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Numerical modelling of ship-induced water motions

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ABSTRACT:

Ship-induced water motions are important becuse of the influence on bank stability. At the moment it is impossible to predict the wash in complex geometries, such as rivers with groyne fields. Therefore, a predicting model is required.
In this study the coupling of the two different numerical models RAPID and TRITON has been investigated as well as the possibilities and limitations with respect to predicting the wash near banks.

The main conclusion is that coupling of RAPID and TRITON is feasible and efficient. Therefore, it is recommended to continue and to improve the coupling of the models.

REFERENCES: order AB 001495 dated April 4, 2000

VER.	ORIGINATOR		DATE	REMARKS	REVIEW		APPROVED BY	
3	H.J.Verheij et al		November 27, 2000	final report	O.Weiler		E.van Beek	

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List of Symbols

a_0	typical wave amplitude
Fnh	Froude number based on water depth and ship speed
FnL	Froude number based on ship length and ship speed
g	gravitational acceleration
h	water depth
h_0	typical water depth
k_0	typical wave number
L	ship length
L_0	typical horizontal length scale
L_{RAPID}	length of the RAPID domain
L_{TRITON}	length of the TRITON domain
$T_{imposed}$	time during which a wave disturbance is imposed
$T_{computation}$	actual computation time
t	time
V_s	ship speed
x	co-ordinate perpendicular to the sailing line and channel axis
x_0	origin of the earth-fixed co-ordinate system
x	co-ordinate in a system moving with the ship
y	ordinate normal to the sailing line and channel axis
z	vertical ordinate
ε	ratio of a_0 and h_0 indicating the relative importance of non-linear effects
η	surface elevation
$\eta_x(t)$	surface elevation in an earth-fixed co-ordinate system
$\eta(x)$	surface elevation in a co-ordinate system moving with the ship
λ_0	deep water wave length
μ	product of k_0 and h_0, indicating the relative importance of linear frequency dispersion
μ_s	inverse product of k_0 and L_0, indicating the relative importance of linear shoaling
Δt	numerical time step
Δx	spatial resolution in x direction
Δy	spatial resolution in y direction

I Introduction

WL|Delft Hydraulics and MARIN have been commissioned by the Road and Hydraulic Engineering Division of Rijkswaterstaat (DWW) by order AB 001495 dated April 4, 2000 to carry out a feasibility study to the possibilities for predicting the ship-induced water motions near the banks of waterways by coupling two different numerical models.

The project has been carried out by WL|Delft Hydraulics and MARIN together, whereas WL|Delft Hydraulics was responsible for the administrative part. Ir. Henk Verheij, dr. ir. Mart Borsboom and ir.Neelke Doorn of WL|Delft Hydraulics and dr.ir.Hoyte Raven of MARIN carried out the study with Mr.Verheij being in charge of the project management. Ir.N.M.Kruyt and ir.W.Leeuwestein were the representatives of the Road and Hydraulic Engineering Division (DWW) and Constructions Division (BWD) of Rijkswaterstaat (RWS). In addition, ir.J.C.K.vanToorenburg and ir.E.Bolt of the Transport Research Centre (AVV) were involved.

2 Objective and approach

Ship-induced water motions are important because of on the one hand their influence on the stability of banks and bed of a waterway, and on the other hand the safety of moored ships. For both categories of aspects the consequences of the ship-induced water motions depend on the following chain of events:

ship wave generation
⇓
wave propagation
⇓
wave conditions at the bank or the moored vessel
⇓
influence on bank stability or response of moored vessel

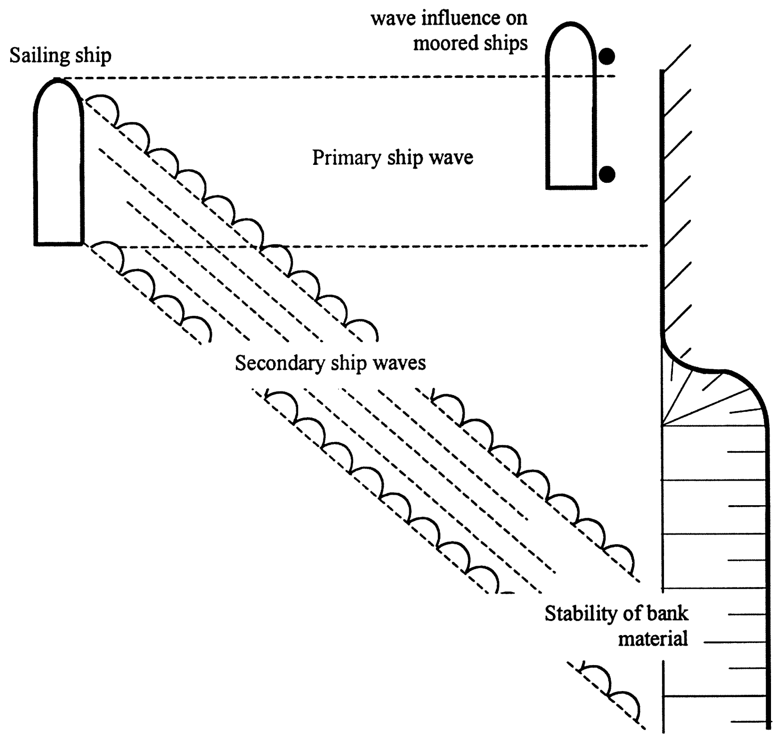

Figure 2.1 Interaction between sailing ship and banks or moored ship

The Dutch Public Works Department is interested in the full chain as far as it concerns the stability of banks subjected to waves generated by passing ships. Up to now, it is possible to predict the ship-induced water motions at the banks for relatively simple situations, such as canals and rivers without groynes and groyne fields. Predicting the ship-induced water motions for rivers with groynes and groyne fields, waterways with harbour basins, channels in lakes, etceteras, is much more complicated. Another problem concerns the wash (here

defined as the primary and secondary ship waves) generated by fast ferries which sometimes create problems for other sailing ships or moored vessels.
Consequently, the Dutch Public Works Department wants to have available in the near future prediction methods for ship-generated waves in simple or complex geometries for their consultancy role. In recent years, MARIN and WL|Delft Hydraulics have developed numerical models for the two components "ship wave generation" and "wave propagation". A combination of these models may fulfil the wish of the Dutch Public Works Department, and if coupling of the models is feasible, a powerful prediction tool could thus be developed. Therefore, the objectives of the present study are:

1. To investigate the possibilities of coupling the two wave codes in order to predict the wash near banks of rivers and canals.
2. To obtain insight into the possibilities and limitations of numerical prediction methods in view of the present requirements and wishes; i.e. regarding the evaluation of bank stability and response of moored vessels.

These objectives will be treated in the next chapters. In the last chapter conclusions will be presented.

3 Numerical models

3.1 Introduction

The Dutch Public Works Department wants to have available a numerical tool for predicting the ship-induced water motions near banks and bed of waterways, in particular for complicated situations. They have presented a list of requirements for such a prediction model:

The method ought to be able to deal with:
1. irregular lateral boundaries of canals and rivers (spurs, harbour basins)
2. non-stationary conditions
3. small keel clearances
4. variations in bed level in sailing direction (gradually and/or suddenly)
5. increasing and decreasing ship speeds
6. presence of other ships in the fairway
7. possibility to implement different ship types

In addition, also requirements are imaginable with respect to:
- the possibility to make predictions "in house"
- availability of hull geometry input data for some standard ship types
- prediction of flow velocities and changes of the wave pattern due to the propulsion systems; prediction of screw race;
- use of the output files for design purposes (bank stability, response of moored ships)
- etcetera

Moreover, the Dutch Public Works Department wants to know the local wave conditions at the banks including for e.g. possible effects of bank material on the wave height and period, as well as the stability of bank material (interaction of waves with the bank). These are the third and fourth component in the chain presented already in Chapter 2:

wave generation
⇓
wave propagation
⇓
wave conditions at the bank
⇓
influence on bank stability

As mentioned earlier, it is envisaged to base a prediction method for these phenomena on existing tools developed by MARIN and WL|DELFT HYDRAULICS as far as possible. The available tools with respect to the prediction of ship-induced water motions will now be presented in this chapter. In particular, two models will be discussed:

- the wave generation code RAPID (section 3.2), and
- the wave propagation code TRITON (section 3.3).

Below we describe the basic methods used and functionality of these codes, and pay specific attention to aspects of interest for the present subject. In addition, in sections 3.2.3 and 3.3.3 remarks will be made about respectively other wave generation codes such as SHALLO, SHIPFLOW, and VSAERO/FSWAVE, and other wave propagation codes, such as SWAN, HYPAN and PHAROS.

3.2 RAPID

3.2.1 General

For the prediction of the ship-generated wave motion and flow in a waterway, a method is required to compute the wave generation. For this purpose the code RAPID will be used, which is described below. Some physical aspects of the generation of a steady wave pattern by a ship in still water (ship wave making) are described in [Kluytenaar et al, 1998].

RAPID calculates the steady inviscid flow around a ship hull, the wave pattern and the wave resistance, and permits to take into account some of the features of the waterway as far as relevant to the wave generation. The method has been developed at MARIN in the period 1990 - 1994 [Raven, 1996], and has subsequently been extended and refined. It now is one of the best known codes world-wide in this field [Raven, 1998]. Since 1994 it has been routinely applied in practical ship hull design at MARIN. Besides, the program is licensed to (at the moment 7) shipyards, institutes and universities, a number that is steadily increasing.

Primary purpose of the method in general is the minimisation of wave making and wave resistance by a proper ship hull form design. Visualisation of the computed results gives a clear view of all features of the wave pattern, hull pressure distribution and streamline direction over the hull. Analysis and expert judgement then indicate which modifications of the hull form should be made. In a few steps a hull form can thus be optimised efficiently and quickly.

RAPID is applicable to the majority of vessels, ranging from tankers to frigates, from sailing yachts to ferries. The code can handle symmetric or asymmetric cases, monohulls or multihulls, deep or shallow water. Special versions exist for hydrofoils or ships with lifting surfaces (e.g. keel or rudder), and for ships in channels.

The flow model used is that of a 3D steady incompressible potential flow around the ship hull. The exact inviscid free-surface boundary conditions are imposed without any further approximation, so the flow model in principle includes all non-linear effects on wave generation and propagation. Moreover, the ship hull is required to be in equilibrium with the hydrostatic and hydrodynamic pressure distribution, i.e. squat is computed and incorporated.

On the other hand, being based on inviscid flow theory, the method disregards the effect of boundary layers, dead water zones behind a transom, or separation of the viscous boundary layer flow at the stern. Consequently, the amplitude of the stern wave system is usually overestimated; very little for slender transom stern vessels, more for fuller hull forms. For a (seagoing) tanker hull, with a thick boundary layer or even flow separation at the stern, the stern wave system may well be overestimated by a factor of 2 or more.

A consequence of the computational approach is that codes like RAPID are typically suited to (rather) near-field rather than far-field predictions. For directly computing wave elevations in the far field, a large free-surface domain is needed, and limits in computer memory are quickly reached. Besides, with increasing distance numerical errors tend to grow. Some possibilities exist to remove or reduce these limitations, and the present project attempts one of those possibilities.

More details on RAPID, including a description of the computational approach, hardware requirements, and its accuracy in general, are found in the Appendix.

3.2.2 Application to predicting ship-induced flows

In brief, RAPID is able to predict the entire inviscid flow field around a ship hull in a variety of steady flow situations. However, in practice several restrictions apply, and certain aspects of the results may be less accurate. Below we try to summarise what possibilities and, in particular, what restrictions the RAPID code has for predicting the physical phenomena relevant to the present field of interest.

<u>prediction of the steady velocity field around the hull</u>
As briefly explained in the Appendix, a panel method is used. The boundary conditions are imposed in a distribution of points ("collocation points"), which are the panel centres on the fixed boundaries (ship hull, channel wall), and collocation points under the panel centres on the free surface. Velocity and pressure are found in all these points, and using the postprocessor VELFIELD can also be determined in arbitrary other points within the area under the free-surface panels.

In this way, the velocity field around the hull, and therefore the ship-induced flow in the waterway, is well predicted in general. However, due to the neglect of viscous effects deviations may occur. Boundary layer and wake of the ship are not represented, the pressure rise towards the stern will be too large, and the displacement effect of the viscous flow is absent.

Viscous effects may also be important for ships in shallow water at small keel clearance, when the space between the bottom of the ship and the bottom of the waterway entirely consists of a boundary layer flow. Bottom boundary layers are absent in the calculations anyway. However, their influence on wave generation will be small in most cases.

prediction of the wave pattern

The wave pattern, consisting of a primary disturbance near the hull and a radiated wave system, is accurately predicted in general, as many comparisons with experimental data have shown. Basically this is true regardless of the type of ship, provided it runs at a 'normal' speed for its design. E.g. a full hull form at high speed creates much wave breaking, and the prediction would be less accurate or even impossible; but a fast ferry, with its slender hull form, presents no particular problem in general.

Since the exact free-surface boundary conditions are imposed, the flow model includes all inviscid steady flow effects, such as wave refraction by flow velocity variations, all higher-order effects on wave shape, height and propagation speed, etc. The interaction of the ship waves with the ship-induced flow field is, therefore, fully included; however, in principle there is no way to impose a nonuniform inflow, in order to compute wave refraction by variations of the current speed. This can be easily shown from the requirement of a steady flow (which means, no longitudinal variations of the flow field in the waterway), and the basic assumption of irrotational flow which then excludes any variation of the longitudinal inflow velocity component in the inflow plane.

A restriction that applies to the hull form is that the waterline entrance may not be a transverse line of substantial extent, such as in some barge-type bows. For such shapes, the flow model applied (steady inviscid flow without wave breaking, and a single-valued free surface shape) probably does not apply anyway. A round bow with a 90 degrees half entrance angle need not present a problem, but for truly barge-type bows some approximation may be required. In a recent application, computations have been made for barge-type bows, but the predicted wave pattern appeared dominated by the waves generated at the corners of the bow, and probably is unreliable due to neglect of wave breaking and insufficient resolution. For applications to e.g. push barges, some additional validation is recommended.

Viscous effects reduce the stern wave system in reality, and this is not taken into account in RAPID. This restriction is discussed more extensively in [Raven, 1998]. Possibilities for taking this into account have been studied [Raven, 1999], and a crude correction method has been developed based on adding an approximate boundary layer and wake displacement thickness to the hull. This did produce a reasonable reduction of the wave amplitude in the test case considered, but further validation would be required.

size of the computational domain

A prediction of the wave pattern is obtained in the area that is covered with free-surface panels. Outside this area, the vertical disturbance velocity quickly falls to zero. Consequently, if one requires a wave height prediction at a large distance from the vessel, a large area needs to be covered with panels. Moreover, the discretisation of the free surface introduces certain numerical errors, which can be decomposed into numerical damping (i.e. a too quick decay of the wave amplitude with distance from the hull, due to errors related with the finite panel size) and numerical dispersion effects (errors in the relation between wave length and wave propagation speed). Both are proportional to some higher order of the panel size. For usual calculations, the errors are small if 20-30 panels per transverse wave length are used on the wave surface.

These errors accumulate with distance: the larger the distance from the ship, the larger the underestimation of the wave amplitudes and the phase errors. Therefore, to accurately predict the wave pattern at larger distances, one needs a fine free-surface panelling to minimise these errors. The requirements of having a large domain and a fine panelling quickly lead to a computational problem of excessive size: the required memory in the computer is dominated by the need to store the system of N equations (if N is the number of panels used), which contains N^2 coefficients. Therefore, alternative methods to estimate the far-field wave elevations may often be needed. These will be discussed in Section 4.2.

It is remarked here that it should be possible to remove most limitations resulting from memory restrictions, by using 'multipole acceleration' or 'precorrected FFT' techniques. Without further describing the mathematical background of these methods, we mention here that these not only lead to a very large computational efficiency for large panel numbers, but also avoid storage of the complete system of equations. However, incorporating this in RAPID would require a substantial amount of development. Another technique that possibly would offer some prospects is domain decomposition, such as proposed by [de Haas, 1997]. Again, a significant amount of R&D would be required.

wave reflections

The free-surface panel domain is of finite extent, and it is observed that waves reflect at the lateral boundaries. However, since below those lateral boundaries the domain is open, the reflection is unlikely to represent anything physical. In particular, this is not a reliable way of modelling channel wall effects. Consequently, the part of the predicted wave pattern that is affected by the reflected waves must be disregarded. In usual application in ship design, this is no major drawback since the near field is of primary concern, and waves reflected at the lateral boundaries only reach the area near the ship's path far aft of the ship. However, in the present field of applications the reflections are more detrimental as will appear in the feasibility study in Section 5, and it may be desired to develop a technique to damp the waves near the outer edge. This is possible by adding terms to the free-surface boundary conditions locally.

On the other hand, the downstream truncation of the domain has very little effect: no reflections occur here, only the very last part of the wave pattern is somewhat unreliable.

shallow water effects on ship wave generation

A variety of shallow water effects on ship wave making exists. A well-known one is the existence of a critical speed; but in addition, the presence of a water bottom changes the flow direction around the hull, increases the pressure variations over the hull, causes a larger sinkage of the vessel, and usually amplifies the wave making.

The best way to model these effects is to mirror the entire source distribution in the bottom. This means that the bottom of the waterway is considered as a symmetry plane of the problem, and by adding the mirror image of the entire source panel distribution the solution will be symmetric. This guarantees that the bottom boundary condition (zero vertical velocity) is exactly met, even outside the panel domain. Moreover, it is computationally efficient since the size of the matrix equation to be solved is not increased.

Alternatively, an area of the water bottom can be covered with panels, at which a condition of zero normal velocity is imposed. This is much less efficient and soon leads to a very large computational problem, but it is the only option if the waterdepth is not uniform. An example of such an application, in which also channel walls and sloping banks were present, can be found in [Raven et al, 1998]. It has been found that the panel density on the bottom, in particular under the vessel, and its extent, are rather critical.

Near the critical speed in shallow water (for a depth Froude number between 0.95 and 1.05, say), the flow becomes very sensitive to all disturbances. The same is true in RAPID. Consequently, the convergence of the iterative process (see the appendix) may become troublesome, and quite close to critical speed a solution cannot always be obtained if the blockage is substantial. The sensitivity of the flow also means a larger effect of the propulsion, which therefore ought to be modelled.

In addition, there may be a larger effect of the lateral truncation boundaries of the free-surface domain. As is seen in e.g. Fig. 2, a ship wave pattern at subcritical speed is contained in a triangular sector with its apex just ahead of the bow. This so-called 'Kelvin wedge' has a half top angle of 19^0 28' at low subcritical speeds, but near critical speed it widens, and large transverse crests may extend all the way from the bow to the edge of the free-surface domain and reflect there.

Moreover, it is known that in the transcritical speed range, unsteady flows occur, such as generation of solitons propagating ahead of a ship in a channel. Such effects are excluded in RAPID. How serious this is, is not known yet.

These effects occurring near critical speed are mainly important if the water depth is small compared with the dimensions of the vessel. For rather large water depths, the influence on the flow, and the expected deviations in a computational prediction, will be less important. Precise limits cannot be given at present.

For supercritical speeds, the prediction is easier again, and a better accuracy may be expected. However, no validation has been done for such conditions so far, so there is no complete certainty about the accuracy of the predictions. In particular for wash-related applications, validation at supercritical speeds is desired.

Kluytenaar et al (1998) give some examples of calculations for subcritical, transcritical and supercritical speeds.

<u>channel effects</u>

A lateral restriction of the waterway leads to 'blockage' effects, which partly are similar to shallow water effects: they increase the pressure gradients along the hull, they reduce the critical speed. In addition they cause reflection of the waves.

Channel walls (if supposed fully reflecting) can be modelled again either by mirroring, or by adding a panel distribution. A complication is that for symmetric cases, mirroring already is present in the symmetry plane. The presence of 2 vertical mirroring planes causes an infinite series of mirrored images. In practice, this series can be truncated when the distance of the images is large enough. The option to represent channel walls by mirroring has, however, not been implemented yet. The option of incorporating channel walls by an additional panel distribution has, simultaneously with the present study, been fully integrated in the latest version of RAPID (version 2000_0) and its pre-processors.

In principle, the free-surface panelling should extend all the way to the channel wall. Only then the flow and pressure at the channel wall can be predicted. However, if the channel is wide, this may lead to excessive panel numbers. For wide channels the coupled Rapid/Triton approach discussed later may be a better option. However, as explained later, this coupled approach does not include an effect from Triton (which includes the channel wall) back to Rapid. Therefore, even in a coupled calculation the effect of a substantial blockage on the ship wave generation should in some way be incorporated in Rapid itself. It could be attempted then to truncate the free-surface panelling at a smaller distance from the vessel, but all the same to mirror in the channel wall; or to use large panels on the outer part of the wave surface until the channel wall. In this way one would expect that blockage effects to some extent would be incorporated. This possibility could be investigated later if relevant.

<u>asymmetric flows</u>
Asymmetric flows may occur due to e.g. an asymmetric hull form, a ship at an angle of heel or leeway, presence of a bank at one side or an asymmetric path in a channel, or combinations of these. To compute such flows, the mirroring in the centreplane needs to be dropped, both sides of the hull and free surface must be panelled, etc. The panel number becomes twice as large, memory and calculation time become at least 4 times as large.

Restrictions apply if the asymmetry is large and lifting effects play a role. We expect that side forces due to leeway or bank suction will not always be accurate. Validation would be desired.

<u>unsteady flows</u>
An important basic assumption underlying the method is that the flow is steady. No time-dependent terms are included at all. Consequently, in principle the following cases cannot be dealt with:

- variation of the ship's speed. For fast ferries it is sometimes observed that the largest wave making occurs during acceleration or deceleration; this can at best be approximated as a quasi-steady effect in RAPID, i.e. a sequence of steady calculations for different speeds is used. How these wave patterns should then be superimposed is not obvious, though.
- variation of water depth or width. Passage of the ship over uneven bottom or through a channel of varying cross section causes variation in time, which again can only be predicted as a quasi-steady phenomenon. It is expected that in many cases this will be accurate enough, at least for the near field. However, in cases in which the water depth is such that waves are near-critical, variations of that depth will have drastic effects and a quasi-steady approximation probably will not work.
- several ships with different speed or heading (e.g. ships on opposite courses). Some of these cases again may be handled as quasi-steady, some cannot.

- variation of the ship's heading. It is known that, if the ship follows a curved path, at the inner side of a curve the waves are focussed. There is no way to compute this in RAPID itself, but perhaps it can be transferred via boundary conditions to a time-domain wave propagation model.

It is to be noted that some of these limitations may be removed or alleviated by coupling with a time-domain wave propagation code such as considered in this study.

propulsion

A ship's propeller causes a screw race, a swirling jet flow that may be important for erosion in certain conditions. Moreover, the propeller modifies the pressure distribution on the hull and elsewhere in the flow. In particular in restricted water, the propeller effect can be substantial.

At present there is no propeller model incorporated in RAPID. The effect on the pressure field, the velocity field forward of the propeller, the wave pattern, trim and sinkage of the vessel, can be modelled by the addition of an actuator disk, a distribution of sinks (negative sources, which 'absorb' fluid) over the propeller disk. The propeller loading is prescribed, and equal to the expected propeller thrust. This is a rather limited modification of the code, which probably is good enough for representing the propeller effect on the wave pattern of the hull and flow around the hull. It does not, however, represent the screw race as such, and will not help to assess erosion effects due to that.

3.2.3 Other ship wave generation models

Besides the RAPID code described here, a few other non-linear steady free-surface potential flow codes exist. The best known ones are SHALLO (developed at HSVA/IFS in Hamburg), SHIPFLOW (developed by Flowtech, Gothenburg), and VSAERO/FSWAVE (developed at IfS Hamburg, and AMI in the US). These methods are briefly reviewed and compared in [Raven, 1998]. Their basic approach is quite similar today, and all of them solve the same potential-flow problem subject to the same exact free-surface boundary conditions and neglecting viscous effects. Reasons to prefer one or another are somewhat secondary, and differences between methods are in details of the numerical treatment. Briefly, our assessment is that SHALLO is numerically less accurate in practice, and has a less accurate modelling of transom stern flows. SHIPFLOW is quite comparable with RAPID, gives very similar predictions and is widely used, but reportedly uses significantly more calculation time and memory due to its less advanced matrix solver. VSAERO/FSWAVE is harder to judge, but seems to be of comparable accuracy with the other ones.

Another class is formed by linear free-surface potential flow models, imposing either the slow-ship linearised free-surface condition or the Kelvin condition. Such linearised methods avoid the need to solve the problem iteratively, and find a solution of the approximate problem in one (sometimes 2) steps. While in principle they therefore could require an order of magnitude less calculation time, little development on these methods has been done for quite some time and the matrix solvers are not up to date, so in reality most require more calculation time than modern non-linear methods.

While the linearised methods do predict a qualitatively correct wave pattern, it has been shown that the quantitative accuracy is substantially less than that of non-linear methods, in particular for diverging bow waves and transom stern flows. This is due to the neglect of non-linear effects in the near field (close to the ship).

However, for the present applications, the linearised free-surface conditions should not be entirely forgotten. If the Kelvin free-surface boundary condition (FSBC) is imposed, a solution can also be obtained by employing a different Green function, and building the solution from the flow fields of "Kelvin sources" ("Havelock sources"). These follow from a complicated analytical expression that is harder to evaluate, but which by definition already satisfies the Kelvin FSBC everywhere on the free surface. Consequently, sources only need to be distributed over the hull (and perhaps the channel bottom and wall), but not over the wave surface. This makes this approach very well suited to far-field wave predictions. On the other hand, it disregards the non-linear effects in the near field, and thereby will underestimate diverging waves by a large amount. In case the wave amplitude in the far-field is requested, this may be a serious disadvantage since this amplitude often is dominated by the wave components at the Kelvin wedge, which are diverging waves.

A very promising use of this formulation is, however, by matching it with a near-field prediction using a non-linear code. In this way the wave generation is modelled accurately, but outside the near field, where non-linear effects are small, the linear Kelvin condition is used. This permits extension to arbitrary distances, in principle also in water of limited but uniform depth. We come back to this topic in Section 4.2.

It has been noted that some of the desired applications considered here contain unsteady effects. A non-linear unsteady free-surface potential flow model would be required to model these. Such methods are being developed, but mostly for other applications such as seakeeping and diffraction problems. In that case the unsteadiness arises from incoming waves, not from variation in waterway dimensions. Extension to other unsteady effects is not always possible, in particular if linearisation of time-dependent components is applied.

An example of a method that does permit to predict ship wave generation in unsteady cases is UM-DELTA, a code developed at University of Michigan. Some good predictions of steady ship wave making have been published. These are computed by imposing steady boundary conditions (except at the free surface) and continuing the calculation until the result has become steady. This is a time-consuming process, and in a recent comparison for a steady ship wave pattern, UM-DELTA required about 60 times more CPU than RAPID. Unless unsteady effects become dominant, we probably need not consider such approaches.

3.3 TRITON

The second numerical model applied in the present study is the (non-linear) time-domain wave model TRITON for the simulation of wave propagation over foreshores. This Boussinesq-type model developed at WL | DELFT HYDRAULICS is described briefly in this section. A more detailed description can be found in Borsboom *et al.* (2000).

3.3.1 General

TRITON has been designed for the modelling of the dynamics of surface waves in shallow coastal regions. Wave propagation in shallow water plays an important role in the physical processes in, e.g., sandy coastal regions and harbour areas. Due to the existence of relatively large waves in shallow water non-linear effects are significant in these regions, especially when compared to wave propagation in deep water. The non-linear effects are to some extent counteracted by frequency dispersion. Standard shallow water models, that are only valid for very long waves, do not take frequency dispersion into account. As a result they tend to overestimate the non-linear behaviour of wave propagation, which makes them unsuited for wave propagation studies.

A computational model for the study of wave propagation in shallow water, should include both non-linear effects and frequency dispersion. A Boussinesq-type model like TRITON meets these requirements. This type of model enables optimisation of the mathematical description of frequency dispersion to high levels of accuracy using a fairly cheap 2DH formulation. This is achieved by eliminating the depth dependence from the equation of irrotational 3D free-surface flow, using a perturbation series of expansion in vertical direction. Moreover, a Boussinesq-type model formulation can be tuned to a certain class of wave behaviour that one wants to study. An efficient model designed for a certain purpose is obtained by modelling only the important phenomena accurately and neglecting the modelling of relatively irrelevant phenomena.

Within the range of existing Boussinesq-type models, each model aims for a certain accuracy of *a)* non-linear effects, *b)* linear dispersion and *c)* shoaling. The accuracy of each of these three aspects should be in balance: Improving linear dispersion without sufficiently improving the non-linear effects might be useless if wave propagation over shallow foreshores is concerned. On the other hand, improving each of the aspects where the three aspects are in balance, might lead to a very complex model which may result in large computing times. The Boussinesq-type model TRITON is a model developed to obtain an accuracy as good as possible within limited computing times. Besides a proper balance between accuracy and computing time also a proper balance was found between the accuracy of the mathematical description and accuracy of the numerical implementation. TRITON has a few unique properties for a Boussinesq-type model:

- The formulation is independent of the vertical reference level for bottom topography and water elevation, which facilitates straightforward practical applications.
- Dispersion and shoaling are modelled in a very compact way, which reduces computing times.
- Both mass and momentum are conserved, which means that the model, besides providing solutions of the applied formulations, also assures that a few basic physical properties are modelled correctly.

<u>weakly reflecting boundaries</u>
If an incident wave is imposed on one of the boundaries of the computational area one has to make sure that outgoing waves are not reflected back. For example, if the incident wave is imposed by prescribing the variation in time of the water level a change of outgoing characteristic information is fed back completely into the domain. To avoid these

unintended reflections TRITON is equipped with absorbing boundary conditions [Borsboom *et al*, 2000].

The absorbing boundary conditions have been obtained from an approximate characteristic analysis, decomposing the wave field in one incoming and one outgoing wave component. Direction and celerity of the incoming component are obtained from the specified incident wave. The local average direction and celerity of the outgoing (reflected) wave are estimated from the difference between computed solution and incident wave. The result is used to impose the incident wave (prescribed water level) in terms of the incoming characteristic. At the other boundaries the incoming characteristic specifies zero velocity. Both conditions lead to very low spurious reflections.

Wave breaking

Another important feature of TRITON is the modelling of wave breaking. Wave breaking is implemented based on a new method by Borsboom where wave breaking is modelled as an eddy-viscosity model in combination with a surface roller. The present version of TRITON can compute breaking waves in a quasi two-dimensional situation provided the direction of wave propagation is within a sector of 45 degrees plus or minus the main wave direction. The applied method allows to increase the size of this sector by a factor of two but this has not been implemented yet. Since the modelling of wave breaking is not relevant for the present study the reader is referred to Van Gent and Doorn (2000) for a more detailed description.

3.3.2 Application to predicting wave propagation

We shall now try to summarise the possibilities and restrictions the TRITON code offers to predict the physical phenomena relevant to the present field of interest.

Wave pattern

TRITON is suitable for modelling wave propagation in coastal regions and harbours. Especially for the wave propagation of short waves, where non-linear effects play an important role, TRITON can be adequately applied and provide valuable information on the wave field.

Boussinesq-type equations are an extension of the standard depth-averaged shallow-water equations. The extension consists of the addition of dispersion terms that alleviate the shallow-water restriction that wave lengths should be large compared to the water depth. The dispersion terms enable Boussinesq-type models to predict the wave transformation from intermediate to shallow water and vice versa, by transferring energy between frequency components.

The range of applicability of a Boussinesq-type model is determined by the values of the non-dimensional quantities ε, μ and μ_s. These numbers are:

- $\varepsilon = a_0 / h_0$, the ratio of a typical wave amplitude a_0 and a typical water depth h_0 that indicates the relative importance of non-linear effects;
- $\mu = k_0 h_0$, the product of a typical wave number k_0 and the typical water depth h_0 that indicates the relative importance of linear frequency dispersion;

- $\mu_s = 1/(k_0 L_0)$, the inverse of the product of typical wave number k_0 and a typical horizontal length scale L_0 over which changes in bottom level occur, that indicates the relative importance of linear shoaling.

(Note: the parameter L_0 is not equal to the deep water wave length λ_0).

The model TRITON is designed for the modelling of wave numbers up to 3.5 times the inverse water depth (i.e. $\mu_{\max} \approx 3.5$). This means that the model reaches its limitations in situations where either the water depth is relatively large or the waves are relatively short. Wave periods as small as 0.5 s can be modelled in water depths up to two decimetres. Wave periods of 5 s can be modelled in water depths of up to 20 m.

The largest possible value of ε is approximately 0.25, so wave amplitudes as large as 5 m can be modelled in water depths of 20 m. The same applies to waves in very shallow water as well (wave heights up to 0.05 m in water depths of a few decimetres).

The value of μ_s can be quite large, but should not be considered separately. Relevant for the maximum value of μ_s is the combination $\mu_s \mu = h_0 / L_0$, which is a geometric parameter indicating the relative steepness of the bottom. The present model requires $\mu_s^2 \mu^4 << 1$. If large wave numbers are to be modelled (up to 3.5 the inverse water depth), then the effect of shoaling must be sufficiently small. The latter means that the bottom slope expressed as h_0 / L_0 should be <<0.025 in the areas where the shortest waves occur. In areas where the wave numbers are not larger than twice the inverse water depth, values of h_0 / L_0 up to 0.25 can be modelled. For example, for a 15 m deep dredged approach channel in a 5 m deep sea depth changes may occur over distances as small as 40 m, leading to slopes as steep as 1:4.

It is possible to extend the model for better linear wave dispersion and shoaling. However, such extensions will increase the complexity and hence the computational costs of the model, and should only be considered if necessary.

Drying and flooding procedure

Many estuaries and coastal embayments contain shallow areas. These shallow areas are dry during low water and are flooded when the tide rises. In TRITON the modelling of drying and flooding has not been included yet. At present the computation stops when one or more grid cells become 'dry'. This also implies that a moving shoreline cannot be modelled yet. If wave run-up or run-down on structures has to be modelled coupling with a model such as ODIFLOCS [Van Gent, 1994 and 1995] is required. Such a coupling has already been tested in the 1-D situation of the Petten Sea-defence [Van Gent and Doorn, 2000].

Irregular geometries

In TRITON the computations are performed on a Cartesian grid. Irregular geometries can be modelled by making cells inactive. The following type of boundary conditions can be imposed: incoming waves (spectral, time signal or Fourier components), outflow (weakly reflecting) boundaries and closed (fully reflecting) boundaries.

Unsteady flows

TRITON is a time-domain model simulating the unsteady behaviour of each individual wave. Therefore, no problems arise if unsteady flows are to be computed (all simulations are computed as if they were unsteady).

Velocity and pressure profile in the vertical

Boussinesq-type equations are an extension of the standard depth-averaged shallow-water equations, to allow a better modelling of surface waves. The point of departure in the derivation of Boussinesq-type models is a perturbation series expansion of the motion of the free surface with respect to its position in rest. The vertical distribution of the pressure and the velocity can be derived from the computed surface elevation.

3.3.3 Other wave propagation models

SWAN

In modelling wave propagation in coastal regions two approaches can be distinguished: spectral wave modelling and time-domain modelling. Spectral wave models are generally applied for larger computational regions since phase-averaging reduces the computational efforts considerably compared to time-domain models that simulate each time increment of each individual wave. In spectral models, however, valuable time information such as time signals is lost however and consequently also individual wave height statistics. Other processes that become more difficult to model are diffraction and the interaction between long waves and short waves since no distinction between bound long waves and free long waves is made. Nevertheless, many procedures have been developed to diminish the effects of these shortcomings, resulting in a wider field of application. One of the most advanced spectral wave models is the model SWAN (Simulating WAves Nearshore).

The model SWAN is a third-generation phase-averaged wave model for the simulation of waves in waters of deep, intermediate and finite depth. It is also suitable for use as a wave hindcast model. The non-stationary SWAN model is based on the discrete spectral action balance equation and is fully spectral. SWAN models wave propagation over the total range of wave frequencies including all possible directions. The latter implies that short-crested random wave fields propagating simultaneously from widely different directions can be accommodated. The wave propagation is based on linear wave theory (including the effect of currents). The processes of wind generation, dissipation and non-linear wave-wave interactions are modelled with state-of-the-art third-generation formulations.

SWAN has not been selected because the wave conditions has to be transferred into wave spectra and this implies the loss of phase information. Besides, ship wave spectra differ fundamentally of wind wave spectra.

HYPAN

The model HYPAN - Hydrodynamic Panel-Method - is a fully non-linear 2D and 3D time-domain wave model, under development at MARIN and WL|Delft Hydraulics under supervision of Twente University. The project is financed by STW. The water motion due to waves is described by the potential flow equation in combination with fully non-linear, unsteady free-surface boundary conditions. Moving boundaries such as for example a translating or rotating wavemaker can be simulated by specifying both position and velocity of the water at these boundaries. The numerical model is limited to the occurrence of the first breaking wave because of the assumption of irrotational motion of the water and the required uniqueness of the location of the water surface.

With the model it is possible to output surface elevation and velocity as well as the hydrodynamic pressure on the boundaries during a specified time interval. With this information it is possible to determine wave characteristics of the generated waves. From the time-record of the pressure on the (wet part of the) wavemaker, required force and maximum power demands can be deduced.

The model can also be used to compute the effect of structures on a flow and subsequently the forces on the structure. In these cases a stationary situation is considered in which far from the structure a uniform flow is imposed on in- and outflow boundaries. The modified flow around the structure induces a pressure which can be computed directly from the flow field.

Since HYPAN is a 3D unsteady method, in principle it could cover both aspects considered in this study, the wave generation by a vessel and the wave propagation over a bottom topography etc. However, applications with substantial forward speed have not yet been tried in HYPAN, and practical limitations in panel regeneration around the moving ship, and in achieving a sufficient resolution of all relevant phenomena in a large domain, would make this unfeasible.

HYPAN has not been selected for four reasons. Firstly, the development of the code is a very slow process and takes much more time than expected. Secondly, the breaking of waves is not included in the code. Thirdly, the coupling of RAPID and HYPAN is expected to be more complicated. Finally, using HYPAN will probably be costly, because of the use of a large number of panels.

PHAROS

The wave model PHAROS has been used extensively in consultancy projects at WL|DELFT HYDRAULICS. It is especially suited for investigating the penetration of short-wave or long-wave energy into large complex harbour lay-outs and harbour basins, as demonstrated recently in local and international port design work. PHAROS can accurately predict the short-wave penetration around coastal structures (e.g. breakwaters) and the resonant behaviour of enclosed areas to incident long waves. In PHAROS the wave field is represented by a time-independent potential in the frequency domain (related to wave amplitude and phase) that is modelled by the mild-slope equation and boundary conditions. The solution is obtained by solving a matrix equation. The effects of wave breaking, bottom friction and current refraction are included using an iterative process. Further, the effects of directional and frequency spreading (short crested, irregular waves) can be accounted for by summing the results for a number of directions and frequencies weighted according to the appropriate spectral energy.

PHAROS has not been selected because the code calculates in the frequency domain which means the loss of information due to the required transformation.

4 Model requirements

4.1 Introduction

In Chapter 3 the numerical models for predicting wave generation and wave propagation, RAPID and TRITON, have been described, and their possibilities and restrictions (when considered separately) have been discussed. However, a combined method obtained by coupling both tools offers some additional possibilities, which will be addressed in the present chapter. Specifically, Section 4.2 discusses whether it is possible to use the presented models RAPID and TRITON for all requirements listed in Section 3.1. In Chapter 5, two applications will be presented of the coupled RAPID+TRITON model:

1. straight canal
2. canal with a changing water width at the water surface

4.2 Possibilities

The models RAPID and the coupled model RAPID+TRITON give the opportunity to predict the ship-induced water motions in a waterway. However, sometimes only RAPID will be required, and in other situations the coupled model. A first indication of the applicability of the models is presented in the next overview. Of course, not all limitations and possibilities can be made clear in this overview, and therefore this will be the subject of the next pages.

Distance ship-bank	bed	width	bank	models
short	horizontal	straight	vertical	RAPID
far away	horizontal	straight	vertical	RAPID + Kochin or spectral reconstruction
short and far away	horizontal	straight	slope	RAPID + SKYLLA
short and far away	horizontal	irregular	slope	RAPID + TRITON + SKYLLA
far away	variable	irregular	vertical	RAPID + TRITON
far away	variable	irregular	slope	RAPID + TRITON + SKYLLA

Some comments are in order to clarify the table.

- RAPID is strictly steady, and therefore is limited to a waterway cross section that is invariable in longitudinal direction. The banks may be sloping, but sufficiently steep.
- If wave propagation over larger distances is to be predicted, the practical limitation of the panel number requires an addition to RAPID. Provided that the water depth is uniform

and large enough, the so-called "Kochin function approach", which adds a far-field extension to the wave pattern computed by RAPID, is the most efficient way.
- If the ship waves are affected by the bottom topography, or their behaviour at an irregular bank is to be predicted, TRITON can predict these effects.
- If the banks are sloping, a model for the wave breaking that occurs near the bank is needed. TRITON can deal with breaking waves. However, also the existing model SKYLLA can then be used, based on the velocity field near the bank predicted by other means (RAPID, or RAPID + TRITON). SKYLLA has the advantage that it takes into account the influences of aspects as the porosity of the bank material.

In this study, the feasibility of coupling only RAPID and TRITON has been considered. The other combinations deal with more simple waterway configurations or less interesting configurations (for instance: vertical banks).

The basic approach for tackling the prediction of the waves is as follows:

- The generation of ship waves, and the evolution of these waves during propagation, is considered as two separate but coupled problems. The former is best treated as a steady problem, since a mature tool is available to predict this. As opposed to this, no reliable, accurate and efficient methods exist for predicting unsteady wave generation by a ship with forward speed. The problem is steady in a ship-fixed co-ordinate system.
- The wave propagation can be dealt with as an unsteady problem. An earth-fixed domain is chosen, and the ship wave pattern enters through a boundary during a certain period of time. The evolution of these waves is then predicted. This has the advantage that effects of bottom topography and irregular bank shapes can easily be incorporated (which is impossible in a steady problem in the ship-fixed co-ordinate system).
- The steady and the time-dependent model are coupled via boundary conditions on an interface. TRITON operates in an 'outer domain' at a distance from the ship and extending to the channel walls or other features of interest. RAPID operates in an 'inner domain' surrounding the ship. The RAPID domain needs to extend beyond the interface. Velocity and wave elevation data on the interface are computed by RAPID. These are converted to input data for TRITON and drive the wave propagation problem. This approach is illustrated in the feasibility study (see Chapter 5).
- The separation into two separate problems obviously disregards certain interactions. In the present case, there is a correct transfer of information from RAPID to TRITON, but no transfer the other way round. This requires that in RAPID we already represent the effect of channel walls on the wave making (by increased blockage).
- Any significant unsteadiness (in the ship-fixed co-ordinate system) should only occur in the outer domain away from the ship. In a narrow channel with a varying cross-section, this is strictly not true. An example in which this plays a role is presented in Section 5.2.

Considering the list of requirements as proposed by the Dutch Public Works Department (reproduced in Section 3.1), the principal restrictions of the coupled approach seem to be the absence of unsteady effects in the wave generation, the absence of viscous effects, and the limitation of the Boussinesq model to not too high wave numbers and not too steep bottom slopes. These limitations have already been discussed during the presentation of the models RAPID (Section 3.2) and TRITON (Section 3.3). Some further remarks are given below.

<u>Irregular lateral boundaries</u>
RAPID requires a constant channel width, whereas this is not necessary for TRITON. In case there is a substantial effect of the waterway geometry on the wave generation, also the variations in the waterway geometry may have an effect on the wave generation. This poses the problem of how to include the resulting unsteadiness in RAPID. Many practical situations probably can be handled by a quasi-steady approximation, i.e. for sufficiently slow variations the instantaneous wave making may be approximated by that in a waterway with a constant cross section equal to that at the instant considered. In certain cases, one might think of some kind of interaction between RAPID and TRITON (i.e. feedback from TRITON to RAPID in the form of e.g. given normal velocities through the interface), but developing this could be a substantial task.

<u>Other non-stationary conditions</u>
Accelerating and decelerating ships may generate large waves, depending on the ship speed relative to the Froude number. Also sailing in a channel with a fluctuating bed level in longitudinal direction has influence on RAPID results. Maybe, here again a quasi-stationary approach sometimes is a possibility.

In general, TRITON is a time-domain model simulating the unsteady behaviour of each individual wave. Therefore, no problems arise if unsteady flows are to be computed (all simulations are computed as if they were unsteady).

<u>Bed slopes</u>
In a model as TRITON the maximum bed slopes are related to the wave numbers to be modelled. In areas where the shortest waves occur the effect of shoaling must be sufficiently small. In other areas the bottom slopes can be steeper. However, it is not possible to model sudden fluctuations in bed level (i.e. discontinuous bed levels) accurately.

<u>Presence of other ships in the fairway</u>
Other sailing or moored ships create a temporary non-stationary situation, which in principle can not be dealt with. However, if the sailing or moored ships are in the 'outer' TRITON domain, the influence on the generated wave system will be small and calculations ought to be possible.
Near moored ships the wave conditions can be determined easily with TRITON. Whether this model can handle a sailing ship within its domain is not clear.

The other requirements have been discussed already or it is expected that implementation will not give big problems. An exception is the possibility to make wave predictions "in house", e.g. at the offices of the Dutch Public Works Departments. This requires powerful hardware, but also sufficient training of the operators.

5 Prediction of wave conditions

The feasibility of the coupled model RAPID+TRITON will be shown by two applications:

1. straight canal
2. canal with a changing water width

5.1 Coupling of RAPID and TRITON

The feasibility study in the first place addresses the question whether a coupling of the wave generation code RAPID, and the wave propagation program TRITON, is possible, efficient and accurate. Specifically, attention is needed for the question to what extent the characteristics of a ship wave pattern are retained by the coupling. The first test case has been designed to answer that question.

In view of the relation of the project with inland waterways, the vessel selected is a cargo vessel for Rhine navigation, CEMT class Va, with main dimensions 110 * 11.40 * 2.0 m (not fully loaded).
The waterway has a depth of h = 4.0 m. For the first test, the width of the waterway is assumed to be infinite. The speed of the vessel has been chosen as 75 % of the critical speed ($Fnh = V_s/\sqrt{(g\,h)} = 0.75$), corresponding with 16.9 km/h = 4.7 m/s. This speed is high enough to permit accurate wave modelling in the Boussinesq approach, and low enough to have only little effect of the water depth on the wave dispersion. The Froude number based on ship length is $FnL = V_s/\sqrt{(g\,L)} = 0.143$.

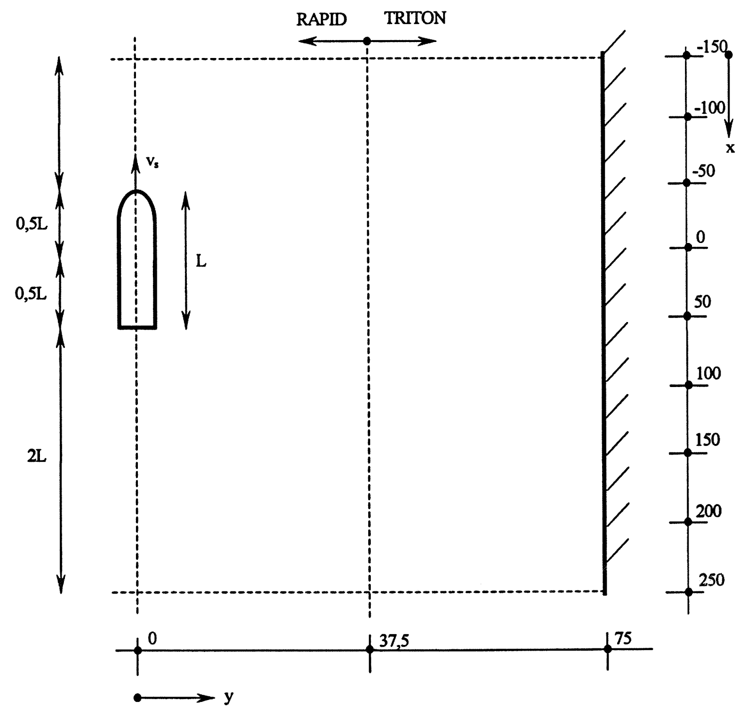

Figure 5.1 Layout for straight canal

The hull surface (one symmetric half) was covered with 1512 hull panels. The free-surface panel domain in RAPID was selected to extend from the symmetry line to a lateral distance of 75 m , and from 1 shiplength upstream of the bow to 2 shiplengths downstream of the stern. The width was subdivided in 22 strips, with a slight expansion of the strip width with distance from the hull. The panel length was chosen as 0.58 m, such that there are 25 panels per transverse wave length. All these parameters have been selected according to the usual guidelines for RAPID, and are known to guarantee a good numerical accuracy. Overall 13750 free-surface panels have been used. The computation time on the CRAY C912 at SARA (on 1 processor) amounted to about 3 minutes per iteration (the 'outer' iteration procedure, for adjusting the wave surface and trim and sinkage), and 18 iterations were required. It is noted that the size of this calculation is relatively large, as a result of the parameters selected and the requirements for the coupling.

In the Figures 1 up to 4 the computed wave pattern is illustrated. The primary and secondary wave system are easily distinguished. Clear 'Kelvin wedges' originate from the bow / fore shoulder and from the stern. Reflections can be observed at the lateral edges of the panel domain; as noted before, these cannot be expected to represent the reflection at a channel wall, and should be regarded as a disturbance in the calculation.

coupling approach

The free-surface panel domain in RAPID had a half width of 75 m. The Boussinesq domain was defined to extend from 37.5 to 72.5 m from the ship symmetry line. Therefore, the two domains overlap, and a comparison is possible between the wave predictions from RAPID, and the predictions from the coupled system RAPID + TRITON. It is noted that at present there are no clear guidelines as to the best location of the interface; to make the assumptions in TRITON valid, it should not be too close to the ship, and to limit the size of the RAPID computation, it should not be too far. This is a subject for further experimentation.

The waves enter the Boussinesq domain along the line y = 37.5 m. However, the more transverse waves in the pattern (those with wave crests almost perpendicular to the ship's course, and propagating mainly in the same direction as the ship) essentially run parallel to this coupling boundary. Consequently, if this would be the only coupling, a very long Boussinesq domain would be required to allow the penetration of all wave components into the domain. Therefore it was decided to let waves also enter the Boussinesq domain along the transverse boundary first reached by the ship (the right-hand side in Fig. 5-2.). This is only possible if there is an overlap between (the usable parts of) both domains.

Conversion of the wave data predicted by RAPID to boundary conditions for TRITON is needed. The RAPID results are steady waves defined in a co-ordinate system moving with the ship, while the TRITON predictions are unsteady in an earth-fixed co-ordinate system. Moreover, in TRITON the velocity field is averaged over the water depth, while in RAPID a 3D velocity distribution is found. The latter obviously can be averaged, but for practical reasons it was decided to attempt a coupling in terms of wave elevations only.

The wave elevations predicted by RAPID are first interpolated to find a longitudinal wave cut at y = 37.5 m, given as an array of points. A second interpolation along this cut is required to find the wave elevation at a given x-co-ordinate in the Boussinesq domain at a given instant in time.

In addition, for the boundary conditions along the transverse boundary, a transverse cut is found by interpolating in the RAPID results at an x-co-ordinate defined by the x-co-ordinate of the Boussinesq domain edge and the time level; followed by a second interpolation along the transverse cut to the desired y-co-ordinates. For all these interpolations, routines were written based on third-degree polynomial interpolations.

set-up of TRITON calculations

As mentioned before the domain of the TRITON calculation covered a rectangular area of 120 m in x-direction and 35 m in y-direction. The computation was performed on a Cartesian grid. The spatial resolution was constant in both directions: $\Delta x = \Delta y = 0.5\,m$. A timestep of $\Delta t = 0.05\,s$ was used, which was approximately one twentieth of the period of the short stern waves. These waves resulted in the highest values for the product $k_0 h_0$ and were therefore normative for the accuracy of this application. The wavelength of these short waves was approximately 10 m. With a bottom depth of 4 m the highest $k_0 h_0$-values were 2.5 which was sufficiently low.

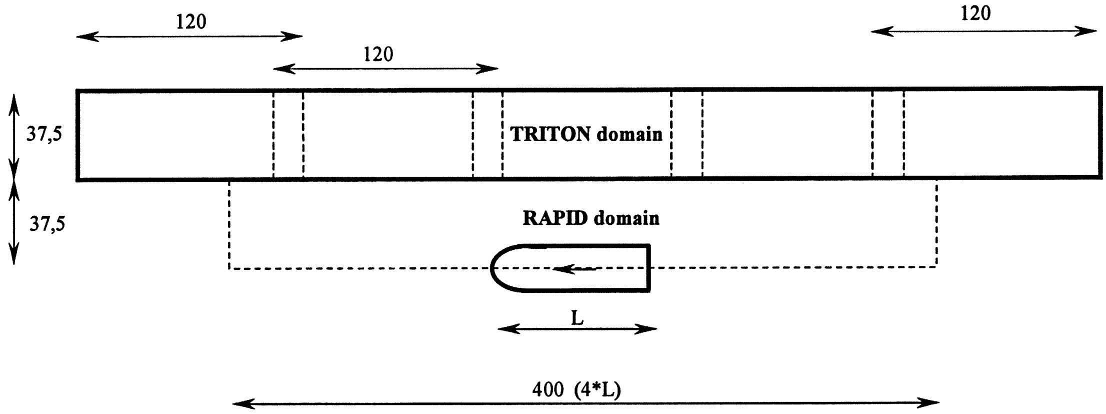

Figure 5.2 RAPID and TRITON domain

At the boundaries x = 120 m and y = 37.5 m a timesignal derived from the RAPID results was imposed. Conversion of the wave data predicted by RAPID to boundary conditions for TRITON was needed. The RAPID results are steady waves defined in a co-ordinate system moving with the ship, while the TRITON predictions are unsteady in an earth-fixed co-ordinate system. Assuming a positive x-direction opposite to the movement of the ship the transformation is given by:

$$x(\tilde{x},t) = \tilde{x} - V_S.t + x_0,$$

with:

$\tilde{x}$ the x-co-ordinate in a co-ordinate system moving with the ship;

x the x-co-ordinate in a earth-fixed co-ordinate system;

x_0 the origin of the earth-fixed system at the start of the simulation;

V_S the speed of the ship.

At the boundaries x = 0 m and y = 72.5 m weakly reflecting boundary conditions were applied.

The time during which a timesignal was imposed at the transverse boundary is related to the dimensions of the TRITON domain and the speed of the ship. With L_{RAPID} the length of the RAPID domain and L_{TRITON} the length of the TRITON domain, the time $T_{IMPOSED}$ during which a wave disturbance is imposed can be computed as follows:

$$T_{IMPOSED} = (L_{RAPID} + L_{TRITON}) / V_S .$$

With $L_{RAPID} = 440\,m$, $L_{TRITON} = 120\,m$ and $V_S = 4.7\,m/s$ this yields $T_{IMPOSED} = 120\,s$. Since it also takes time for the waves to travel through the computational domain, the actual computation time $T_{COMPUTATION}$ is higher than the time $T_{IMPOSED}$ during which a wave disturbance is imposed: $T_{COMPUTATION} = 150\,s$.

The computation time on a Pentium II-PC amounted to a little more than 2 hours. It is noted that the computation was also performed on a grid with half the spatial resolution (resulting in a factor 4 reduction in the number of grid points) and a timestep twice as big. In this case the whole computation took only 18 minutes. Comparison of the results showed no significant differences, indicating that the resolution of the coarse grid was sufficiently high.

discussion of results

Figure 5 shows the surface elevation as computed by TRITON. This figure consists of five 'TRITON-areas' (at 5 moments) which are converted into a co-ordinate system moving with the ship. The fact that those five areas smoothly merge into one another indicates that the reflections at the left side of the TRITON domain are negligibly small. It also indicates a good agreement between the wave propagation as computed by TRITON and the boundary conditions obtained from RAPID.
When we add the RAPID-results between y = 0 m and y = 37.5 m Figure 6 is obtained. The blue line denotes the interface where the coupling is made. The 'Kelvin wedges' which originate in the RAPID area continue properly in the TRITON domain. At x = 180 m reflections can be observed at the lateral edges of the panel domain.

A more quantitative comparison can be made when comparing surface elevations along a longitudinal cut. For this purpose the surface elevation on a single output location in the TRITON domain as a function of time ($\eta_x(t)$) must be transferred to a steady signal as a function of co-ordinate $\tilde{x}$ in a co-ordinate system moving with the ship ($\eta(\tilde{x})$). There is some freedom in choosing the location in the TRITON domain from which the timesignal is converted. If a location close to the right boundary is chosen, a comparison between both signals will result in a too optimistic view, since the wave propagation is computed over a small distance only. If the x-co-ordinate is chosen close to the left boundary of the TRITON domain the computational results might be more affected by spurious reflections from the boundaries at x = 0 m and y = 72.5 m. As a compromise a location in between is chosen, at x = 50 m.

Figure 7 shows the comparison along three different longitudinal sections. At a distance of y = 50 m from the centreline of the ship the agreement between both results seems to be relatively good. The computed primary waves almost exactly coincide. There is also a good agreement between the computed phases of the secondary wave system. TRITON slightly overestimates the wave amplitudes which is a known shortcoming of the model and is due to boundary effects (Note: the effect has nothing to do with the wave propagation; it does not increase or decrease with the distance). While in general TRITON predicts larger wave amplitudes in this wave cut than RAPID, the reverse is true at some locations with x > 200 m. It is easy to show from the geometry of the Kelvin wedge that here bow waves reflected at the lateral boundary of the RAPID domain have reached this wave cut. As can be observed in Fig. 6, the same is true for reflected waves in TRITON. Since neither of these reflections correctly represent any physical reflection, agreement between both cannot be expected.

The agreement along the section at y = 60 m is slightly less but still not too bad. Bow wave reflections can be expected for x > 150 m, but are not too obvious here. At y = 70 m, comparison is not quite meaningful: especially the RAPID results are disturbed by the effect of the lateral edges. As close to the boundary as this not only there are reflections, but also the wave amplitudes are reduced due to the truncation of what should be an infinite panel distribution.

5.2 Canal with a changing water width

The first coupled calculation described above provided an opportunity to check the accuracy of the coupling procedure and the comparability of the two wave models used, since the TRITON domain basically duplicated a part of the RAPID domain. For a second case, Rijkswaterstaat expressed a preference for an application which would not be possible by using just one of the flow models. Again the same vessel is considered as before, with the same speed of 16.9 km/u in a water depth of 4.0 m. However, the vessel now is supposed to sail in the centre of a canal with a width of 200 m, with a step increase to 300 m. The prediction of interest is the behaviour of the ship wave pattern where the channel wall recedes.

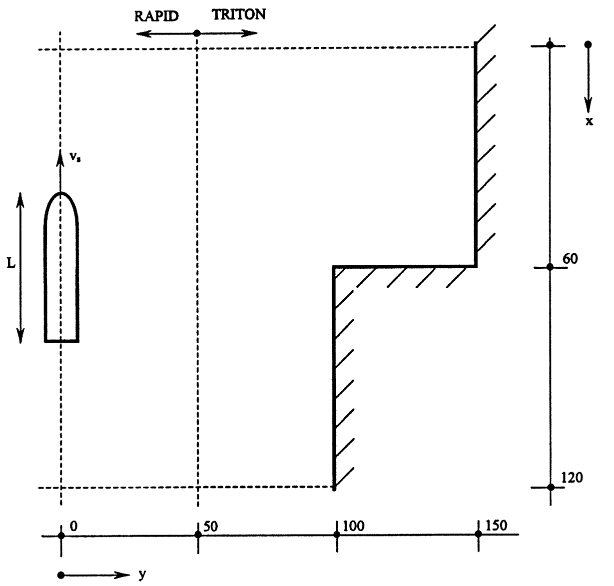

Figure 5.3 Layout situation for canal with changing water width

A first assessment of the magnitude of channel effects can be made using the simple one-dimensional theory of Kreitner [Kreitner, 1934]. This assumes a uniform distribution of the overspeed ('return flow'; the flow velocity in the waterway next to the ship, generated by the ship and directed opposite to its sailing direction) next to the vessel, which then is entirely determined by the reduction of the cross-section due to the blockage. The overspeed leads to a decrease of the water level (easily found from Bernoulli's equation) which further reduces the local channel cross section. The sinkage of the ship is assumed to be equal to the decrease in water level.

Using a simple routine based on this theory, for the approximate blockage (ratio of ship midship sectional area to channel sectional area) of 0.0285 for the narrow part of the channel, and a depth Froude number of 0.75, an average overspeed of 0.0851 . V_S. The average water level depression would then be 0.20 m. For the wide part of the channel at the same ship speed we would get an overspeed of 0.0506. We thus might expect a change in the ship wave generation during the transit from the narrow to the wide part of the channel.

On the other hand, for relatively wide channels such as this, Kreitner's theory is not accurate. The distribution of the overspeed is far from uniform over the entire cross-section. As a matter of fact, in unrestricted width there is already a substantial additional water level depression near the vessel, and the presence of the channel walls does not add much to this. In the RAPID calculations, we found the following values for the sinkage of the vessel:

deep water:	0.04 m.
shallow water:	0.19 m
shallow channel:	0.23 m

Consequently, in the near field the effect of the channel walls is far smaller than Kreitner's theory indicates, and this supports the basic approximation in the coupled approach that the effect of the varying channel width (and the resulting unsteadiness) is felt mainly in the outer (TRITON) domain.

The RAPID calculation has been made in two stages:
- a new calculation for shallow water of infinite width;
- a continuation run in which the channel walls were incorporated, for the case of a 200 m channel width.
The channel wall was represented by 418 * 6 = 2508 panels. The vertical distribution of panels over the depth of the channel was somewhat coarse, and will be insufficient to produce accurate wave reflection; but the main purpose here was to include the blockage effect and the resulting effect on the wave generation. Also for the water surface a slightly coarser and less extensive panelling has been used, in order to limit the number of panels. The domain now extended from 0.9 L ahead of the bow (L = ship length = 110 m), to 1.4 L aft of the stern; and from the centreline to the channel wall at y = 100 m 27 strips of 418 panels were used.

The first calculation essentially reproduced the results of the previous case, some differences arising from the smaller extent ahead of the bow, the somewhat coarser panelling and the greater lateral extent that delays the reflections. It seems that the non-matching upstream boundary condition may affect the results over a larger area in restricted water than in infinite water, and for quantitatively accurate results a significantly larger extent would be needed.

Figures 8 and 9 compare the wave pattern found for both cases. Fig. 9 illustrates how, due to the channel walls, the primary disturbance (e.g. the yellow area representing the water level depression next to the ship) extends all the way to the channel wall. However, the difference is modest, in particular near the ship. Therefore, the question how to deal with the effect of the transition in channel width on the wave generation is not too important in this application.

Figure 10 compares the longitudinal wave cut at y = 37.5 m (the location of the interface with TRITON), for the infinite width and the channel case. It appears that the presence of channel walls has a rather mild effect at this location, and is primarily seen in a larger primary disturbance and a slightly larger wave amplitude. While in principle the infinite-width wave elevations would be the correct ones to impose on the interface once the ship is far enough beyond the step in channel width, we have disregarded this difference in the present calculation. This is one example of what the limitation to steady wave generation means in practice.

Figure 11 shows that at y=75 m. the difference is larger, as expected, since this is closer to the channel wall. This is inside the Boussinesq domain, in which the sudden change in channel width is correctly included. Therefore, we expect that the largest part of the unsteady effects is properly represented in the present coupled solution.

The domain of the TRITON calculation covered a rectangular area of 120 m in x-direction and 100 m in y-direction. The varying width of cross-section was modelled by inactive grid cells in the upper-right corner. The layout of the computational area of the TRITON model is given in Figure 12. The spatial grid resolution was constant in both directions: $\Delta x = \Delta y = 1.0\,m$. A timestep of $\Delta t = 0.05\,s$ was used.

The passage of the ship through a channel of varying cross section causes variation in time. In the RAPID computation in principle this could only be modelled as a quasi-steady phenomenon (i.e. two separate calculations for both channel widths); but as argued above this was not needed here. However, with the varying cross-section the TRITON computation is not only unsteady in a fixed frame of reference but also in a grid moving with the ship. For this reason it is not possible to transform the results obtained with TRITON back into the co-ordinate system moving with the ship and to compare them with RAPID.

Figures 13, 14 and 15 show the surface elevation after 50, 70 and 90 seconds respectively. Figure 16 shows timeseries of the surface elevation at the locations $x = 30m; y = 100\,m$ and $x = 30m; y = 130\,m$. No comparison with other results can be made, hence no conclusions about the accuracy of the computations can be drawn. However, the results do show that a coupling of the wave generation code RAPID, and the wave propagation program TRITON is possible.

6 Conclusions and recommendations

The present study of possibilities for predicting ship-induced flow phenomena of interest for waterway bank protection, and the feasibility study carried out, allow to draw the following conclusions:

- **with respect to the coupling of RAPID and TRITON and the results of the test calculations:**
  1. The coupling of RAPID and TRITON has been successful and relatively straightforward.
  2. RAPID had already been validated for situations with a straight lateral boundary. TRITON had been validated before for other situations. For the first test case the TRITON domain overlaps with the RAPID domain, and a validation of the coupled approach was possible by comparing the two solutions. This indicated a very good agreement for the wave phase angles, and a reasonable agreement for the wave amplitudes, which were slightly overestimated in the TRITON domain.
  3. The second calculation considered a situation with a step change in channel width, leading to a wave pattern that is unsteady in a ship-fixed co-ordinate system and consequently could not be predicted by RAPID alone. however, the coupled approach appeared able to predict the wave behaviour near the banks, with largely plausible results. However, further validation was not possible because of the lack of data for this case.

- **with respect to the possibilities and limitations of a coupled RAPID+TRITON model:**
  1. RAPID allows to predict the wash for monohulls and multihulls, sub- and supercritical speeds, deep and shallow water and channels. The predicted wave pattern includes all the particulars of the ship form, speed and water depth considered, without relying on any empirical input. In addition, the flow velocity and pressure at the bottom and banks can be predicted.
  2. Principal restrictions of RAPID for the present class of applications are the strictly steady approach, and limitations in the size of the domain due to the finite panel number. Both restrictions can be partly eliminated by coupling with a wave propagation code such as TRITON.
  3. Because RAPID is a stationary model, in principle it does not permit to predict the wave pattern in instationary situations, but only as far as the unsteadiness seriously affects the wave generation. This is the case e.g. for accelerating/decelerating *fast* ships, or variable and *small* water depth or width. However, some unsteady problems may be considered as quasi-stationary.
  4. Moreover, if the unsteadiness is largely confined to the outer TRITON domain, the present coupled procedure gives the correct representation. The second example given, for the step change in channel width, is such a case. Water depth variations are no problem for TRITON although they have to be gradual in the present code.
  5. TRITON includes a wave breaking model and in principle, also a drying and flooding procedure (not implemented yet). The applicability of TRITON code is at the moment limited with respect to wave dispersion and shoaling, but it may be improved.

Summarising: coupling of the different codes RAPID and TRITON has proven to be feasible and potentially very efficient. Already after this feasibility study, the coupled approach offers the prospect of predicting various phenomena of interest. We believe that a coupled method can provide a most useful tool to study (if not, predict) wave phenomena: Even while not all aspects are already included and some cannot be included at all, and even if the quantitative accuracy in certain cases may be less, it may permit to study the physics of interest, to easily vary waterway parameters, to understand scarce experimental data collected in reality, or to identify critical areas where measurements are desired. The animations of the computed results delivered with this report show how illustrative and illuminating numerical predictions can be to understand practical problems.

Nevertheless, some further development and validation is required to include more of the flow phenomena and to better establish the range of applicability and accuracy. The following recommendations are given:

- The present report mentions various possible extensions or improvements. A follow-up project would be desired in which the possibilities of a coupled RAPID+TRITON code are investigated in detail. Such a project should start with a further study of the different ideas for improvement, and should indicate the time and costs required to develop these. Subsequently, various projects should follow to carry out the proposed improvements.
- The numerical results of the presented example with the changing water width need to be validated, and other cases should be added.
- The applicability of TRITON may be improved with respect to the limited wave dispersion and shoaling.
- The applicability of RAPID may be improved with respect to reduction of spurious wave reflections at the lateral boundaries, an approximate representation of viscous effects on the stern wave system using a displacement thickness concept, and addition of a model for the propeller effect.
- To overcome the restriction of RAPID to a rather near field, a coupled representation of the far-field wave system based on Kochin functions or wave spectra is a useful addition.
- The coupling of RAPID and TRITON may be improved with respect to the interface location and matching of the velocity field at the interface.
- The procedure should be further streamlined to ease practical applications.

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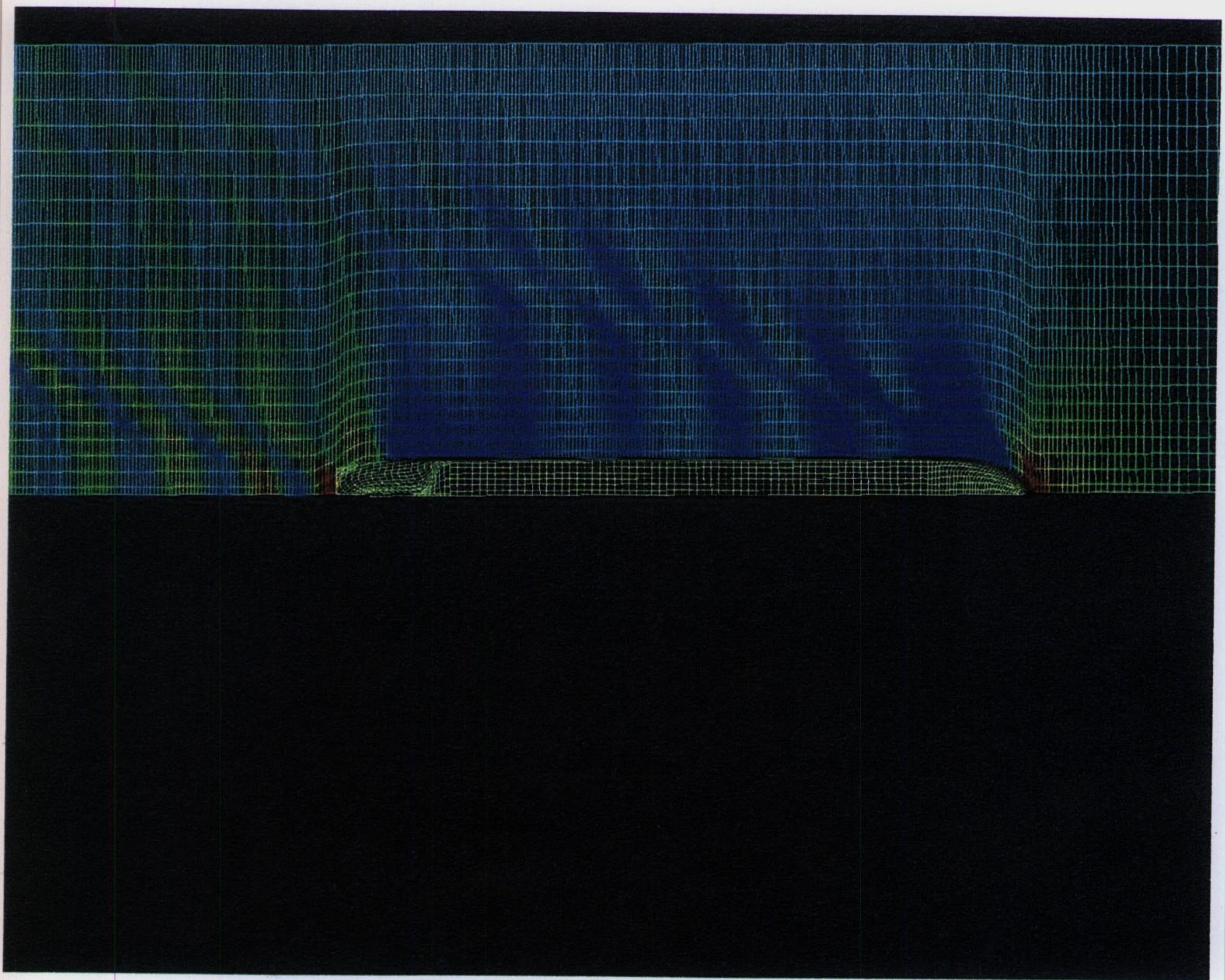


Figure 1 Panel distribution used in RAPID

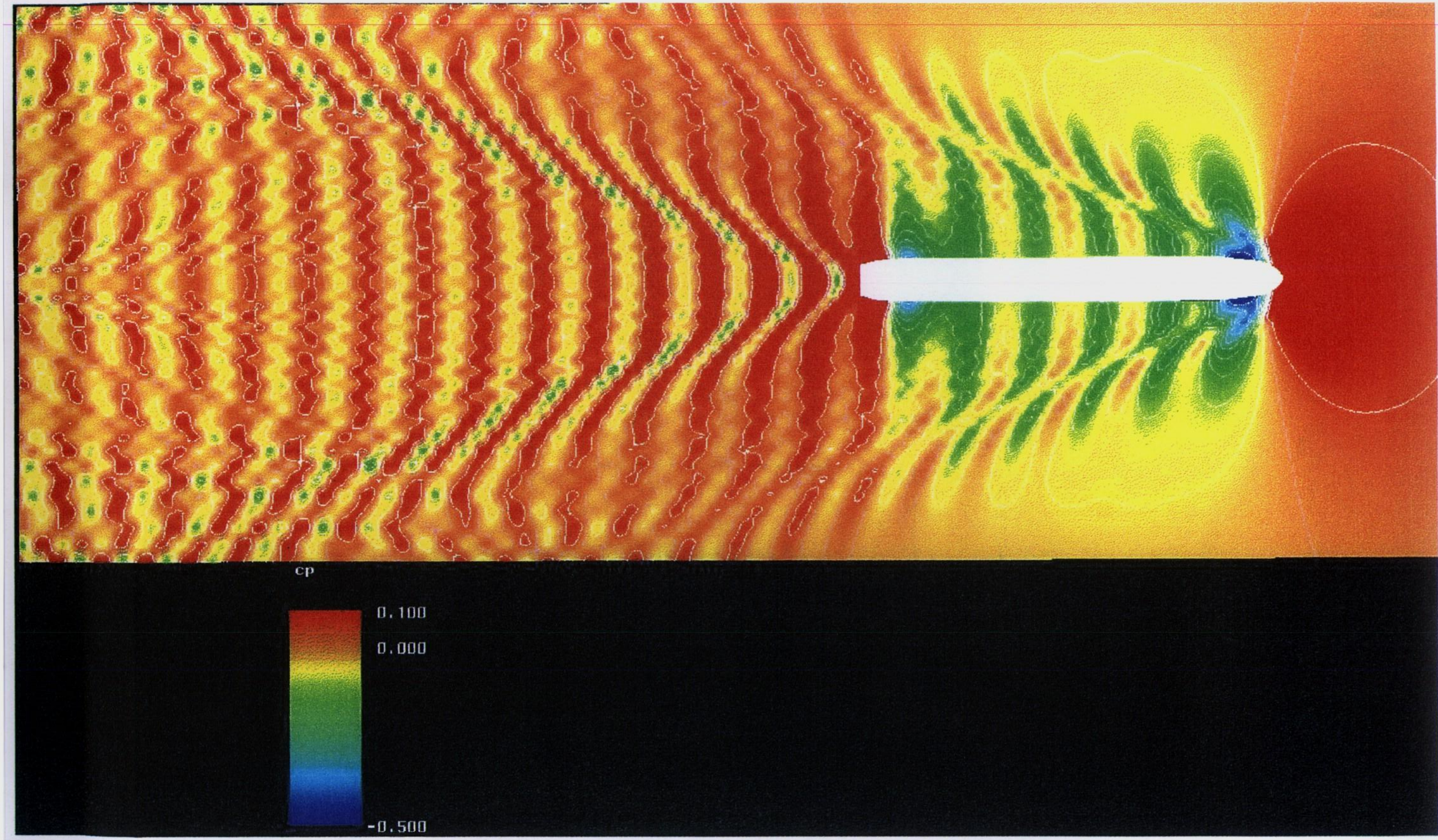


Figure 2 Overview of the generated wave pattern

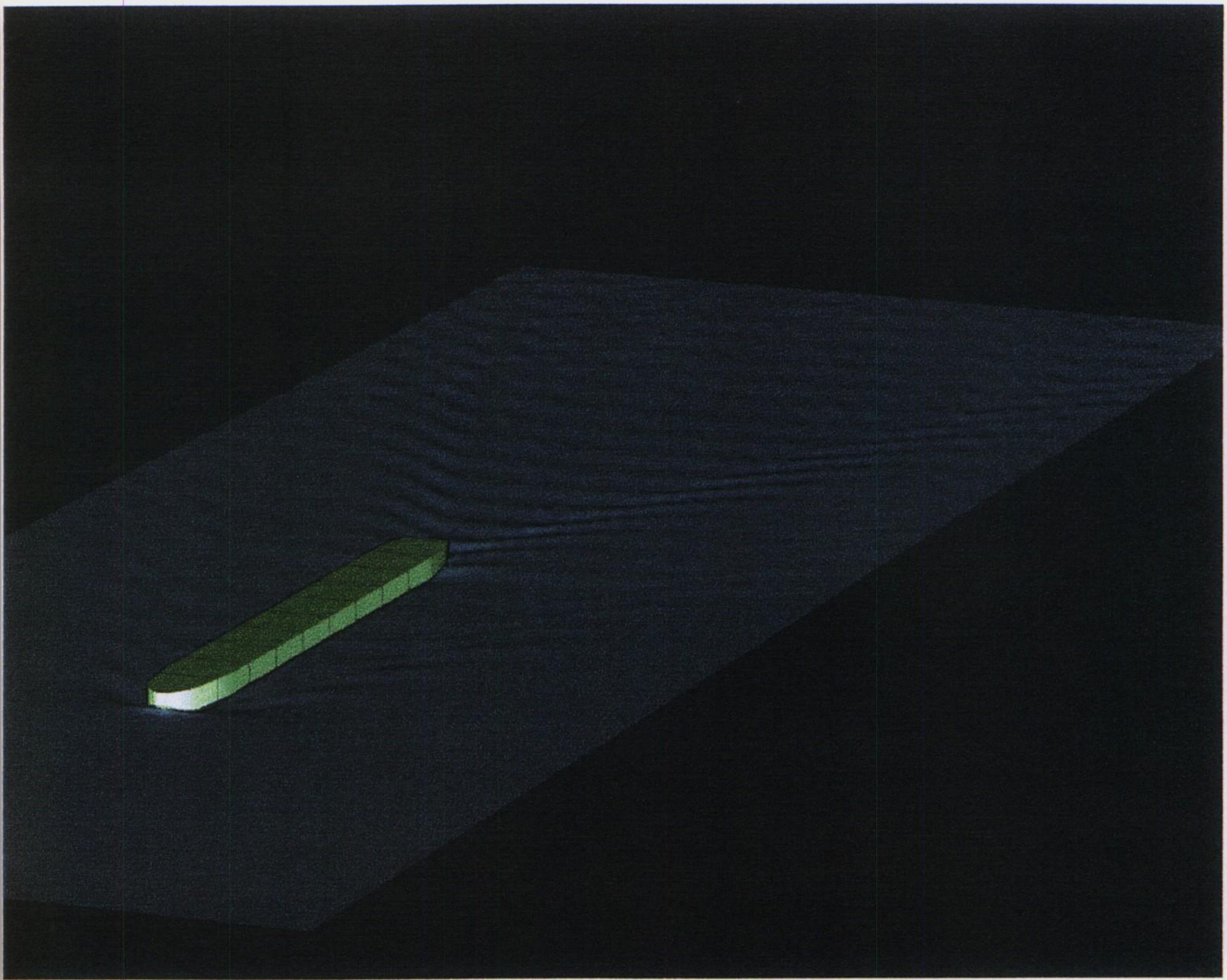


Figure 3 Birds eye view of the generated wave pattern

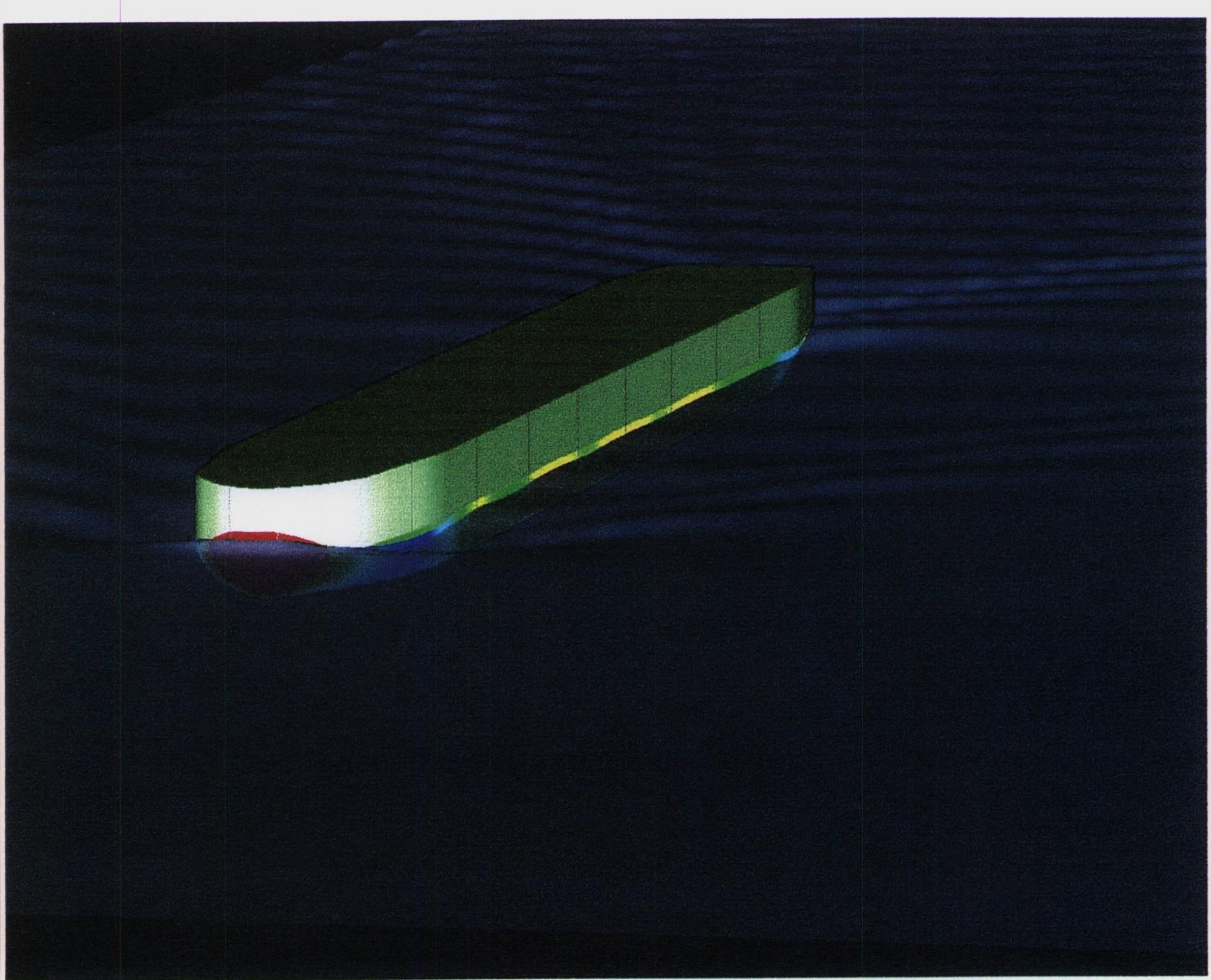


Figure 4 Detail of the birds eye view of the generated wave pattern

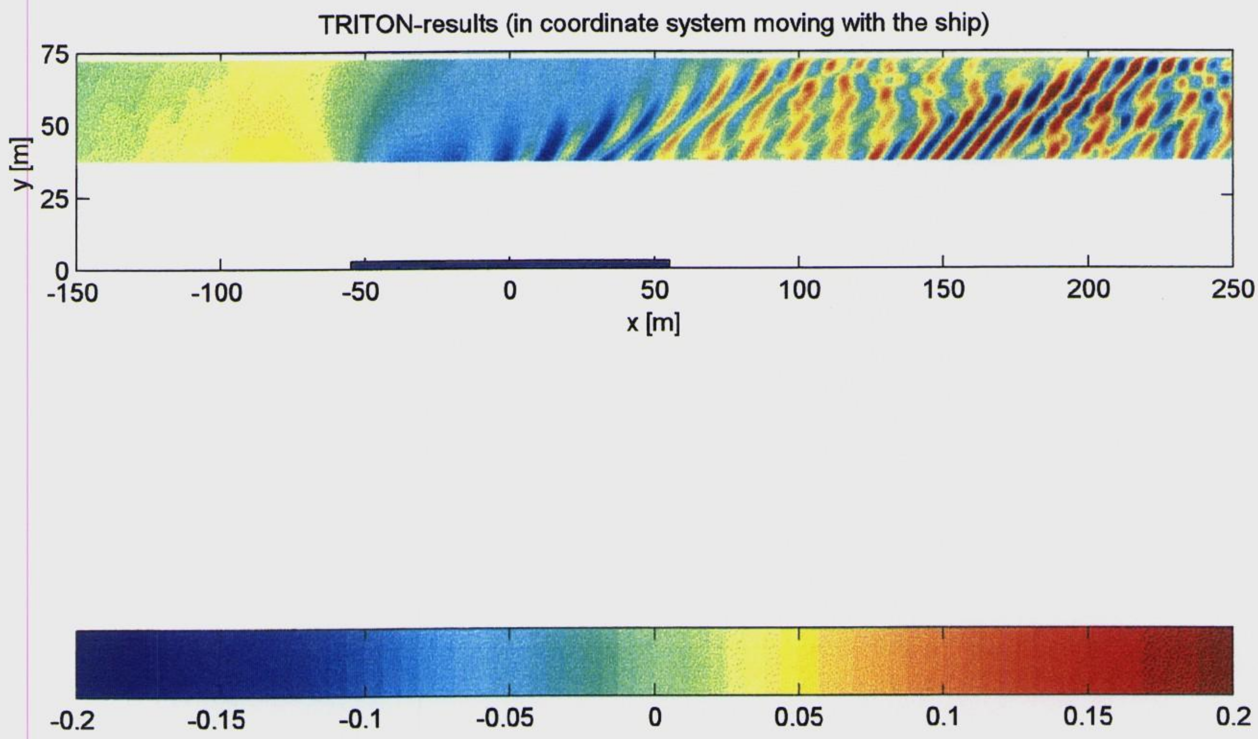


Figure 5 Surface elevation in the TRITON domain

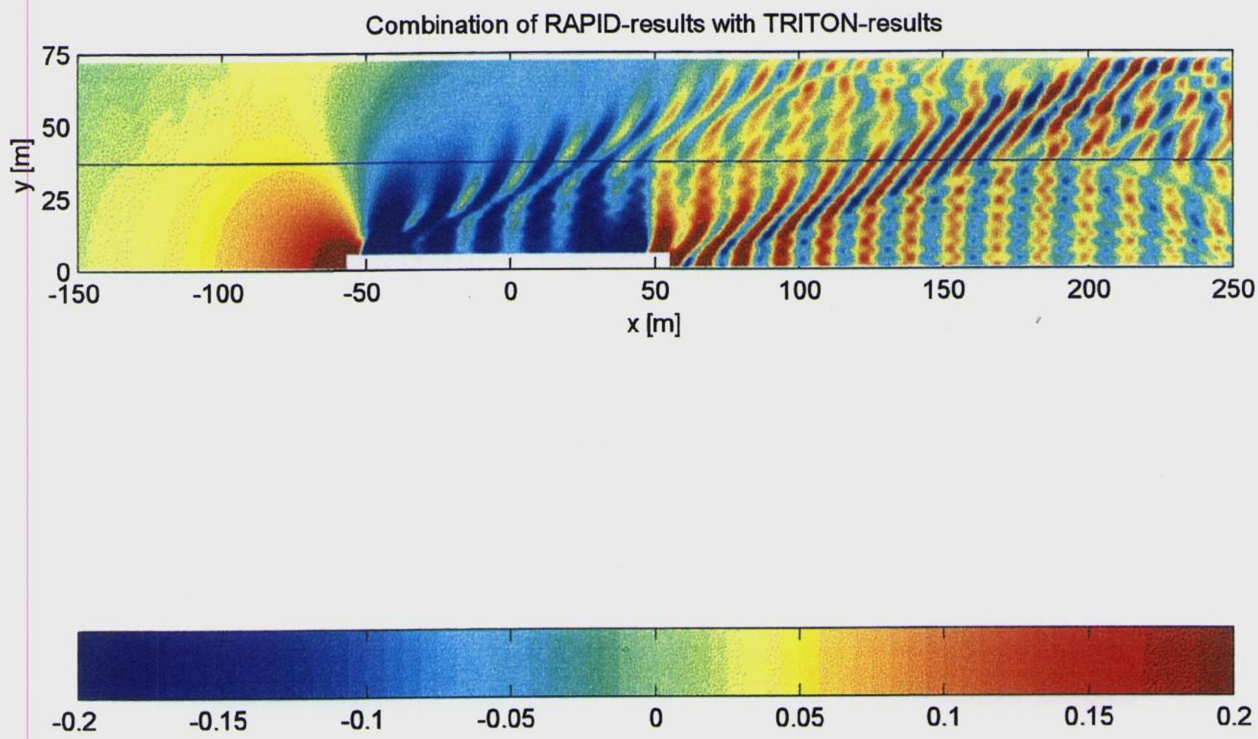


Figure 6 Surface elevation in the RAPID+TRITON domain

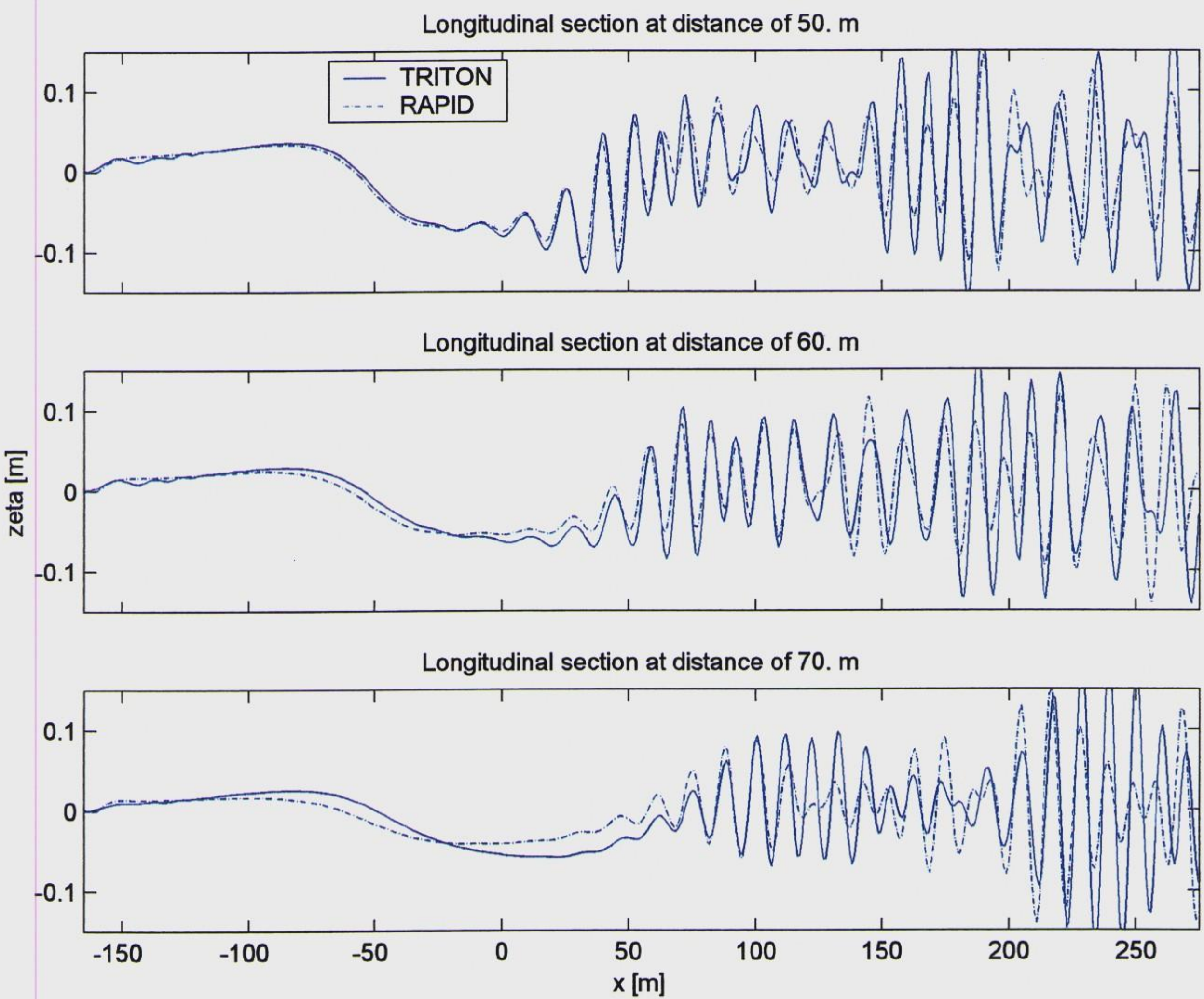


Figure 7 Water level fluctuations at different longitudinal distances of the sailing line

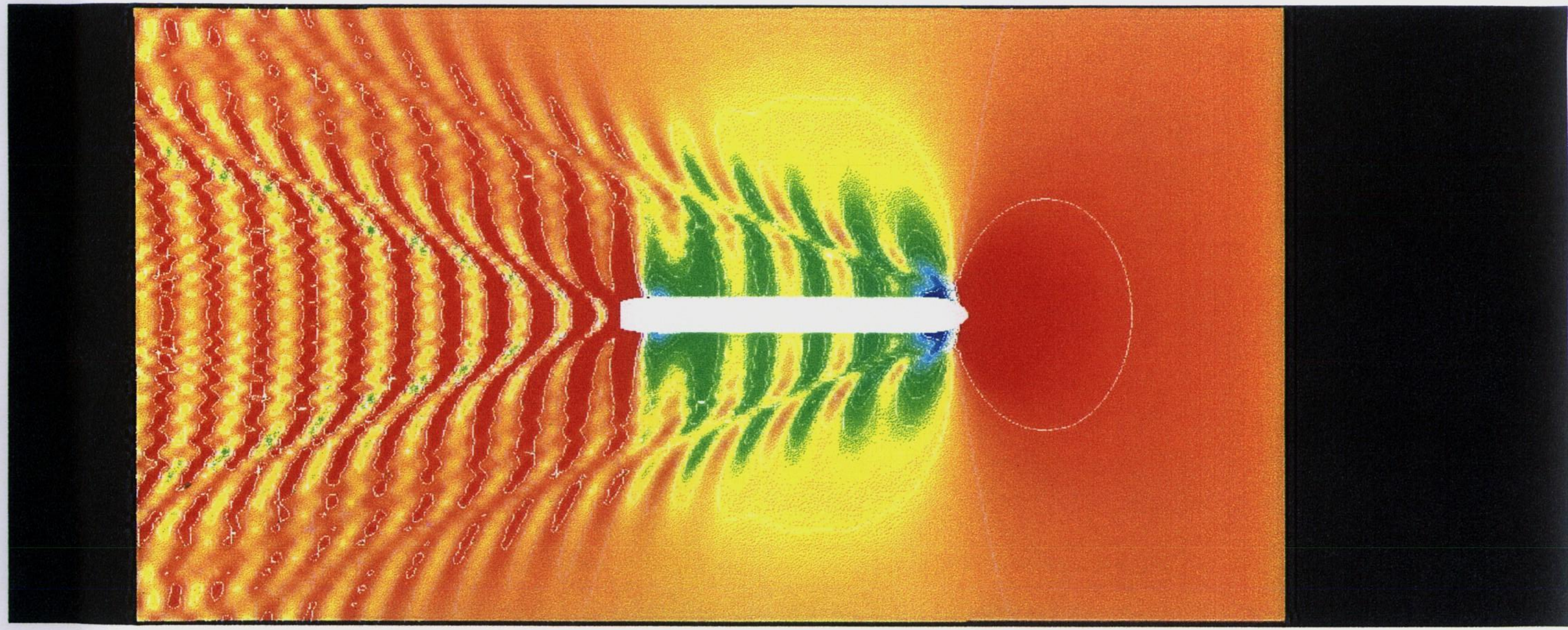


Figure 8 RAPID wave pattern (infinite width channel)

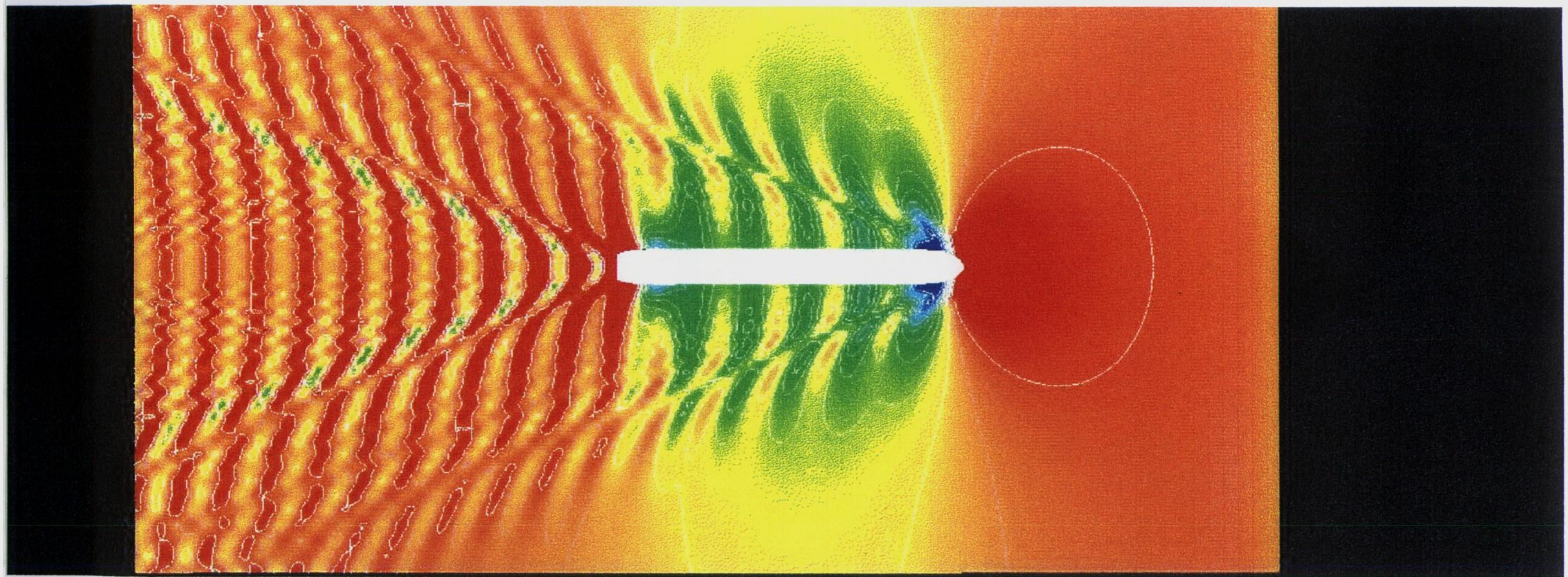


Figure 9 RAPID wave pattern (channel width 200 m; vertical banks)

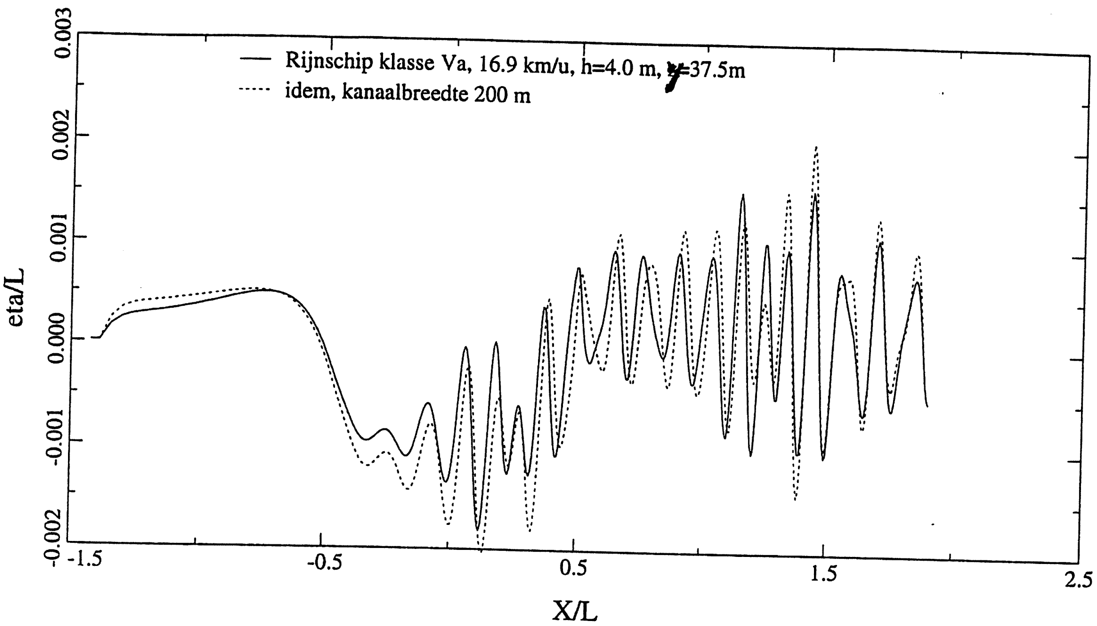


Figure 10 Comparison of the longitudinal wave cut at 37.5 m (RAPID)

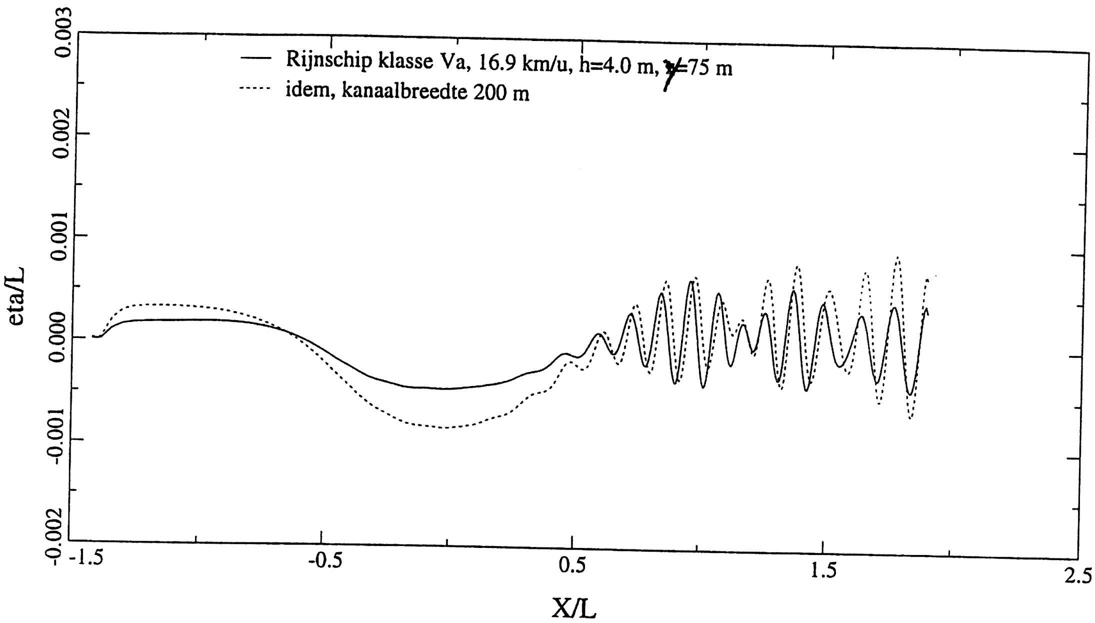


Figure 11 Comparison of the longitudinal wave cut at 75 m (RAPID)

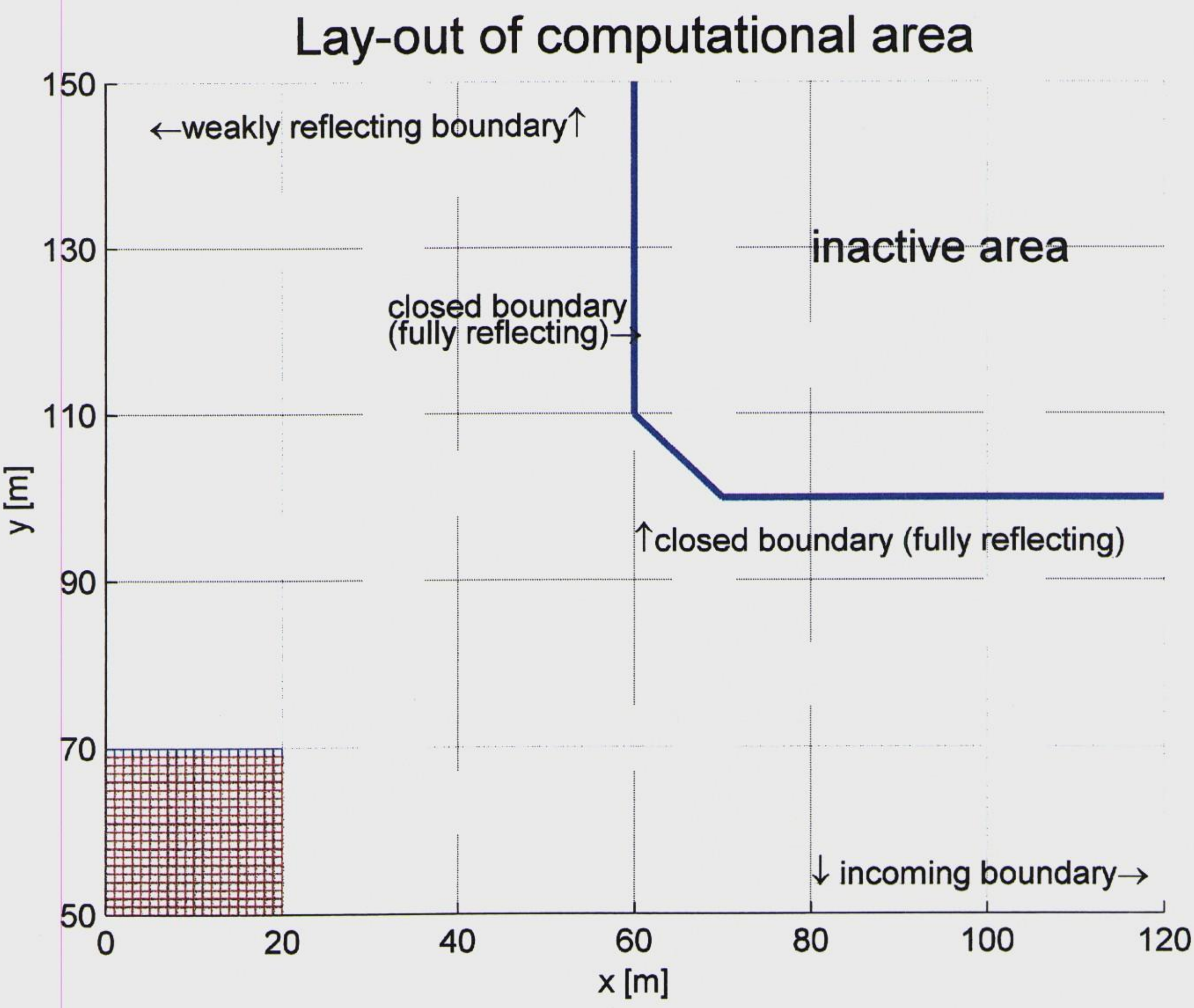


Figure 12 Layout of the TRITON computational domain

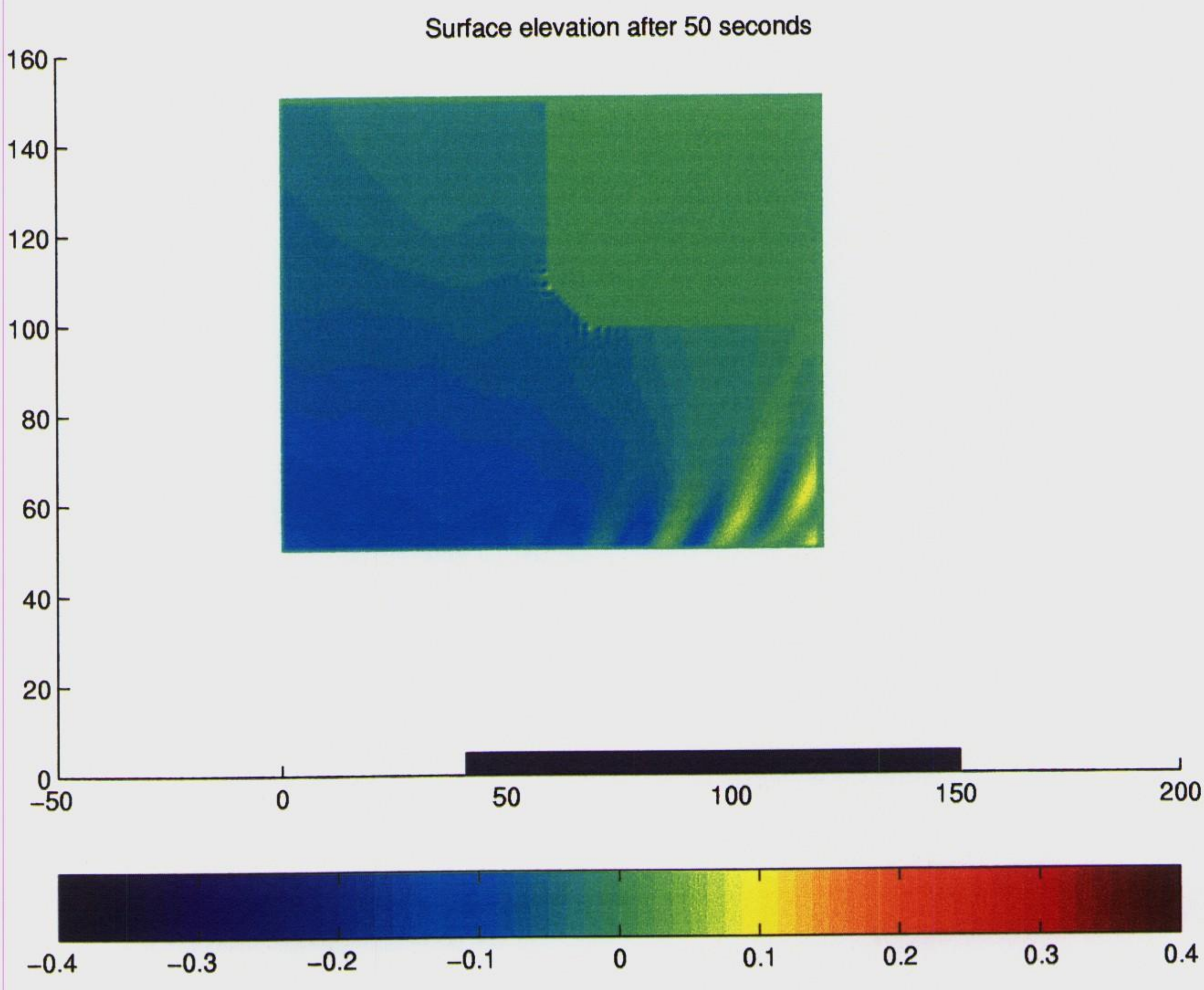


Figure 13 Surface elevation after 50 seconds

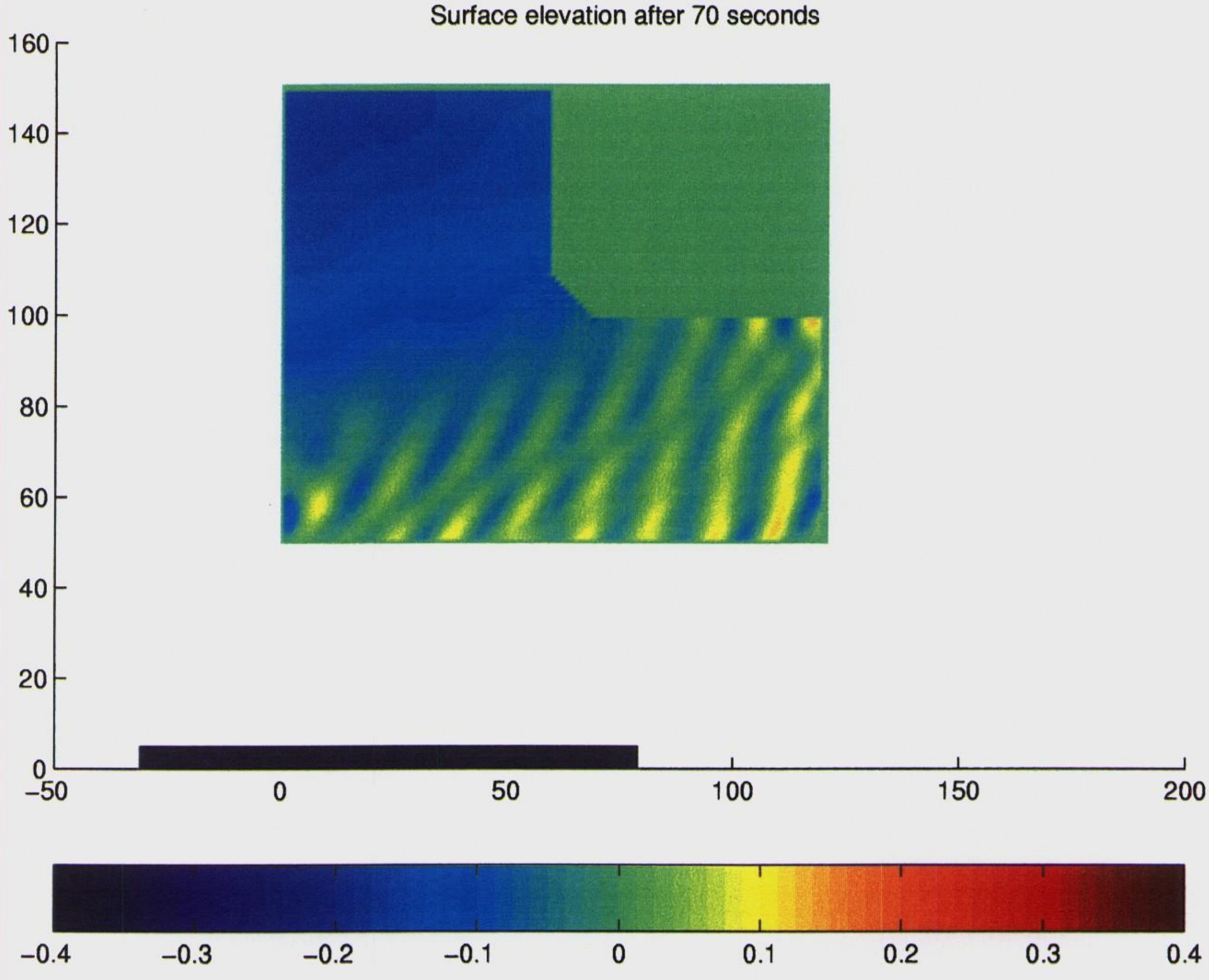


Figure 14 Surface elevation after 70 seconds

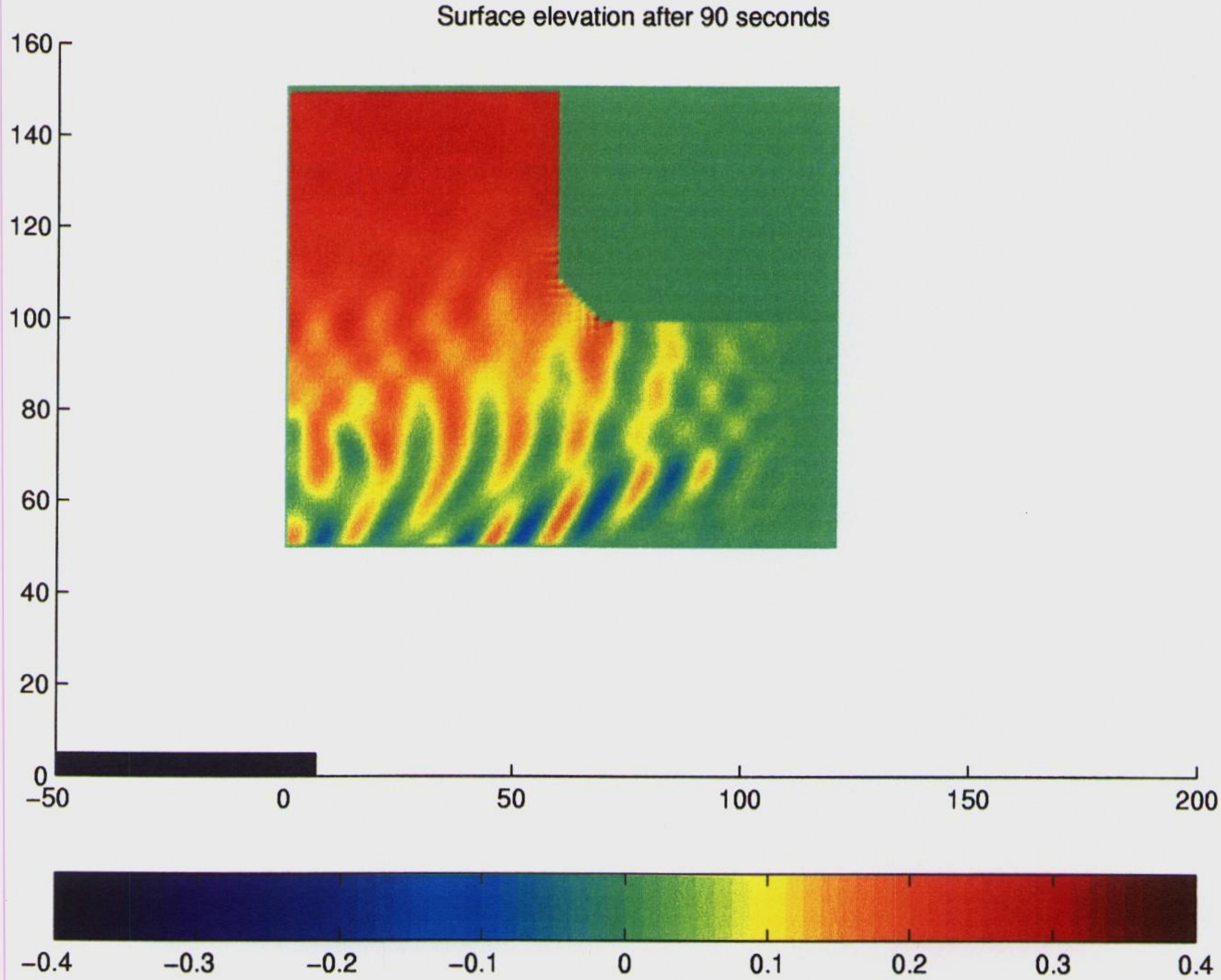


Figure 15 Surface elevation after 90 seconds

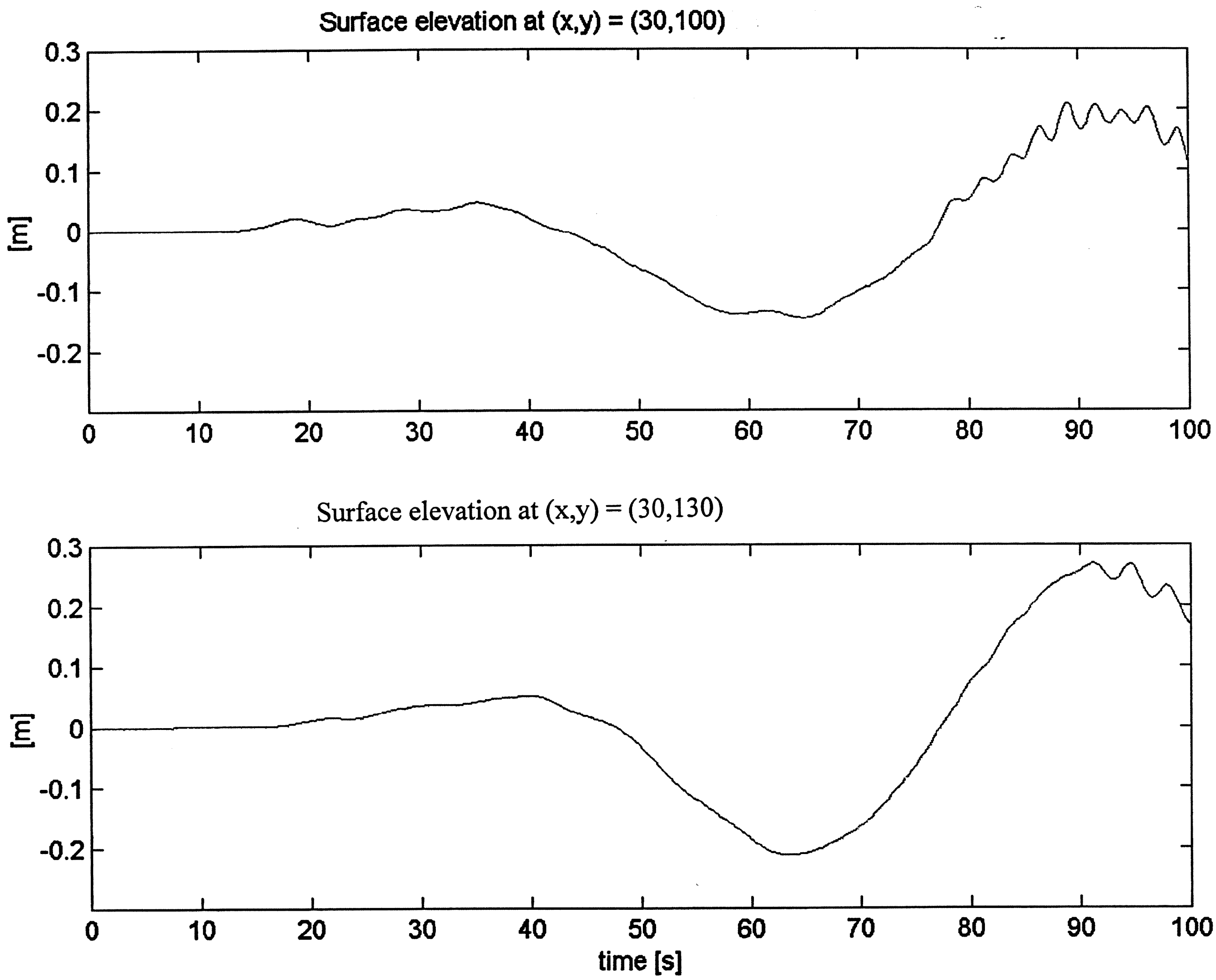


Figure 16 Surface elevation at (x,y) = (30,100) and (x,y) = (30,130)

A Description of the RAPID code

Computational approach
The flow model used is that of a 3D steady incompressible potential flow around the ship hull, satisfying the Laplace equation for the velocity potential. The exact inviscid free-surface boundary conditions are imposed, which require that the flow is tangential to the wave surface, and that the sum of hydrodynamic and hydrostatic pressure at the wave surface is equal to the atmospheric pressure. At the hull, and if relevant at the bottom of the waterway or on channel walls, the flow is required to be tangential again. Moreover, the ship hull is required to be in equilibrium with the hydrostatic and hydrodynamic pressure distribution, i.e. squat is computed and incorporated.

The free-surface boundary conditions, and due to the unknown trim and sinkage also the hull boundary condition, are non-linear. The solution of the resulting non-linear free-surface problem is found in an iterative procedure. The flow field and wave surface are repeatedly updated until all boundary conditions are met. Simultaneously the dynamic trim and sinkage of the hull are adapted.

Each iteration solves a linearised intermediate problem using a panel method. The ship hull surface is subdivided in a large number (1000-3000) of small surface elements, which each bear an unknown 'source density', i.e. they emit fluid at an unknown rate. Similarly, source panels (2000 - 20000) are distributed over a plane at a small distance above the wave surface. The latter 'raised-panel' feature substantially improves the accuracy and stability of the method. The entire flow field is now defined to consist of the uniform inflow from ahead (equal to minus the ship speed) plus the sum of the induced velocity fields of all N source panels (which, at this stage, still contain the unknown source strength as a proportionality constant).

The hull and free-surface boundary conditions, which are equations for the velocity components, are imposed in a set of N discrete points ('collocation points'), which are the centres of the hull panels, and points under the free-surface panels on the actual wave surface. Using the expressions for the velocity field in terms of the N unknown source strengths, we obtain a large system of N equations for the unknown source panel strengths. which is solved using an iterative algorithm (preconditioned GMRES). From the resulting new source strengths, the new velocity and pressure field are easily found. Updates of the wave surface and velocity distribution at the wave surface are thus obtained, which form the basis for the next iteration.

Generally, convergence is obtained within some 10-20 iterations. The iteration process in many cases requires no user intervention, but for more critical cases the user may need to direct the iteration process by a clever selection of relaxation factors, trim and sinkage adjustments or even a variation of the speed or water depth.

Accuracy
Extensive validations have been carried out. The predicted flow and wave pattern have been found to be accurate; for slender vessels, the agreement with measured wave elevations is often very good, while for fuller hull forms, somewhat larger deviations are found.

Being based on inviscid flow theory, the method disregards the effect of boundary layers, dead water zones behind a transom, or flow separation. Consequently, the amplitude of the stern wave system is usually overestimated; very little for slender transom stern vessels, more for fuller hull forms. For a (seagoing) tanker hull, with a thick boundary layer or even flow separation at the stern, the stern wave system may well be overestimated by a factor of 2 or more.

Wave breaking or spray are not modelled. Extensive wave breaking near the hull may reduce the radiated wave amplitudes, and an overestimation may again result.

The figures below illustrate the level of agreement with experimental data, for a recent validation study for a large container ship in deep water. It is obvious that deviations are essentially limited to the stern wave area, in which effects of separation and wave braking were present in the model experiments.

Input and output

The geometry of the hull is represented by a panel distribution, usually generated from a hull surface representation in a CAD system. Interfaces exist for generating RAPID input files directly from e.g. the naval CAD systems NAPA, TID or GMS. A free surface panelling is generated automatically based on parameters to be selected by the user.

Calculations can then be made for the conditions specified by the user. A graphical user interface helps preparing the input, running the code and analysing the results.

The output consists of the velocity and pressure distribution on the hull, the wave pattern, the wave profile along the hull, the wave resistance, the dynamic sinkage and trim, the actual wetted surface area at speed, the far-field wave spectrum, etc. If channel walls have been incorporated, the velocity and pressure distribution on those is given as well. A postprocessor permits to compute the velocity and pressure in arbitrary other points in the flow domain.

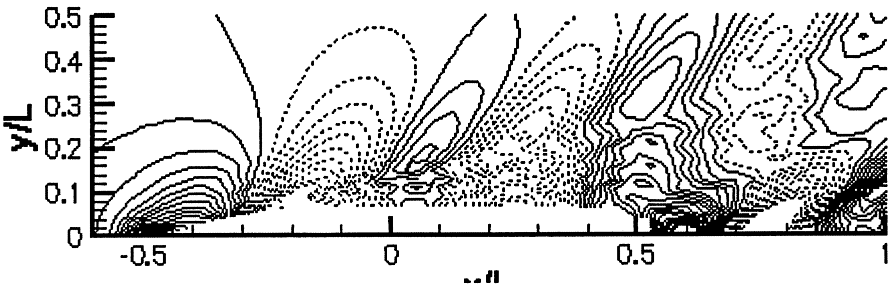
Hardware requirements

RAPID exists in versions for supercomputers, UNIX workstations and PC's. A complete calculation with e.g. 5000 panels per symmetric half typically takes half an hour on a Pentium PC, or about 2 minutes on a Cray C90 supercomputer.

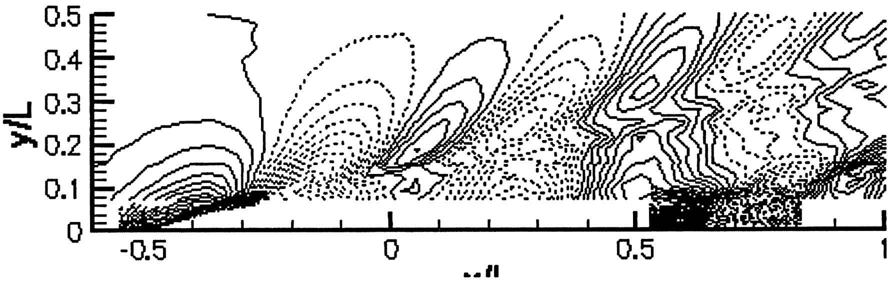
If N panels are used (per symmetric half), the (full) matrix representing the boundary integral problem has N^2 elements. Efficient solution requires these to be in core memory. In addition, there is some 10-20% extra memory needed for other variables. Consequently, for the current maximum allowable memory on the CRAY C90 of SARA, which is 512 Mwords = 4 Gb, the maximum number of panels is about 21100. On a PC with e.g. 128 Mb (= 32 Mwords) RAM, the maximum panel number is about 5275.

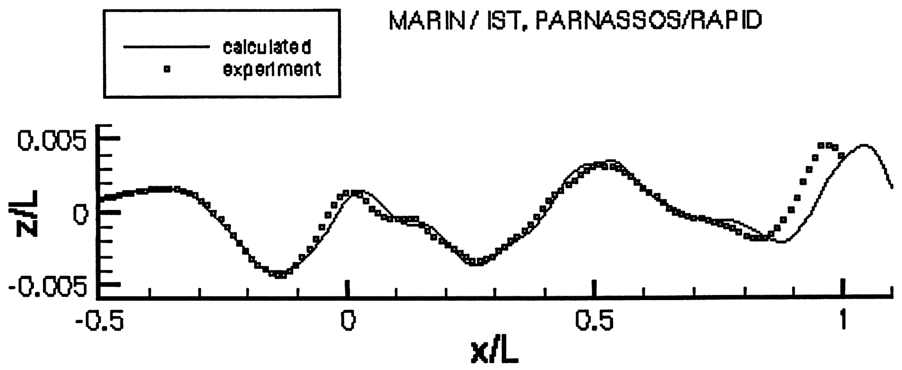
Unpropelled KCS, global wave contours, computed

MARIN / IST, PARNASSOS/RAPID



Unpropelled KCS, global wave contours
Fr = 0.26, Re = 1.4 x 10^7, KRISO EFD data





The number of panels on one symmetric half of the ship hull usually is 1000 to 3000. The number of free-surface panels needed can be quite appreciable. These panels are arranged in longitudinal strips. The longitudinal panel density as a rule is selected to have at least 25 panels per transverse wavelength. This results in $25 /(2 \pi FnL^2)$ panels along the hull. Ahead and astern of the ship there must be a sufficient length of the domain; ahead, to avoid a non-matching inflow condition (in particular in shallow water); astern, to have enough of the wave pattern in the domain. Consequently, the number of panels longitudinally may be 2 to 3 times larger than the number given above. The total number of free-surface panels is found by multiplying this by the number of strips on the free surface, which in common applications is 10 - 20, but may be larger for special applications in wide channels. The width of the panel strip adjacent to the hull is about 0.02 L in general.

A consequence of these requirements is that codes like RAPID are typically suited to near-field rather than far-field predictions. Besides, with increasing distance to the hull the wave amplitude tends to be slightly underestimated due to an accumulation of numerical wave damping effects.

B TRITON: Time-domain wave model

The numerical model TRITON is a time-domain model which can simulate the wave propagation over foreshores. The Boussinesq-type model TRITON developed at WL | DELFT HYDRAULICS is described briefly in this section. A more detailed description can be found in Borsboom *et al.* (2000-a,b).

Boussinesq-type wave models are in principle suitable to model wave propagation in coastal regions and harbours. Especially for the wave propagation of short waves, where non-linear effects, dispersion and shoaling play an important role, this type of model can be adequately applied and provide valuable information on the wave field which cannot accurately be obtained from many other types of models (*e.g.*, time series of surfaces and velocities in shallow regions).

Within the range of existing Boussinesq-type models, each model aims for a certain accuracy of *a)* non-linear effects, *b)* linear dispersion and *c)* shoaling. The accuracy of each of these three aspects should be in balance: Improving linear dispersion without sufficiently improving the non-linear effects might be useless if wave propagation over shallow foreshores is concerned. On the other hand, improving each of the aspects where the three aspects are in balance, might lead to a very complex model which may result in large computing times. The Boussinesq-type model applied here is a model developed to obtain an accuracy as good as possible within limited computing times. Besides a proper balance between accuracy and computing time also a proper balance was found between the accuracy of the mathematical description and accuracy of the numerical implementation. In addition, the applied model has a few unique properties for a Boussinesq-type model:

- The formulation is independent of the vertical reference level for bottom topography and water elevation, which facilitates straightforward practical applications.
- Dispersion and shoaling are modelled in a very compact way, which reduces computing times.
- Both mass and momentum are conserved, which means that the model, besides providing solutions of the applied formulations, also assures that a few basic physical properties are modelled correctly.

The equations of the 2D Boussinesq-type model, which is applied in a 1D situation here, can be written as follows:

$$\frac{\partial h}{\partial t} + \nabla \cdot \mathbf{q} = 0 \tag{B.1}$$

$$\frac{\partial \mathbf{u}}{\partial t} + \left[\nabla^{T}\left(\overline{\mathbf{u}}\mathbf{q}^{T}\right)\right]^{T} + \nabla P = p_b \nabla h_R \tag{B.2}$$

with $P = g\dfrac{\tilde{h}^2}{2}$, $\quad p_b = g\left(\dfrac{3\tilde{h}}{2} - \dfrac{h}{2} + \dfrac{h}{4}\nabla h \cdot \nabla \zeta\right)$ (B.3)

and $\tilde{h} - \alpha h^2 \nabla^2 \tilde{h} - \beta h \nabla h_R \cdot \nabla \tilde{h} = h + \left(\dfrac{1}{3} - \alpha\right) h^2 \nabla^2 h + \left(\dfrac{1}{2} - \beta\right) h \nabla h_R \cdot \nabla h$ (3.4)

The unknowns in these equations are the total water depth h and the depth-integrated velocity vector **u**; the bathymetry is described with respect to some arbitrary reference level h_R. From these variables the water elevation with respect to the reference level $\zeta = h - h_R$ and the depth-averaged velocity vector $\bar{\mathbf{u}} = \mathbf{q}/h$ are obtained. Auxiliary variable $\tilde{h}$ is a function of h, defined implicitly by Equation B.4. This equation realises a so-called [2,2] Padé approximation of linear dispersion and the first order effect of linear shoaling that can be adjusted by respectively α and β. The value of these parameters should be 0.4 or slightly lower. Auxiliary variables P and p_b have been introduced because of their physical meaning. From the conservative form of momentum equation (B.2) it can be seen that P and p_b must represent respectively the depth-integrated pressure and the pressure at the bottom, both divided by the density that is assumed constant.

Wave breaking is implemented based on a new method by Borsboom where wave breaking is modelled as an eddy-viscosity model in combination with a surface roller. Wave breaking is implemented as an eddy-viscosity model as for instance also applied by Kennedy *et al.* (2000):

$$\frac{\partial}{\partial x_w} h \nu_t \frac{\partial \bar{u}_w}{\partial x_w} \qquad \text{(B.5)}$$

where x_w is the propagation direction of the wave, h is the water depth, $\bar{u}_w$ is the depth-averaged flow velocity in x_w-direction and ν_t is the turbulence-viscosity coefficient, which is uniform over the depth. For the determination of ν_t use is made of the concept of surface rollers (Schäffer *et al.*, 1992). The idea behind this concept is as follows: Wave breaking is assumed to initiate if the slope of the local water surface exceeds a certain value for ϕ_{ini} and assumed to finish if the slope of the local water surface becomes below a certain value for ϕ_{ter}. The water above the tangent of this critical slope is assumed to belong to the roller. This slope is assumed to vary in time while being constant in space within each surface roller:

$$\tan\phi = \tan\phi_{ini} + (\tan\phi_{ter} - \tan\phi_{ini}) \exp\left[-\ln 2 \frac{t - t_b}{t_{1/2}} \right] \qquad \text{(B.6)}$$

The turbulence-viscosity coefficient that is used in the present model is scaled with the height of this surface roller:

$$\nu_t = f_p \, \delta (c - \bar{u}) \qquad \text{(B.7)}$$

where δ is the roller height, c is the local wave celerity modelled as $c = \sqrt{gh}$ and f_p is the parameter that is used for scaling.

The model makes use of four coefficients of which the values are based on a sensitivity-analysis using a selection of tests from the present data-set. These coefficients are kept constant in all computations. The initial angle of the surface for which breaking starts ϕ_{ini} is estimated to be in the order of 15° which exponentially changes to the terminal breaking angle ϕ_{ter} which is in the order of 10°. The parameter $t_{1/2}$ is a measure related to the time required for the wave to pass through the breaking process. The following value $t_{1/2} = T_m/10$ is used. The amount of energy dissipation can be scaled with the parameter f_p for which a value of 30 has been used.

Another important aspect of the model is the modelling of weakly reflecting boundaries, based on the concepts by Borsboom *et al.* (2000-a,b). For a detailed description refer is made to the mentioned literature.

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