Development of a Model for Coastal Waves and Floating Structures

Vijay Panchang
School of Marine Sciences
University of Maine
Orono, ME 04469.
(Presently at: NOAA Sea Grant, Silver Spring, MD 20910)
phone: (301)713-2435 fax: (301)713-0799 email: vijay.panchang@noaa.gov
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LONG-TERM GOAL

Our long-term goal is to develop a comprehensive model to predict coastal surface gravity waves in any harbor (or in any open coastal region also) and their effect on floating objects (e.g. ships and docks) in confined waters. Recent theoretical and applied research will be converted into a practical tool that eliminates the limitations of existing nearshore wave models used by the Navy or the Army Corps of Engineers.

OBJECTIVES

We wish to further develop and provide to the DoD a wave transformation model that includes refraction, diffraction (by bathymetry and structures, islands, etc.), reflection, dissipation by friction and breaking, and the effect of tidal (or other currents) on wind waves and swell. The goal is to make the model simultaneously satisfactorily reliable and efficient (for rapid (possibly onboard) utilization and integration with other models). A further goal is to develop a three-dimensional module (to be interfaced with the wave model) that will utilize predicted wave fields to estimate forces on floating structures in a harbor. Both models will be a part of a suite of flow and wave models (e.g. WAM/SWAN, STWAVE, ADCIRC) that can be used for simulating the overall coastal environment.

APPROACH

The base model, developed previously, is a 2d, finite-element, elliptic, combined refraction-diffraction model that describes the propagation of water waves over an arbitrarily varying sea-bed for the full spectrum of practical wave conditions, irrespective of wave directions and domain shape. Current work involves development of modeling techniques and code modifications to enhance the versatility, reliability, and efficiency of the model. This includes incorporation of new features like improved open and coastal boundary conditions, dissipation mechanisms (breaking and friction), wave-current interaction, wave-wave interactions, steep-slope effects, faster solution techniques, and field validation. This work is done by Professor Panchang and his students at the University of Maine, with the active collaboration of Dr. Z. Demirbilek of the Army Waterways Experiment Station.

WORK COMPLETED

(a) Improving the treatment of open boundaries. Existing models of this category are based on the assumption that the domain exterior of the model domain is of constant depth. This assumption leads

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to spurious predictions. We have constructed a new treatment for the open boundaries based on the assumption that the exterior region can be represented by two one-dimensional sections, one on either side of the model domain, with depths varying in the offshore direction. This is ready for operational use and is found to produce far more acceptable results in harbor applications than previous models.

(b) Improving the treatment of coastal boundaries. For partial reflectivity, existing coastal boundary conditions are accurate only for waves approaching the boundary in a normal direction. We have developed a new nonlinear boundary condition for all angles of wave approach at the internal boundaries. A paper describing this work has been accepted for publication, but the new method is not yet operational.

(c) Improving the speed of model operation. Until recently, model iterations were highly time-intensive, rendering spectral and nonlinear simulations difficult. Code-related issues were therefore tackled, in concert with Dr. Demirbilek and the High Performance Computing staff at the Army WES, to develop a version of the model suitable for parallel processors. Grid construction and graphics were also enhanced with the help of Dr. Demirbilek and Brigham Young University. We identified the most appropriate iterative schemes for rapid solution of the model equations. We investigated the GMRES and the Biconjugate Gradient methods proposed by British researchers as appropriate for this type of model. For practical problems with complex shapes, however, these methods gave marginal, if any, advantage compared with the original schemes developed by Panchang et al. (1991). Further, it was found that only the original schemes were suitable for the inclusion of currents. Modifications were also made to the code to enable DoD users to exploit Cray's proprietary very fast, direct solvers when possible. As a result, after grid-generation, simulations for most harbors can be performed in a matter of minutes. This may be of particular importance when dealing with naval applications involving predictions. (However, this "direct solver" version of the model is available only to DoD users). These developments have been implemented in operational versions. Some of these efforts led to Dr. Demirbilek's recognition through "The Most Efficient Engineering Methodology" Award at the International Supercomputing Conference. The increase in speed now renders it possible to tackle the simulation of wave-wave interactions.

(d) Inclusion of dissipation. Wave breaking algorithms (based on the work of Dally et al. (1985), Battjes and Jansen (1978), Chawla and Kirby (1998), Isobe (1999), and Massel (1992)) and spatially-varying bottom friction were developed and incorporated into the model. The breaking effects were satisfactorily tested against lab data and field data in the North Sea. A paper describing breaking effects in such models has been prepared. Although both the dissipation mechanisms are operational, the effects of variable friction coefficients for harbor entrance losses have not yet been explored.

(e) Validation. In addition to a very large set of "controlled tests" (against analytical solutions or hydraulic model data), simulations of over thousands of frequency and directional components were performed for Barbers Point Harbor, Kahului Harbor, and Los Angeles/ Long Beach Harbor. Modelled resonance effects were found to compare well against field/lab data in Barbers Point and LA/LB harbors. (Comparisons have not been performed for Kahului Harbor as yet). Simulations of waves in Ponce de Leon Inlet and near FRF Duck were also performed for short waves. (These studies are continuing).

(f) Wave-current interaction: The code was modified to include the effects of steady currents, per

Kirby (1984). For the present, the traditional definitions of the wave angles have been used (and not our development in (b)). Two test-cases were successfully simulated: waves propagating through a gyre and waves near a beach with a rip current. We are now planning to simulate hydraulic model tests performed by Jane Smith and others at the Army WES pertaining to wave-current interaction in an inlet. As we proceed, more complex case will demand that we address the problems of open boundary conditions (that include currents) and wave angle definition.

(g) 3d model development. Base code was constructed for 3d simulations in a sub-domain that can include floating (or other) objects like a ship, dock, or pier. It is based on the boundary integral equation method. Basic tests with specified wave boundary conditions were successfully performed for plane wave propagation in an open region and around a pier. This code is capable of taking wave output from another wave model on sub-domain boundaries. We are working on coupling techniques to obtain the combined 2d and 3d solutions simultaneously.

(h) Include steep-slope effects. This work has been completed, based on extensions to the equations developed by Massel (1993) and Chamberlain and Porter (1995), and although tested, the extensions need to be incorporated into the DoD operational version. These extensions are automatically activated if the slopes are steep; no user-control is needed.

(i) A technical manual and user instructions with test-cases were prepared, describing the current model (published by the Army WES). Done in the previous fiscal year.

(j) Wave-wave interaction: will be tackled so that this model provides essentially the same level of nonlinearity as Boussinesq models, and yet retain all the advantages of the finite-element elliptic models. This involves modifying the governing equation per Kaihatu and Kirby (1995) and Tang and Ouellette (1997), who have already established the basic methodology (but with simple forward-propagating models). Their methodology will be applicable to the fully elliptic CGWAVE. The developments in (c) above will ameliorate computational issues greatly.

RESULTS

As noted above, many improvements have been implemented in the currently operational version. Space permits the demonstration of only a few results. No single existing model can obtain all of these results, demonstrating the model's comprehensive nature.

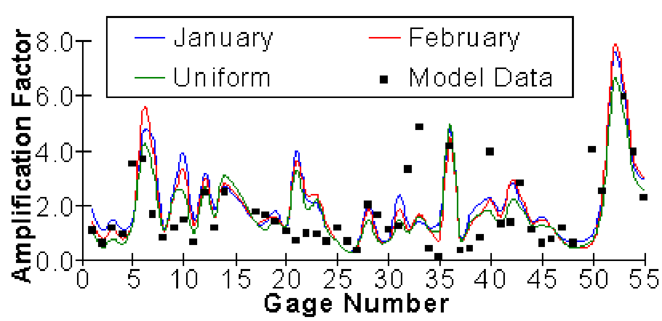

Fig. 1. Wave height comparison at a number of gage locations in Los-Angeles/Long Beach Harbor.

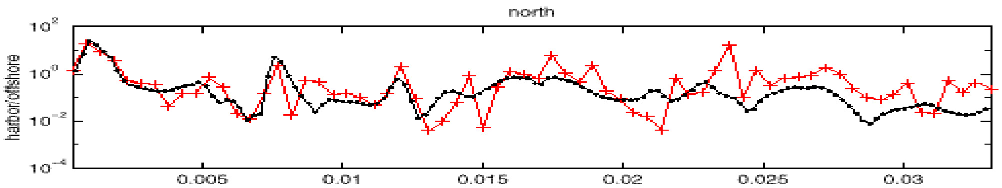

Fig. 2. Amplification factors vs frequency in Herz (resonance curve), model (red line) vs data (black line) for one location in Barber's Point Harbor.

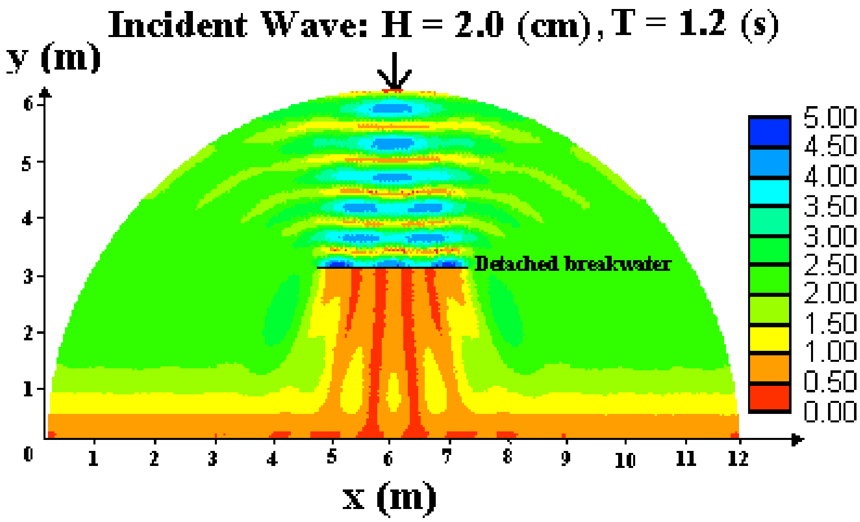

Fig. 3. Simulated wave heights due to reflection, shoaling, refraction, diffraction, and breaking near a detached breakwater on a sloping beach. Results compare very well against lab study of Watanabe et al. (1984).

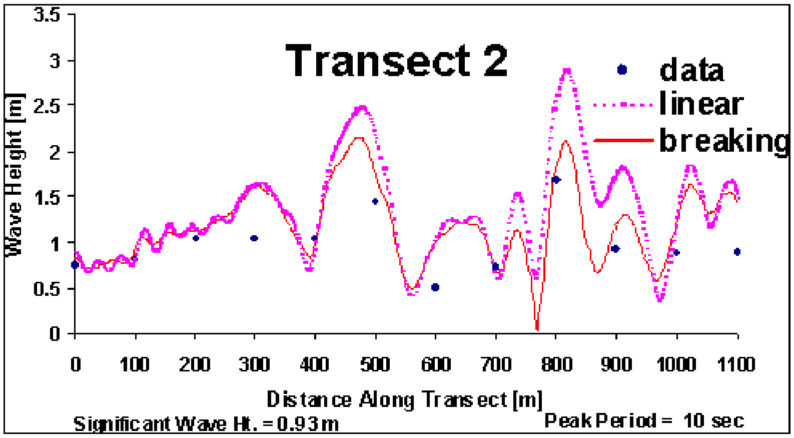

Fig. 4. Wave height comparison along a longshore transect in Ponce de Leon inlet, Florida.

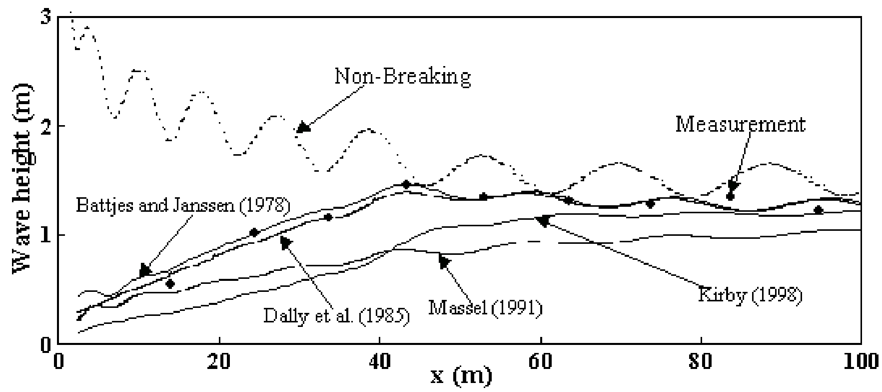

Fig. 5. Simulation of wave reflection, shoaling, and breaking off North Sea coast. Data from Massel (1992).

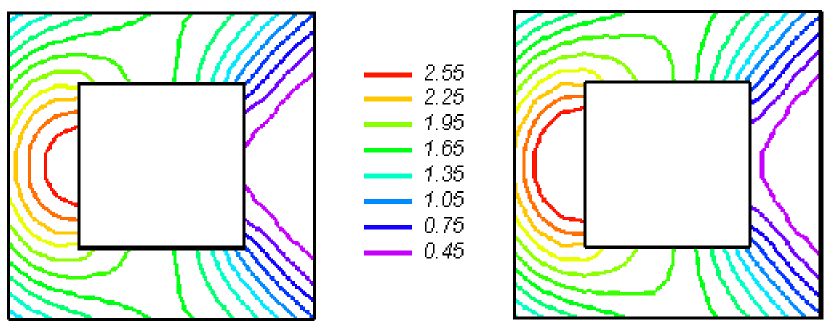

Fig. 6. Wave amplification comparison for wave scattering around rectangular pile; new 3d model (left) vs analytical results (right).

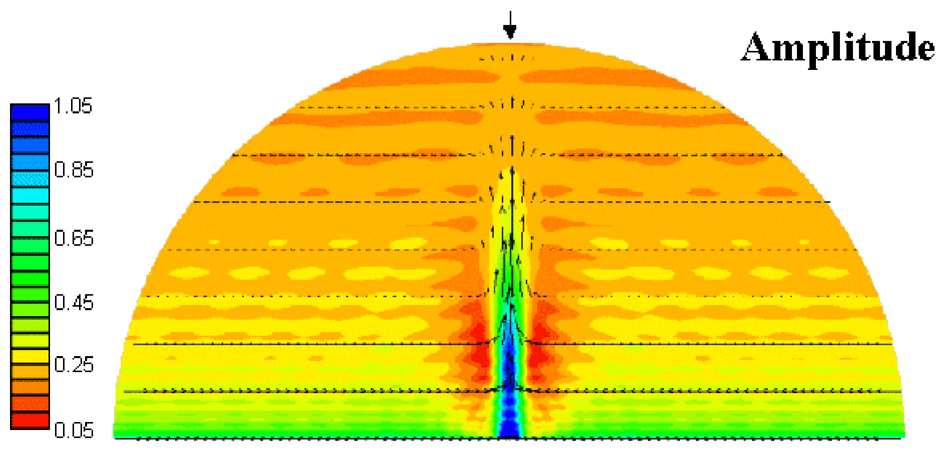

Fig. 7. Simulated wave amplitudes around a rip current (match benchmark solutions of Kostense et al. (1988) very well). Max. current 1.06 m/s; beach slope 1/50; incident wave amp 0.2 m, period 8 s.

IMPACT/APPLICATIONS

The model will provide the Navy with a very sophisticated tool for predicting waves in coastal regions such as harbors, which have arbitrary shapes and depths. The second module will enable estimation of wave forces on structures such as ships, LCAC's, etc. These predictions, if obtained with reliability and efficiency, may influence naval operations such as amphibious or loading and unloading activities. From a civilian perspective, the model is being used by the Army Corps of Engineers in the Aguadilla and Milwaukee harbor projects (contact: Dr. Demirbilek).

TRANSITIONS

We are working with Dr. Demirbilek of the Army WES to transfer this technology to other DoD users (in view of his expertise and his proximity to DoD personnel in Stennis). Recent versions of the model have been transitioned to Dr. Demirbilek and assistance was provided in modifying the code for DoD's high-end computing technology. (In fact, even U.Maine users do not have access to this fast "official" version of the model!) Dr. Demirbilek actively guides our model development to suit DoD needs. We have also worked with Dr. Larry Hsu of the NRL regarding his usage of the model. Modeling for the LA/LB harbor was done at the request of Prof. Synolakis (USC) and for Barbers Point and Kahului harbors in collaboration with Dr. Okihiro (SIO). One version of the model was transitioned to Prof. Ouellet (Laval University) for application to Ste. Therese de Gaspe harbor.

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PUBLICATIONS

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