The MIT/Marine Industry Collegium
Opportunity Brief #38

Modeling of Coastal Processes: Circulation, Dispersion, and Waves

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The MIT Marine Industry Collegium

MODELING OF COASTAL PROCESSES: CIRCULATION, DISPERSION, AND WAVES

Opportunity Brief #38

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Preface

This Opportunity Brief is based on a workshop entitled Modeling of Coastal Processes: Circulation, Dispersion, and Waves. The workshop, sponsored by the MIT Marine Industry Collegium of the MIT Sea Grant Program, was held in Cambridge, Massachusetts on May 22, 1984. The workshop was held to provide Collegium members with an opportunity to discuss recent developments in the modeling of coastal circulation, dispersion, and wave heights.

Participants in the workshop included Collegium members, MIT faculty and staff, Sea Grant representatives from MIT and the University of Maine, and students. Circulation and Dispersion modeling was discussed by Professor Jerome Connor and graduate student Joannes Westerink, both of the MIT Department of Civil Engineering. Eulerian-Lagrangian Transport Modeling was presented by Dr. Eric Adams and graduate student Antonio Baptista of the MIT Energy Laboratory and Department of Civil Engineering. Professor Bryan Pearce and graduate student Vijay Panchang of the Department of Engineering, University of Maine, spoke on Wave Heights in the Gulf of Maine and on a Model for Development of Wave Spectra in Bays. Professor Ole Madsen and Dr. Hans Grabber of the MIT Department of Civil Engineering addressed the topic of a wind, wave and current model for finite water depth.

The author is responsible for the conclusions presented herein. Any opinions or conclusions expressed are those of the author and do not necessarily reflect the views of the MIT Sea Grant College Program or of MIT.

Through Opportunity Briefs, workshops, and other interactions, the Collegium provides a means for technology transfer among academia, industry, and government. For additional information about the Collegium or the research presented in this Brief, contact the Marine Industry Advisory Service, MIT Sea Grant Program, 292 Main Street, Cambridge, MA 02139, or call either (617) 253-4434 or (617) 253-7092.

Margaret Linskey
October 30, 1984

<u>TABLE OF CONTENTS</u>

1.0. Business Perspective

Wind, waves and tides all interact and affect the circulation of water in coastal environments. Circulation patterns must be known in order to predict the distribution and dispersion of such elements as pollutants, red tide larvae, and heated effluents originating from power plants in fragile coastal environments. Two computer models dealing with circulation and dispersion as they are driven by tides and wind stresses were developed under MIT Sea Grant funding in the mid-1970's. These models, CAFE and DISPER, were first introduced to the Collegium membership at a March 17, 1977 workshop entitled "Computer Models for Environmental Engineering and Research in Near-Coastal Environments." At that time Professor Jerome Connor of MIT, Professor Barbaros Celikkol of UNH and Professor John Wang of the University of Miami reported on applications of CAFE and DISPER. These models have been widely distributed and have been used in many academic and industrial applications.

This Opportunity Brief describes some substantial changes and modifications in these models that will enable users to model circulation at very much lower cost. In the past, huge computational requirements and the high cost of computer time frequently inhibited the use of these models. In cases for which the improved programs can be used, the cost of computer time will no longer be prohibitive.

In near coastal environments, wave heights and wave spectra are important in understanding the effects of waves on beaches, in the design of coastal structures, and also in certain aspects of pollution transport and pollution control. This Opportunity Brief discusses two methods for modeling design wave heights in nearshore environments. University of Maine researchers have developed a method for modeling steady-state wave spectra and significant wave heights in bays with complicated bathymetry. MIT researchers present a model that incorporates the dissipation effects of finite water depth in predicting wind-generated waves.

2.0 Tidal Embayment Analysis (TEA): An Enhanced Water Circulation and Dispersion Model(1)

2.1 Analysis of Circulation using Frequency Domain Techniques

Up and down the New England coastline there are many small, essentially closed tidal embayments which are ideal for small harbors and marinas. Coastal communities feel increasing pressure to develop these areas but are concerned with the environmental impact of low flushing rates and periodic dredging. Among the many natural processes which depend on the tidal and wind drive circulation in enclosed embayments are nutrient export from coastal marshes and the transport of red tide (paralytic shellfish poisoning) cysts.

About a decade ago, MIT Sea Grant supported a study for calculating the circulation of materials in the 100-km long Massachusetts Bay. Two widely used models resulted: CAFE, for water movements, and DISPER, for dispersion of dissolved substances. Because of the models' structure, they cost less to run for the main part of the Bay than for smaller semi-enclosed regions only 1 to 10 km across, the reason being that the same water moving at the same speed across a much larger area can be tracked with fewer measurements.

The CAFE and DISPER models work very well when applied to fairly regular domains such as a large bay, but problems arise with the irregular boundaries and topography of craggy embayments. A model such as CAFE is extremely expensive to run because the small grid requires many, very closely spaced time steps. A smaller region might require time steps 10 to 100 times smaller than a large region, making CAFE and DISPER prohibitively expensive to run.

At the May 22, 1984 workshop, Professors Stolzenbach, Connor, Adams and graduate student Joannes J. Westerink of the MIT Department of Civil Engineering reported on the adaptation of CAFE and DISPER in a new project, named TEA (Tidal Embayment Analysis). They are developing an alternate strategy for such computations based on frequency domain analysis, in which the frequency is known (for example, the tidal period), while amplitude and peak variation can be calculated.

Four basic assumptions are involved in the TEA model:

1. Depth variations of velocity are sufficiently unimportant to permit the use of a single "depth averaged" velocity.

2. The hydrostatic pressure is basically uniform.

3. There is only one liquid involved, thus resulting in a constant density fluid.

4. Turbulence does not play a major role, i.e., there is negligible momentum dispersion.

TEA would be applicable in any semi-enclosed region with a well defined point where the tide enters and recedes. Since the model is meant for shallow water circulation problems it doesn't take into account stratification and therefore wouldn't be appropriate for estuaries or other significantly stratified water.

When frequency domain analysis is used, there are no requirements for small time steps imposed by the small grid sizes (which are a needed characteristic for the coastal irregularities in small bays). As a result, circulation modeling is both faster and more economical than time domain analysis.

The frequency domain or harmonic method of accounting for time dependence offers a very attractive alternative to the time stepping procedure used in time domain analysis. The harmonic method is based on the assumption that the tidal forcing frequency is known, and thus time dependence can be eliminated from the governing equations. This method has the advantage of being a rather natural approach due to the periodic nature of tides. Further, it removes the time-stepping limitations, allowing the generation of quasi-steady-state equations. Long term simulations are thus possible and results can be stored in an efficient form (reducing the amount of computer memory required). Additional efficiencies are achieved by the elimination of "cold start" problems, i.e., starting transients encountered in time domain analysis.

A linear version of the circulation model for TEA has been completed and accepts input very similar to CAFE. The program computes water movement throughout a period of specified frequency for given values of tidal elevation changes and wind stress. For typical problems, TEA runs up to 100 times faster than CAFE and has no difficulty handling small finite element grid sizes.

An example is a direct comparison that was run using data from the Millstone power plant in Waterford, Connecticut. Using a Honeywell 68/DPS, CAFE was used to analyze one tidal cycle. The run time was 20 hours. A comparable analysis was done with TEA on a VAX 11/780 (a relatively less powerful machine), with a run time of 2.5 minutes.

The new model has been applied to three case studies in New England, at power generating plants in Massachusetts and Connecticut, and to a pond on Cape Cod that is implicated as a source of red tide organisms. These case studies will compare computed circulation and dispersion with actual water movements inferred from available field data. In addition, the studies will provide an opportunity to systematically investigate the relative influence of natural forces (wind, tide) and manmade activities (dredging, pipelines, etc.) on net circulation and flushing.

Future work might include studying the flushing rate in and around marinas. Would bacterial contamination from shipboard wastes, and the oil and gas spilled during refueling be trapped in the harbor and pollute it heavily, or would they be swept to sea, perhaps to taint shellfish flats on the way? Answers to these questions are crucial and can be found using TEA.

While the frequency domain technique is not new, Stolzenbach says that "in terms of implementing it in a practical domain, we think that probably nobody else is doing it so extensively." However, he adds that TEA still only solves linear problems while CAFE handles some nonlinear ones, "so we can't match CAFE yet one for one."

If tides were a perfectly linear problem, water would move back and forth with no net motion and no flushing. Stolzenbach mentions, "The nonlinearities contribute to a net motion superimposed on the total motion. The effect of combined tides is for water that was in a semi-enclosed region to finally make its way out. A creeping slow motion is really the net difference of all the tidal movements."

The work on TEA is supported by MIT Sea Grant and the MIT Energy Lab's Electric Utilities Program.

2.2 Analysis of Dispersion using Eulerian-Lagrangian Techniques

The older circulation model CAFE and its updated version TEA compute water velocities. Two dimensional models of dispersion use two variables as inputs: water depth and water velocity. When the sought-after variable is concentration of heat, salt, sewage effluent, or radioactivity, the dispersion model DISPER or its unnamed updated version is used. Just as input for DISPER comes from CAFE, input from the new model proceeds from TEA. Users feed in the water depths and velocities, and the model computes concentrations of the above constituents.

Adams et al. refer to the combined methods as the Eulerian-Lagrangian technique. In the Eulerian part the equations are solved with a fixed domain by finite element method for the diffusion. The convective transport, done by the method of characteristics, is a Lagrangian technique because it follows the flow.

Adams and his colleagues are attempting to improve the method by taking a different approach. After a time step, which can be quite long compared to a time step in most Eulerian models, the user wants to know the concentration at all grid points in the domain. From the results of CAFE or TEA the user knows the velocity as a function of space and time, and can integrate backward to figure out where the particles started from. This results in 100 trajectories with known endpoints but whose beginning points one must solve for. The researchers need information on the current frequently to be able to resolve what the current is doing.

Typically the current changes with the tide every six hours or so. The new dispersion model is drawn with a rectangular grid as if it were being used for finite difference instead of finite element. The method of characteristics which is applied to the transport equation has been done in a finite difference context more often than a finite element. Others used the E-L method with finite difference.

The new model connects the method of characteristics used with the convection part to the finite element part for diffusion. The finite element can be highly irregular and form complicated geometry more economically than with finite difference modeling, which involves a more or less regular grid pattern. When a discharge has to be resolved with bathymetry or when a complicated shoreline demands a more resolved grid, the finite element method is a definite benefit.

These models are also distinguished by the sophisticated interpolation. In general the parcels of water which end up on a grid point do not start on a grid point, making interpolation necessary to obtain concentrations at the beginning of the time step. Linear interpolation is simplest but is not very accurate because each of the numerous time steps must be rounded off and averaged. Instead, the researchers use a quadratic interpolation method consistent with the quadratic interpolation functions found in the finite element approach. More complicated interpolations tend to be more accurate, but also require more grid points and take longer to calculate. The new method should be at least as cheap as DISPER and considerably more accurate.

An immediately useful component is to apply the combined dispersion and circulation models to more realistically simulate discharge situations. These would be classified as far-field models, as opposed to near-field models which would resolve the flow right around an outfall. The researchers are looking at ways to interface the near-field and the far-field models.

An example of a practical application of what could happen if near and far field models were to be interfaced is described below. Once-through cooling for power plants involves pouring large quantities of heated water into ambient receiving waters. Predicting the extent of the resulting thermal plume is an important component of environmental impact assessment and a necessary step in licensing procedures. Important questions to consider include: How much previously discharged heated water is re-entrained into the discharge plume due to tidal reversals, wind shifts and other unsteady water movements? What is the source of the entrainment flow to the near-field mixing region? How does the momentum of the discharge affect the general circulation within the water body and consequently the natural transport of organisms? How can one separate warming from power plant discharge and warming from natural processes such as the sun beating on water in shallow embayments?

3.0 Coastal and Oceanic Wave Height Modeling

3.1 Estimates of Design Wave Heights in the Gulf of Maine

Probability estimates of most extreme wave conditions expected during the lifetime of an offshore structure are needed for engineering studies for the design and certification of offshore structures. Similar data are needed for problems of coastal engineering design and sediment transport. Reliable estimates of extreme wave statistics require a long time base of statistical observations from which to estimate the extreme significant wave heights expected in a 50 or 100 year time period. The only method available at the present time for constructing wave statistics therefore is based on a wave hindcast approach using historical wind fields to estimate historical wave fields and thus to estimate the statistics for the periodicity of storms and waves.

University of Maine researchers are studying ways to generate wave height information for the Gulf of Maine by means of a model which calculates synoptic wind velocities for Northeast storms and uses that information in numerical wave hindcast models. A parametric wave model was used with a set of the 22 strongest Northeast storms from a 32 year record, and the wave heights at each grid point of the model for each storm were used to generate the extreme wave statistics. Professor Bryan Pearce and graduate student Vijay Panchang both of the University of Maine Department of Civil Engineering presented the results of this project and gave details about their current work on developing a method for modeling steady state wave spectra in bays with complex bathymetry.

The brief discussion of the design wave height estimation which follows is based on a University of Maine/University of New Hampshire Sea Grant report entitled, Estimates of Design Wave Heights in the Gulf of Maine. (2)

The objective of this research was to generate long term extreme wave statistics for the Gulf of Maine using hindcast wave data. Large ocean waves are generated predominantly by strong winds accompanying a storm; occurring over a 32-year period from 1944 to 1976. The entire region was divided into smaller rectangular grids, and wind velocities at each grid-point were obtained by feeding certain characateristics of the storm into a "Northeaster" wind field model that was developed by Stone & Webster Corporation. The wind field so generated was utilized by a deep water, hybrid parametric wave model that was developed by Gunther et al. in 1979 at the Haydraulics Research Station, from which wave-height estimates at each grid-point were obtained (3). Finally, a distribution of the Weibull family was used to estimate the long-term wave statistics, vis., the 50-year and 100-year wave heights (4).

3.1a Computation of the Wind Field

Characteristic parameters of fifty-five severe northeast storms that were responsible for high storm tide elevations along the New England coast are considered to be more frequent in the northwestern Atlantic Ocean and are therefore used in this study instead of hurricanes.

A set of the strongest northeast storms to pass through the Gulf of Maine region has been prepared by Stone and Webster Engineering Corporation. The Stone and Webster wind model enables one to define certain synoptic parameters like pressures, maximum radius, storm track, etc., from which surface wind velocities, needed as input to the wave model, can be calculated.(5)

Storm central pressure, maximum peripheral radius and coordinates of the storm center at each instant of time are entered into the model. For each instant of time, the program goes from point to point in the grid and employs a geostrophic approach to calculate wind speed and direction at each point.

3.1b Analysis and Results

It was mentioned earlier, that the Northeaster program solved the geostrophic wind velocity equations for each time-step at each point of the grid system. The wind model and the wave model discretized the corresponding equations using the same grid. The extent of the grid was chosen to approximately correspond with the average length scale of a northeast storm, i.e, 500-1000 nautical miles. The finite difference scheme inputs wind speed and direction at each point and computes the significant wave height, H_s, for that point.

According to the aforementioned Sea Grant report:

> The boundary conditions play an important role in the choice of the grid. Wave heights calculated near the model boundary are not appropriate because of the limitations on the fetch imposed by the presence of the boundary. When wind is directed into the model at a boundary, the boundary is assigned near-zero energy _a priori_, and a fixed fetch equal in length to one-half of the grid spacing is used to generate waves in the first grid. Consequently, acceptable estimates of the wave heights are obtained only some distance away from the boundaries. A sensitivity study was therefore done by progressively expanding the grid until it was so large that the area of interest was free from the fetch-limiting effects of the model boundaries.
>
> Each square in the original grid is 32.9 nautical miles on a side, and the mesh contains 11 columns. Values at all points of the grid cannot be calculated because the proximity of the model boundary to the Gulf of Maine reduces the computed wave heights there by limiting the fetch.

Computing the wave heights for the eastern portion of the grids was done more successfully. The eastern grid contained squares 27.4 nautical miles on a side, and it had 21 rows. The wave heights calculated were now different from the values obtained in the first attempt. The computations gave larger wave heights due to the increased fetch. This second grid was then extended further to the east using 26 columns instead of 20. The data showed that while the wave heights in the easternmost areas are different, there is little or no change in the first section which covers the Gulf of Maine, indicating that an extension in the east-west dimension of the grid from 20 to 26 columns does not alter the computed wave heights of the Gulf of Maine. It can therefore be inferred that the area of interest is free of the fetch limiting effects of the boundaries when the second grid system was eventually chosen to calculate the extreme wave conditions. (6)

A brief analysis of the uncertainty of the extrapolated wave heights was done. Neglecting possible inaccuracies in the hindcast data, uncertainty in the wave height, corresponding to a given return period, exists because the storms used in the extrapolation procedure represent only a small sample of the total storm population. The small sample size causes two problems in developing an adequate probabilistic model for estimating design wave heights: 1, a reliable distribution function defining the storm population cannot be chosen and 2, the parameters calculated are only sample estimates. It is therefore desirable to obtain confidence limits for the extrapolated values. Figure 1 shows where the 100-year significant wave height is 10.72 meters, a point arbitrarily chosen for the uncertainty analysis, and the 90% confidence limits were constructed in Figure 2 by the method illustrated in Viessman, et al., 1977, (7) and attributed to Beard (1962) (8). It was found that the 90% reliability band for the 100-year significant wave height at point 308 is between 9.81 meters and 12.21 meters. Figure 2 also illustrates the final wave height distribution for point 308. The dashed lines represent the 90% reliability band.

3.1c Wave Model for Coastal Bays

In addition to adapting available wind field models to the Gulf of Maine case, Sea Grant supported Pearce et al. to develop a wave model for determining steady state wave spectra in bays.

The technique includes the effects of local generation of waves and their propagation in areas of varying bottom topography. Consider for example wave propagation in a small (relative to the size of a northeast storm) converging bay with complex topography. The object is to determine extreme wave conditions at the inland end of the bay for design purposes. The wave propagation is strongly influenced by the local bathymetry, and local wave generation is governed by high winds which may be treated as fairly constant over a brief length of time (3 or 4 hours, etc.).

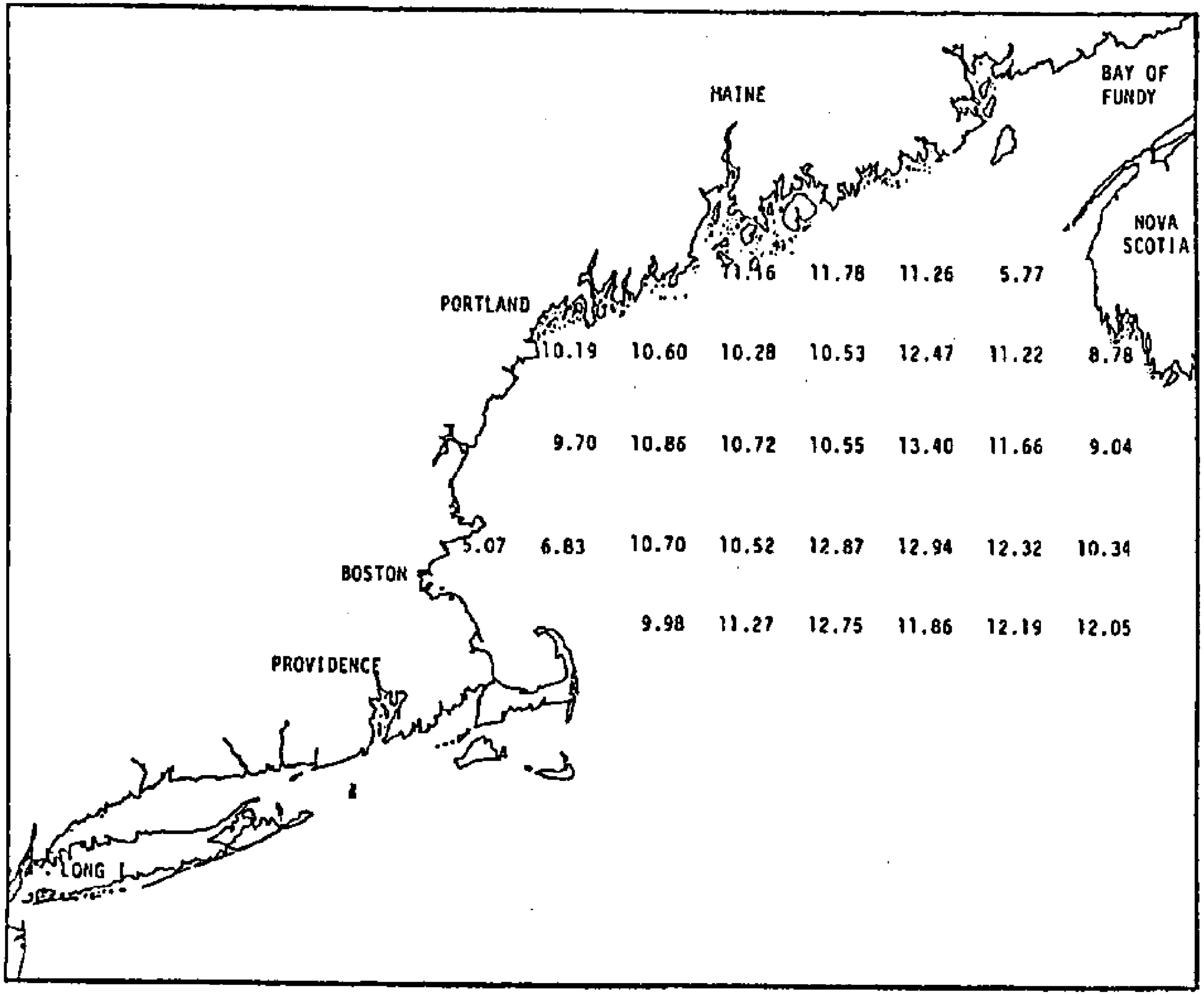

Figure 1: 100-Year Significant Wave Heights (in meters) in the Gulf of Maine
Source: Estimation of Design Wave Heights in the Gulf of Maine, UMO/UNH Sea Grant report no. TR-MSG-83-4.

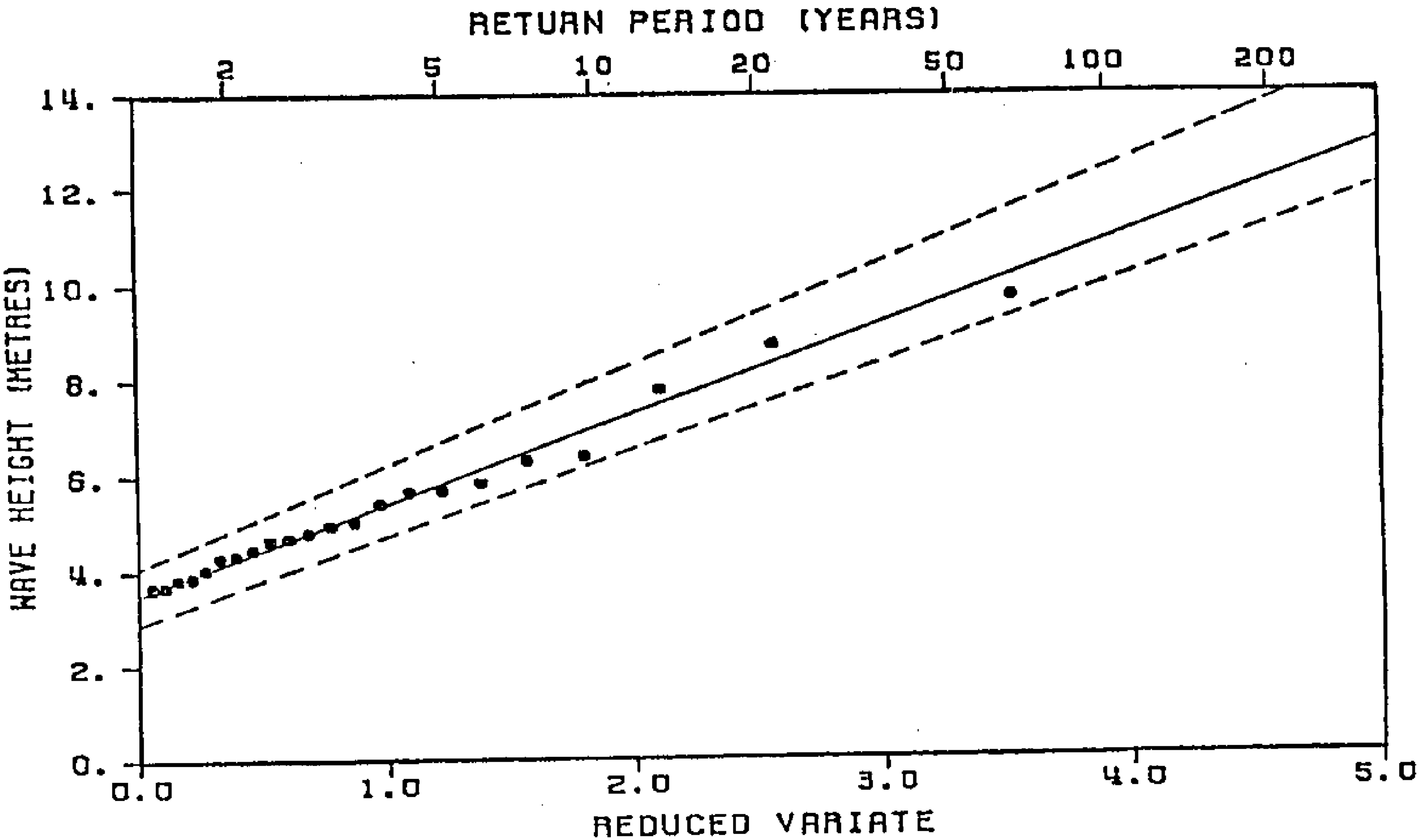

Figure 2: Wave Height Distribution for Point 308. The Dashed Lines Represent the 90% Reliability Band

Source: Estimation of Design Wave Heights in the Gulf of Maine, UMO/UNH Sea Grant Report No. TR-MSG-83-4

Following are excerpts from a recent Journal of Hydraulics Engineering article by Pearce et al.

> The wave model is based on the mild-slope equation derived by Berkhoff (1972). The advantage of combining the refraction/diffraction method over conventional methods of studying wave propagation (Booij, 1981) is the elimination of problems such as caustics. Solving this elliptic equation is difficult, however, the parabolic approximation developed by Radder 1929 may be applied to coastal areas of complex bathymetry.
>
> Strong, steady wind conditions over time scales of 1-2 hours characterize northeastern type storms. Typical length scales of the bays in question, are of the order of tens of kilometers.
>
> While the parabolic scheme with all its inherent assumptions offers an excellent way to study waves predominantly along the wind direction, the effect of local generation due to strong onshore winds cannot be ignored, particularly for determination of design conditions at the end of the bay. A source function is therefore built into the parabolic approximation along the lines of Dalrymple, et al. (1984) and Booij (1981) who included dissipation. As the source function contains a variable of the equation, a solution process is described that does not alter the nature of the equation, so that the Crank-Nicholson method may still be applied.
>
> To test validity of this approach, a source function was developed. Recourse was taken to the JONSWAP results (Hasselmann, et al., 1973) and the parametric wave models (Hasselmann, et al., 1976); Gunther et al., 1979. The parametric source terms described in Gunther, et al. (1979) are converted into functions of frequency for use in the parabolic scheme. These were compared to observed source functions. Using the source function so obtained, the parabolic scheme was applied to a range of frequencies to simulate a case of spectral evolution observed during the JONSWAP experiment. (9)

The results indicate that this is a suitable method of investigating spatial transformations of wave spectra in bays for the conditions described above. The offshore (or incoming) wave spectrum must be known. This paper has discussed the use of deep-water source functions for inclusion in the wave propagation equation. While it can be argued that most of the generation would be in deep water in a fairly deep bay of limited lateral extent, for shallower water different source terms may be applied.

3.2 Effects of Finite Water Depths on a Wind Driven Wave Model

The following section is based on a proposal Professor Ole Madsen submitted to Sea Grant in spring 1984. The most significant environmental factors to consider when designing and operating coastal and offshore facilities are the wave and current conditions associated with severe storms. To obtain sufficient information on these conditions, researchers often supplement limited field data with hindcast wave and current conditions obtained from numerical models which use available meteorological data on historical storm events. Most of the existing wind wave models have been developed and/or applied only for deep water conditions. Therefore, deep water wave hindcasts are often used to predict wave conditions in situations where the deep water assumption is violated. Since the waves in a severe storm might be affected by the bottom in water less than 200 m deep, wave hindcasting or forecasting on the continental shelf should account for the effects of finite depth.

Finite depth effects include the interaction between the near-bottom wave motion and the bottom sediments, when the waves may generate bottom ripples and/or significant near-bottom sediment transport resulting in a considerable loss of wave energy. Using a simple model to account for wave attenuation through bottom friction, Professor Ole Madsen and a graduate student Hans Grabber of the MIT Department of Civil Engineering calculated significant design wave heights of 6 m to 12 m water off the New Jersey coast, while a model not considering bottom friction resulted in a wave breaking height greater than 10 m. Thus, incorporating the effect of wave-bottom sediment interaction in a finite depth wind wave model may considerably decrease design wave conditions and result in significantly lower construction costs for offshore structures. In addition, the depth refraction and shoaling of the waves as they propagate in water of slowly varying depth will change the wave characteristics, and these effects should be accounted for in a finite depth wind wave model. (10)

The Collegium workshop held on May 22, 1984 addressed the development of a general numerical model capable of forecasting wind wave characteristics in water of finite depth. The numerical model extends the existing deep water wind wave model developed at the Max Planck Institute for Meteorology and at the University of Hamburg to account for finite depth effects. Four tasks are necessary to accomplish the objective.

The first task includes finite depth effects in the nonlinear wave-wave interaction source term and a source term accounting for wave energy dissipation through the interaction between wave motion and bottom sediments in the wave energy transport equation. This model will be applied to wind wave generation in finite depth water to produce design graphs of wave heights and periods as functions of wind speed, fetch and bottom sediment characteristics, as well as spectra for fully developed wind waves in finite water depth.

A general numerical algorithm for the combined depth and current refraction of waves will be developed for the second task. The third task will simplify existing theories for the combined wave-current interaction with a rough bottom to establish a relationship for the bottom frictional resistance experienced by a current in the presence of waves, and incorporate this in a numerical model for wind-induced currents and set-up.

The fourth task will combine the results of the three previous tasks into a complete and general model to predict wind generated waves, currents and set-up in water of finite depth.

The final product would be in the form of a computer program with a user's manual which will enable interested parties to obtain a copy of the program and implement it on their own computer.

3.2a Wave-Current Interaction Modeling Effort

As waves propagate over a movable bed from deep to shallow water the near-bottom orbital velocity increases. At the same time the bottom shear stress associated with the wave motion increases and reaches a critical value for which the bottom sediments start to move. Seaward of the point of initiation of sediment motion, the bottom roughness is that of the grain size of the bed material. Just shoreward of the point of initiation of motion, the movable bed deforms and exhibits ripples which correspond to a bottom roughness larger than the grain size by orders of magnitudes. As the waves progress into shallow waters the near-bottom flow intensity increases and the ripples will be smoother than they were at the point of incipient sediment movement, i.e., the roughness due to ripples will decrease. However, as the near-bottom flow intensity increases, so does the rate at which sediment is transported. The existence of a layer of moving sediment grains affects the apparent roughness of the bed. Thus, as the waves propagate into very shallow water the ripples essentially disappear and bottom roughness is governed by the moving sediments.

Figure 3(a) shows the variation of wave height as a wave of $T = 15$ sec. period and initial, deep water wave height $H_o = 1$ m climbs a 1 on 100 sloping beach consisting of 0.1 mm sediments. Notice that the wave attentuation due to bottom friction becomes appreciable only in very shallow water. Figure 3(b) shows the variation of the wave friction factor. Note that no sediment movement, initiation of motion, gradual decay of ripples while sediment transport rates increase as the depth decreases.

The values of the wave friction factor shown in Figure 3(b) are of the order 0.03 to 0.3 which is orders of magnitude greater than the friction factors normally encountered when calculating bottom shear stresses

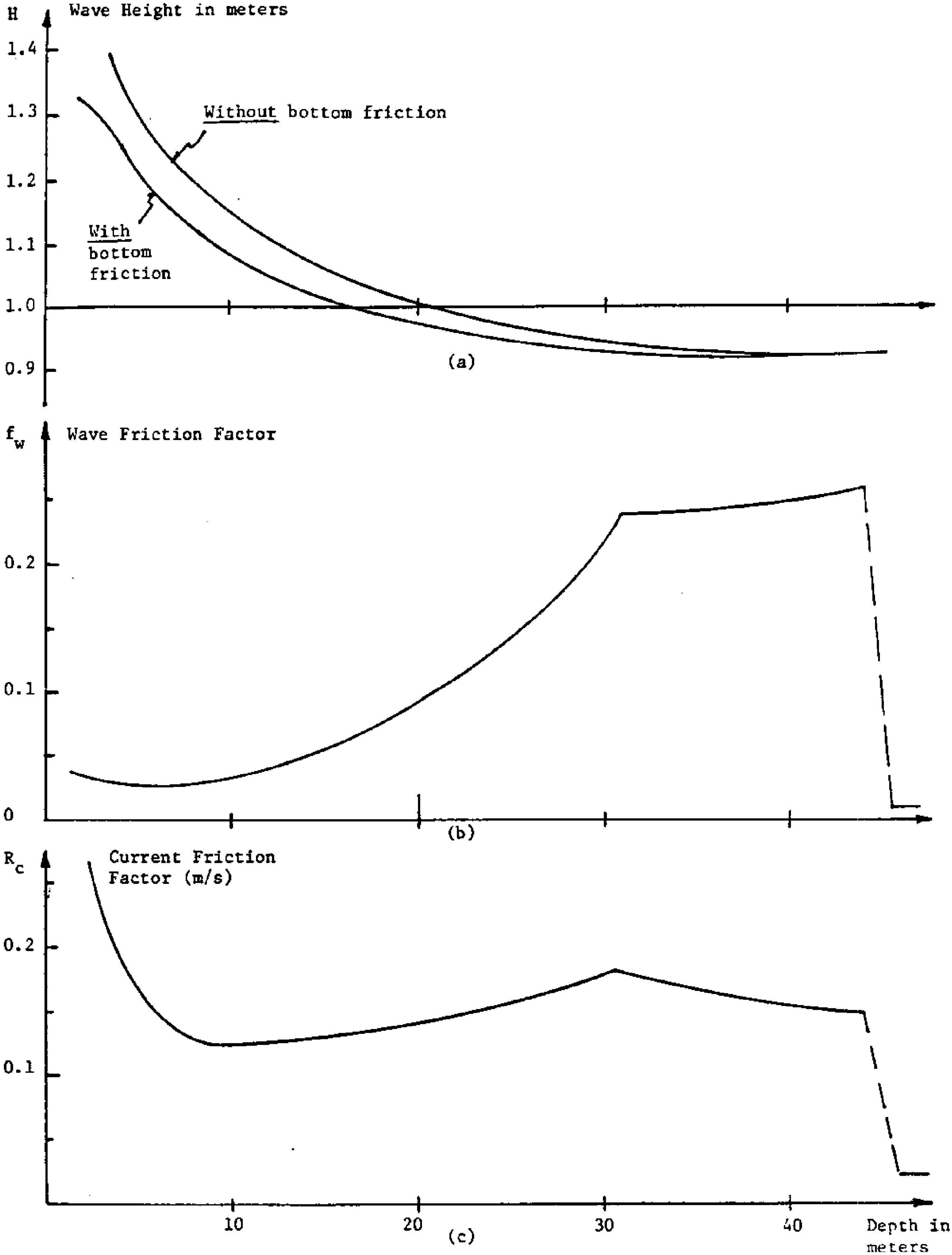

Figure 3: Wave Height & Friction Factors (for details see text).

associated with steady currents. This effect of the presence of waves, i.e., the existence of a very high turbulence intensity near the bottom, affects the shear stress experienced by a current superimposed on the wave motion.

Figure 3(c) shows the variation of the linearized friction factor R_c obtained under the assumption that the current velocity, U_{100}, is 0.10 m/s. R_c reflects the presence of waves in much the same manner as does f_w, the wave friction factor, in Figure 3(b). The range of values of R_c, from 0.02 m/s before the sediment is moving to roughly 0.15 m/s shoreward of the point where sediment transport is initiated, should be compared with the value of R_c obtained from an analysis which completely disregards the presence of waves. For a current velocity, U_{100} = 0.1 m/s, and an assumed bottom roughness of 2 cm, the value of R_c obtained for a pure current is 0.0003 m/s, i.e., a factor of about 70 lower than the lowest value obtained when the presence of waves is accounted for. The implications of this observation are clearly that near-bottom currents and hence also the near-surface currents will be greatly overestimated if the presence of waves and their effect on the bottom shear stress experienced by a current are neglected.(11)

Madsen considers the entire offshore industry with its activities on the continental shelf as potential supporters and users of his current research. The development of a complete numerical model capable of predicting storm waves, currents and mean sea level elevations is essential for purposes other than establishing design forces. Waves as well as currents are involved in the advection of oil spills and are essential to the general operation of offshore facilities, such as shipping, cleanup and rescue, and storm warning systems. Also, knowledge of wave and current conditions is a necessary prerequisite for a rational approach to sediment transport processes on the continental shelf and in coastal waters. The numerical model could be widely used by agencies such as the US Army Corps of Engineers and state coastal zone management offices.

Economic benefits expected from an improved ability to predict wind waves in finite water depths has been estimated at tens of millions of dollars per year for each of the various categories: offshore structures, submarine pipelines, breakwaters, coastal erosion preventive measures and marine operations.

4.0 What Lies Ahead in Modeling

As computers have become smaller, faster, and less expensive, the cost of running models has decreased. This trend should continue, thus lowering costs still further. However, to take full advantage of the advances in computer hardware, three key issues must be addressed.

1. Application of models to important bays and harbors
2. The need for improved verification programs.
3. The need to get models into the hands of users.

4.1 Application of Models to Important Bays and Harbors

The technology exists to create models for virtually any bay or harbor. Such models would be valuable in helping to set policies and make decisions about competing priorities in the development and use of coastal areas: marine transportation, for example, or recreation, or, in the case of Boston Harbor, sewage disposal.

More work needs to be done to make models more representative of the real world. Existing models, such as CAFE, DISPER, and TEA are two dimensional. Three dimensional models are needed in order to determine the effects of rapidly changing depths and other variables which cause velocity to be a strong function of depth.

Modeling techniques would stand to benefit from improved communication between civil engineers, who tend to concentrate on shallow water monitoring and coastal phenomena, and oceanographers, who are more concerned with the outer continental shelf and the deep ocean.

Another way to improve models is by making them easier to work with, i.e. more user friendly. This includes: human engineering, documentation, and user support.

4.2 Verification Programs

Complex models require verification, by comparison of results obtained from numerical models and field observations. Existing measurement techniques are adequate, but funding is lacking. More consistent funding of data acquisition programs would result in valuable, long-term baseline data that could be used for model verification.

Once regional models are completed, a logical next step would be to set up monitoring stations to detect anomolies in the predicted circulation patterns.

4.3 Access to Models

Making models widely available to industry or academia through a depository of some sort would result in benefits to all involved. There would be cost savings, because each group would not have to develop and run its models independently of the others. Also, there would be benefits in terms of more enlightened decisions arising from the wider use of accurate, well-tested models.

Universities, industry, and government each have a role to play in advancing the development and application of the models discussed in this Brief. University researchers should continue to improve model accuracy, reliability, and efficiency -- and to ensure that these models yield relevant results. They must work to fit actual data into their numerical models.

Industry can play a role in making models more "user friendly", encouraging more widespread use and helping government agencies to apply the models in a realistic fashion.

Government agencies are well positioned to gather data as are some conservation groups and more collaboration between these groups and university researchers would certainly be desirable. Such collaboration would most likely result in modeling techniques and practices that were less expensive, more efficient, and more accurate.

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