SEA21 - FORECASTING OPERABILITY OF MARINE INSTALLATIONS*

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1 GENERAL APPROACH

The operability of marine installations like harbors or offshore terminals depends on the wind/wave conditions in open sea in a rather complicated way. The major factors, limiting the operability, are:

- Ability of ships to enter/exit the installation
- Cargo handling limitations for berthed ships

An integrated numerical model is being developed at CAMERI, to simulate, based on the predicted wind/wave conditions at deep sea, the entire physical process, from a deep sea storm to motion of moored ships. In order to simplify the simulation, we separate the physical process into three stages: wave shoaling from deep sea to the harbor entrance, wave diffraction and harbor oscillations, and wave-ship interaction in the harbor. Since the periods of resonance of the harbor and of the horizontal modes of motion (surge, sway, and yaw) of the moored ship, are in the range of long waves (more than about 20 seconds), and since the long waves are better transmitted into the harbor, it is very important to consider the long waves contribution to the ships motion in the harbor. Most of the energy in the long waves range, which exists at the harbor mouth, is a result of nonlinear wave-wave interactions in the shoaling zone. The dimensions of the harbor are assumed to be small enough to neglect nonlinear interaction within the harbor. The process is illustrated in Figure 1.

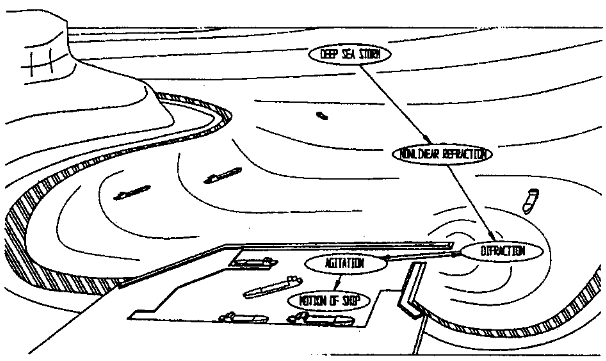

Figure 1: Illustration of the physical process, simulated by the model

The system will employ (at the first stage) the following numerical models:

- A nonlinear shoaling model, which will take as input frequency-directional spectrum at deep sea, and transform it into a new spectrum which characterizes waves at the harbor entrance. For later use this spectrum is decomposed into frequency/direction matrix.

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- A linear agitation model, which produces maps of amplification coefficients and other wave parameters for each frequency/direction combination.
- A ship motion model, which computes responses of berthed ship in six degrees of freedom to input wave of unit height for each frequency/direction combination. To calculate characteristic ship motions during a storm, the above responses are multiplied by the corresponding amplitudes of the frequency/direction wave spectrum. The characteristic ship motions are used to predict operability, according to appropriate criteria.
- A navigation model, which will determine whether a specific ship with given loading conditions will be able to enter or exit the harbor.

The linear models will be run in advance and their results will be stored in look-up tables, whereas the nonlinear parts have to be executed in real time. The pilot version of the system will be installed at Haifa harbor by November.

2 DESCRIPTION OF MAJOR SYSTEM COMPONENTS

2.1 *Nonlinear shoaling model*

While several models are capable of describing of the nonlinear shoaling process (for example, different implementations of the Boussinesq equation), for the Haifa pilot Alexandru Sheremet has developed a semi-nonlinear model based on results of his D. Sc. thesis (Sheremet, 1996). In this approach, the original problem has been split into two problems linearly coupled; the first one, the linear shoaling and refraction of wind-waves over slowly varying bathymetry, is based on the geometrical optics approximation for steady conditions and negligible currents. The second one is a numerical model for the simulation of the long-wave generation based on an elliptic mild slope equation with a forcing term due to the wind waves.

In the elliptic equation no a-priori assumptions are made about the shape of the free surface. It provides a natural way to deal with the directionality of the wave spectrum. However, the integration of the equation on a realistically large domain requires very high numerical effort, taking into account many runs required to get the statistical picture.

WKB expansions bring the original elliptic equations to forms that no longer are capable to describe wave reflection. In exchange, one obtains a simpler evolution equation, more readily understood and much easier to solve. The basic assumptions of the model are that the gradient of the water depth is small (the mild slope assumption), the varying bathymetry affects the waves evolution on the same scale as the leading order nonlinear wave interactions, and the effect of background currents and wave setup/set down is negligible.

The shoaling model requires full spectral information about the sea state at the starting point (deep water), that is, both information about the spectral density and about the modal phases. As a rule, the former is available, but the phases are unknown. For any single run, the model generates the set of corresponding phases randomly, under the assumption that they are uniformly distributed. To obtain a statistical picture of the wave evolution, the results of a large number of such runs have to be averaged. Experience has shown, that the average results become rather stable for about 100 to 200 runs.

2.1.1 *Basic Equations*

The present work is based on the nonlinear mild slope equation, describing the spatial evolution of the amplitudes of the spectral components over arbitrary (mildly sloping) bathymetry (Sheremet, 1996). A unidirectional shoaling model may be derived from it by means of the WKB expansion, neglecting the wave reflection by the shore and assuming that the free surface may be represented as a superposition of slowly modulated plane wave of the form

$$Ae^{i(\theta-\omega t)}; \quad \mathbf{k}=\nabla\theta; \quad \omega^2 = g\,|\mathbf{k}|\,tanh(|\mathbf{k}|\,h), \tag{1}$$

where θ is the phase function and the underlying assumption is that the wave-number vector k and the amplitude A are slowly varying functions of position. The resulting equation is:

$$\frac{1}{2}A\nabla\cdot\mathbf{C}_g + \mathbf{C}_g\cdot\nabla A = \int_{-\infty}^{\infty}\mathbf{W}_{0:1,2}A_1A_2e^{-i\Delta^{\theta}_{0:1,2}}\delta^{\omega}_{0:1,2}d\omega_{1,2} \tag{2}$$

with

$$\mathbf{W}_{0:1,2} = \frac{1}{8\pi}(2\mathbf{k}_1\cdot\mathbf{k}_2 + (\sigma_1\sigma_2)^2 + k_1^2\frac{\sigma_2}{\sigma} + k_2^2\frac{\sigma_1}{\sigma} - \sigma^2\sigma_1\sigma_2)$$

Here $\mathbf{C}_g = C_g\mathbf{k}/k$ is the group velocity vector, $\sigma_j^2 = \omega_j^2/g$, $\delta^{\omega}_{0:1,2}d\omega_{1,2}$ is shorthand for $\delta(\omega_0 - \omega_1 - \omega_2)d\omega_1 d\omega_2$, $\Delta^{\theta}_{0:1,2} = \theta_0 - \theta_1 - \theta_2$ and $A_1A_2 = A(\ldots,\omega_1)A(\ldots,\omega_2)$.

Equation (2) does not describe wave reflection and thus is simpler to solve numerically than its elliptic counterpart. However, due to the nonlinearity, the information about the modal amplitudes and phases at a given point may be obtained only if all the upstream dependencies related to that point are resolved, that is, if the history of all the waves reaching that point is known. The key step in the further simplification of the problem is to somehow do away with the nonlinearity, while still preserving the essential mechanisms responsible for the long waves generation. This may be done by assuming that in the domain of interest the long waves amplitude is significantly smaller than the amplitude of the wind waves (we leave aside for the moment the problem of the exact definition of the long and wind waves bands). If β denotes the order of magnitude of the ratio of the long- to wind-wave amplitudes, the leading order mechanism (in β) that transfers energy to the long waves is the triad interaction involving two components in the peak of the spectrum. The energy feedback from the long waves to wind waves is of higher order.

At the leading order in β, the equation separates into:

$$long\,waves: \quad \mathbf{L}(A_L) = \mathbf{N}(A_W, A_W) \tag{3}$$

$$wind\,waves: \quad \mathbf{L}(A_W) = 0 \tag{4}$$

where $\mathbf{L}$ and $\mathbf{N}$ are notations for the linear and nonlinear operators acting on the unknown wind- and long-waves amplitudes (A_W and A_L respectively).

The evolution of the wind-waves is *linear* and is independent of the long-waves evolution. The wind-waves system may be integrated by fast standard ray methods to obtain the wave field at any point. The long-waves system of equations is also linear, with a forcing term due to the wind-waves modes. The code developed to integrate the wind wave equations uses conventional ray methods. The numerical approach to the long-waves problem is presented the following subsections.

2.1.2 *The long waves generation model*

The numerical model used to solve the wind-waves equation deals with a fully directional spectrum. The discrete version of Equation (2), needed also for numerical integration purposes, is then:

$$\frac{1}{2}A_{\bar{\jmath}}\nabla\cdot\mathbf{C}_{g,\bar{\jmath}} + \mathbf{C}_{g,\bar{\jmath}}\cdot\nabla A_{\bar{\jmath}} = -i\sum_{\alpha,\beta}\mathbf{W}_{(\bar{\jmath},\alpha,\beta)}A_\alpha A_\beta e^{-i\Delta^{\theta}_{\bar{\jmath}:\alpha,\beta}}\delta^{\omega}_{\bar{\jmath}:\alpha,\beta} + i\sum_{\alpha,\beta}2\mathbf{W}_{(\bar{\jmath},-\alpha,\beta)}A^*_\alpha A_\beta e^{i\Delta^{\theta}_{\beta:\bar{\jmath},\alpha}}\delta^{\omega}_{\beta:\bar{\jmath},\alpha} \tag{5}$$

where $\mathbf{C}_{g,\bar{\jmath}} = C_{g,\bar{\jmath}}\mathbf{k}_{\bar{\jmath}}/k_{\bar{\jmath}}$ is the group velocity vector and

$$\Delta^{\theta}_{\bar{j}:\alpha,\beta} = \theta_{\bar{j}} - \theta_\alpha - \theta_\beta \qquad \nabla\theta_{\bar{j}} = \mathbf{k}_{\bar{j}}$$

Defining the wave ray as a curve everywhere tangent to the group velocity vector, after some quite standard transformations, one may write the linear term of equation (5) along the ray corresponding to mode "$\bar{j}$":

$$\frac{1}{2}A_{\bar{j}}\nabla\cdot\mathbf{C}_{g,\bar{j}}+\mathbf{C}_{g,\bar{j}}\cdot\nabla A_{\bar{j}} = (\frac{C_{g,\bar{j}}}{\sigma_{\bar{j}}})^{1/2}\frac{d}{ds}(A_{\bar{j}}C^{1/2}_{g,\bar{j}}\sigma^{1/2}_{\bar{j}}) \quad (6)$$

where $s_{\bar{j}}$ is the coordinate along the ray corresponding to the spectral mode "$\bar{j}$".

Introducing the notation:

$$B_{\bar{j}} = A_{\bar{j}}(C_{g,\bar{j}}\sigma_{\bar{j}})^{1/2} \quad (7)$$

one may write for the long-wave spectral mode "$\bar{j}$" the equation:

$$\frac{dB_{\bar{j}}}{ds_{\bar{j}}} = i(\frac{\sigma_{\bar{j}}}{C_{g,\bar{j}}})^{1/2}\sum_{\alpha,\beta\in W} 2\mathbf{W}_{(\bar{j},-\alpha,\beta)}A^*_\alpha A_\beta e^{i\Delta^{\theta}_{\beta:\bar{j},\alpha}}\delta^{\omega}_{\beta:\bar{j},\alpha} \quad (8)$$

where W is the set of indices corresponding to the wind-wave band.

The problem is now an initial value problem for the long waves along the ray. To solve it, one needs to know the geometry of the long-wave ray and the wind-wave field along it, which may be calculated using Equation (4). Note that Equation (3) does not provide any information about the geometry of the long-wave ray; moreover, the long waves are nearly absent from the deep water spectrum (the long waves arise as a result of the nonlinear interactions, mainly in relatively shallow water) and therefore the ray cannot be computed from the deep water spectral data. In deep water, however, the second order long waves of radial frequency $\omega_{\bar{j}}$ for example, may be represented as a superposition of bound waves forced by pairs of wind waves (see Sheremet 1996, App. A) of the form:

$$T_{\bar{j},\alpha,\beta}A^*_\alpha A_\beta e^{i\int(\mathbf{k}_\beta-\mathbf{k}_\alpha)dr} \quad (9)$$

where $\mathbf{k}_L$ denotes the wave-number of the long wave, T the interaction coefficient and

$$\omega_{\bar{j}} = \omega_\beta - \omega_\alpha$$
$$\mathbf{k}_L = \mathbf{k}_\beta - \mathbf{k}_\alpha$$
$$\omega_L = gk_L tanh(k_L h)$$

In deep water, a directional wind-wave spectrum will generate a complex, directionally spread spectrum of bound long-waves; however, if the wind-wave spectrum has a well defined peak and small angular spread, the main part of the energy in the locked long-wave band is concentrated on the direction of the peak.

Although the above heuristics are expected to fail at some point in shallower water, as the long waves will approach the status of the free waves, for the purpose of the present model, which is intended to simulate the long-wave generation up to the entrance of a harbor, at 10m-20m depth, the simplification we shall adopt in the sequel will be to identify the long waves rays with the spectral peak ray.

2.1.3 *Practical implementation*

The approach outlined in the preceding subsection allows for breakup of the whole numerical simulation into two distinct steps, as shown schematically in the following Figure 2.

The first package of programs does calculations related to the geometry of the problem and stores the results in files to be used by the second package. It requires only geometrical data such as the bathymetry matrix, the direction and the wavelength of the spectral peak in deep water. Given the deep water wind-wave spectrum, the spectral peak propagation ray up to the target point (harbor entrance) may be computed. The relevant parameters at this stage are only the peak frequency and direction in deep water. The data related to the ray (points, depth, refraction factor along the ray) are stored in a file. Once the spectral peak ray is computed,

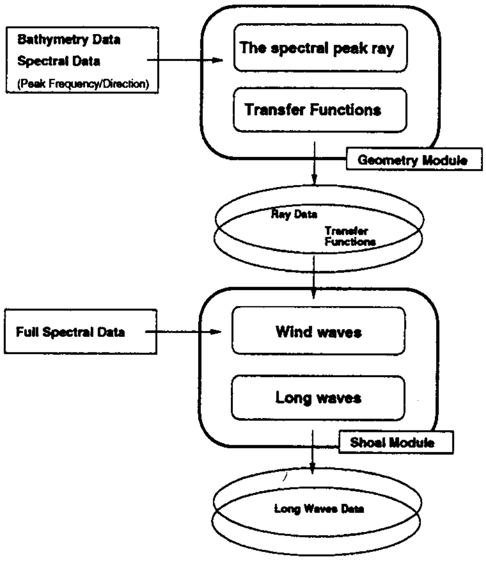

Figure 2: The components of the nonlinear shoaling model

a second module is brought in to compute the transfer functions for all the points that describe the ray. The transfer functions are stored in a separate file for future use. Any incoming deep water spectrum having the given direction and peak wave-length will be refracted and shoaled using the data produced by this module, so that the data is, in a certain sense, of general use.

The actual shoaling is done by the second package of programs. The data required is the full deep-water directional wind-wave spectrum, which is processed along the ray and using the transfer functions computed at the previous step. This package is itself designed to work in two steps:

- The linear refraction/shoaling model computes the transformation of the wind-waves along the given spectral-peak ray. For each point of the ray, it computes the corresponding refracted/shoaled directional spectrum. Then, for each frequency in the spectral representation, it computes the peak direction and integrates the spectrum over the directions such as to replace the directional spread at the given frequency with a single mode propagating in the direction of the peak (at that frequency). The data is saved in a file.
- The last module computes the "nonlinear" generation and shoaling of the long wave band using the Equations (3). First the phases of the wind-wave modes along the ray are computed with respect to the first point of the ray, generating a set of ready-made phases for all the wind-wave frequencies. A "realization" is generated by translating these phase arrays by random numbers uniformly distributed between 0 and 2π. For each such realization Equations (3) are integrated to obtain the long-wave spectrum at the target point. For a physically meaningful result, the results for a number of such realizations have to be averaged.

In the present approach the full structure of the actual directional spectrum plays a role only at the later stages in the calculations; the first two modules deal only with the geometry of the problem, so that two spectra having the same peak parameters will be treated by the first group of programs in the model as the same spectrum, irrespective of the significant wave-heights, for example. This would allow the first package to be run only once for a given direction and peak frequency. Moreover, due to the inherent error in measuring directions, one could say that a given ray together with the corresponding transfer functions is representative of a certain angular aperture. Ray and transfer functions could then be pre-computed for discrete values of the propagation angles, and used directly by the second group of modules.

2.2 *The agitation model*

Many different numerical models were developed for harbor agitation. Our primary task was to choose the optimal one for our purposes, taking into account specific conditions within harbors. In a fully developed harbor there is a relatively small and well determined entrance;

short waves, entering the harbor, undergo significant diffraction just beyond the entrance, so their amplitudes reduces quickly, and no significant long wave generation *within* the harbor can be expected. Thus, a linear model will be appropriate for this purpose, with all the advantages that linearity provides. Another reason to use a linear monochromatic model, is the partial reflection from breakwaters and other marine structures. From the agitation point of view, this is the most important phenomenon in harbors. As determined by many field measurements and laboratory experiments, the coefficients of partial reflection vary significantly with wave period. In a time domain model, like that based on the Boussinesq equation, it is very difficult (if at all possible) to introduce boundary conditions or near-boundary sponge layers, which describe wave reflection correctly for all periods. So we have chosen the Elliptic Mild Slope (EMS) equation as the optimal one. This equation was originally derived by Berkhoff (1972). It is a linear equation describing the propagation of monochromatic waves over a bottom of slowly varying depth and accounting for refraction, reflection, diffraction and interference. The Elliptic Mild Slope Equation for purely harmonic motion

$$\phi(\mathbf{x},t) = Re\{\psi(\mathbf{x})e^{-i\omega t}\} \tag{10}$$

reads

$$\nabla \cdot (cc_g \nabla \psi) + k_u^2 cc_g \psi = 0 \tag{11}$$

for the complex potential $\psi(\mathbf{x})$, where $k_u(\mathbf{x})$, $c(\mathbf{x})$, and $c_g(\mathbf{x})$ are respectively the wavenumber, the celerity and the group velocity of linear waves in water of constant depth equal to the local depth at point $\mathbf{x}$.

The boundary conditions for (11) are:

$$\frac{\partial \psi}{\partial n} = 0 \tag{12}$$

for fully reflecting walls and

$$\frac{\partial \psi}{\partial n} = ik_u \psi_{in} \tag{13}$$

for a fully reflecting wavemaker, where n is an outward normal, and ψ_{in} is the prescribed potential of the incoming waves.

Partial reflection is modelled by introducing of sponge layers along the structures, in which artificial damping is present. The exact equations for such sponge layers depend on the numerical approach.

The EMS implementation currently in use at CAMERI is MIKE21 EMS developed by DHI. CAMERI has purchased it several years ago for a rather large project: the development of Haifa and Ashdod harbors. CAMERI gained a lot of experience with this model, it was extensively tested and calibrated against physical models of the same harbors. This model solves the hyperbolic form of the mild slope equation by introducing pseudo-fluxes and by removing the harmonic dependency using complex variables and pseudo-time (see Madsen and Larsen, 1987).

Generally, the EMS model is used to compute the agitation database, which is further used by the ship motion modules. This model runs only at CAMERI. The required wave directions are determined from wave statistics for each location. The set of frequencies includes the standard ones (20 equally spaced frequencies, from 1/160 Hz to 20/160 Hz), and possibly additional resonant frequencies, which can be determined from simple geometrical considerations, or by running a time domain model with a continuous spectrum. A model based on Saint Venant equation, developed at CAMERI, will be used for this purpose (see Sladkevich and Rubin, 1992). As this model runs with fully reflecting boundaries, the resonant effects will be overestimated. Thus only the strongest resonants must be picked out for further validation by monochromatic model, running with partial reflection.

As we mentioned above, the proper choice of reflection coefficients is extremely important. Separate sets of reflection coefficients were carefully chosen for external breakwaters, for internal sides of breakwaters and seawalls, and for beaches. They were extensively verified against experiments with monochromatic waves of various periods and directions for both Ashdod and Haifa harbors. An example for the Haifa harbor is given in Figure 3.

Currently a new EMS module is being developed at CAMERI. When available, it will provide many advantages:

- ability to work with sloped and curvilinear boundaries, not just grid-aligned
- high-order model with less grid points per wavelength
- any number of phased array wavemakers, so directional spread can be introduced
- improved sponge layers.

2.3 *The ship motion model*

2.3.1 *The VIP (Vessel In Port) model*

The VIP model is basically a three dimensional wave diffraction program, which solves numerically the linear wave-body interaction problem for a floating body of general geometry. The program implements the Boundary Elements Method with a wave source Green's function. The basic code was developed as a part of a D. Sc. thesis (Drimer, 1994), which was limited to a box shaped vessel. The generalization of the model for a body of general geometry, was made as a part of Sea21 project.

The uniqueness of the VIP model is its ability to solve the hydrodynamics of a vessel berthed to a quay in a port. In the classical linear wave-body hydrodynamic problem, at open sea, the exciting flow field is defined by the theoretical velocity potential function of a monochromatic plane wave. However, the flow field inside a port is much more complicated. In order to solve the diffraction problem for a vessel in port, a special interface program reads the binary output file of the agitation module, and calculates the values of the velocity potential and its derivatives at the centroids of the boundary elements of the

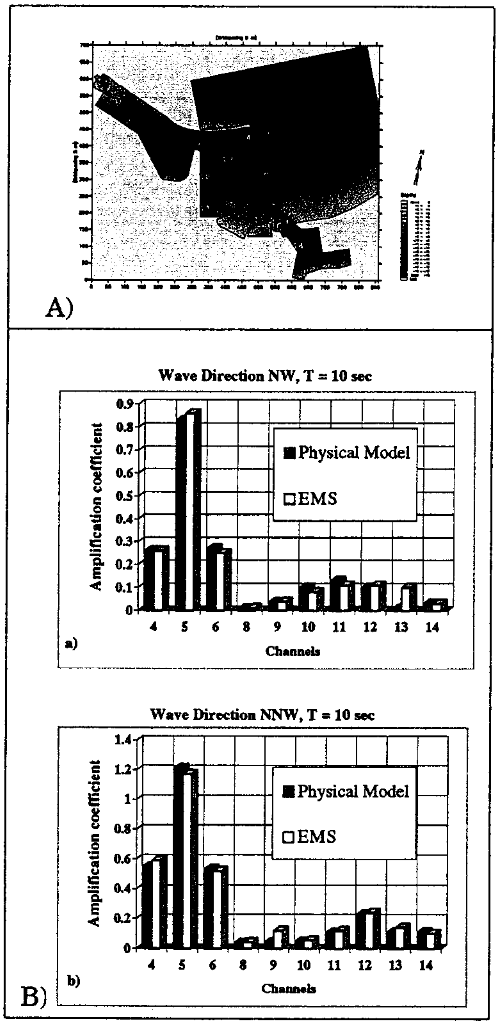

Figure 3: Comparison between the results of numerical and physical models for the Haifa harbor:
A) Location of wave gauges in the physical model
B) Comparison histograms:
a) Waves from NW, T = 10 sec; b) Waves from NNW, T = 10 sec

ship model. These values are then transferred to the VIP model as an input for the evaluation of the exciting forces applied on a vessel in port, instead of the open sea exciting forces.

The scattering problem (a fixed vessel is excited by the harbor flow field), as well as the six radiation problems (the vessel oscillates in one degree of freedom, with a unit amplitude, and radiate waves in a domain which was otherwise calm), are solved with boundary conditions which represent the vertical quay at which the vessel is berthed. The results of the radiation problems are the added mass and damping coefficients. The re-reflection of waves by all boundaries except the quay at which the ship is berthing, is neglected.

After solving the seven hydrodynamic problems (diffraction and six radiation problems), the exciting forces and the hydrodynamic coefficients are substituted in the equations of motion of the ship, which are solved to obtain the amplitudes of motion of the moored ship.

The VIP model as well as the EMS-VIP interface program were developed in CAMERI.

2.3.2 *Ship characteristics*

Detailed ship characteristics are used in the analysis. They include general dimensions, loading conditions and exact shell geometry, which is approximated by finite number of boundary elements. An example is given in Fig. 4. The figure presents the three hulls in the same scale.

The resolution of the numerical representation was verified by means of comparison of calculated hydrodynamic coefficients and exciting forces, with published experimental results.

Beside the shell geometry, some hydrostatic and dynamic properties are needed as an input for the ship motion analysis; these include: metacentric heights, roll and pitch periods, waterline area and waterline moments of inertia.

In order to obtain the appropriate roll and pitch periods, the corresponding moments of inertia were calibrated according to the following process:

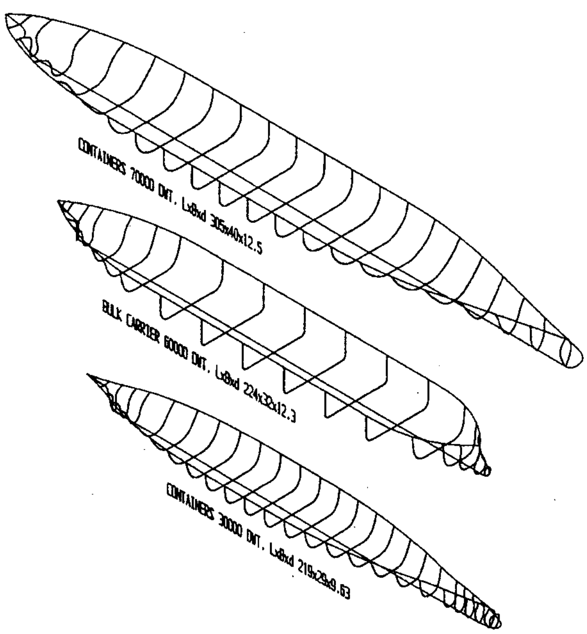

Figure 4: Isometric view of the wetted surface of three typical ships

The natural periods of oscillations are given by:

$$(\frac{2\pi}{T_4})^2 = \frac{G_{Mt}\Delta}{I_{44} + a_{44}} \qquad for\ roll$$

and

$$(\frac{2\pi}{T_5})^2 = \frac{G_{Ml}\Delta}{I_{55} + a_{55}} \qquad for\ pitch$$

Where:

T_4 - roll period

T_5 - pitch period

G_{Mt} - transverse metacentric height

G_{Ml} - longitudinal metacentric height

Δ - displacement

I_{44} , I_{55} - roll and pitch moment of inertia, respectively

a_{44} , a_{55} - roll and pitch added mass, respectively

a_{44} and a_{55} were evaluated by applying the VIP model for a ship in an open sea, for the given roll or pitch periods. Then I_{44} and I_{55} were calculated to satisfy the above equations.

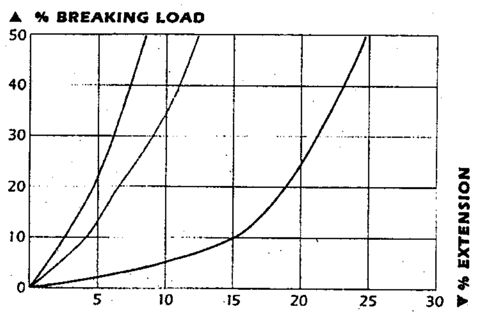

Figure 5: Typical deflection curves of mooring lines

2.3.3 *Representation of mooring*

In general the reaction of the mooring system is nonlinear. Examples of load deflection curves of mooring lines, are given in Fig. 5

In the linear numerical model only one spring constant may be used for each mooring line. The approach used to handle this difficulty was to solve the equations of motion with two different mooring types and then to make a logical engineering decision among the resulting amplitudes of motion.

The two mooring types are:

1. Free mooring
2. Actual mooring, where each mooring line is represented by the spring constant appropriate for the line used by the actual ship. This spring constant is determined from linearization around equilibrium state due to steady forces (like wind, current or wave drift).

The consideration of the free mooring is required, because the purely linear system has very strong resonances, which do not exist or are largely attenuated in a real (nonlinear) physical system. In the case of such resonant behavior, the appropriate motions are taken from the free mooring case.

The restoring forces of the modes heave, roll and pitch are dominated by hydrostatic forces, which may be considered linear for small amplitudes of motion. These modes of motion are

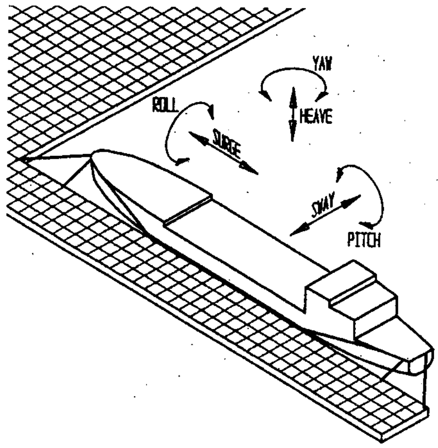

Figure 6: Six degrees of freedom of a moored ship

hardly affected by the mooring restoring forces. Hence, free mooring is used for the heave, roll and pitch equations of motion.

The six modes of motion are illustrated in Figure 6.

2.3.4 *Prediction of operability*

The final results of the entire modeling process are operability conditions of the berthed ships. Disturbance to loading or unloading operations may be caused by large motions of the vessel which disturb the cargo handling, or by the breakage of mooring lines.

In the present numerical models the operability criteria consider movements of ships and do not account for mooring forces. The nonlinear reaction curves of the mooring lines make it very difficult to predict reliable mooring forces using a linear model. Practically, the combination of the motion criteria, which were adopted, and the characteristics of typical mooring systems, make the probability of occurrence of a line breakage prior to exceeding of the motion criteria to be very small. In general, a stiff mooring system will reduce movements of ships but will break before a compliant mooring system which enables larger movements. The approach used for the representation of mooring (see 2.3.3), where two mooring systems are investigated, is expected to provide reasonably good predictions.

After reviewing several operability criteria, which were published or used in the past (PIANC reports, PIANC, 1995), as well as several reports about problems during operation, which happened at the Haifa East quay, CAMERI decided to use the following operability criteria, based on characteristic ship motions, for Haifa East:

Operability criteria

Characteristic ship motion (2*Sqrt(2)*RMS)

Type of Vessel	Surge	Sway	Heave	Roll	Pitch	Yaw
	m	m	m	deg	deg	deg
Container	0.8	0.5	0.5	2.0	0.8	0.6
Bulk Carrier	1.0	0.8	0.5	3.0	0.8	1.5

For other harbors appropriate criteria will be derived based on local conditions, and in cooperation with the client.

2.3.5 *Future developments*

The nonlinear reactions of mooring lines and fenders cause in many practical situations motions of the moored ship which exceed the limit of applicability of a simulation approach based on linear dynamics in the frequency domain. The range of validity of the model may be increased in such a situation by adopting a combined frequency-time domain approach. The principle of this approach is first to solve the linear hydrodynamic problem for a set of frequencies, and then to transform the obtained hydrodynamic coefficients to retardation functions which are substituted in a set of integro-differential equations of ship motions in the time domain. The equations of motion in the time domain may handle nonlinear effects such as nonlinear reactions of mooring lines and fenders, nonlinear roll damping and others. This approach has been used in the past for oil terminals in the open sea, but not for a vessel in port. This time domain approach is now under intensive development at CAMERI, and significant progress has already been achieved.

Another important module currently under development at CAMERI is the Navigation In The Approach Channel module, that should become an integral part of future Sea21 installation in harbors. This module will get its input data regarding waves from the wave database, built by the EMS module, regarding currents from the current database, built by the the hydrodynamic module, regarding winds from the local prognostic data and regarding tides from a harmonic tide predictor. The navigation module will determine whether a particular ship with specific loading conditions will be able to enter or exit the installation safely at any time within the 48 hours prognostic period.

3 AUXILIARY MODULES

3.1 *Objective Oriented Wave Forecasting*

The purpose of this auxiliary module is to determine the site targeted, forecasted wave and wind parameters. This is necessary if the deep sea wave and wind forecast, being drawn from the external information source (like a local weather bureau, etc.), is available on a large scale only. The module is working in real-time mode, and is activated automatically each time when a new data forecast is retrieved. It analyzes the wave propagation from the given locations in the deep sea to the neighborhood of the target site, taking into account the local wind and bathymetry. The output of this module includes the forecasted wave and wind parameters in the vicinity of the target site. These data serve as a basis for the whole structure of the Sea21 system. If the required prognostic data in the neighborhood of the target location is available, this module is deactivated.

3.2 *Wave and Wind Measurements and Prognostic Data Correction*

Sea21 is able to retrieve data automatically from local wave and wind measuring equipment (radio buoys, for example), with the desired frequency, and to store them. When measured data are available, the Prognostic Data Correction (PDC) module can be utilized. The PDC module will be activated each time when new data (forecast or measurements) are retrieved. The just obtained prognostic data will be analyzed, and corrected if needed, in accordance with the measurements. The PDC module will utilize an algorithm of statistical trend analysis, based mainly on previous experience. It means that, the more "experienced" the program becomes with time, the more reliable and precise the forecast of the wave and wind parameters will be.

3.3 *Harbor and near shore hydrodynamics*

The hydrodynamic module, which also requires "in-house" computations, will be employed in cases where currents are important. It can be used to precompute the current fields for the region of interest for a set of most typical wind/wave conditions.

The 3-D numerical model, developed at CAMERI (see Sladkevich, Militeev and Kit 1997), provides accurate, reliable solutions for the near-shore zone. This 3-D model is able to take into account temperature variations in the water, as well as the concentration of dissolved contaminants and other passive scalars. This hydrodynamic model was already successfully applied in several projects.

4 PRACTICAL REALIZATION

All computational modules are linked together by the Graphical User Interface (GUI, see Fig 8). The GUI ensures continuous, managed activity of the system, provides easy access to the stored information, and allows user-friendly, simple data input and output. The automation feature of the interface guarantees minimum requirements from the operator. The human interference will be required only in the case of possibly dangerous weather conditions. The GUI manages communication to the external information sources and automatic data retrieval. The wide range of communication methods, including the direct modem connection and the Internet http and ftp connection, is supported by Sea21. The system provides automatic communication error correction, and the operator is notified in the case of unrecoverable error occurrence.

4.1 *Possible system configurations*

Being a modular, multi-purpose system, Sea21 may be pre-designed and installed to suit the customer's specific needs and interests. A wide range of system installations can be constructed with different levels of sophistication. The main goal of each one of them is to facilitate improved usage of a certain marine installation, taking into account the local conditions and its specific requirements. A few possible configurations are described below.

- **Local wave forecasting**
  The output of this simplified system is a wave field in the local region of interest, forecasted up to 48 hours. The installation includes a pre-programmed personal computer, GUI, a communication module, a data correction module (if needed), and an Objective Oriented Wave Forecasting module. This system was designed for operators of marinas and small (fishing) harbors, who are interested in a more detailed wave forecasting than that available from the media.

- **Operability Forecasting for an Open Sea Terminal**
  The output of such a system, in addition to local wave and current fields, is a fore-

cast concerning the possibility to run loading/unloading operations, the need to reinforce the mooring system, and in extreme conditions the need to leave the terminal. The installation includes a pre-programmed personal computer and most of the system modules, as needed. This system may be installed at any type of loading/unloading terminals in open seas, like multi buoy terminals, mono buoy terminals and jetty type terminals.

- **Operability Forecasting for Ships Berthing in a Harbor**
  This is the most sophisticated system, which includes all the relevant software modules. The operator is provided with all the forecasted data available, including local wave and current field and operability conditions for all ships berthed in the port, as well as measured waves, wind and currents, where applicable.

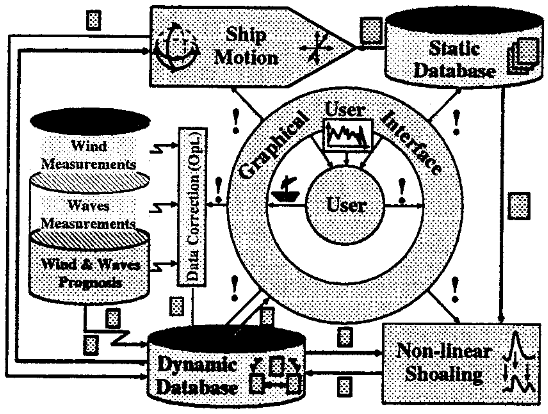

Figure 7: Simplified structure of the Sea21 system

4.2 *How does the system work*

The most heavy numerical tasks, requiring a large amount of computer time, are carried out in advance at CAMERI. The results are stored in the form of look-up tables, covering all the statistically possible cases. These results, together with the invariable data, like port layout, region and harbor bathymetry, characteristics of vessels, mooring and fendering systems, etc., compose the so-called static database. The results of all the calculations performed "on-site" are stored for a required period of time in the dynamic database. The Figure 7 presents a simplified data flow chart of the system. Detailed structure is given in Figure 9. The working cycle of the system is as follows:

- The large scale deep water wave and wind prognostic data are automatically retrieved from the external source (local weather bureau, etc.), by modem connection or via the Internet connection, with a desired frequency (2 - 4 times per day, as needed).
- Further, these data are transformed to yield the near site deep water wave and wind prognostic data, if needed.
- Where applicable, measured wave and wind data are automatically retrieved with a high frequency (each 3 - 6 hours). The prognostic data correction, based on measurements, allows to avoid rough mistakes in the near site deep water wave and wind prognosis.
- The prognostic data are analyzed and, if a specified criterion is not exceeded, the system remains in the sleep-mode. Otherwise, the non-linear refraction module is activated. This module computes the wave spectrum transformation from deep water to the port entrance, including long wave generation. The results obtained are reanalyzed, and if normal "near-port conditions" are obtained, the system returns to the sleep-mode.
- If there is any change of conditions for the worse, the operator is notified both by visual and audio alarms, and is prompted to enter data related to ships scheduled to be in the port within the following 48 hours. The behavior of vessels, that the system was noti-

fied about them, is calculated automatically. The data stored in the static database are consequently retrieved and interpolated in accordance to the current conditions. This provides the wave and current fields in the port. In addition, harmonic predictor provides the tidal information.

- In the last stage of the cycle, the Vessel-In-Port module computes the operability conditions for the ships berthed in the harbor.

The operator has access to any required data stored in the system and may force the system, at any time, to leave the sleep-mode.

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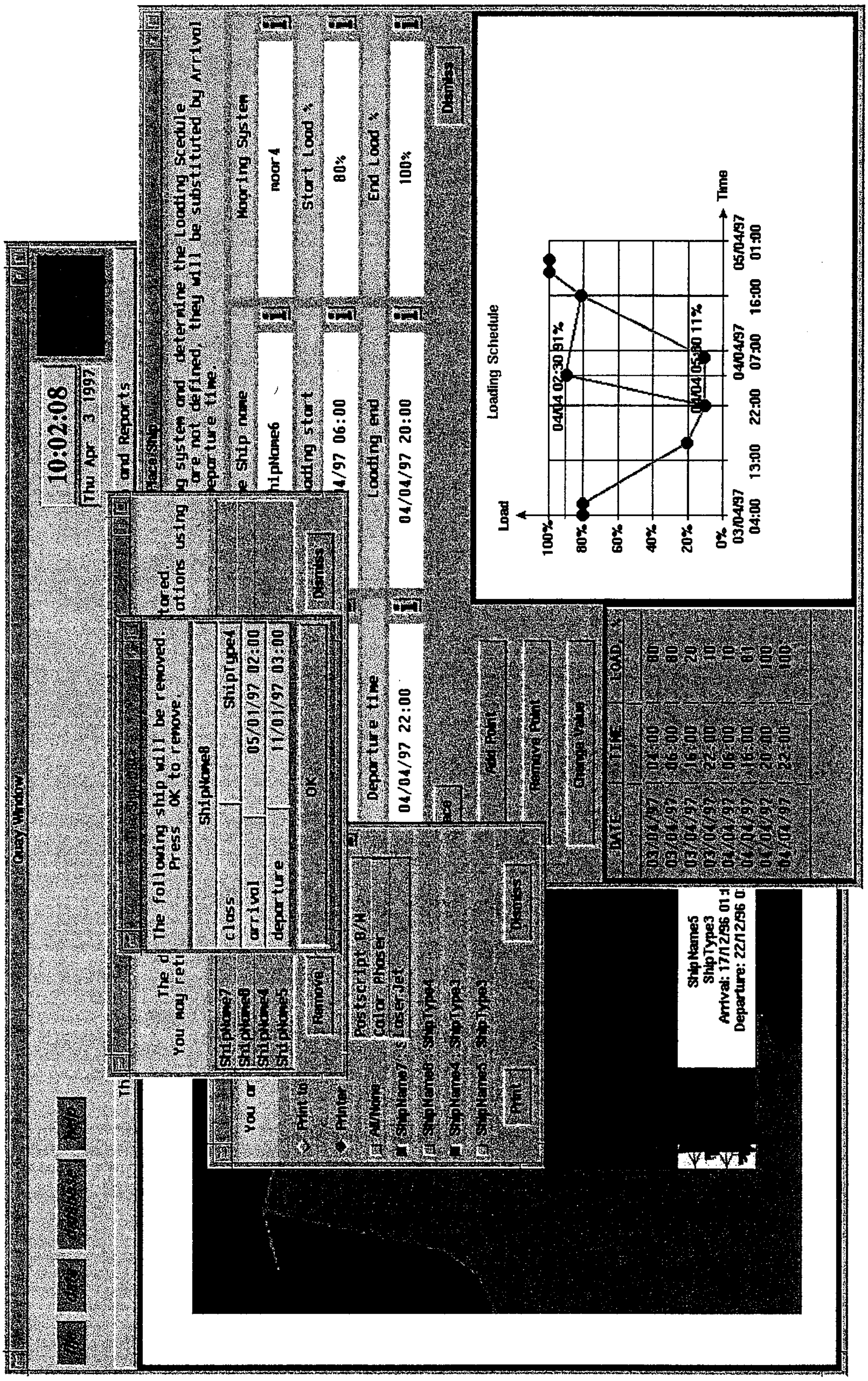
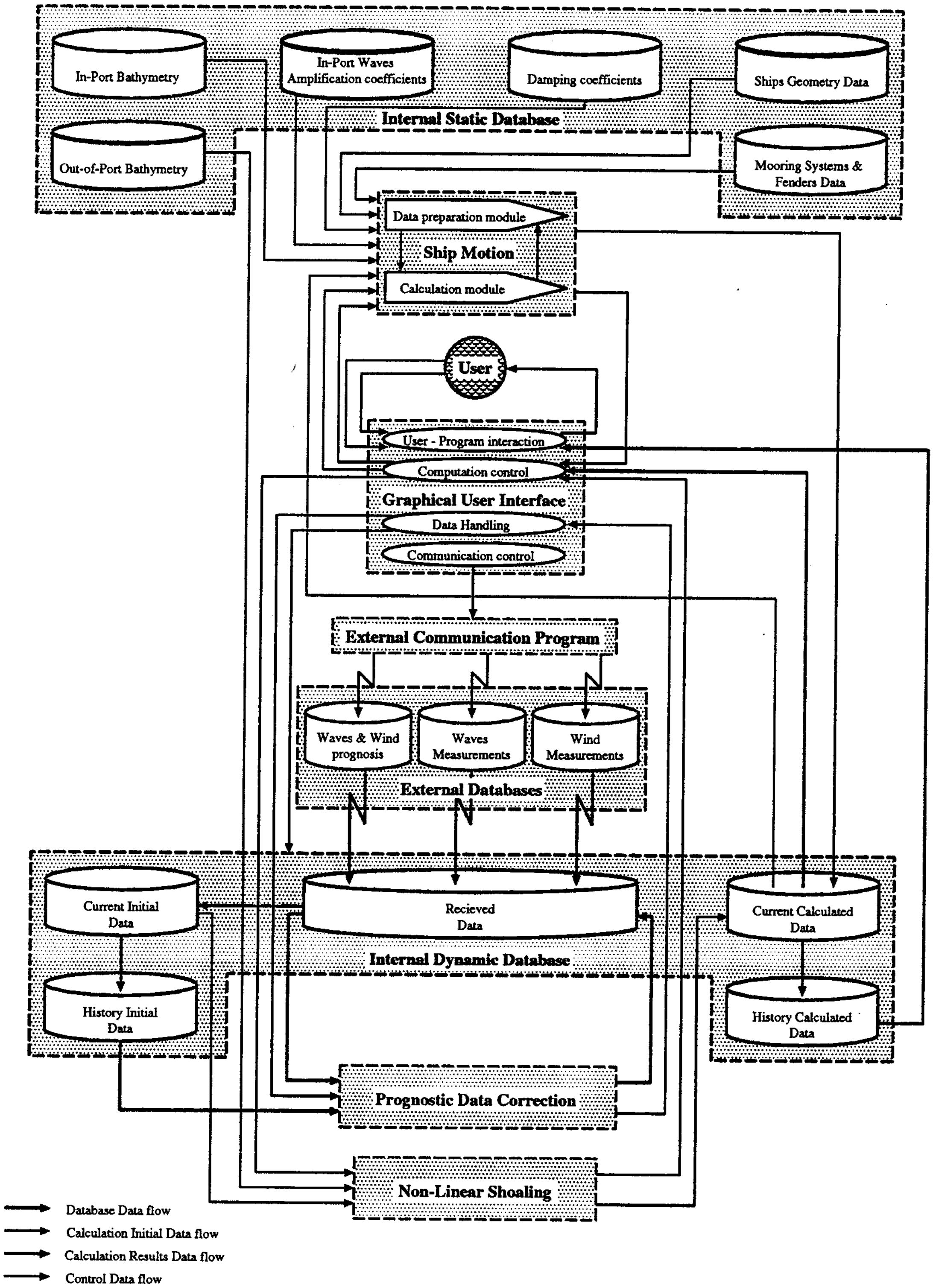


Figure 8: Sea21 GUI at work



The Sea21 program's modules interaction

Figure 9: Detailed structure of the Sea21 system