation have the undesirable effect of allowing high-wave number noise (i.e., noise with rapid lateral variation) to propagate rapidly across the computational grid. This effect has been described in detail by Kirby (1986a), and is usually found in association with the start of surf zones around complicated planforms such as island shores. The resulting noise component may be damped by the application of various types of smoothing filters. The three-point moving average filter described by Kirby (1986a) has been found to be heavy-handed in practical applications, and has been replaced in present versions of the REF/DIF 1 model by a damping filter included in the governing differential equation, whose effect is centered around the lateral wave number, which spread rapidly in the undamped model. A full description of the damping method and a range of tests may be found in Kirby (1993).

(6) Examples of REF/DIF1 results laboratory verification. REF/DIF 1 (and the parabolic approximation model in general) are capable of providing a detailed picture of the water surface in the region of study if the

grid resolution is sufficiently high. This picture includes the geometry of crests and troughs as well as the location of regions of high or low wave height resulting from short-crestedness of the wave field. Since irregular waves in the field usually lead to a fairly smooth spatial variation in wave height estimates (after statistical averaging), a more stringent test of model accuracy is provided by comparison to laboratory tests with monochromatic waves. Parabolic models have been tested against data of this type in a number of studies, including Berkhoff, Booij, and Radder (1982); Tsay and Liu (1982); Kirby and Dalrymple (1984), Panchang et al. (1990), and Demirbilek (1994). The results showed that the higher-order parabolic approximation, together with nonlinear correction to the wave phase speed, can correctly predict the distribution of wave heights and nodal points in the evolving wave field. Figure II-3-10 shows the bathymetry input to REF/DIF1 for a simulation of wave propagations at Revere Beach, MA. Figure II-3-11 shows the wave heights calculated by the models.

(7) Data requirements for REFDIF.

(a) REF/DIF 1 computes a grid-based wave evolution over an arbitrary bathymetry and current field. To run the model, the user must provide, at minimum, an array of depth values h on a grid with regular spacing in x and y. The model always assumes that x is the preferred direction, or the direction in which the computation marches. No provision is made at present for relating the model coordinate system to a global coordinate system. If the user wishes to include the effects of tidal currents in the model study, then arrays of velocity components U and V must also be provided for the same regular grid used to specify h values. This information establishes the geometry for the model run.

(b) The user must also specify the form of the wave train at the offshore boundary. This may be done by specifying a combination of one or more monochromatic waves at the offshore boundary, or the offshore wave field may be specified at the first grid row by means of input data. The user's manual provided in Kirby and Dalrymple (1992) should be consulted for more details about the input data.

(c) The model provides the user with a grid of computed wave heights and directions on the same geometric grid used for input. In addition, the complex amplitude values are provided and may be used to reconstruct plots of the computed wave field, if these are desired and if the grid resolution is fine enough to permit it. For larger-scaled model areas, this last step is often not feasible, as it requires 5 to 6 grid points per modeled wave length in the input bathymetry grid. A version of REF/DIF capable of simulating wave spectra has recently been released.

d. STWAVE.

(1) Introduction.

(a) STWAVE is a steady-state spectral model for predicting wave conditions in coastal areas. It solves the complete radiative transfer equation (Equation II-3-1) including both propagation effects (refraction, shoaling, diffraction, and wave-current interactions) and source-term effects (wave breaking, wind inputs, and nonlinear wave-wave interactions). STWAVE was developed under the premise that waves in nature should be treated as nonlinearly interacting stochastic wave components rather than as deterministic nonlinear waves. This is particularly relevant when dealing with wave transformations over distances of hundreds of thousands of wavelengths (typical of many coastal wave transformation studies). At much shorter distances a deterministic, long-crested approximation can provide an appropriate framework for understanding and interpreting wave behavior. At longer distances, theoretical and empirical evidence

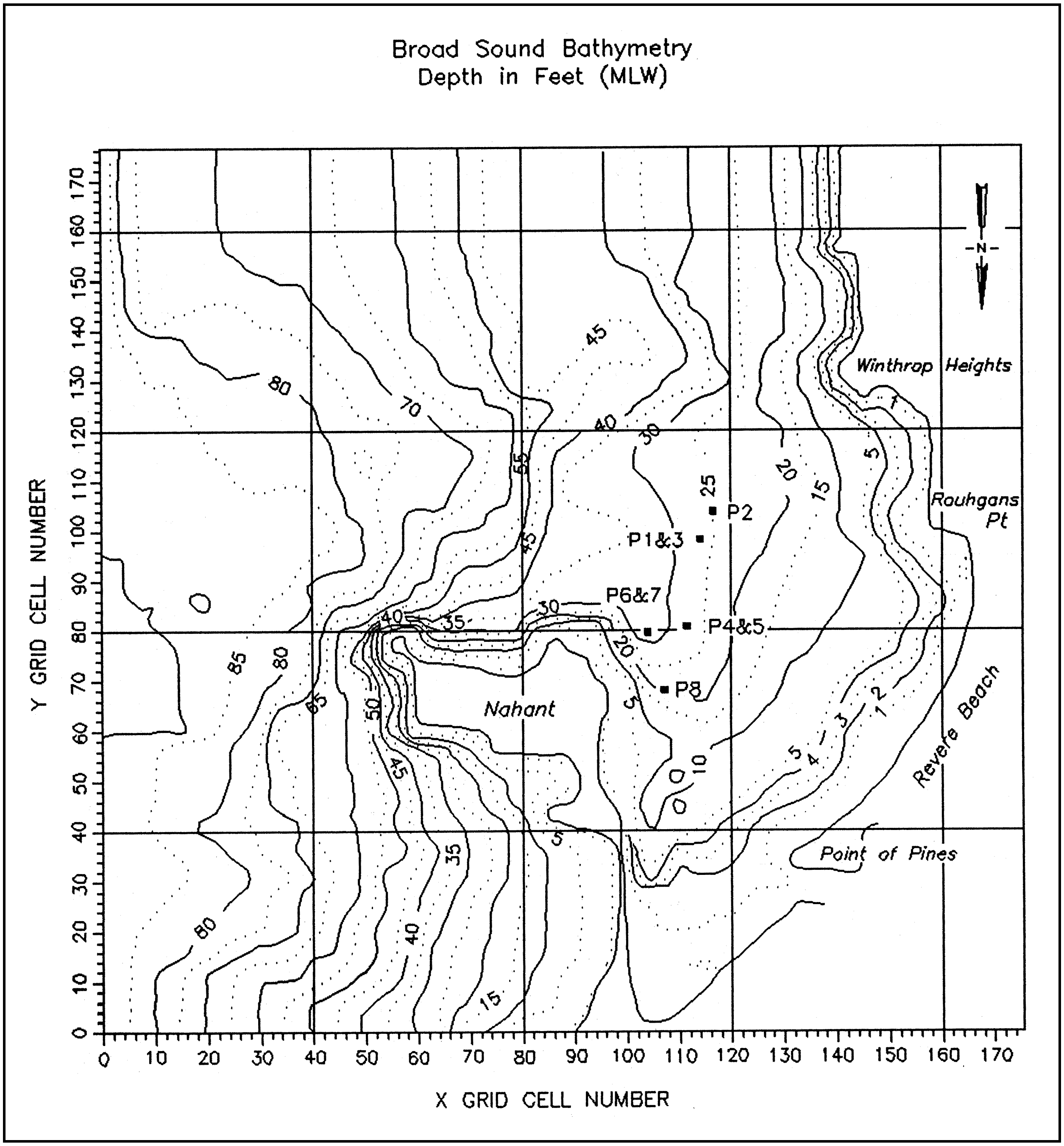

Figure II-3-10. Bathymetry input to REF/DIF1 for a simulation of wave propagations at Revere Beach, MA

strongly supports a stochastic approximation for wave phenomena (West 1981). Over small distances, near discontinuities in a wave field (such as breakwaters), STWAVE can incorporate wave phase information into its solution; otherwise, it uses a random-phase approximation for its diffraction and combined refraction-diffraction (CRD) calculations. Theoretical details of STWAVE can be found in Resio (1993).

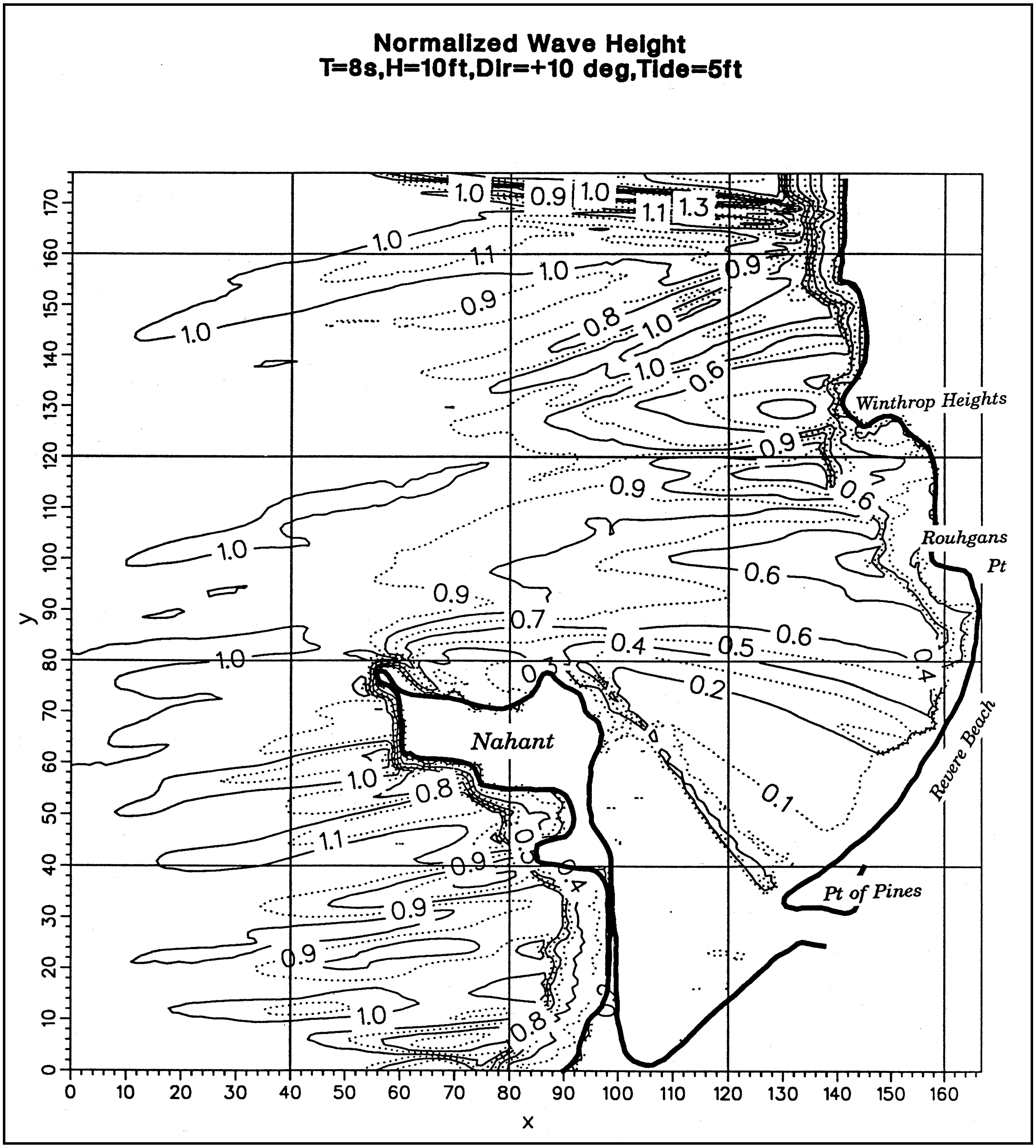

Figure II-3-11. Wave heights calculated by REF/DIF 1

(b) The following two assumptions have been inherent in essentially all previous steady-state models for predicting nearshore wave transformations:

- Predictions based on unidirectional, monochromatic wave theories can provide solutions that are equivalent to the behavior of naturally occurring directional wave spectra.

- Nearshore transformations are dominated by conservative processes (refraction, shoaling, and diffraction) and hence nonconservative effects (energy sinks and sources) can be neglected as a first approximation.

(c) A corollary to the first assumption above is that increased accuracy in deterministic propagation estimates translates into commensurate increases in accuracy in real-world applications. Unfortunately, laboratory studies by Thompson and Vincent (1984) and Vincent and Briggs (1989) have clearly demonstrated that the first assumption is not valid unless the wave field is narrow-banded in both frequency and direction. Thus, for most coastal wave predictions to be accurate, they must solve all wave components and not just a hypothetical "dominant" component. This presents significant problems for wave models that solve only one wave component at a time, since wave energy traveling in one direction can be "scattered" into another direction via diffraction. Hence, diffraction causes wave components in a spectrum to interact and attempts to solve the CRD equation on a component-by-component basis have difficulty properly accounting for this effect. STWAVE overcomes this problem by using a piecewise solution method that simulates the propagation of all wave components simultaneously.

(d) Returning to the second assumption above, field and laboratory data presented in Bouws, Gunther, and Vincent (1985) and Resio (1988) show that nonconservative effects, rather than conservative propagation effects, dominate wave transformations in many coastal areas, particularly during storm conditions. Moreover, the form of many of the source terms affecting shallow-water wave transformations is such that they depend on energy content within the entire wave spectrum. Methods that solve for each component of the spectrum independently cannot provide suitable estimates of coupled source terms. STWAVE is formulated in a manner that permits straightforward solution of these processes.

(2) Examples of STWAVE results. The following comparisons are intended to demonstrate the importance of various terms in coastal wave transformations and the ability of STWAVE to handle these terms.

(a) Spectral versus monochromatic calculations. Figure II-3-12 compares predicted wave heights behind a shoal using STWAVE, for a unidirectional, monochromatic wave and for a JONSWAP spectrum with a spectral peak frequency of 0.1 Hz and a $\cos^4$ angular distribution of energy. Monochromatic calculations from the laboratory study of Vincent and Briggs (1989), while mathematically accurate, do not reasonably represent propagation effects in a wave spectrum with natural frequency and direction energy spreads.

(b) Effects of coupled source terms. Figure II-3-13 compares spectral transformation over 1:30, 1:100, and 1:500 slopes for the same JONSWAP spectrum as above with a mean approach angle to the coast of 30 deg, for the case of no source terms and for the case of wave breaking and nonlinear wave-wave interaction source terms included. This comparison suggests that CRD effects account for only about 5 percent of the total energy variations in coastal waves passing over moderate to shallow slopes. This finding is consistent with those of Resio (1988) and helps to explain why nearshore wave spectra tend strongly toward self-similar forms during local storms (Bouws, Gunther, and Vincent 1985; Resio 1987; Miller and Vincent 1990).

(c) Wind effects. Figure II-3-14 shows the differences in wave transformations with and without a 20-m/sec onshore wind over an offshore profile typical of the U.S. east coast. In this example, waves at the seaward boundary are set to the same JONSWAP spectrum as Examples 1 and 2. These results show a marked difference between the two cases. This difference is consistent with theoretically expected wind input and indicates that, particularly during storm conditions, neglecting wind input can lead to significant misestimations of wave conditions.

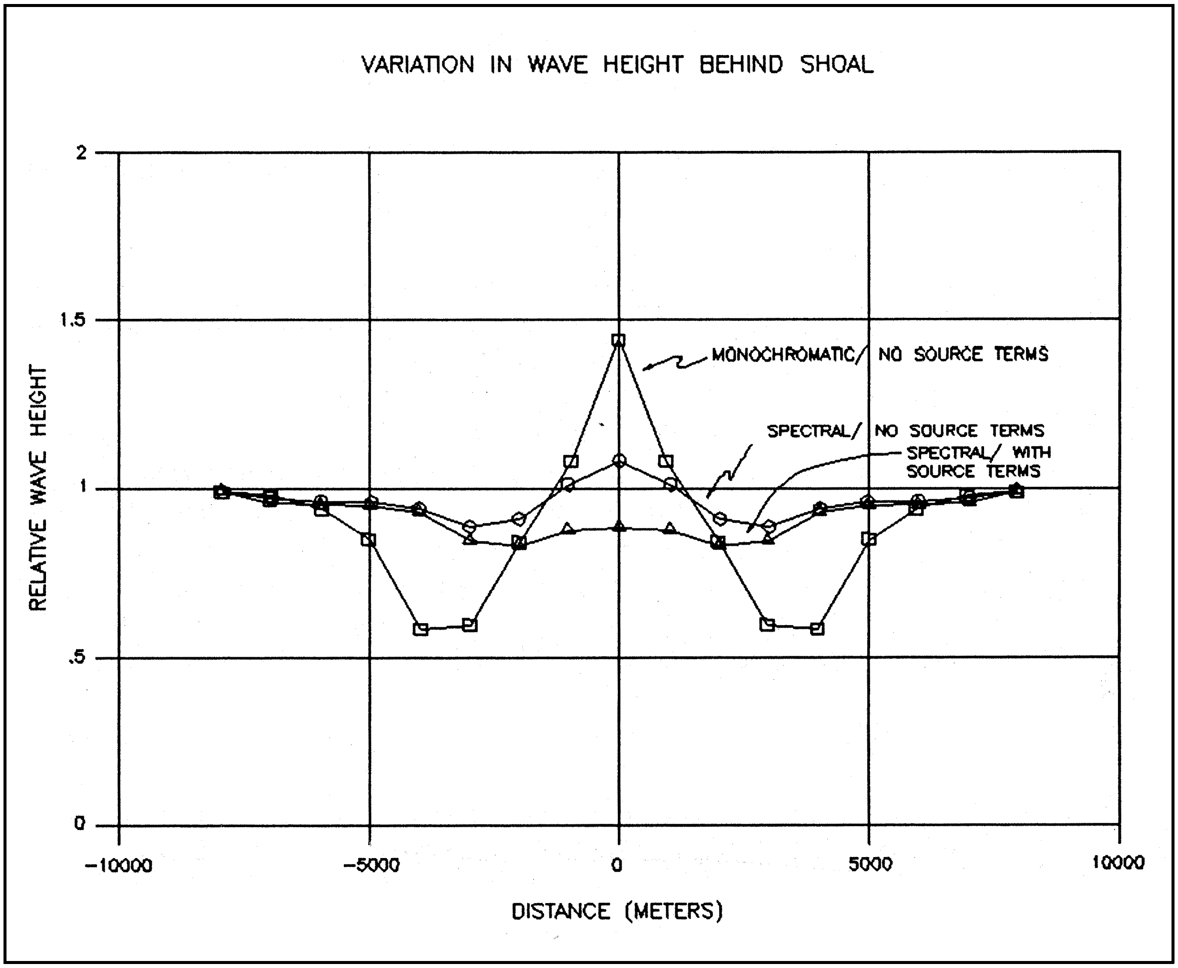

Figure II-3-12. Spectral model results compared to laboratory measurements for broad directional spectrum

(3) Data requirements for STWAVE. In STWAVE, a square grid mesh covers the computational domain. Water depth must be supplied at each node. If currents are included, a current must be supplied at each point. Wave characteristics are computed at each of these grid points. The model requires an input directional spectrum for the outer boundary and information about wind speed and direction and bottom friction coefficients.

e. Limitations.

(1) Each model has natural limitations reflecting its theoretical basis. The references provided discuss these in some detail. If strictly interpreted, each model has a narrow range over which it is valid. Almost all of these models are regularly used to simulate conditions outside a strict interpretation of limits, with the results often effectively accurate. Considerable judgement and experience are required to determine if the simulation is valid.

(2) The following limitations indicate where the model may or may not be useful. RCPWAVE may be inaccurate for waves crossing behind shoals, or in the vicinity of structures. Wave approach directions should not be too oblique relative to the offshore boundary. REF/DIF1 can allow for some structures and islands but again should not use waves with highly oblique wave angles (In both RCPWAVE and REF/DIF1,

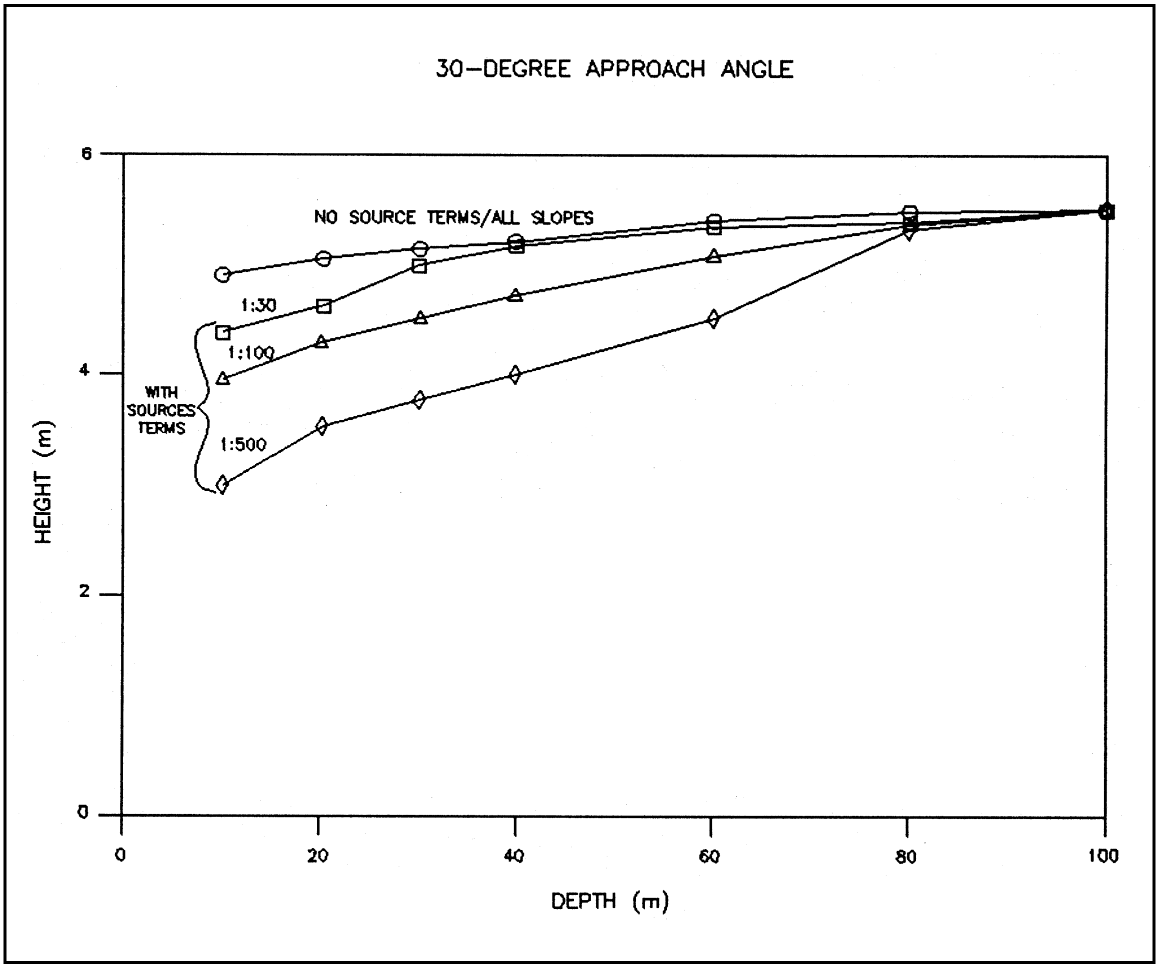

Figure II-3-13. STWAVE results for a 1:30 sloping beach

the oblique angle dilemma often can be resolved by using a different grid). STWAVE may underrepresent wave focussing for very narrow swell.

II-3-6. Guidance for Performing Wave Transformation Studies

a. Introduction.

(1) The preceding parts of this chapter provide the engineer with an understanding and some techniques for taking a wave condition offshore of a project or nearby and transforming it to the site of interest. In practice, an engineer will typically consider a suite of wave conditions perhaps representing different storms, different seasonal characteristics, and different water levels (particularly in shallow water or at the beach if there is a high tide or storm surge to be considered). Selection of the conditions for project design studies is a very important component of any coastal engineering study and Part II-2 and Part II-3 both treat this problem.

(2) Transformation analyses are needed because there is often a lack of site-specific data. In some instances, a cursory transformation analysis may be required to help decide whether an offshore or nearby site is adequate for determining offshore boundary conditions. Typically this may be approached by setting up one of the transformation procedures described and running a small set of wave conditions that might span

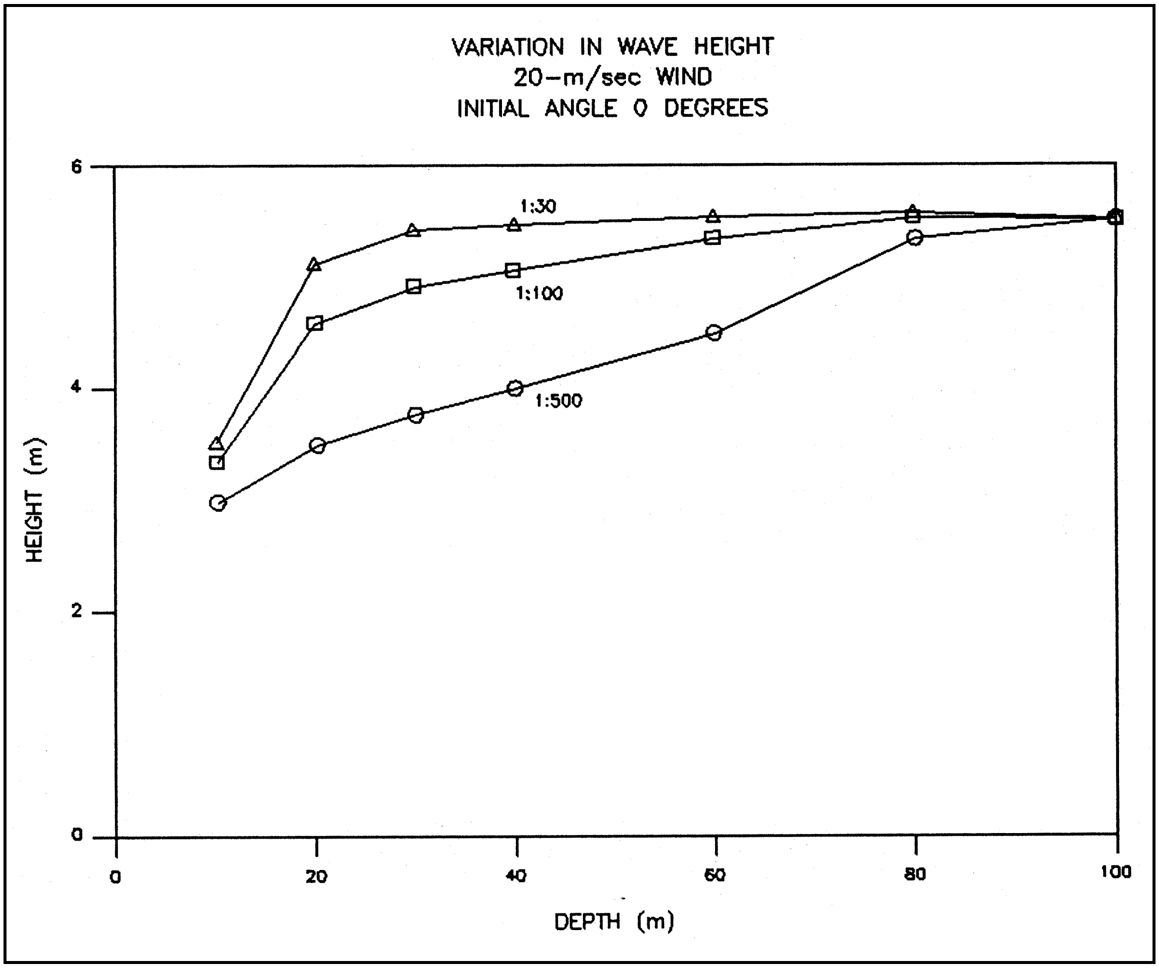

Figure II-3-14. STWAVE results for CHL's Field Research Facility at Duck, NC

the final set to be studied. As an example, waves of a certain period or direction offshore may not propagate to the site, and the engineer can thus ignore such wave conditions in a more detailed study.

(3) Some of the decisions and actions an engineer will need to make in performing a wave transformation analysis follow.

b. Problem formulation. At the initiation of the study, the engineer should clearly understand what wave information must be produced for the site, how it will be used, and the accuracy required. The engineer should gather all pertinent bathymetry data, water level data, and nearby wave data. Aerial photography of the site can be very useful by providing the engineer with indications of wave propagation patterns, areas of offshore breaking, etc., that a transformation procedure should properly simulate. Short-term gauge records can be used in checking the procedure. Again, a short-term gauging program is desirable.

c. Site analysis. The physical characteristics of the site and any ancillary information should be carefully scrutinized so that the engineer can understand how irregular the bathymetry is, the presence of significant currents, shoals, canyons, islands, structures, etc., that would be important in selecting the offshore or nearby site for a source of data input, for selecting the transformation procedure used, and in understanding what problems may arise in the analysis. Usually this type of knowledge is gained through experience, and a consultant may be required to assist someone unexperienced in such analyses. If time permits, one of the advanced models could be set up and run in an exploratory mode to help the engineer understand possible problems.

d. Selection of input data site. Based on project formulation and site analysis, offshore/nearby sites are evaluated in terms of any feature that would preclude their use (see Part II-3-1d). In particular, the use of nearby sites in similar depths of water must be evaluated in terms of whether waves reaching the site have broken. As an example, if waves at a nearshore site have propagated over a shoal where breaking can occur, there is no way to "unbreak" the waves. So they cannot be used to eliminate offshore wave conditions. In general the offshore data site will need as a minimum information on **wave height, period, and direction.** If adequate data are not available, methods for hindcasting, as described in Part II-2, may be used to simulate the information required. The methods of Parts II-2 and 3 should be used to develop the wave information to be transformed.

e. Selection of wave transformation method. Table II-3-2 provides guidance on the applicability of the various methods described in this chapter. It does not provide guidelines for all cases. With some skill, the models described can be pushed somewhat beyond their inherent limitations (but such results must be carefully scrutinized and used conservatively). In very complicated cases or in cases in which a time-dependent model is required, use of an expert consultant to provide assistance is recommended. In some complicated cases, a physical model may be required.

Table II-3-2
Guidance for Selection of Wave Transformation Methods

Case	Fig.II-3-6 or ACES	NMLONG	RCPWAVE	REFDIF1	STWAVE
Planar topography (no shoals, etc)	yes	yes	yes	yes	yes
Highly Irregular Bathymetry					
Swell, no structures	no	no	yes	yes	yes
Swell, structures	no	no	no	yes	yes
Complicated directional Spectra, but narrow frequency spectra	no	no	no	yes	yes
High winds or broad band frequency spectra	no	no	no	no	yes
Irregular Bathymetry, High resolution Computations Near Structure					
Swell	no	no	no	yes	no

f. Calibration/verification. After the method is set up, it is important to check the calculations with observations if at all possible. If measured wave data are not available, then aerial photographs can be helpful in deciding if the model reproduces observed wave patterns. If no wave data or photographs are available, the method should be applied to a range of heights, periods, and directions and the results should be carefully scrutinized for odd or unstable results. If the calculations are overly sensitive to small variations in input data, a careful decision should be made as to whether the technique should be applied. A physical model may be appropriate in situations with very irregular bathymetry, complicated or multiple structures, reefs, and where currents are important.

g. Post-processing.

(1) Plotted results should be carefully examined for any signs of computational instability. These typically are unreasonable variations in height or direction over short distances.

(2) The techniques provided in this chapter, if used carefully by an experienced engineer, can provide very useful information in a wide range of cases. However, there are some cases where they simply will not work. Anyone who applies these techniques should understand the limitations of the techniques, and be versed in understanding when they have been used inappropriately. The user should be aware that the models can provide realistic-looking answers that unfortunately are just wrong.

II-3-7. References

Abbott, Peterson, and Skovgaard 1978
Abbot, M. B., Peterson, H. M., and Skovgaard, O. 1978. "On the Numerical Modelling of Short Waves in Shallow Water," *Journal Hydraulic Research*, Vol 16, No. 3, pp 173-203.

Bagnold 1946
Bagnold, R. A. 1946. "Motion of Waves in Shallow Water - Interaction Between Waves and Sand Bottoms," *Royal Society of London*, Vol 187, pp 1-18.

Barnett 1968
Barnett, T. P. 1968. "On the Generation, Dissipation, and Prediction of Wind Waves," *Journal of Geophysical Research,* Vol 73, pp 6879-6885.

Berkhoff 1972
Berkhoff, J. C. W. 1972. "Computation of Combined Refraction - Diffraction," *Proceedings, 13th International Conference on Coastal Engineering,* American Society of Civil Engineers, Vol 1, pp 471-490.

Berkhoff 1976
Berkhoff, J. C. W. 1976. "Mathematical Models for Simple Harmonic Linear Water Waves, Wave Diffraction and Refraction," Publication 1963, Delft Hydraulics Laboratory, Delft, The Netherlands, April.

Berkhoff, Booij, and Radder 1982.
Berkhoff, J. C., Booij, N., and Radder, A. C. 1982. "Verification of Numerical Wave Propagation Models for Simple Harmonic Linear Water Waves," *Coastal Engineering,* Vol 6, pp 255-279.

Bouws et al. 1987
Bouws et al. 1987. "Similarity of the Wind Wave Spectrum in Finite Depth Water; Part 2: Statistical Relations Between Shape and Growth Stage," *Deutsche Hydogr. Z.,* Vol 40, pp 1-24.

Bouws, Gunther, and Vincent 1985
Bouws, E, Gunther, H., and Vincent, C. L. 1985. "Similarity of Wind Wave Spectrum in Finite-Depth Water, Part I - Spectral Form," *Journal of Geophysical Research*, Vol 85, No. C3, pp 1524-1530.

Bretschneider and Reid 1953
Bretschneider, C. L., and Reid, R. O. 1953. "Change in Wave Height Due to Bottom Friction, Percolation and Refraction," *34th Annual Meeting of American Geophysical Union.*

Dally, Dean, and Dalrymple 1984
Dally, W. R., Dean, R. G., and Dalrymple, R. A. 1984. "Modeling Wave Transformation in the Surf Zone," Miscellaneous Paper CERC-84-8, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Dean and Dalrymple 1991
Dean, R. G., and Dalrymple, R. A. 1991. *Water Wave Mechanics for Engineers and Scientists*, World Scientific Pub. Co., Teaneck, NJ.

Demirbilek 1994
Demirbilek, Z. 1994. "Comparison of REFDIF Model and CERC Elliptical Shoal Laboratory Data," Memorandum for Record, dated 18 June 1994, for the Coastal Inlets Research Program, Coastal Engineering Research Center, Vicksburg, MS.

Demirbilek and Webster 1992a
Demirbilek, Z., and Webster, W. C. 1992a. "Application of the Green-Naghdi Theory of Fluid Sheets to Shallow-Water Wave Problems; Report 1: Model Development," Technical Report CERC-92-11, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Demirbilek and Webster 1992b
Demirbilek, Z., and Webster, W.C. 1992b. "User's Manual and Examples for GNWAVE, Final Report," Technical Report CERC-92-13, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Dobson 1967
Dobson, R. S. 1967. "Some Applications of a Digital Computer to Hydraulic Engineering Problems," Technical Report No. 80, Department of Civil Engineering, Stanford University, Stanford, CA.

Ebersole 1985
Ebersole, B. A. 1985. "Refraction-Diffraction Model for Linear Water Waves," *Journal of Waterways, Port, Coastal, and Ocean Engineering*, American Society of Civil Engineers, Vol III, No. WW6, pp 939-953.

Ebersole, Cialone, and Prater 1986
Ebersole, B. A., Cialone, M. A., and Prater, M. D. 1986. "RCPWAVE - A Linear Wave Propagation Model for Engineering Use," Technical Report CERC-86-4, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Forristall and Reece 1985
Forristall, G. Z., and Reece, A. M. 1985. "Measurements of Wave Attenuation Due to a Soft Bottom: The SWAMP Experiment," *Journal of Geophysical Research*, Vol 90, No. C2, pp 3367-3380.

Harrison and Wilson 1964
Harrison, W., and Wilson, W. S. 1964. "Development of a Method for Numerical Calculation of Wave Refraction," Technical Memorandum No. 6, Coastal Engineering Research Center, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hasselmann 1962
Hasselmann, K. 1962. "On the Non-Linear Energy Transfer In A Gravity-Wave Spectrum - General Theory," *J. Fluid Mech.*, Vol 12, pp 481-500.

Hasselmann 1963a
Hasselmann, K. 1963a. "On the Non-Linear Energy Transfer In A Gravity-Wave Spectrum - Part 2," *J. Fluid Mech*., Vol 15, pp 273-281.

Hasselmann 1963b
Hasselmann, K. 1963b. "On the Non-Linear Energy Transfer In A Gravity-Wave Spectrum - Part 3," *J. Fluid Mech*., Vol 15, pp 385 - 398.

Hasselmann et al. 1973
Hasselmann et al. 1973. "Measurements of Wind-Wave Growth and Swell Decay During the Joint North Sea Wave Project (JONSWAP)," *Deutsche Hydrograph. Zeit.,* Erganzungsheft Reihe A (8^0), No. 12.

Hedges 1976
Hedges, T. S. 1976. "An Empirical Modification to Linear Wave Theory," *Proc. Inst. Civ. Engrs*., Vol 61, pp 575-579.

Jensen et al. 1987
Jensen, R. E., et al. 1987. "SHALWV - Hurricane Wave Modeling and Verification; User's Guide to SHALWV: Numerical Model for Simulation of Shallow-Water Wave Growth, Propagation, and Decay," Instruction Report CERC-86-2, No. 2, U.S. Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg, MS.

Jonsson 1978
Jonsson, I. G. 1978. "Combinations of Waves and Currents," *Stability of Tidal Inlets*, Per Bruun, ed., Amsterdam, Elsenir, pp 162-203.

Kirby 1984
Kirby, J. T. 1984. "A Note on Linear Surface Wave-Current Interaction Over Slowly Varying Topography," *Journal of Geophysical Research*, Vol 89, pp 745-747.

Kirby 1986a
Kirby, J. T. 1986a. "Higher-Order Approximations in the Parabolic Equation Method for Water Waves," *Journal of Geophysical Research*, Vol 91, pp 933-952.

Kirby and Dalrymple 1983
Kirby, J. T., and Dalrymple, R. A. 1983. "A Parabolic Equation for the Combined Refraction-Diffraction of Stokes Waves by Mildly Varying Topography," *J. Fluid Mech*., Vol 136, pp 453-466.

Kirby and Dalrymple 1984
Kirby, J. T., and Dalrymple, R. A. 1984. "Verification of a Parabolic Equation for Propagation of Weakly-Nonlinear Waves," *Coastal Engineering*, Vol 8, pp 219-232.

Kirby and Dalrymple 1986a
Kirby, J. T., and Dalrymple, R. A. 1986a. "Modeling Waves in Surfzones and Around Islands," *J. Waterways, Port, Coastal and Ocean Engrg*., Vol 112, pp 78 -93.

Kirby and Dalrymple 1986b
Kirby, J. T., and Dalrymple, R. A. 1986b. "An Approximate Model for Nonlinear Dispersion in Monochromatic Wave Propagation Models," *Coastal Engineering*, Vol 9, pp 545-561.

Kirby and Dalrymple 1992
Kirby, J. T., and Dalrymple, R. A. 1992. "Combined Refraction/Diffraction Model REF/DIF 1, Version 2.4.; Documentation and User's Manual," Research Report CACR-92-04, Center for Applied Coastal Research, University of Delaware.

Kraus 1991
Kraus, N. C. 1991. "NMLONG: Numerical Model for Simulating the Longshore Current," U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Leblond and Mysak 1978
Leblond, P. H., and Mysak, L. A. 1978. "*Waves in the Ocean*," Elsevier Scientific Pub. Co., Amsterdam-Oxford, NY.

Leenknecht, Szuwalski, and Sherlock 1992
Leenknecht, D. A., Szuwalski, A., and Sherlock, A. R. 1992. "Automated Coastal Engineering System; User Guide and Technical Reference, Version 1.07," U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Miller and Vincent 1990
Miller, H. C., and Vincent, C.L. 1990. "FRF Spectrum: TMA with Kitaigoredskii's F^4 Scaling," *Journal of Waterway, Port, Coastal, and Ocean Engineering*, Vol 116, No. 1, pp 57-78.

Noda 1974
Noda, E. K. 1974. "Wave-Induced Nearshore Circulation," *Journal of Geophysical Research*, Vol 79, No. 27, pp 4097-4106.

Noda et al. 1974
Noda, E. K., et al. 1974. "Nearshore Circulations Under Sea Breeze Conditions and Wave-Current Interactions in the Surf Zone," Technical Report No. 4, Tetra Tech, Inc., Pasadena, CA.

Panchang et al. 1990
Panchang, V. G., Pearce, B. R., Wei, G., and Briggs, M. J. 1990. "Numerical Simulation of Irregular Wave Propagation Over Shoal," *J. Waterway, Port, Coastal, and Ocean Engrg*., Vol 116, pp 324-340.

Penny and Price 1944
Penny, W. G., and Price, A. T. 1944. "Diffraction of Waves by Breakwaters," Directorate of Miscellaneous Weapons Development History No. 20 - Artificial Harbors, Sec 3D.

Peregrine 1976
Peregrine, D. H. 1976. "Interaction of Water Waves and Currents," *Advances in Applied Mechanics*, Academic Press, New York, Vol 16, pp 9-117.

Phillips 1977
Phillips, O. M. 1977. *The Dynamics of The Upper Ocean*, 2nd ed., Cambridge University Press.

Radder 1979
Radder, A. C. 1979. "On the Parabolic Equation Method for Water-Wave Propagation," *Journal of Fluid Mechanics*, Vol 95, Part 1, pp 159-176.

Resio 1981
Resio, D. T. 1981. "The Estimation of Wind-Wave Generation in a Discrete Spectral Model," *Journal of Geophysical Research*, Vol 11, pp 510 - 525.

Resio 1987
Resio, D. T. 1987. "Shallow Water Waves. I - Theory," *J. Waterway, Port, Coastal and Ocean Engr*., American Society of Civil Engineers, Vol 113, pp 264-281.

Resio 1988
Resio, D. T. 1988. "Shallow Water Waves II - Data Comparisons," *J. Waterway, Port, Coastal and Ocean Engr*., Vol 114, pp 50-65.

Resio 1993
Resio, D. T. 1993. "STWAVE: Wave Propagation Simulation Theory, Testing and Application," Department of Oceanography, Ocean Engineering, and Environmental Science, Florida Institute of Technology.

Shore Protection Manual 1984
Shore Protection Manual. 1984. 4th ed., 2 Vol, U. S. Army Engineer Waterways Experiment Station, U.S. Government Printing Office, Washington, DC.

Smith and Vincent 1992
Smith, J. M., and Vincent, C. L. 1992. "Shoaling and Decay of Two Wave Trains on a Beach," *J. Waterways, Port, Coastal and Ocean Engr.,* Vol 118, No. 5, pp 517-533.

Sobey and Young 1986
Sobey, R. J., and Young, I. R. 1986. "Hurricane Wind Waves - A Discrete Spectral Model," *J. Waterway, Port, Coastal and Ocean Engineering*, Vol 112, No. 3, pp 370-389.

SWAMP Group 1985
SWAMP Group. 1985. "*The Sea Wave Modeling Project (SWAMP): Principal Results and Conclusion*," Plenum, New York, p 256.

SWIM Group 1985
SWIM Group. 1985. "A Shallow Water Intercomparison of Three Numerical Prediction Models (SWIM)," *Quarterly Journal of the Royal Meteorological Society*, Vol 111, pp 1087-1112.

Thompson and Vincent 1984
Thompson, E. F., and Vincent, C. L. 1984. "Shallow-Water Wave Height Parameters," *J. Waterway, Port, Coastal and Ocean Engr*., American Society of Civil Engineers, Vol 110, No. 2, pp 293-299.

Tsay and Liu 1982
Tsay, T. K., and Liu, P. L. -F. 1982. "Numerical Solution of Water-Wave Refraction and Diffraction Problems in the Parabolic Approximation," *Journal of Geophysical Research*, Vol 87, pp 7932-7940.

Vincent and Briggs 1989
Vincent, C. L., and Briggs, M. J. 1989. "Refraction-Diffraction of Irregular Waves Over A Mound," *J. Waterway, Port, Coastal and Ocean Engrg*, American Society of Civil Engineers, Vol 115, No. 2, pp 269-284.

WAMDI 1988
WAMDI. 1988. "The WAM Model - A Third Generation Ocean Wave Prediction Model," *Journal of Physical Oceanography*, Vol 18, pp 1775-1810.

Weggel 1972
Weggel, J. R. 1972. "Maximum Breaker Height," *Journal of the Waterways, Harbors, and Coastal Engineering Division*, Vol 98, No. WW4, pp 529-548.

West 1981
West, B. J. 1981. "On the Simpler Aspects of Nonlinear Fluctuating Gravity Wave (Weak Interaction Theory)," *Lecture Notes in Physics 146*, Springer-Verlag, New York.

Young 1988
Young, L. R. 1988. "A Shallow Water Spectral Wave Model," *Journal of Geophysical Research*, Vol 93, No. C5, pp 5113-5129.

II-3-8. Definitions of Symbols

$\vec{k}$ — Wave number vector (Equation II-3-4)

θ — Angle between the plane across which energy is being transmitted and the direction of wave advance [deg]

ρ — Mass density of water (salt water = 1,025 kg/m^3 or 2.0 slugs/ft^3; fresh water = 1,000kg/m^3 or 1.94 slugs/ft^3) [force-$time^2$/$length^4$]

φ — Velocity potential at the free surface [$length^2$/time]

ω — Wave angular or radian frequency (= $2\pi/T$) [$time^{-1}$]

Ω — Wave phase function (Equation II-3-3)

C — Wave celerity [length/time]

C_g — Wave group velocity [length/time]

d — Water depth [length]

E — Total wave energy in one wavelength per unit crest width [length-force/$length^2$]

$E(x,y,t,f,\theta)$ — Directional spectrum where x,y represents a location in geographic space, t represents time, and f,θ represents a particular frequency-direction component

h — Water depth [length]

H — Wave height [length]

k — Wave number (= $2\pi/L = 2\pi/CT$) [$length^{-1}$]

K_r — Refraction coefficient [dimensionless]

K_s — Shoaling coefficient [dimensionless]

L — Wave length [length]

$-_o$ — The subscript 0 denotes deepwater conditions

T — Wave period [time]

U — Ambient current vector (Equation II-3-30) [length/time]

φ — Velocity potential at the free surface [$length^2$/time]

II-3-9. Acknowledgments

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