PART II

Long Period Waves, Storm Surges and Wave Groups

Martin County shoreline, Florida. Photo courtesy of Applied Technology & Management, Inc. and Aerial Photography, Inc.

CHAPTER 98

Uncertainties in the Validation of Harbor Wave Models

Zeki Demirbilek[1], Bingyi Xu & Vijay Panchang[2]

Abstract

Various sources of uncertainties contributing to the difficulties in the validation of harbor wave models with field measurements are discussed in this paper. Some aspects of a new theoretical formulation for removing these uncertainties for estimates of waves in harbors are presented. Implementation of the new formulation is illustrated for waves incident on a planar beach by comparing numerical model predictions to the closed-form analytical solution for normal incident waves and to the results from an one-dimensional Helmholtz equation for oblique waves.

Introduction

Reliable modelling of coastal hydraulic phenomena is vital for commercial and military activities, including harbor design, shoreline evolution, navigation, ship motion during loading/unloading operations, dredging, design of structures, harbor wave agitation, contaminant transport, just a few to name. Military coastal hydraulics deals with amphibious operations, mooring forces, mine movement, and others. Computer models presently play an important role in the ever-increasing coastal activities in some countries, and in the past two decades, industrial activity in the coastal and offshore environment worldwide has witnessed a phenomenal growth. Many nations have quite liberal policies to promote the development of new ports and harbors to meet the need for growing exploration and transport of petro-products, aquaculture, and commerce by shipping. Ongoing and future investment by governments, international participants, and the private sector will further accelerate the use of numerical wave prediction models for coastal projects and design studies.

Although a number of mathematical models have been successfully developed

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[1] U.S. Army Engineer Waterways Experiment Station, Coastal and Hydraulics Laboratory,
3909 Halls Ferry Road, Vicksburg, MS 39180-6199

[2] Department of Civil and Environmental Engineering, University of Maine,
Orono, ME 04469-5706

worldwide for coastal hydraulics, wave modelling confronts us with numerous complexities in the physics and the numerics. Many available models have been developed in a somewhat ad-hoc manner with the immediate needs of a project in mind, and time and budgetary constraints have often taken priority over rigorous model evaluation and systematic development. In fact, many model solutions are perforce accepted at face value, even though model sensitivity to grid resolution, open boundary conditions, parameters associated with various mechanisms, model assumptions, etc. are almost never tested.

This paper addresses a general discussion of some of the key uncertainties in the validation of harbor wave models. Using a state-of-the-art wave model called "CGWAVE", model uncertainties are discussed for a simple application, waves transforming over a plane sloping beach. The CGWAVE model is developed by the US Army Corps of Engineers and the US Navy in collaboration with the University of Maine, for civil and military applications. CGWAVE is a comprehensive and sophisticated finite-element nearshore wave prediction model that can be used for predicting wave climate either in open-coast type applications or in harbors of irregular bathymetry which are surrounded by complex land boundaries and protective structures such as jetties, breakwaters, or islands.

The model CGWAVE is based on the elliptic mild-slope wave equation and can simultaneously simulate the effects of refraction, diffraction, reflections by bathymetry and structures, dissipation due to friction and breaking, and nonlinear amplitude dispersion. The computational capabilities of CGWAVE model permit the modeling of large coastal regions. The model has been compared to several academic test-cases and laboratory data for complex bathymetries (e.g. Panchang et al. 1990, 1991, 1996; Xu and Panchang 1993; Panchang et al. 1993; Panchang & Xu 1995; Xu et al. 1996). The governing equations of CGWAVE pass, in the limit, to the deep and shallow water equations, making this model applicable to a wide range of frequencies, including short wind waves, swell, and infra-gravity waves.

Harbor Models and Applications

The three most widely-known elliptic wave models are HARBD (Chen and Mei 1974; Mei 1983; Chen & Houston 1987), PHAROS (Kostense et al. 1986), and CGWAVE (Panchang et al. 1991; Xu, Panchang & Demirbilek 1996). These steady-state models may either use finite-element or finite-difference schemes for solving the governing equations and associated boundary conditions for calculating the linear wave oscillations in harbors of arbitrary configuration and variable bathymetry. Effects of bottom friction and boundary absorption (reflection) are included. Boundary reflection is based on a formulation similar to the impedance condition in acoustics, expressed as a function of the wavenumber and reflection coefficient.

For modeling waves over an arbitrary depth, these models divide the water domain into near- and far-regions. The near-region, also known as the model domain

(Fig. 1), that includes the actual harbor, is bounded by an offshore boundary, in the form of a semi-circle for HARBD and PHAROS models, and a semi-circle or rectangular-box boundary for CGWAVE. The offshore boundary is a mathematical artifice and typically is located some distance offshore of the harbor entrance. The near-region encompasses the entire harbor area and all its protective marine structures, and part or all of the entrance and approach navigation channels. Water depth in the near-region is generally variable, overlaid with a finite-element triangular-mesh whose grid resolution is determined by the project-specific design wave conditions. Element attributes such as water depth and bottom friction are specified at the centroid of each element. For those elements along the solid boundaries (land or structure), a reflection coefficient is assigned to each element.

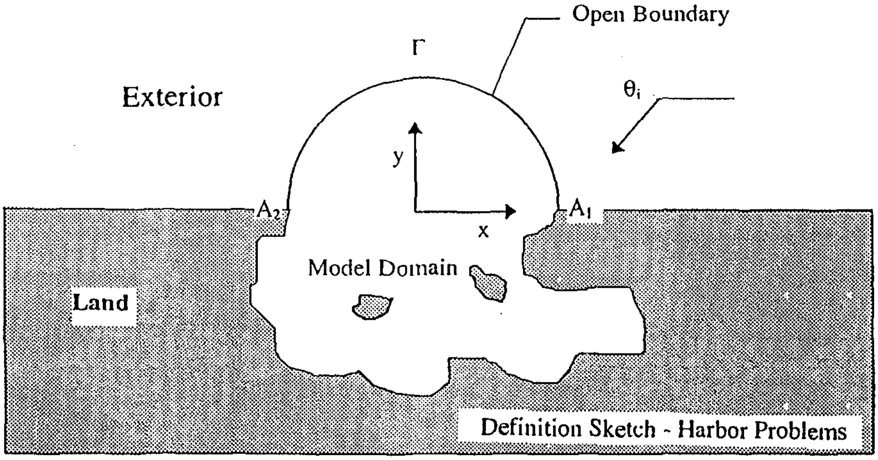

Figure 1. Near- and Far-regions (Model & Exterior Domain) & Open Boundary, Γ.

The far-region, also known as the exterior domain (Fig. 1), of the elliptic wave models covers the domain outside the offshore boundary of the near-region, and is bounded by the coastline and deepwaters of the sea, extending to infinity (Fig. 2). Water depth in the far-region is assumed to be constant for HARBD and PHAROS models, whereas it is treated as variable depth in the CGWAVE model (Fig. 3). Bottom friction and reflection are neglected in the far-region. The constancy of water depth in the far-region for HARBD and PHAROS models permits a simpler analytical solution of waves at the expense of introducing some undesirable depth-discontinuities at the interface between the near-region and the coastlines on either side of the harbor entrance. These discontinuities are one of the major source of difficulties in the validation of elliptic wave models. CGWAVE avoids this problem by considering the water depth in the far-region to be piece-wise continuous by allowing the water depth to change in the cross-shore direction as waves approach the coastlines and the harbor. This is one of the major differences between CGWAVE and all other existing elliptic models. In CGWAVE, the wave field in the far- and near-regions is obtained by solving the one-and two-dimensional Helmholtz equations, respectively. These two solutions are mathematically coupled along the offshore boundary of the modeling domain to obtain the complete wave field estimates in the combined regions.

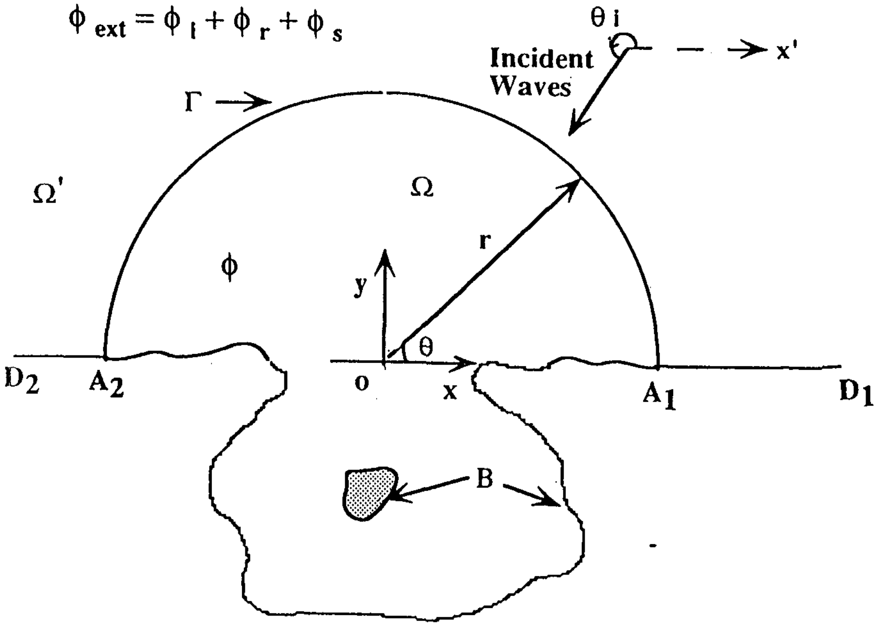

Figure 2. Collinear and Fully-reflective Exterior Coastlines.

Elliptic wave models require a wave period and direction as input, as well as the three-dimensional coordinates for the near-region finite-element mesh. For CGWAVE, grid coordinates for the far-region are also required. In addition, models may require certain parameters for their numerical solvers, which vary from model to model depending on the specific numerical algorithms used to solve the linear system of equations. CGWAVE model uses a Galerkin formulation for dicretizing its equations. The resulting matrix equations are solved iteratively using the so-called conjugate gradient method (CGM). The CGM (Panchang et al. 1991; Li 1994) is a powerful, iterative scheme for solving system of equations without any matrix inversion. The iterative solution scheme of CGWAVE significantly improves our wave modelling capabilities in the nearshore when large domains have to modelled using highly refined grids. While the basic model developed so far incorporates all the nearshore wave transformation mechanisms noted earlier and also includes a graphical user interface, a number of important questions remain. These remaining issues introduce uncertainties into the predictions of models as described in the following sections of this paper.

Uncertainties due to Model Assumptions

Traditional elliptic harbor wave models such as HARBD and PHAROS are based on the assumptions that the exterior sea region outside the computational finite-element grid is of constant depth and that exterior coastlines are collinear and fully reflecting (Figs. 2 & 3). These assumptions are generally not true for most practical applications and their effects on model predictions are substantial (Xu, Panchang, and Demirbilek 1996), resulting in unreliable simulations. This is not surprising since the exterior geometry varies arbitrarily, and the unrealistic bathymetric representation used by modelers should invariably has an adverse influence on model predictions.

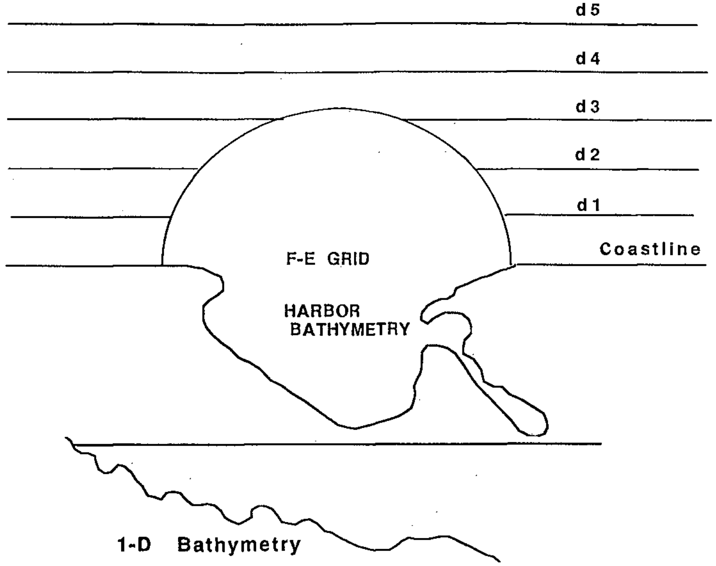

Figure 3. Exterior Domain Bathymetry Representation for CGWAVE model.

A solution to this problem has been to extend the near-region as far as possible to minimize the effects of these assumptions. But, this practice in turn introduces some prohibitive computational resource demands that are difficult to meet. An alternative solution has been developed (Xu, Panchang, and Demirbilek 1996) that eliminates such demands by invoking the use of parabolic approximation as the open boundary condition for the scattered waves. Theoretical details and implementation of this innovative method are omitted here since several illustrations of it practical applications have been presented in that paper.

The requirement that exterior coastlines are fully reflecting is particularly troublesome, almost always giving rise to extremely large wave amplitude estimates and rapidly varying wave patterns in the exterior region of the modeling domain. This has been illustrated by the authors (see Fig. 2 in Xu, Panchang, and Demirbilek 1996), in which CGWAVE predictions for Toothacher Bay, Maine were obatined by forcing CGWAVE to mimic a HARBD-like solution. In this application, using full reflection from exterior coastlines of low reflectivity did clearly lead to erroneous model results, and made the said assumption very problematic. The parabolic approximation treatment of the scattered waves developed by Xu, Panchang, and Demirbilek (1996) does in deed overcome this requirement and allows the modeler much greater flexibility for tackling realistic applications.

In fact, there are a number of sources that give rise to uncertainties in the predictions of elliptic models, including:

- model set-up/open boundary location
- coastal reflectivity
- grid resolution
- parameters (dissipation, etc.)
- forcing (input)

These uncertainties make the validation and comparison of models to field measurements difficult. A brief discussion of the role played by the open boundary in these uncertainties is presented next.

Uncertainties due to Open Boundary

Figure 2 depicts the open boundary Γ, shown as a semi-circular boundary that separates the near-region Ω from the far-region Ω'. The solution of problem, expressed in term of the velocity potential Φ, in the far-region (exterior region) consists of the incident (Φ_i), reflected (Φ_r), and scattered (Φ_s) components, respectively. Both HARBD and PHAROS make use of the Bessel-Fourier series for representation of Φ_s. This traditional approach for determining Φ_s requires (1) depths in the exterior-region Ω' be constant, (2) exterior coastlines A_1D_1 and A_2D_2 be fully-reflecting, and (3) exterior coastlines A_1D_1 and A_2D_2 be collinear. All three requirements which are unrealistic for practical applications, can be avoided using the parabolic representation of Φ_s (Xu, Panchang, and Demirbilek 1996). Advantages of this new approach are that it eliminates requirements (2) and (3). A novel approach for eliminating requirement (1) has also been developed by the same authors and was presented in the ICCE'96. Their proposed solution for eliminating the requirement #1 was to represent the bathymetry in the far-region by a piece-wise continuous one-dimensional (1-D) bathymetry (Fig. 3) to solve the 1-D Helmholtz equation for $\Phi_0 = \Phi_i + \Phi_r$ in the exterior domain. This 1-D solution for Φ_0 and the parabolic solution of Φ_s are then used along the open boundary Γ for coupling of the solutions of the near- and far-regions. Figure 4 presents an illustration of this method for predicting waves on a 3-km long planar beach with a slope of about 1:50 and offshore depth of 54 m. CGWAVE predictions for this problem are next discussed for different incident wave conditions, for both normal incident and oblique waves, and model predictions are compared to the closed-form analytical J_0-solution (Mei 1983) of this problem.

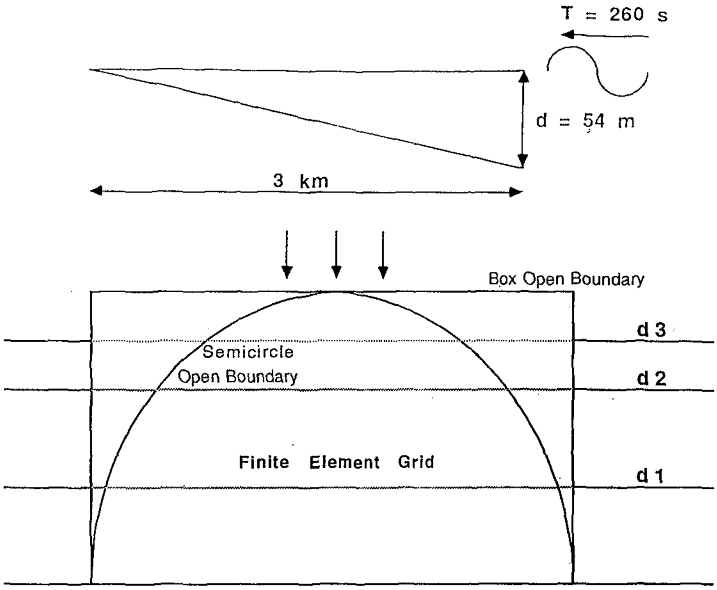

Figure 4. CGWAVE Model Setup for a Planar Beach of About 1:50 Slope.

Discusssion of Waves on a Sloping Beach

In the comparison of CGWAVE to the analytical solution, we examine the performance our model CGWAVE for different sizes of the semi-circle and the cross-shore extent of the exterior domain. Due to space limitations, model results will only be presented at three on-offshore cross-sections. We choose cross-sections 1 and 3 at 500 m from the left- and right-edge of the semi-circle, respectively, and cross-section 2 at the center of the semi-circle. Since the open-boundary related effects manifest themselves mainly near that boundary, the greatest differences between the model predictions and the analytical solution should occur at cross-sections 1 and 3, and the least difference at cross-section 2. In addition, as the size of the semi-circle decreases, the effect of the boundary should become more dominating throughout the entire domain. Conversely, for a larger semi-circle, these effects should be localized in the vicinity of the open boundary.

Figures 5 and 6 represent model versus the analytical solution results for a 3-km domain (i.e. diameter of the semi-circle is 3 km) for normal and oblique incident waves, respectively, of 260 sec period. The agreement between the model and J_0 solution in all three cross-sections is excellent for both normal and oblique incident waves. Since the J_0-solution is for normal incident waves, we provide in Figure 6 a true comparison of the CGWAVE model estimates to the solution from a one-dimensional Helmholtz equation, the exact solution of this problem for 30-degrees

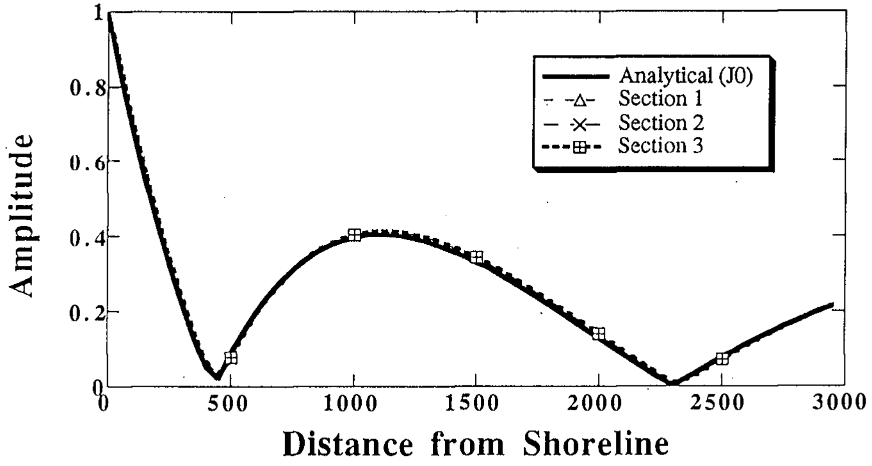

Figure 5. Comparison of CGWAVE Model Predictions versus Analytical Solution at Three Cross-sections for a 3-km Planar Beach (Normal Incident).

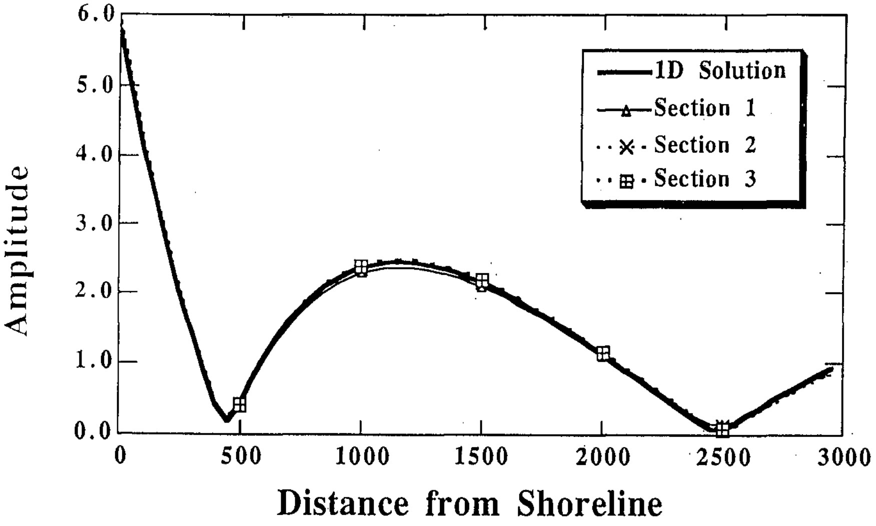

Figure 6. Comparison of CGWAVE Model Predictions versus 1-D Solution (Helmholtz Equation) at Three Cross-sections for a 3-km Planar Beach (Oblique Incident).

oblique waves from left of the normal to the boundary. Model compares extremely well to this solution also at all three sections.

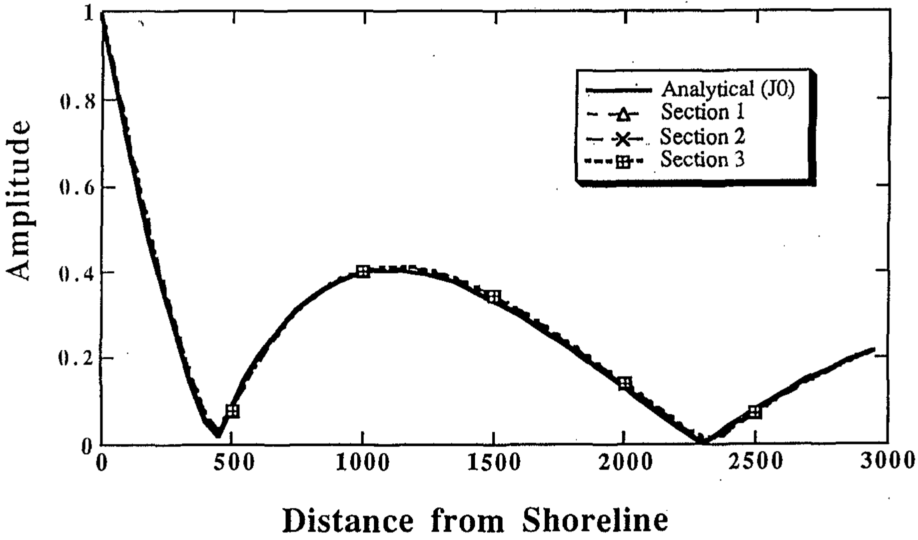

Figure 7. Comparison of CGWAVE Model Predictions versus Analytical Solution at Three Cross-sections for a 2-km Planar Beach (Normal Incident).

The results of CGWAVE model for a 2-km domain are presented in Figs. 7 and 8. For this smaller domain, model estimates still compare exceptionally well to the predictions from the J_0-solution and 1-D Helmholtz equation even though the modeling domain has been reduced by 30 percent. This shows that CGWAVE results are robust and do not vary as the domain size varies.

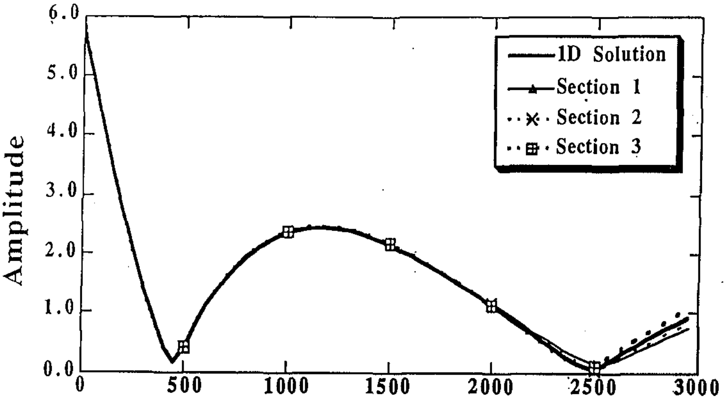

Figure 8. Comparison of CGWAVE Model Predictions versus 1-D Solution (Helmholtz Equation) at Three Cross-sections for a 2-km Planar Beach (Oblique Incident).

Lastly, model results at cross-section 1 are shown for a domain size ranging from 1.5 to 6 km in Fig. 9. We can clearly see a slight change in the model results when the domain size is varied four-fold, but overall, CGWAVE predictions do not show any strong dependence to the size of the modeling domain.

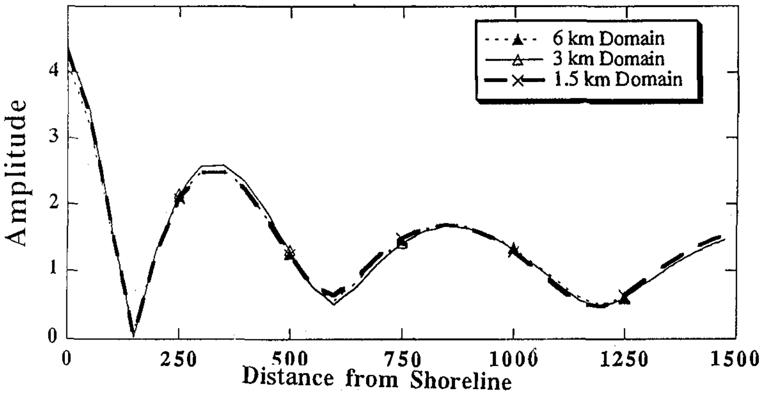

Figure 9. Comparison of CGWAVE Model Predictions versus Analytical Solution at Cross-section 1 for Varying Widths of Beach (Normal Incident).

Conclusions

Elliptic wave models that use the traditional mathematical formulation for wave estimates in the offshore and inside the harbors impose some unrealistic demands as described earlier in this paper. Exterior depth variations in the outside areas of the harbor neglected by these models and the position of the semi-circular open boundary become rather problematic in the field application of these models. Presented here is a discussion of some solutions for eliminating the effects of these undesirable demands. We have demonstrated here the implementation of the proposed solutions for waves on a plane sloping beach by providing a comparison of the model predictions and analytical and approximate solutions.

Our proposed solutions are compromises between an account of the effects of the field bathymetry and radiation boundary condition. The presented model results show that the proposed solutions work very well and that a negligible contamination occurs due to relaxation of the open boundary condition. The suggested solutions eliminate the need to select a constant depth in the exterior region. Our new formulation of the scattered waves greatly reduces the sensitivity of model predictions to the position of the open boundary. Efforts are underway now to evaluate these new ideas implemented in the CGWAVE model for Kahului, Barbers Point, and Oceanside harbors using field measurements.

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References

Chen, H.S., and Mei, C.C. (1974) "Oscillations and Wave Forces in an Offshore Harbors," Rep. 190, Massachusetts of Technology, Cambridge, MA.

Chen, H.S., and Houston, J.R. (1987) "Calculation of Water Oscillation in an Coastal Harbors: HARBS and HARBD User's Manual," Rep. CERC-87-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Kostense, J.K., Meijer, K.L., Dingemans, M.W., Mynett, A.E., and Bosch, P. (1986). "Dissipation in Arbitrarily Shaped Harbors of Variable Depth," Proc. 20th Internat. Conf. Coastal Engr., 2002-2016.

Li, B. (1994). "A Generalized Conjugate Gradient Model for the Mild Slope Equation," Coastal Engr., 23, 215-225.

Mei, C. C. (1983). *The Applied Dynamics of Ocean Surface Waves*, Wiley, New York.

Panchang, V. G., W. Ge, B. R. Pearce, and Briggs, M. J. (1990). "Numerical Simulation of Irregular Wave Propagation over a Shoal," J. Waterway, Port, Coastal and Ocean Engg, vol. 116, No.3, 324-340.

Panchang, V. G. , B. R. Pearce, W. Ge, and Cushman-Roisin, B. (1991). "Solution to the Mild-Slope Wave Problem by Iteration," Applied Ocean Research, 13, No. 4, pp 187-199.

Panchang, V. G., B. Xu and Cushman-Roisin, B. (1993). "Bathymetric Variations in the Exterior Domain of a Harbor Wave Model," Proc. Internat. Conf. Hydroscience & Engg, Washington DC. Ed. S. Wang. 1555-1562.

Panchang, V. G. and Xu, B. (1995). "CGWAVE: A Coastal Wave Transformation Model for Arbitrary Domains," Tech. Report, Dept. of Civil and Environmental Engineering, University of Maine, Oct. 1995.

Panchang, V.G., B. Xu, and Demirbilek, Z. (1996). "Wave Models for Coastal Wave Prediction; A Review," Handbook of Coastal Engineering, Ed. J. Herbich (in print).

Tsay, T.-K., and Liu, P. L.-F. (1983). "A Finite Element Model for Wave Refraction and Diffraction," Applied Ocean Research, 5, No.1, 30-37.

Xu, B. and Panchang, V. G. (1993). "Outgoing Boundary Conditions for Finite-Difference Elliptic Water-Wave Models," Proceedings, The Royal Society of London, Series A. v441, 575-588.

Xu, B., V. G. Panchang and Demirbilek, Z. (1996). "Exterior Reflections in Elliptic Harbor Wave Models," Journal of Waterway, Port, Coastal, and Ocean Engr., Vol.122, 118-126.