WAVE-L: An integrated numerical model for wave propagation forecasting in harbor areas

Ch. Makris[1*], Th. Karambas[1], V. Baltikas[1], Y. Kontos[1], A. Metallinos[2], M. Chondros[2], A. Papadimitriou[2], V. Tsoukala[2], C. Memos[2]

[1]Department of Civil Engineering, Aristotle University of Thessaloniki, Thessaloniki, 54124, Greece
[2]School of Civil Engineering, National Technical University of Athens, Zografos, Athens, 15773, Greece
[*]Corresponding author: cmakris@civil.auth.gr

Abstract

In this paper we present the evolvement of an integrated numerical model (WAVE-L) for the simulation of wave propagation and transformation in areas around and inside ports and harbors. WAVE-L is a high-resolution phase-resolving wave model based on the hyperbolic mild-slope equations, capable of simulating the transformation of complex wave fields over varying bathymetries in harbors and coastal areas in the vicinity of ports. The modeled wave processes include shoaling, refraction, diffraction, total and partial reflection from structures, energy dissipation due to wave breaking and bottom friction in a combined way. The new version of WAVE-L incorporates wave generation simulated on any boundary (longitudinal, lateral or oblique) with corresponding expansion of peripheral sponge layers, providing potential to spatially restrict the computational field in areas adjacent to ports, thus reducing demand of computational time and resources. Moreover, the modified WAVE-L version is able to simulate quasi-irregular, multi-directional waves, whose generation and propagation may furthermore account for various angles and directions simultaneously. WAVE-L is one-way coupled to coarser implementations of an open-sea spectral wave model and a 2-DH hydrodynamic circulation model for storm surges that provide input and boundary conditions. WAVE-L model is thoroughly validated against experimental data on diffraction and multidirectional spectral wave propagation; pilot implementations of it are carried out at the Greek port basin of Thessaloniki. The ultimate goal is to create a tool for high-resolution operational forecasts of wave conditions around and inside significant ports with high traffic load and commercial value (project Accu-Waves).

Keywords Wave model, Wave propagation, Harbor areas, Ports.

1 INTRODUCTION

1.1 Theme of research

In this paper we present the evolvement of a classic, integrated numerical model for the simulation of wave propagation and transformation in coastal areas around and inside ports and harbors. The model is called WAVE-L and it is based on the 2-DH depth-integrated harmonic hyperbolic formulation of the mild-slope equation for wave propagation. Its integrated version under development is intended as a crucial part of a computational tool that will provide reliable 3-day forecasts at 3-hour intervals on prevailing sea states in areas near the certified pathways of port approaches and in regions inside harbor basins (project Accu-Waves; http://accuwaves.eu/). WAVE-L's results will support safer navigation and maneuvering around harbor structures for ships and vessels accessing ports.

1.2 Scope of research

Main goal of this study is to formulate new features of the WAVE-L model in order to make it fully operational, quick and robust for high-resolution forecasts of both monochromatic and spectral wave fields around and inside port basins. A secondary aim is to thoroughly calibrate and validate the WAVE-L model against experimental data of wave propagation and transformation in the field and laboratory flume scales (Vincent and Briggs 1989; Yu et al. 2000). Furthermore, we intend to further manipulate the Fortran codes of the WAVE-L model in order to produce results integrated into a single-suite modeling system for automated operational forecasting of wave characteristics in and around fifty significant ports worldwide (project Accu-Waves; http://accuwaves.eu/). Ultimate goal of research is to develop an operational ensemble of hydrodynamic numerical models (Memos et al. 2019), i.e. an open-seas spectral wave model for wind-induced irregular waves and a barotropic storm surge model for 2-DH hydrodynamic circulation that will provide input data and boundary conditions for the WAVE-L model to produce maps of high-resolution wave height, period and direction data at 3-hour/3-day forecasts for the said ports.

2 METHODOLOGY

2.1 Numerical model

The new version of the previously developed WAVE-L model (Karambas and Samaras 2017) is an evolved rendition of the HARBOUR-L model (Karambas et al. 2010). WAVE-L is a high-resolution phase-resolving wave model based on the hyperbolic mild-slope equations (Copeland 1985) and it is capable to simulate the transformation of complex wave fields in harbors and coastal areas in the vicinity of ports with varying bathymetries (Watanabe and Maruyama 1986). In these areas the modeled wave processes include propagation, transformation, shoaling, refraction, diffraction, total and partial reflection from structures, wave-current interaction, energy dissipation due to depth-limited wave breaking and bottom friction in a combined way (Christopoulos et al. 2012).

2.1.1 Basic equations and assumptions

The basic continuity and momentum equations (mass and quantity of motion conservation, respectively) can be derived by replacing both pressure and velocity distributions that correspond to linear theory (for small amplitude waves) in the linearized Navier-Stokes equations (valid for periodic wave propagation from deep to shallow waters), and thus for numerical simulations of wave transformation in 2-DH (depth-averaged) formulation they can be written as:

$$\frac{\partial \eta}{\partial t} + \frac{\partial (U_w d)}{\partial x} + \frac{\partial (V_w d)}{\partial y} = 0 \tag{1}$$

$$\frac{\partial U_w}{\partial t} + \frac{1}{d}\frac{\partial (c^2 \eta)}{\partial x} - \frac{1}{d}\frac{g\eta}{\cosh(kd)}\frac{\partial d}{\partial x} = v_h \frac{\partial^2 U_w}{\partial x^2} + v_h \frac{\partial^2 U_w}{\partial y^2} - f_b \sigma U_w \tag{2}$$

$$\frac{\partial V_w}{\partial t} + \frac{1}{d}\frac{\partial (c^2 \eta)}{\partial y} - \frac{1}{d}\frac{g\eta}{\cosh(kd)}\frac{\partial d}{\partial y} = v_h \frac{\partial^2 V_w}{\partial x^2} + v_h \frac{\partial^2 V_w}{\partial y^2} - f_b \sigma V_w \tag{3}$$

where η is the wave-induced free-surface elevation, d is the still water depth of the sea, U_w and V_w are the depth-integrated horizontal velocity components along the x and y axis, respectively, $k=2\pi/L$ is the wavenumber, L is the local wave length, c is the wave (phase) celerity, $\sigma=2\pi/T$ is the wave angular frequency, f_b is the normalized bed friction coefficient, v_h is the horizontal eddy viscosity coefficient.

Depth-limited wave breaking in shoal areas can be modeled by using the eddy viscosity concept for Reynolds stresses via a coefficient v_h in the r.h.s. of the momentum equations (Eqs. 2, 3), which is given by (Battjes, 1975), where D defines the energy dissipation due to wave breaking, and coefficient Q_b can be derived based on the assumption of a Rayleigh distribution for wave trains in nearshore areas from the following equations:

$$v_h = 2h\left(\frac{D}{\rho}\right)^{1/3} \tag{4}$$

$$D = \frac{1}{4} Q_b f_s \rho g H_m^2 \tag{5}$$

$$\frac{1-Q_b}{\ln Q_b} = \left(\frac{H_{rms}}{H_m}\right)^2 \tag{6}$$

where f_s is the mean spectral frequency ($f_s=1/T_m$, T_m mean spectral wave period), H_m is the maximum wave height with $H_m=\gamma d$, γ is the wave breaking parameter ($\gamma\approx0.55$-1.0), Q_b is the percentage of breaking waves at a particular depth d, and H_{rms} is the root-mean-square wave height $H_{rms}=2(<2\eta^2>)^{1/2}$ and brackets < > denote time-averaged values. It is inferred that for the total prevalence of breaking waves $Q_b=1$ whereas for non-breaking waves $H_{rms}<<H_m$, i.e. $Q_b<<1$. This modeling approach can describe breaking of random waves in complex bathymetries, conforming to the requirements of operational random wave forecasts and consequent newly added features of WAVE-L (see §2.1.2). Bottom friction energy dissipation is modeled using the linearized (normalized by local depth d) terms in the r.h.s. of the momentum equations (Eqs. 2, 3) in *x*- and *y*-directions of the Cartesian horizontal plane. The linearized bottom friction coefficient f_b is a function of the wave-induced velocity and the wave friction coefficient f_w, following the relationship:

$$f_b\sigma = \left(\frac{1}{2} f_w \sqrt{U_w^2 + V_w^2}\right)/d \tag{7}$$

2.1.2 Innovative features

In the new proposed version of the WAVE-L model, wave generation can be simulated both on lower-'South' and lateral boundary simultaneously, with corresponding expansion of the peripheral sponge layers (Larsen and Dancy 1983) by an exponential damping factor of wave energy content, $DF(x)$ as:

$$DF(x) = \exp\left[\left(b^{-x/\Delta x} - b^{xs/\Delta x}\right)\ln 2\right] \tag{8}$$

where x_s is the width of the sponge layer, b=1+r_s+exp(-1/r_s) where r_s=10/t_s (t_s is the number of grid points inside the sponge layer). In this way, we are now capable to spatially restrict the computational field in areas adjacent to harbors and thus reduce demand of computational time and resources.

Moreover, the existing version of the model is modified to simulate multi-directional, quasi-irregular waves (spectral waves propagating with single group celerity). The generation and propagation of spectral waves may furthermore account for several different angles and directions simultaneously, practically following the modeling approach of Lee and Suh (1998) that provides the directional spreading function $D(f,\theta)$ by the Fourier series representation for the wrapped normal spreading function (see also Vincent and Briggs 1989) as:

$$D(f,\theta) = \frac{1}{2\pi} + \frac{1}{\pi}\sum_{n=1}^{N} \exp\left[-\left(\frac{n\sigma_m}{2}\right)\right] cos[n(\theta - \theta_m)] \tag{9}$$

where N is the number of terms in the series, θ_m is the mean wave direction (0° or 45° in our test cases), and for each case of θ_m, σ_m the directional spreading parameter (either 10° or 30° in our tests).

Partial and full reflection of incipient waves from harbor structures are modeled based on an updated version of the Karambas and Bowers (1996) modeling approach of an extra dissipation term in the momentum equations inserting a turbulent eddy viscosity coefficient, which is calculated via a system of complex equations (based on a complex wave number K) of the friction coefficient f_s, thus allowing to solve them iteratively for given values of the reflection coefficient R_s from literature.

2.2 Application study

Pilot implementation of the new WAVE-L model is carried out at the three largest Greek harbors, namely the ports of Patra, Piraeus and Thessaloniki (Figure 1). Fine resolution bathymetric depth charts are produced by digitizing 1:5000 maps of the Hellenic Navy Hydrographic Service (HNHS; https://www.hnhs.gr/) and interpolating by the Kriging method. The mild-slope equation model is one-way coupled to a coarser 3rd generation spectral wave model (TOMAWAC) for input boundary conditions; the port area of typically ≤10 Km^2 (Figure 1) is integrated in larger domains. It also receives input of local changes in bathymetry, viz. mean sea level elevation, from a barotropic 2-D hydrodynamic circulation model for storm surges (HiReSS; Makris et al. 2019).

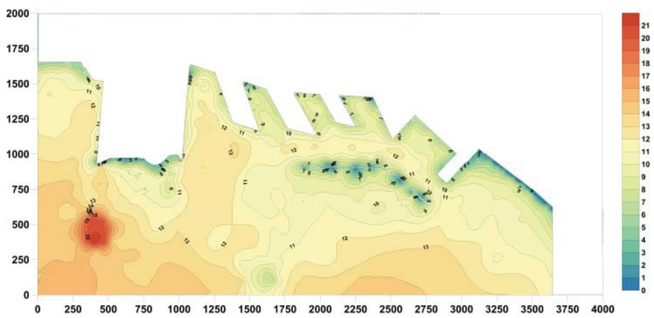

Figure 1 Bathymetry chart of Thessaloniki Port basin (six jetties and piers and one protective breakwater); contours and color bar refer to depth. X- and Y-axis refer to distances in m from arbitrary start point.

3 RESULTS

The results mainly concern gridded fields and relevant maps of wave characteristics (height, period and angle of propagation direction) for both regular and quasi-irregular wave fields of very high spatial resolution, i.e. discretization step of $dx \leq 2$m, at 3-hourly time intervals covering the needs of 3-day forecasts, leading to 24 representations of sea-states per daily model implementation. Model results support the approaching procedures of vessels to port and harbor basins.

3.1 Model validation

Evaluation of the WAVE-L model's performance is conducted by comparisons of simulation results with experimental data of multi-directional irregular wave diffraction around semi-infinite breakwaters and through breakwater gaps (Yu et al. 2000; Li et al. 2000). The elliptical shoal experimental setup by Vincent and Briggs (1989) with a directional spectral wave generator is also numerically reproduced with WAVE-L as a test. Figure 2 presents satisfactory comparisons of model results against experimental data of both implementations, in terms of normalized wave heights H/H_o, H_o is the offshore wave height (upper graphs), and diffraction coefficient K_D (lower graphs), respectively. All cases refer to new WAVE-L model implementations for spectral waves in several directions.

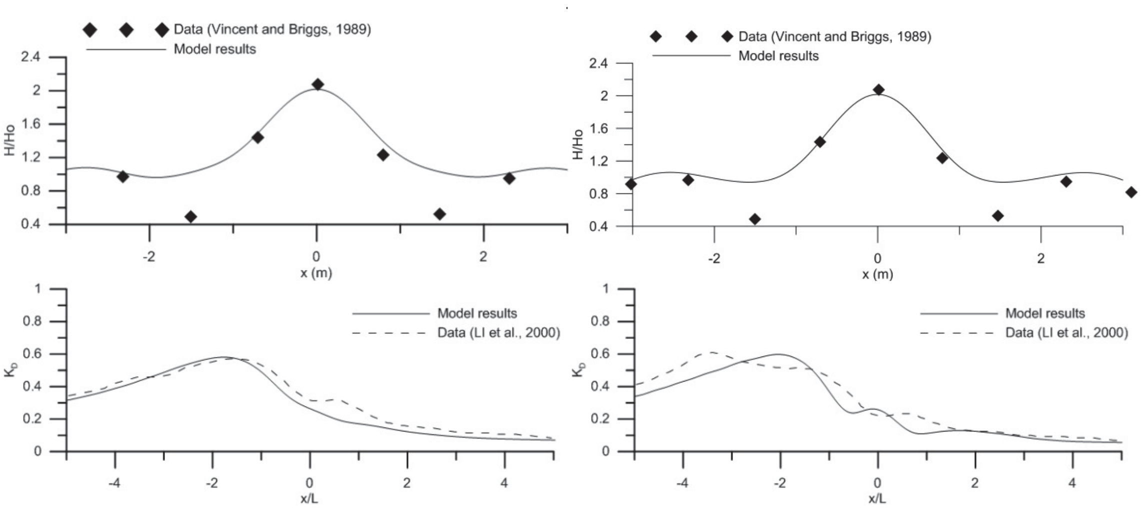

Figure 2 Comparisons of WAVE-L modeled results against experimental data of Vincent and Briggs (1989) and Li et al. (2000), in terms of normalized wave height H/H_o (upper graphs), for spectral waves in experimental cases U3 and B3 [left and right graphs, respectively], and diffraction coefficient K_D (lower graphs) for experimental data of unidirectional irregular waves (spreading parameter $s=\infty$ and initial angle of propagation $\theta_o=45°$) and multi-directional irregular waves ($s=19$ and $\theta_o=45°$) [left and right graphs, respectively].

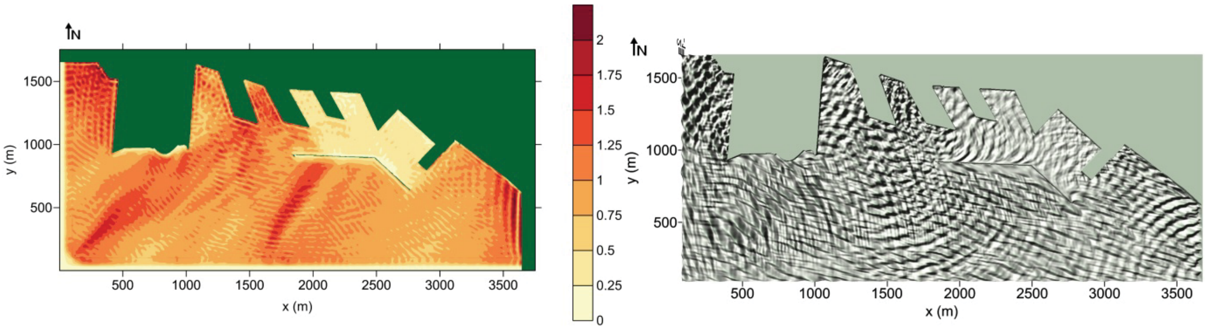

Figure 3 Results charts in the Thessaloniki Port basin for significant wave height H_s (color bar in m) [left graph] and surface elevation η [right graph] for quasi-irregular multi-directional wave fields, respectively.

3.2 Case study

Figure 3 presents plotted results concerning simulated fields of gridded data (dx=2m) for H_s (left panel) and η (right graph), depicting steady state conditions of extreme cases (H_o=2m) for southern seas as narrow spectral wave fields. The protection offered by the sub-aerial breakwater is obvious in the first case, as transmitted H_s is decreased by diffraction reaching hardly up to 1/4 of the offshore wave height on the open boundary. Reflection patterns of quasi-irregular surface elevation are also visible in the port basin fir the second case of spectral wave propagation, i.e. multidirectional harsh southern sea states.

4 CONCLUSIONS

WAVE-L is validated by comparisons of model output against experimental data by classic laboratory physical simulations for regular and spectral waves. It is proven to adequately simulate the wave propagation in nearshore areas over uneven bottoms and specifically inside harbors, around and on the leeward side of breakwaters, incorporating wave-structure interaction and plausible diffraction modeling. The new WAVE-L results will hopefully address significant needs such as safe spatial and temporal planning of navigation towards and inside ports, port operations to and from mooring sites, while facilitating the ship-pilot and port-navigator consultation. This should eventually allow for more efficient management of the navigation and towage services, such as berth positions assignment according to short-term weather forecasting. The presented Thessaloniki Port case corroborates that.

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