WAVE MODELLING IN THE WISE GROUP

L. Cavaleri[1] and L.H. Holthuijsen[2]

ABSTRACT

The WISE group is a group of investigators who have agreed to jointly (i) study the physical processes affecting waves in shallow water, (ii) develop numerical codes to explicitly represent these processes in operational models and (iii) verify these wave models in real coastal conditions. The group meets once per year in Europe or North America to discuss progress and coordinate future plans. Since the first meeting in 1993, interesting results have been obtained in all of the three aspects, including operational third-generation spectral wave models for shallow water (one of which has been released in public domain).

INTRODUCTION

When in 1992 the highly successful third-generation wave model WAM for ocean applications (WAMDI group, 1988; Komen et al., 1994) was completed, several members of the WAM group turned their attention to coastal regions where of course they encountered coastal engineers with their large diversity of wave models notably the second-generation HISWA model (Holthuijsen et al., 1988). In the following year, these WAM members and members of the HISWA group and others met and decided to jointly approach the study of Waves In Shallow water Environments (WISE). In this first meeting the WISE group agreed to develop (operational) wave models for coastal regions in which all relevant physical processes would be represented explicitly. Three tasks were correspondingly defined: (i) to study the physical processes affecting waves in shallow water, (ii) to develop numerical codes to represent these processes in operational models and (iii) to verify these wave models in real coastal conditions. We wish to emphasize that the WISE group does not necessarily exhaust all the activities in the field. However, it includes a fairly large and comprehensive part of it.

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[1] Istituto Studio Dinamica Grandi Masse, 1364 San Polo, 30125 Venice, Italy

[2] Delft University of Technology, Department of Civil Engineering and Geosciences, Stevinweg 1, 2628 CN Delft, the Netherlands

THE WISE GROUP

The WISE group is an informal group of some 50 active members (individuals) from some 15 countries, mostly from Europe and N. America but also from Australia, Japan, S. America and the Middle East. The home institutions of these members are both public and private with a wide range of interests from applied research to daily marine operations (e.g., ministries, harbour authorities, army & navy, universities, research institutions, consultants). The WISE group as a whole is coordinated by the present authors. The group meets once every year, alternating between Europe and N. America. Meetings were held in Thessaloniki (Greece, 1993), Ensenada (Mexico, 1995), Venice (Italy, 1996), San Francisco (USA, 1997) and Leuven (Belgium, 1998). The next meeting shall convene in Annapolis (USA, 1999). The WISE group has three working groups corresponding to the above three tasks. Each group communicates and coordinates common interests (e.g., joint funding, exchange of visiting scientists and students, computer codes and observational data). During the meetings, scientific and operational progress in each group is reported in plenary meetings which are also used to discuss common interests such as large-scale joint efforts, funding opportunities and sharing of data and computer codes. The WISE meetings are organized in a very informal way, without any written report or proceedings, and with an open continuous discussion during and after the individual presentations. The latest findings are regularly shown at the meeting for constructive discussion about future steps. The WISE group as such is not funded by any agency but some (subgroups of) WISE members are funded contingent on their participation in the WISE group and their willingness to share results with other WISE members.

SHALLOW-WATER WAVE MODELS

Two families of numerical wave models can be used effectively in shallow-water. These are (a) phase-resolving models which are based on vertically integrated, time-dependent mass and momentum balance equations and (b) phase-averaged models, which are based on a spectral energy (or action) balance equation. The phase-resolving models require a spatial resolution that is a small fraction of the wave length. They are therefore limited to relatively small areas of the order of a dozen wave lengths (i.e. order of 1 km). The phase-averaged models do not require such fine resolution so that they can be used in much larger areas, the limitation being the size of the ocean basin (with the conventional resolution of 50 - 100 km for ocean applications). The reason for using both models is that some processes cannot be adequately handled in one or the other. For instance, diffraction and triad wave-wave interactions can at present not or only approximately be modeled in phase-averaged models whereas wind-generation cannot be modeled in phase-resolving models with any operational feasibility. Since the first WISE meeting in 1993, the role of these types of models in the group has evolved. The interest of most WISE members is aimed at the region between the deep ocean and the surf zone (it includes islands, shoals, tidal flats and estuaries; e.g., Fig. 1). This has resulted in a support-oriented role of the phase-resolving models (source of basic results) and an operationally-oriented role for the phase-averaged models (source of operational products). It must be emphasized that this evolution in the WISE group does not distract from the operational importance of the phase-resolving models in small-scale areas where they may well perform better than any phase-averaged model (in particular when diffraction is important).

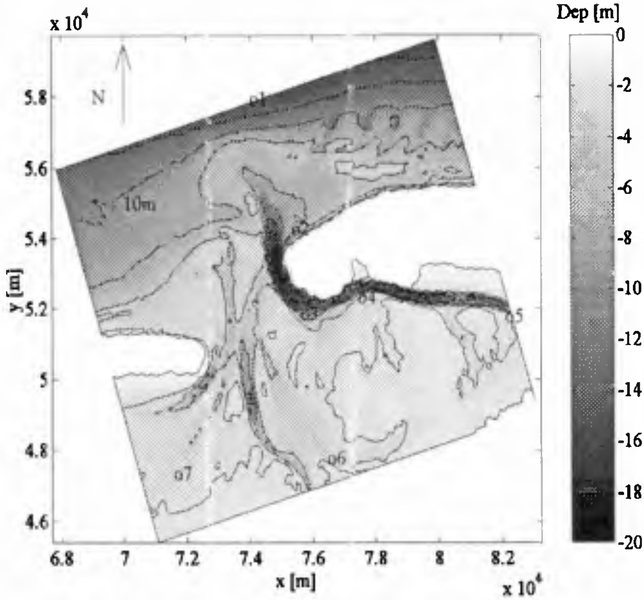

Fig. 1 An example of the type of area of interest to the WISE group: the Nordemeyer Seegat (Germany). Depth contour lines with 2 m interval.

Phase-averaged energy balance models are often formulated in terms of the two-dimensional energy density varying in spectral space, geographic space and time, $E(\sigma,\theta;x,y,t)$. The energy balance can then be written as (e.g. Hasselmann et al., 1973):

$$\frac{\partial}{\partial t}E + \frac{\partial}{\partial x}c_x E + \frac{\partial}{\partial y}c_y E + \frac{\partial}{\partial \sigma}c_\sigma E + \frac{\partial}{\partial \theta}c_\theta E = S \tag{1}$$

The first term in the left-hand side of this equation represents the local rate of change of energy density in time, the second and third term represent propagation of energy in geographical space (with propagation velocities c_x and c_y in x- and y-space, respectively). The fourth term represents shifting of the relative frequency due to (time) variations in depths (with propagation velocity c_σ in σ-space). The fifth term represents depth-induced refraction (with propagation velocity c_θ in θ-space). The expressions for these propagation speeds can be taken from linear wave theory (e.g., Mei, 1983; Dingemans, 1997). Interactions with ambient currents are readily included by extending all of these propagation speeds consistent with linear wave theory and by replacing energy density in the balance equation by action density (defined as the energy density E divided by the relative frequency σ). This formulation is for Cartesian coordinates. It is readily changed into a formulation in spherical coordinates for applications on oceanic scales. The term S $(=S(\sigma,\theta))$ at the right hand side of the action balance equation is the source term in terms of energy density representing the effects of generation, dissipation and nonlinear wave-wave interactions.

The most important phase-resolving models are Boussinesq models. These are essentially wave propagation models without source terms and they are commonly formulated in terms of the surface elevation and some depth-averaged velocity (the long-wave equations corrected for the vertical velocity distribution), e.g.:

$$\begin{aligned}
&\frac{\partial \eta}{\partial t} + \frac{\partial \{(h+\eta)u_x\}}{\partial x} + \frac{\partial \{(h+\eta)u_y\}}{\partial y} = 0 \\
&\frac{\partial u_x}{\partial t} + u_x \frac{\partial u_x}{\partial x} + u_y \frac{\partial u_x}{\partial y} = -g\frac{\partial \eta}{\partial x} + \sum C_x \\
&\frac{\partial u_y}{\partial t} + u_x \frac{\partial u_y}{\partial x} + u_y \frac{\partial u_y}{\partial y} = -g\frac{\partial \eta}{\partial y} + \sum C_y
\end{aligned} \tag{2}$$

in which η is the sea surface elevation, h is mean water depth, u_x and u_y are the depth averaged velocity components in x- and y-direction respectively, g is gravitational acceleration and $\sum C$ is the sum of all correction terms to represent effects of the vertical velocity distribution. Some Boussinesq models include processes of dissipation by adding particular boundary conditions at the surface, notably a roller to represent depth-induced breaking (e.g. Schäffer et al., 1993).

Recent developments which integrate the two approaches of the energy balance and the Boussinesq models are reported below.

ACHIEVEMENTS

Most of the progress in task (i) of WISE has come from the phase-resolving models, providing input for the development of the phase-averaged models. The most fundamental development here has been an explicit formulation for the evolution of wave phases in shallow water which can be used in energy balance models. It involves the introduction of the bispectrum. Representing the random surface elevation in the Boussinesq equations as the sum of a large number of harmonic components with complex amplitudes eventually leads to evolution equations for amplitudes and biphases (or the bispectrum). The bispectrum $B(\sigma_1,\sigma_2)$ is defined as the Fourier transform of the third-order correlation function $R(\tau_1,\tau_2)$, analogous to the definition of the energy density spectrum $E(\sigma)$ which is defined as the Fourier transform of the second-order correlation function $R(\tau)$:

$$\begin{aligned}
E(\sigma) &= \int_{-\infty}^{+\infty} R(\tau)\exp(-i\sigma\tau)\, d\tau \\
B(\sigma_1,\sigma_2) &= \int_{-\infty}^{+\infty} R(\tau_1,\tau_2)\exp[-i(\sigma_1\tau_1 + \sigma_2\tau_2)]\, d\tau_1\, d\tau_2
\end{aligned} \tag{3}$$

where τ, τ_1 and τ_2 are time lags. The essence of the bispectrum is that it represents the coupling between triads of wave components with phases φ_l, φ_m and φ_{l+m}. Madsen and Sørensen (1993) thus obtained a discrete spectral version of the (phase-resolving) Boussinesq model which explicitly formulates the triad wave-wave interactions. In deep water these interactions can be ignored but in shallow water they often generate a secondary, high-frequency peak in the wave spectrum. This spectral Boussinesq model is phase-resolving in the sense that the phases of the wave components are an integral part of the formulation (in contrast to the random-phase assumption in phase-averaged models). Because of its spectral nature, it allows a blending with phase-averaged models in a hybrid approach: the energy balance equation (partially dependent on the biphases) can be supplemented with a phase evolution equation (which in turn depends on the energy spectrum). The first step in implementing this explicit formulation of triad interactions in a phase-averaged model was taken by Eldeberky and Battjes (1995). They used an approach somewhat similar to the discrete interaction approximation (DIA) of the quadruplet wave-wave interactions of Hasselmann et al. (1985) for deep water. Eldeberky and Battjes consider only self-self triad interactions for uni-directional waves in their model (the lumped triad approximation, LTA, Eldeberky, 1996) and they avoided the use of an explicit phase-evolution equation by locally estimating the biphase $\varphi_l + \varphi_m - \varphi_{l+m}$ from the local wave steepness and local relative water depth (Ursell number). The next step, i.e. to fully blend the spectral energy balance model with a bispectral model has been taken by Herbers and Burton (1997). They explicitly compute the biphase and the energy density of short-crested waves on a plane beach in the absence of generation and dissipation. It should be relatively straightforward to expand this propagation model to arbitrary bathymetry. But adding source terms to represent the effect of generation and dissipation of wave energy on the biphase seems difficult.

Another phase-resolving model, the mild-slope equation (Berkhoff, 1972) is the basis for attempts to include diffraction in phase-averaged models. The essence is that diffraction modifies the conventional dispersion relationship from the linear wave theory and consequently the refraction term in the phase-averaged models (the propagation velocity c_θ in θ-space, Booij et al., 1997; Rivero et al., 1997):

$$c_\theta = \frac{c_g}{k}\frac{\partial k}{\partial m} + \frac{c_g}{2(1+\delta)}\frac{\partial \delta}{\partial m} \tag{4}$$

where $\delta = \nabla\cdot(cc_g\nabla a)/k^2cc_g a$ and in which k is the separation constant (e.g. Dingemans, 1997), determined from linear wave theory with $\sigma^2 = gk\tanh kd$ (normally referred to as the wave number $2\pi/L$ where L is the wave length but not in this context where the difference is essential). The phase speed is c, the group velocity is c_g and m is the direction normal to the wave direction. The first term in the right-hand side of Eq. (4) is the conventional refraction representation and the second term is obviously the diffraction addition in terms of the amplitude a of a harmonic wave. A spectral formulation of diffraction (i.e. in terms of energy or action density) is not available. Since the second-order derivatives in the expression for δ are linear in amplitude, an ad-hoc approach would be to replace the amplitude by the square root of energy density $E = E(\sigma,\theta)$ per spectral wave component $\delta \approx \nabla\cdot(cc_g\nabla\sqrt{E})/k^2cc_g\sqrt{E}$. Preliminary attempts to compute diffraction in this way are being made (Booij et al., 1997; Rivero et al., 1997), but an adequate numerical formulation has not yet been developed.

Progress with phase-averaged modelling in this task (i) as been mostly in depth-induced breaking. It has been observed in laboratory conditions (e.g., Battjes and Beji, 1992; Vincent et al., 1994) that depth-induced wave breaking of waves with a unimodal spectrum hardly affects the shape of the spectrum (the changes in spectral shape are mostly due to triad wave-wave interactions). This has led to a simple spectral version

(Eldeberky and Battjes, 1995) of an earlier expression for the overall dissipation of waves breaking in shallow water that is based on a bore model (Battjes and Janssen, 1978; Thornton and Guza, 1983). Outside the WISE group Elgar et al. (1997) have shown with a detailed analysis of observations that the dissipation is often proportional with the square of the frequency. But the effect of this on the spectrum seems often to be masked by the simultaneous effects of triad wave-wave interactions (Chen and Guza, 1997). More observations in the surf zone will further contribute to the understanding of this phenomenon.

In task (ii) the main progress has been achieved with new numerical codes of phase-averaged models and adaptations of the WAM code. A serious problem with the codes of phase-averaged ocean wave models such as the WAM model (but also similar third-generation models such as the WAVEWATCH model, Tolman, 1991) for applications in shallow water is that their numerical schemes are explicit. This implies that they are subject to the Courant criterion of numerical stability: the time step in the computations is limited by the spatial resolution of the model. In open ocean applications this is usually not a problem (the spatial resolution is of the order of 100 km and the propagation time step is of the order of 15 min). For coastal applications however this is a problem because the required spatial resolution is often of the order of 100 m or less and the corresponding time step would be about 10 s or less in water of 10 m depth. This is operationally unacceptable and new ways for integrating the energy balance have to be found. One successful optimization has been to use a larger time step for integrating the physical processes than for wave propagation (the WAVEWATCH model, Tolman, 1991; the WAM model, Luo et al., 1997). This permits reasonably efficient computations down to a spatial resolution of about 1 km (in particular on vector machines, as these models vectorize well). Another attempt is being made with a hybrid scheme: piecewise propagation along rays between grid points (in the TOMAWAC model of Benoit et al., 1996). This numerical scheme is unconditionally stable but time steps larger than corresponding to the spatial resolution (i.e. $\Delta t > \Delta x / c_g$) ignore the variations in the physical processes at that spatial resolution since spatial variations in the processes are not considered within the time step Δt. This approach is therefore still subject to the Courant criterion (for reasons of spatial resolution of the physical processes rather than numerical stability). An implicit scheme that avoids the stability problem has been developed by Booij et al. (1996) in their SWAN model. It sweeps through the computational area in four 90° quadrants with an upwind scheme that is unconditionally stable and does not suffer from the limitation of the hybrid approach. However, the present implementation is based on a first-order, upwind scheme which is rather diffusive. This seems acceptable for small-scale regions (25 km or less) but it needs to be replaced by a higher-order scheme for larger scales. It operates on arbitrarily small spatial resolution (varying from 1 km to 10 m in field conditions to 0.1 m in laboratory conditions). A third-order upwind scheme is presently being developed in SWAN for Cartesian and spherical coordinates (which would allow long-distance propagation over the oceans). The TOMAWAC model and the SWAN model are extensions of the WAM model in the sense that they supplement the processes that are represented in the WAM model (Cycles 3 and 4 of that model) with the LTA of the triad wave-wave interactions, spectral depth-induced wave breaking and several options for bottom friction. Vectorization has not been considered in the design of SWAN as it is aimed at relatively small (nonvectorizing) computers. Like the WAM model, to all intents and purposes the SWAN model is available in the public domain (home page, http:// swan@ct.tudelft.nl).

To validate numerical wave models that are being developed, a standard test bank is under construction containing academic cases of wave propagation in deep and shallow water with and without ambient currents for which analytical solutions are available. Real field cases with detailed observations are also included. Some are fairly complex (e.g., tidal inlets), others are sufficiently simple that they can be generalized (e.g. idealized fetch-limited wave generation).

The wave models often need coupling to other models, either to be driven by models such as atmospheric and circulation models or to drive other models such as circulation models (with wave induced radiation stresses) and morphodynamic or ecological models. Also, some wave models need to be nested into other wave models to achieve high-resolution results or to shift to other physical processes (e.g. to include diffraction). Work in these aspects is being carried out at several levels in the WISE group. From a scientific point of view the effect of wind variations in coastal regions is being investigated by coupling coastal atmospheric models with coastal wave models (in particular orographic and boundary-layer effects along mountainous coastlines and behind barrier islands). The effects of tidal currents on the coastal wave climate are similarly investigated by coupling coastal wave models with tide-driven coastal circulation models. To numerically accommodate such interactions with circulation models, the TOMAWAC model is formulated on a triangular grid and the SWAN model has recently been adapted to operate on a non-orthogonal curvi-linear grid. To carry out computations from large scale to small scale, the SWAN model can be nested into the WAM model (SWAN accepts output directly from the WAM model; Luo and Flather, 1997). To pre- and post-process the input and output of such sets of models (both numerically and graphically), dedicated tools are being developed based on ARCINFO (Kaiser, 1994), ARCVIEW and MATLAB.

In task (iii) a number of fairly large field campaigns has been carried out with very useful results. A most interesting field campaign was carried out in nearly ideal shallow-water generation conditions in Lake George in Australia (e.g. Young and Verhagen, 1996). The observations of this campaign provide much needed characteristics of the wind-induced growth of waves in limited water depth. It has already served (and will continue to do so) to verify or calibrate models of the WISE group. Several other large field campaigns have been executed off fairly open coasts along the east coasts of the USA and England and along the rather convoluted coast in the north of the Netherlands and Germany. It is expected that the wave models of WISE members will be verified against these observations. Such verification has already been carried out for the SWAN model (Figs. 2 and 3). The rms-error of the significant wave height and mean wave period computed with SWAN in these (and other, similar) conditions was typically about 10% of the incident values (note that locally the relative error can be much larger as the local waves may be much lower).

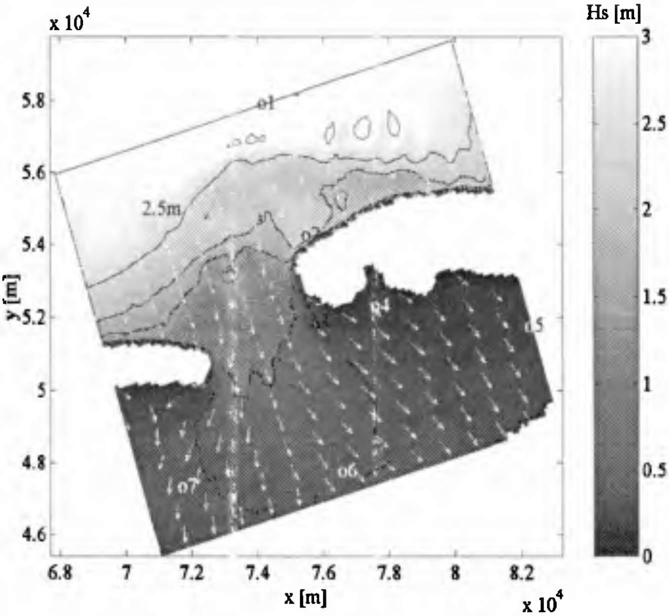

Fig. 2 Significant wave height and mean wave direction (unit vectors) computed with the SWAN model in the Norderneyer Seegat (Germany, see Fig. 1; six buoy locations indicated). Significant wave height contour line interval 0.5 m.

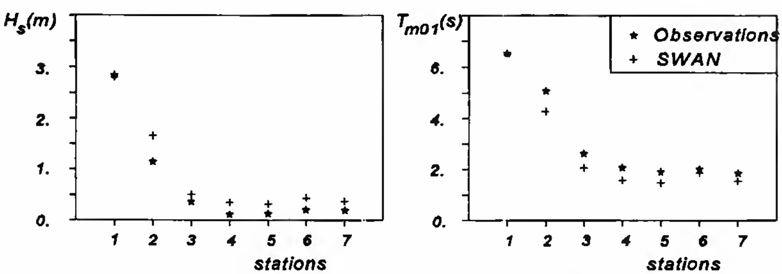

Fig. 3 The significant wave height and mean wave period in the Norderneyer Seegat (Germany, see Fig. 1) observed at the six buoy locations of Fig. 2 and computed with the SWAN model.

OUTLOOK

Although considerable progress has been made in the WISE group over the last few years, several basic aspects are still unresolved and the verification of the existing computer codes has been rather limited. Moreover, the numerical quality of the present codes pose unnecessary constraints on their operational applicability. With the present and future R&D programs of WISE members, these aspects will improve. In addition, relatively new model technology such as real-time data assimilation based on buoy and satellite observations will be introduced in the forecasting of waves in coastal regions. The outlook for these developments is optimistic because both in Europe and in the USA, funding is available to continue research and development at an increased pace. With the release of the SWAN model in the public domain, next to the WAM model, these developments can be concentrated in two widely available, supplementary computer codes.

ACKNOWLEDGEMENTS

The achievements in the WISE group are a credit to individual members who, we hope, have benefited from the discussions and interactions with other members. The group as a whole proceeds with its own momentum which we, as chairmen, hope to maintain with our logistical efforts.

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