CHAPTER 32

A HYDRODYNAMIC MODEL FOR COMPUTER AIDED HARBOUR ENGINEERING

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Abstract

Coastal Hydrodynamic analyses are basic for the planning and assessment of activities in that area. An important application of these analyses is harbour lay-out and location. In this paper, hydrodynamic results of a numerical model based on Boussinesq-type equations are presented in the issue of Computer Aided Harbour Engineering. This model achieves overall second-order accuracy and has efficient modules of pre- and post-processing of information. The model has been used as a CAD tool for the planning and design of Spanish harbours. Its flexibility and economy of operation allow the model to be used, in the future, as a module of a global expert system for CAD harbour lay-out. This global expert system will provide a fully automatic design process. The output of this system will consist in the final optimized harbour configuration, considering all imposed constraints and requirements.

1. Introduction

Computer-aided harbour engineering has become a subject of considerable economic importance. The inputs for the design process are an initial harbour geometry, expected environmental conditions and a set of lay-out design specifications. Hydrodynamic descriptions of wave propagation, sea level oscillations and associated currents are provided by numerical 2-D models, usually based on shallow water Boussinesq-type equations. Analyses of obtained results are now performed by an expert engineer. From here, the appropriate modifications in geometry are carried out by an iterative process until a final optimized configuration is reached.

In this paper both the numerical model describing the flow and the expert system designing the optimal lay-out configuration (in lieu of the engineer) are presented. The first one is being used for commercial applications while the second one is under development. Nevertheless, the general structure of the system has already been defined.

2. Hydrodynamic Model Equations

The model is based on Boussinesq-type shallow-water e-

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quations. They are similar to the Airy equations but include an additional term due to the vertical acceleration effect which, in turn, induces a non-hydrostatic pressure distribution. Alternatively, these equations include frequency-dispersion effects to the leading order.

The governing equations are obtained applying a perturbation technique to the vertically integrated continuity and momentum equations (Peregrine, 1967). From the perturbation analysis different sets of equations may be obtained for various orders of approximation. It is important to point out that the various long-wave equations available are always simplifications of the actual problem (prototype) with a degree of approximation depending on the physical characteristics of the phenomenon considered. These mean, in turn, different truncation errors that may be evaluated in terms of dimensionless parameters, ε and σ.

$$\varepsilon \equiv \frac{\eta}{h} \tag{1}$$

$$\sigma \equiv \frac{h}{L} \tag{2}$$

in which η is the free-surface elevation, h is the water depth and L is a typical wave length. These parameters define the URSELL parameter, which characterizes the relative importance of nonlinearity and dispersion.

$$Ur = \varepsilon/\sigma^2 \tag{3}$$

Most of the hydrodynamic conditions that can be found inside of a harbour are due (associated) to short-waves with $Ur = O(1)$, i.e. $\varepsilon = O(\sigma^2)$. In such cases, Boussinesq equations result from the vertical integration of mass and momentum conservation equations, with an associated error of $O(\varepsilon^2)$or more generally $O(\varepsilon^2, \varepsilon^2, \varepsilon^4)$.

The set of non-linear differential equations to be discretized are similar to the ones used by other authors (Abbot, 1981),(Hauguel, 1980) and have been developed with detail elsewhere (S.-Arcilla and Monsó, 1985). The following simplifying hypotheses are required in the derivation:
1. Newtonian, isotropic and incompressible fluid.
2. Slowly varying bottom topography.
3. Water depth is always small with respect to the wave length (i.e. $\sigma^2 \ll 1$).

The main variables of the problem (velocities, pressure and free-surface elevation) are expressed as power series:

$$f = f_o + \varepsilon f_1 + \varepsilon^2 f_2 + \ldots \tag{4}$$

in which f is any of these variables with the exception of vertical velocities that are written as:

$$\omega = \sigma(\omega_o + \varepsilon\omega_1 + \varepsilon^2\omega_2 + \ldots) \tag{5}$$

The resulting vertically integrated equations are:
1. Mass conservation:

$$\frac{\partial \eta}{\partial t} + \nabla \vec{Q} = 0 \qquad (6)$$

2. Momentum conservation:

$$\frac{\partial \vec{Q}}{\partial t} + \frac{Q}{H} \nabla \vec{Q} + (\vec{Q}\nabla) \frac{\vec{Q}}{H} + gH\nabla\eta = \frac{1}{2} Hh \frac{\partial}{\partial t} \nabla (\nabla h \frac{\vec{Q}}{H}) - \frac{1}{6} Hh^2 .$$

$$. \frac{\partial}{\partial t} \nabla (\nabla \frac{\vec{Q}}{H}) \qquad (7)$$

in which:

$$\vec{Q} = (p,q) \qquad (8)$$

$$p = \int_{-h}^{\eta} udz \qquad (9)$$

$$q = \int_{-h}^{\eta} vdz \qquad (10)$$

$$H = \eta + h \qquad (11)$$

$$\nabla = (\partial/\partial x, \partial/\partial y) \qquad (12)$$

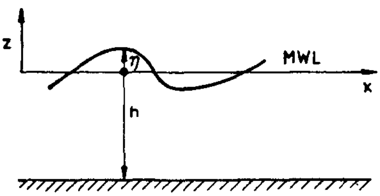

Fig.1: Definition sketch.

To simplify the resulting expressions, terms due to Coriolis forces, wind and bottom stresses, atmospheric pressure gradients, etc. have not been included in the equations. These terms do not introduce significant additional difficulties from the point of view of the numerical solution and shall not, therefore, be here considered.

The linear long-wave equations are easily derived from (6) and (7) and may be written as:

$$\frac{\partial \eta}{\partial t} + \nabla \vec{Q} = 0 \qquad (13)$$

$$\frac{\partial \vec{Q}}{\partial t} + gh\nabla\eta = 0 \qquad (14)$$

These lower order relation can be used for manipulating the third-derivative terms as demonstrated by (Long, 1964).

3. Hydrodynamic Model Numerical Solution

3.1. Discretization

The system of partial differential equations (6)and(7) can be discretized by means of an Abbot-type alternating direction implicit finite-differences scheme.

The resulting algorithm is centred both in space and time and is solved by means of a double sweeping technique along both coordinate axes x and y. This technique allows the solution of the implicit equations without having to resort to matrix inversion operations, always cumbersome and time consuming.

This scheme is consistent with the original system of differential equations and it may also be shown to be conditionally stable and convergent (S.-Arcilla and Monsó, 1986). The overall truncation error is now of second order and can be improved to third-order with suitable correction terms added to the difference equations and appropriate centering of the convective and Boussinesq terms (Abbott, 1984).Time centering can be achieved by adequate averaging in time and accumulation of information in intermediate levels, as e.g. in (Abbott, 1973) and(S.-Arcilla and Monsó, 1986). An additional trick to improve centering of derivatives is what is usually known as "side-feeding". With this technique inconsistent approximations are introduced in the fractional (auxiliary) time steps that balance themselves to centered and consistent approximations when viewed over a complete time cycle.

Side-feeding is a device by which we can make use of information produced in the immediately preceding sweep to improve the approximation of cross-derivatives.

The right way of doing it is to reverse the sense of column and row computations so that the most up-to-date information comes from different directions in the individual stages (sweeps).This balances the inconsistency in space-derivative approximations when using values in different time levels. An alternative approach is to use quasi-Newton approximation techniques to achieve second-order discrete schemes compatible with the algorithmic structure.

3.2. Solution algorithm

In the Abbott-Ionescu type of schemes (1968) 4 discretized equations are employed. The first group of 2 equations (continuity and x-momentum) is solved with a double sweep along the x-axis in which p is raised a full Δt timestep while information on η is accumulated in an intermediate timelevel. As pointed out in some previous papers η^{n+1} is only an intermediate value of a dependent variable in the fractional step scheme and is not representative of a true water level at time $(n+1/2)\Delta t$. In the second half time-step, η is raised from $t+\Delta t/2$ to $t+\Delta t$, while q is raised a full Δt,using the second group of two equations, continuity and y-momentum, with a double sweeping along the y-axis. The corresponding accumulation information is schematized in fig.2 and the staggered disposition of the problem variables is showed in fig. 3.

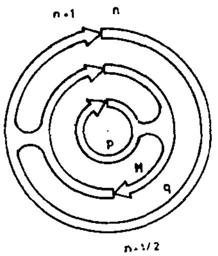

Fig.2: "Clock diagram"representing the accumulation of information in the scheme using an intermediate time-level.

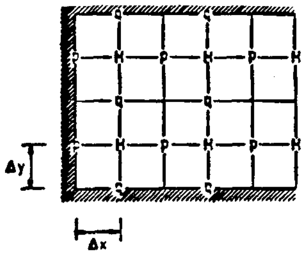

Fig.3:Staggered spatial disposition of the problem variables (H,p,q)once both horizontal and vertical sweepings have been completed.

The full non-linear version of the scheme, however, requires η, p, q values at every nodal point. This is obtained by means of either consistent 2nd-order interpolation or additional double-sweeps.

One step further is a side-feeding scheme, advancing from time level n to time level n+1 by means of a fourfold division of the time step with the following algorithmic structure:

1. Sweep in y direction, laid down with decreasing x.
2. Sweep in x direction, laid down with decreasing y.
3. Sweep in x direction, laid down with increasing y.
4. Sweep in y direction, laid down with increasing x.

In this scheme side feeding is introduced to improve centering in the cross-derivative terms. These terms remain centered when viewed over a complete timestep, while making extensive use of "falsification" in each of the individual stages.

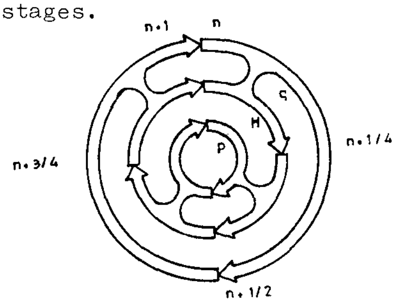

Fig.4:"Clock diagram" representing the accumulation of information in the scheme using 3 intermediate time-levels.

In figure 4 we represent the information accumulating properties of this scheme adapted from the one presented in (Abbott, 1988).

Close to the boundaries, application of side-feeding presents essentially the same problems as other alternative computations of convective, cross momentum and Boussinesq terms. Information on all dependent variables η, p, q at the boundaries is needed but not always known. To solve this problem, estimates of the variables have to be provided. Extrapolation can always be used, but may introduce 1st. order truncation error that can spread all over the domain and even introduce unstable components.

Another source of error present in these schemes is the unappropriate centering of the coefficients in the discretized equations. The difficulty arises when their form is not algorithmically compatible with the employed tri-diagonal algorithmic structures (i.e. they cannot be directly introduced without resorting to iteration).

Furthermore, if one looks for a higher accuracy, it is necessary to add correction terms to obtain third order truncation errors because 2nd order differences introduce an error which is of the same order and type as terms in the momentum equation (Boussinesq terms) describing vertical acceleration.

An order-of magnitude analysis has shown that the third order correction terms corresponding to convective, cross-derivatives and Boussinesq terms are much smaller than other terms.

Apart from the numerical schemes,already presented, we are now implementing an "implicit leap-frog" scheme which is both space and time staggered. Here, from the mass conservation law (4), four discretized equations are obtained. If side feeding is considered as well, 8 discretized equations have to be solved. For the linear 2-D case those 4 equations (excluding side-feeding) are the following:

$$\frac{1}{\Delta t}(\eta^{n+1/2}_{j,k}-\eta^{n-1/2}_{j,k})+\frac{1}{4\Delta x}(P^{n+1}_{j+1,k}-P^{n+1}_{j-1,k}+P^{n-1}_{j+1,k}-P^{n-1}_{j-1,k})$$

$$+\frac{1}{2\Delta y}(q^{n}_{j,k+1}-q^{n}_{j,k-1})+0 \qquad (15)$$

$$\frac{1}{2\Delta t}(P^{n+1}_{j,k}-P^{n-1}_{j,k})+\frac{gh}{4\Delta x}(\eta^{n+1/2}_{j+1,k}-\eta^{n+1/2}_{j-1,k}+\eta^{n-1/2}_{j+1,k}-\eta^{n-1/2}_{j-1,k})=0 \qquad (16)$$

$$\frac{1}{\Delta t}(\eta^{n+3/2}_{j,k}-\eta^{n+1/2}_{j,k})+\frac{1}{2\Delta x}(P^{n+1}_{j+1,k}-P^{n+1}_{j-1,k})+$$

$$+\frac{1}{4\Delta y}(q^{n+2}_{j,k+1}-q^{n+2}_{j,k-1}+q^{n}_{j,k+1}-q^{n}_{j,k-1})=0 \qquad (17)$$

$$\frac{1}{2\Delta t}(q^{n+2}_{j,k}-q^{n}_{j,k})+\frac{gh}{4\Delta y}(\eta^{n+3/2}_{j,k+1}-\eta^{n+3/2}_{j,k-1}+\eta^{n+1/2}_{j,k+1}-\eta^{n+1/2}_{j,k-1})=0 \qquad (18)$$

In Fig. 5 the clock diagram of this time is shown.

The advantages of this algorithm with respect to classical ADI schemes are:

1. Symmetric treatment of all variables respect to x and y axes, i.e. total isotropy.

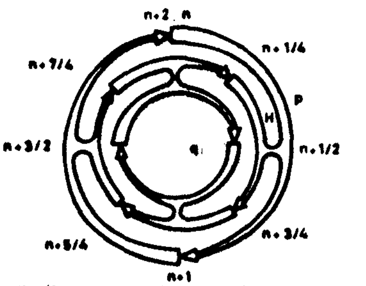

Fig.5:"Clock diagram"of the implicit space - time staggered algorithm

2. Splitted discretized mass equations staggered in space and time.
3. Better time-centering of H, as used in the coefficients.
4. No fractioned step correction on the continuity equation is needed to obtain better performance.
5. Easier implementation of open boundary conditions.

The main disavantage is that all variables are calculated at different time levels, but this is not a severe limitation.

3.3. Boundary conditions

The number of boundary conditions required by the hyperbolic system presented in the previous section is determined by the number of characteristic lines (in 1-D) or surfaces (in 2-D) defined in the considered area (Daubert and Graffe, 1967). The conditions must also define a well-posed problem and allow the exit of waves generated inside the domain.

In recent literature (Verboom et al., 1983) there have been several references to weakly reflecting boundary conditions developed for the 1-D linear hyperbolic equations. These conditions are based on the Riemann invariants for the 1-D case, but are not a good approximation to the physical problem when waves are either not planar or obliquely incident to the open boundary. The use of weakly reflecting conditions in the aforementioned cases induce a non-physical reflection, even though far from boundary the results may be still acceptable. This explains the satisfactory engineering performances of many existing models, in spite of the limitations of their formulation for boundary conditions.

(A.S.-Arcilla and J.L. Monsó, 1986) presented a new approach to treat open boundaries. This new condition allows a reduction of the degree of spurious reflection which,in turn, means an improved accuracy of the model results. In this paper an improvement to the latter approach is proposed. It is based on a linear superposition of the in- and out-going mass-flux vectors, $\vec{Q}$ and free-surface elevations, η, on the open boundary line. This may be written as:

$$(p,q) \equiv \vec{Q} = \vec{Q}_i + \vec{Q}_s \equiv (p_i + p_s,\ q_i + q_s) \qquad (19)$$

in which

i,s: sub-indexes denoting incident (ingoing) and reflected (out-going) waves respectively.

$$\eta = \eta_i + \eta_s \qquad (20)$$

The "in-going" values of the variables are known from the specified boundary conditions, and the three additional equations still required to solve the problem are the mass, x-momentum and y-momentum conservation laws.

3.4. Calibration

The presented numerical models have been first calibrated in linearized versions. The non-linear models have been subsequently tested with solitary and cnoidal waves which are analytical solutions of the differential equations when no frictional stresses, Coriolis forces, etc. are considered. Phase and amplitude errors were likewise studied for these non-linear versions, finding excellent results except for the case in which the wave height was an important part of the water depth (i.e. near wave breaking). A sample result is shown in figure 6.

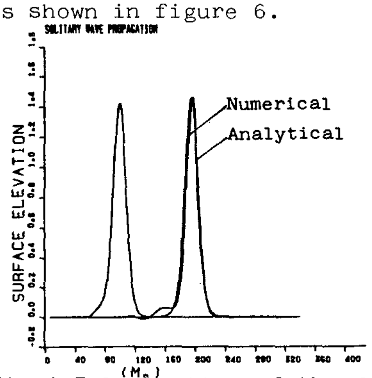

Fig.6: Illustration of the differences obtained with analytical and non-linear equations for 1D wave propagation along a canal of uniform depth.

Once the models had been calibrated with the standard type of boundary conditions, specific tests were designed to ascertain the performance of the open boundary condition described above. One of the most severe test-cases is a square domain with four open sides in which the direction of wave incidence coincides with one of the diagonals. An illustration of the results obtained for this case appears in figure 7. The contour-lines of the disturbed free-surface are, as should be, nearly parallel and perpendiculary oriented to the wave propagation direction.

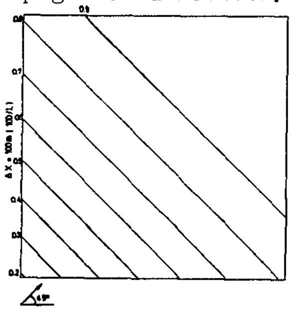

Fig.7: Contour-lines of the disturbed free surface for a square domain with 4 open sides and oblique wave incidence.

4. Expert System

Artificial Intelligence and Expert Systems (E.S.) are a relatively recent advance in civil engineering. The scope of E.S. projects is usually defined by experts rather than by knowledge engineers. For this reason there is still much work to be done by experts in this field.

With such a system access to high-level expertise can be made readily available to project engineers. This reduces overall costs and eliminates time-delays produced as a result of the expert's prior commitments. From an operational standpoint, inmediate access to expert knowledge can significantly reduce non-productive times for labour. Moreover, the capability of the programme to incorporate feed-back information from the engineers can be used to improve its performance.

The basic structure of these programms consists in a knowledge base and an inference mechanism. In the E.S. we are developing, the knowledge representation method is based on production rules. These rules consist in a set of conditions (such as width of harbour entrance, orientation of breakers, depths, etc.) and a set of actions (such as harbour lay-out and bathymetry modifications, etc.). When all conditions in a particular rule are true, the corresponding actions are executed. The conditions are contained in the "IF" part of the rule and the actions in the "THEN" part. Because humen experts are not always certain about these rules, conditions and actions may incorporate some associated uncertainty factors. This allows a more realistic representation of the expert's knowledge, based on this degree of confidence in each rule.

The inference mechanism consists of two different methods, viz. forward-chaining and backward-chaining. In both forms the program acquires information either in the form of a question to the engineer or by means of accessing other programs and data bases.

In backward-chaining systems, the program possesses a built-in method to guess an initial solution, i.e. it assumes one particular harbour lay-out configuration. The system then attempts to prove that the assumption is correct, by requiring confirmation of all the prerequisite conditions for this particular lay-out to the expert engineer or by using its own inference capabilities. If the solution is disproved, the program chooses a different possible lay-out configuration and proceeds to test this new solution in the same manner.

In a forward-chaining system, the program has no "a-priori" knowledge of possible harbour lay-outs. It uses the acquired information to evaluate the tree of possibilities, as it progresses through the solution procedure. Information is gathered until the list of possible causes of problems has been narrowed down as much as possible. The reasoning progresses from an initial to a final state, in which the program has reached its goal.

We have selected a backward-chaining strategy, more suitable for our case, because we usually start from an initial lay-out, either imposed by the client or proposed by the expert engineer. This try-and-error or back-tracking technique is usually followed in most design processes. However, it is obvious that the aim of CAD researchers must be the completion of the forward-chaining system applied to harbour layout design. This strategy would give an optimal geometric configuration of the harbour with respect to the rules supplied with a minimum of subjective influences.

It is also possible to use a mixed strategy combining both forward-chaining and backward-chaining approaches. The main advantage of this strategy is that the engineer only needs to supply data which are relevant for the problem considered.

In current state-of-art, numerical models are used only in a post-design phase, to evaluate the performance of a final lay-out design, which will be modified only if the obtained results are unacceptable. Because of the time and cost required for a new lay-out analysis, numerical models are used primarily for verification, rather than for feedback or iterative-design improvements.

Our proposed global expert system has the following characteristics:

1. The entire modeling process is carried out on the computer using a combination of interactive and automatized modeling procedures.
2. Expert knowledge is used in the modeling software to increase the level of automatization and to aid the engineer in making better decisions.
3. The engineer is relieved of the need to make rudimentary calculations.
4. The engineer can always ask why the programmed modeling rules pretend to model a particular geometric configuration of the harbour.

The result will be not only a drastic reduction in the time and effort required, but also an improved reliability in the designing process.

5. Engineering Applications

In this section, results from an existing numerical model for wave propagation, based on Boussinesq-type shallow-water equations are presented in the context of harbour lay-out. This model is the basis for the improvements herein proposed.

The first case presented belongs to the wave propagation analysis carried out to design the new lay-out of the Bilbo Harbour in the North Coast of Spain.

The main aim of the study was to improve the hydrodynamic design of the harbour lay-out. The overall plan dimensions were approximately 7 Km. x 5 Km. which required more than 10^5 grid-points in the discretization.

The inputs for the runs were irregular time-series of free-surface elevations generated from a Jonswap spectral density function. This simulated wave record was made to enter the domain from different directions through the open boundary.

Figures 8 and 9 depict the contours of equal variance for two different geometries of the Bilbo Harbour. It is easy to understand now these and similar results may be used to estimate the lay-out design.

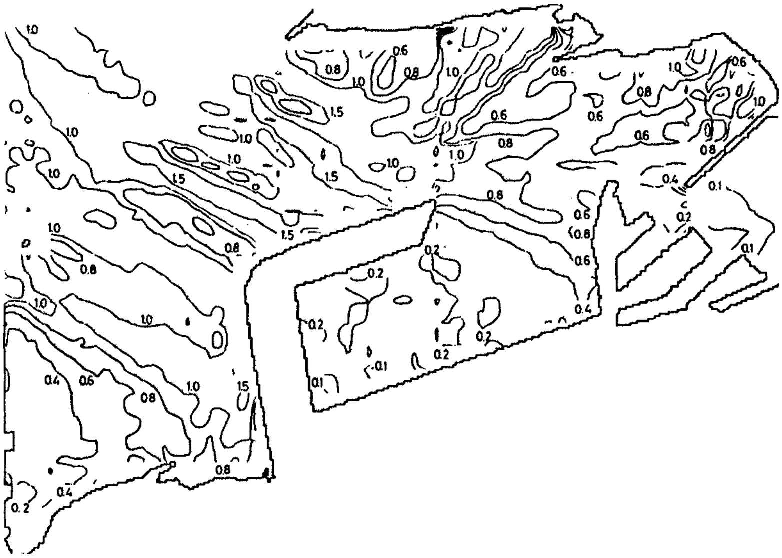

Fig.8: Isolines of variance for the wave propagation problem in the new Bilbo Harbour (Superport).

Fig.9: Isolines of variance for the wave propagation problem in the new Bilbo Harbour (Superport).

The second example presented is an application of the system to design the entrance of a harbour in the Catalonia Coast. After some variations in entrance geometry and wave climate conditions, a final optimized configuration was obtained. Figures 10 and 11 show two possible lay-outs.

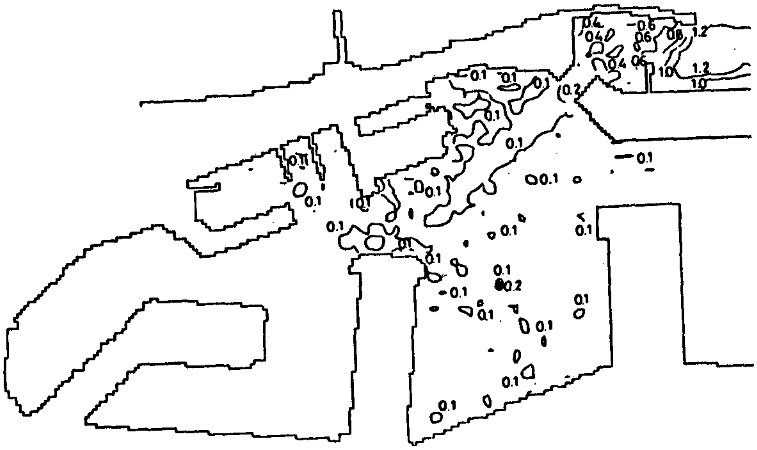

Fig.10: Equal variance contour-lines and entrance lay-out for the second example presented.

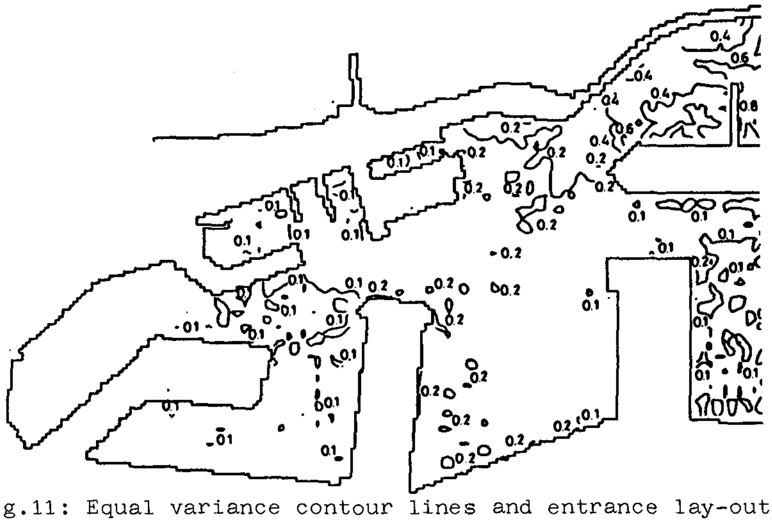

Fig.11: Equal variance contour lines and entrance lay-out for the second example presented.

The last case presented is an application of the system to design the lay-out of a marina at the Canary Islands, Spain. In this example we had to design the width and depth of the canal, including the entrance configuration, so as to obtain a better overall performance from a hydrodynamic standpoint (i.e. to provide shelter) without interfering with the set of operational constraints imposed. Some sample results corresponding to different entrance lay-outs are shown in figures 12 and 13.

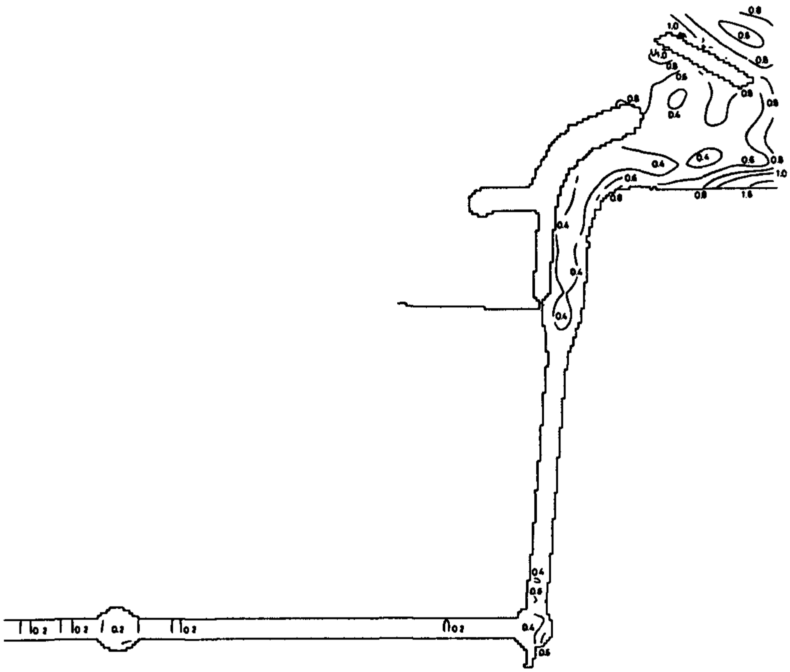

Fig.12: Marina lay-out and variance isolines

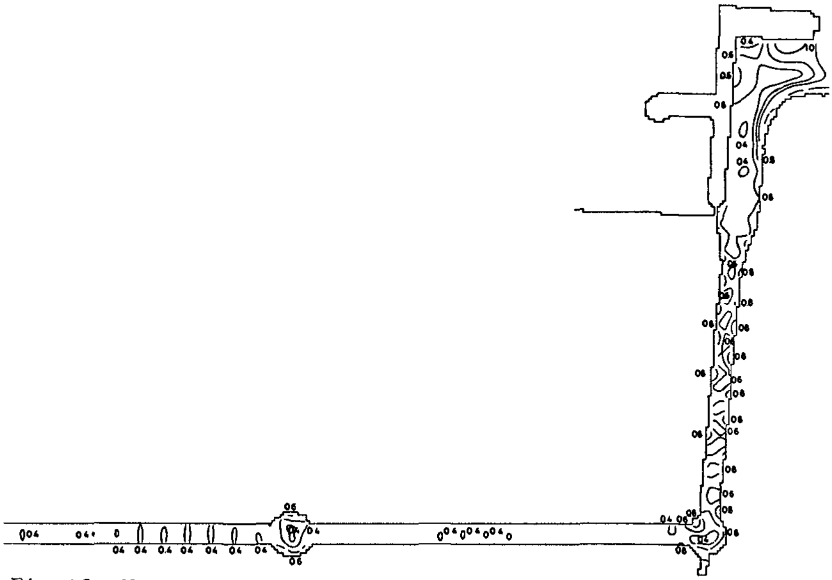

Fig.13: Marina lay-out and variance isolines

6. Conclusions

In this paper, a CAD expert system for harbour lay-out is presented. The system is based in previous experience acquired by the use of hydrodynamic numerical models for wave-current propagation. Some of the obtained results have been presented together with a new, improved numerical scheme.

The most important conclusions are the following:

1. A new ADI scheme has been presented combining the virtues of the leapfrog-scheme with the efficiency of ADI schemes. In this algorithm all the variables are evaluated at different time-levels. This allows a better centering of the discretized mass conservation equations together with a total isotropy of performance.

2. The proposed open boundary condition provides an improvement over former weakly reflecting conditions. This, in turn, means a higher degree of accuracy in the simulations.

3. A new third order scheme, which is now being developed is expected to provide improved results with finite amplitude wind waves in which the wave height is an important part of the water depth. This means a reduction of the number of mesh points, for the same truncation error.

4. The use of a numerical model, based on Boussinesq-type equations, as a module of a global expert system both from technical and economical standpoint will make it possible to obtain an improved design for harbour layouts.

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