CHAPTER 75

Simulation of sandfill building stages with numerical flow models

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The paper describes the application of two dimensional vertically integrated models (WAQUA system), the results being used for the calculation of sandlosses during sandfill closure operations.
Investigations with test models, physical scale models as well as numerical models, are presented to prove that the WAQUA system is not only suitable for large scale applications, but also for the simulation of detailed flow patterns.

1. Introduction

A large part of the Netherlands lies below mean sea level. It is protected from floods by dikes and dunes (see figure 1).
In the twentieth century massive construction programs have been carried out to increase the safety of the low lands against storm floods. In former ages the defence merely consisted of building dikes. Only this century projects have been executed to shorten the exposed coast-line. This began in 1932 with the closure of the Zuiderzee, and continued more recently with the Delta Plan in the south-west of the Netherlands.

The rivers Rhine, Meuse and Scheldt formed the Dutch Delta. By its nature the area is flat and low. In the past the Delta was flooded several times. The most recent catastrophic flood disaster happened in 1953 when 150.000 hectares were inundated and more than 1800 people lost their lives (see figure 2).
Immediately after the situation had been restored, the Delta Plan was drawn up to prevent future disasters. According to the plan, all the estuaries had to be closed, except for the entrances to the harbours of Rotterdam and Antwerp.

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figure 1 The Netherlands without dykes

figure 2 Situation flood 1953, flooded area are shaded

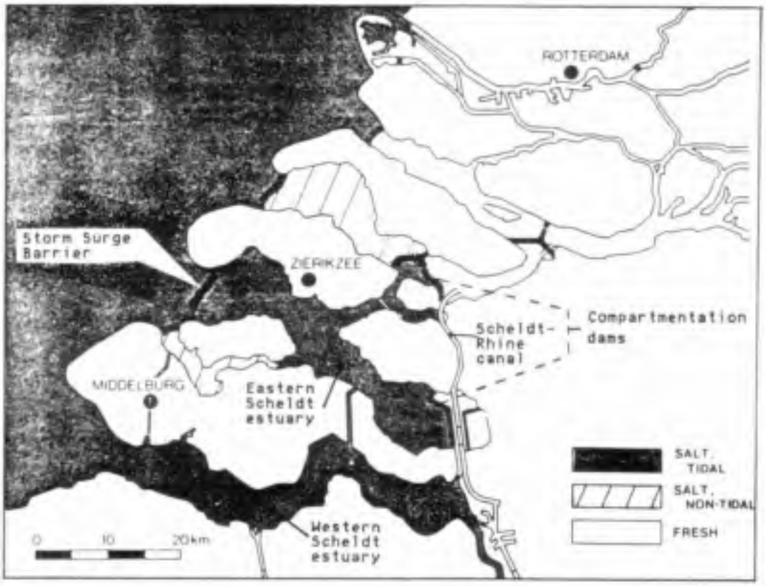


figure 3 The Delta project.

All planned closures but one were executed between 1956 and 1972.

However, contrary to the initial plan, the Government decided in 1976 to build a storm surge barrier in the mouth of the Eastern Scheldt instead of a massive dam. This with the aim to maintain the tide in the estuary under normal conditions, but to eradicate the chance of flooding of the country during storm surges.
The reason for this decision was that it became apparant that the Dutch society in the mean time came to realize that preserving the original environmental conditions in the Eastern Scheldt, with its unique aquatic life and its function as a nursery room for the North Sea, must be considered as a goal, equally important to the safety requirement.

The construction of the storm surge barrier implies the division of the Eastern Scheldt estuary into compartments. In the largest western compartment the tide is maintained, but the eastern part will become a tide-free fresh water lake:
- to prevent salt intrusion into the (agricultural) hinterland
- to provide a tide-free Scheldt-Rhine canal.

The ultimate lay-out of the Delta project is shown in figure 3.

The costs of the projects in the Eastern Scheldt amount to about $4,000,000,000.-. The construction of the storm surge barrier requires the major part of the budget. Related to the compartmentation projects approximately $300,000,000.- are to be spent.

The design and execution of major hydraulic structures is only possible when sufficient data are available.
Until now physical scale models were built to study flow conditions, and in some cases other relevant hydraulic phenomena, during building stages and in the future situation. The past decade, however, numerical flow models developed rapidly.
For the design of the storm surge barrier both physical scale models and numerical models were built. The principles of the applied numerical model based on the WAQUA system will be explained in chapter 2.
The confidence gained in the capability of numerical models to reproduce current patterns nearby the storm surge barrier (Klatter e.a., 1986) led to the decision to investigate whether numerical models can be used to compute current pattern near the planned sandfill closures of the compartmentation dams, without the additional use of tests in physical scale models. The performed tests will be descripbed in chapter 3.
The results of the tests led to the decision to rely entirely on numerical models for the design and execution of the sandfill operations in the closure gaps of the compartmentation dams (see for location figure 3).
Chapter 4 will discuss the results of these investigations.

2. WAQUA system

2.1. Numerical formulation

The model is based upon the so-called vertically integrated semi-momentum equations:

$$u_t + uu_x + vu_y - fv + gz_x + gu(u^2+v^2)^{0.5}/(C^2H) - K(u_{xx}+u_{yy}) = F^{(x)}$$

$$v_t + vv_y + uv_x + fu + gz_y + gv(u^2+v^2)^{0.5}/(C^2H) - K(v_{xx}+v_{yy}) = F^{(y)}$$

$$z_t + (Hu)_x + (Hv)_y = 0$$

in which:

- u = velocity in x direction (vertically integrated)
- v = velocity in y direction (vertically integrated)
- z = water elevation above some plane of reference
- h = water depth below plane of reference
- $H = h + z$ = total water depth
- f = coriolis parameter
- g = acceleration due to grafity
- C = Chezy coefficient for bottom roughness
- $F^{(x,y)}$ = external forcing functions of wind stress or barometric pressure
- K = viscosity coefficient

The computations are made on a staggered rectangular grid system. The equations are solved by means of an Alternating Direction Implicit Method (Leendertse 1967, Stelling 1983).

2.2. Modeling system

For successful model investigations with numerical models a system of interlocking programs is required for data handling, simulation and graphical representation. The system used in this investigation has three major parts, namely, the Input Data Processor, the simulation program and the Simulation Data Display system.
Particularly noteworthy is that the WAQUA system possesses a number of facilities for simulating physical phenomena and the effects of hydraulic structures. The most important are:

- several procedures for the simulation of flooding and drying of intertidal flats (moving boundaries);
- a facility to simulate weirs and sluices whose flow characteristics can be varied with time;
- the possibility to represent narrow dams like groynes and breakwaters;
- the possibility to simulate the discharge of heat and effluents and the intake of cooling water at any location in the computational grid;
- (offline) nesting of models.

The system is designed to be used by civil engineers. Its operation requires no special knowledge of the computer science aspects of data handling and manipulation.

A large number of successful models have already been set-up and operated for tidal regions all over the world (ROOS et.al. 1985, Verboom et.al. 1984, Thabet et.al. 1985).

3. Detail models for sandfill closure gaps

3.1. Theoretical background

Numerical models based on the vertically integrated semi-momentum equations (which are based on the assumption of nearly parallel flow lines and hydrostatic pressure distribution) cannot be straightforward applied in the direct vicinity of hydraulic structures. The flow pattern is basically three dimensional, with flow separation and vertical and horizontal vortices directly downstream of the structure. These three dimensional effects and the additional dissipation of energy in the deceleration zone of the flow are responsible for the pronounced drop in the energy line (or water surface) at the structure. In civil engineering practice, these losses are usually refered to as "form losses", and expressed in terms of weir or gate formulae.
When applying two dimensional models, special measures have to be taken to introduce the energy drop at structure site. This is usually done by expressing "internal boundary conditions" based on the - presumably known - weir or gate formulae. This was the case for the storm surge barrier at the estuary mouth (Klatter et.al. 1986).

The case is different for sandfill closures. Sandfill bodies have flat slopes (1:15 or flater) in all directions. Hence no flow separation and associated "form losses" will take place. Accordingly two dimensional models can in principle be applied for such "structures", provided that the local energy losses not counted for in the semi-momentum equations can be locally incorporated.
These additional local losses are discussed below (see also figure 4).

First the friction losses. This factor dominates the energy drop over the closure gap. Because of the accelerating flow at the closure gap, the boundary layer will become thinner, causing the Chezy factor to drop and hence friction losses to (relatively) increase in the area around the closure gap. Downstream of the gap the change in the friction depends very much on the topography. The corresponding value of C will increase up to its original value over some distance.

Another coefficient which appears to be important is the viscosity factor K. From theoretical approximations we know, that this factor is 0.1 to 10 m2/s, dependant upon the local flow condition. This is only valid, when the numerical viscosity of the system is zero.

A coefficient which is not incorporated in the equations given in section 2.1 is the factor which described the influence of the vertical distribution of the velocity on the advection terms, $B(uu_x+vu_y)$ and $B(vv_y+uv_x)$. Under normal conditions the B value is approximately 1.1. In strongly diverging flows this factor may increase up to a maximum of 1.4. Because the B value is not implemented in the WAQUA system, the resulting energy losses were taken into account by adapting the friction coefficient, see section 3.2.

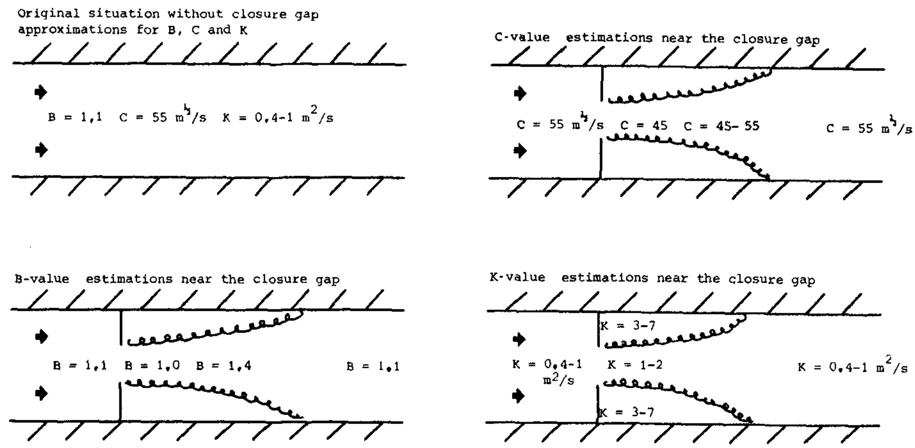


figure 4 Distribution of the values of some coefficients near the closure gap
note: Given C-value corresponds to water depths of the channels at compartmentation dam site

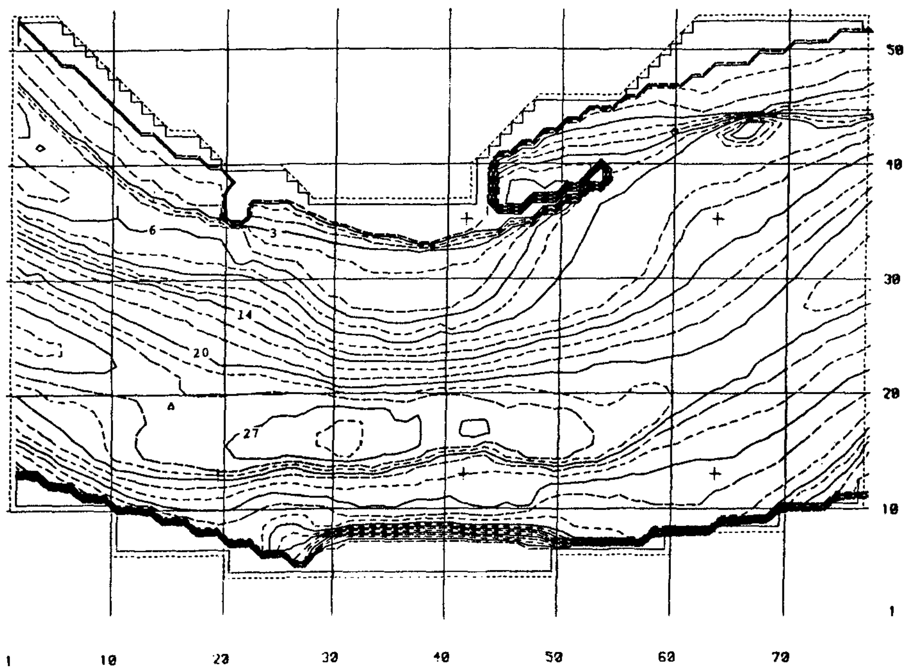


figure 5 Bathymetry of the test model

3.2. Verification tests

The test program

After the decision to investigate whether the WAQUA system is able to compute flow patterns around a sandfill closure, a test program was designed, based upon the comparison between a physical scale model and a numerical model of the same area.
An existing physical scale model was temporaraly changed in order to simulate the characteristics of a sandfill closure gap, see figure 5.
At the same time a numerical model with a grid size of 45 meters of the same area was built, to be able to compare measurements and calculations.
Five representative building stages of a sandfill closure were defined and one after another tested in the physical scale model.
The measured velocity distribution at the upstream and downstream edge of the physical scale model were used as boundary conditions for the numerical model.

Test results

The numerical model proved to be able to reproduce the current pattern fairly accurately.
Figures 6 and 7 show some of the investigated flow patterns. The measured flow pattern as well as the calculated distribution are shown.

As discussed in section 3.1., extra energy losses due to changes in the boundary layer and to the influence of the vertical velocity profile on the advection terms were introduced by increasing the bottom friction of the model.
Experiments proved that the Chezy factor must be decreased to a value of 35-40 to make up for these effects. Note that this value is only valid for geometries and water depths like the ones investigated.

Very low viscosity factors proved to give the best results, as far as the horizontal distribution of the velocity and diversion of the flow downstream of the gap are concerned.
After some tests we decided to use for all the applications a viscosity factor of 1 m2/sec.

The physical scale model is a stationary model. This implies that a changing tidal situation could not be simulated, only max. flood tide and max. eb tide were therefore investigated.

4. Applications

4.1. Tholense Gat model

In 1985 a fine grid model of the final gap in the southern compartmentation dam was built.
The model is situated at the northern edge of the dam, near the coast of the island of Tholen. It has a grid size of 30 meters and a time step of 20 seconds. The number of active grid cells is approximately 3000.
The boundary conditions of the model are generated by a 100 meter grid sized far field model.

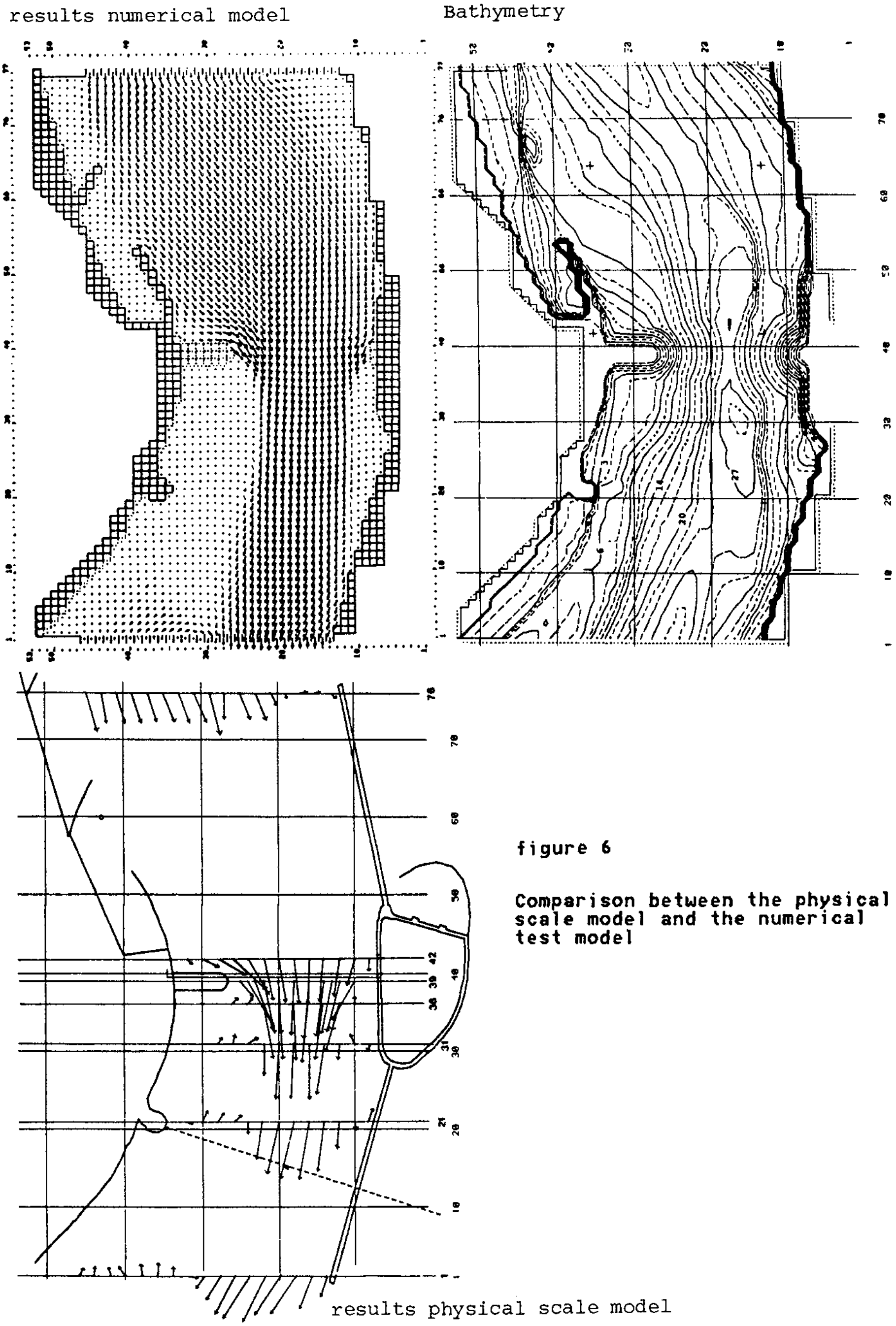
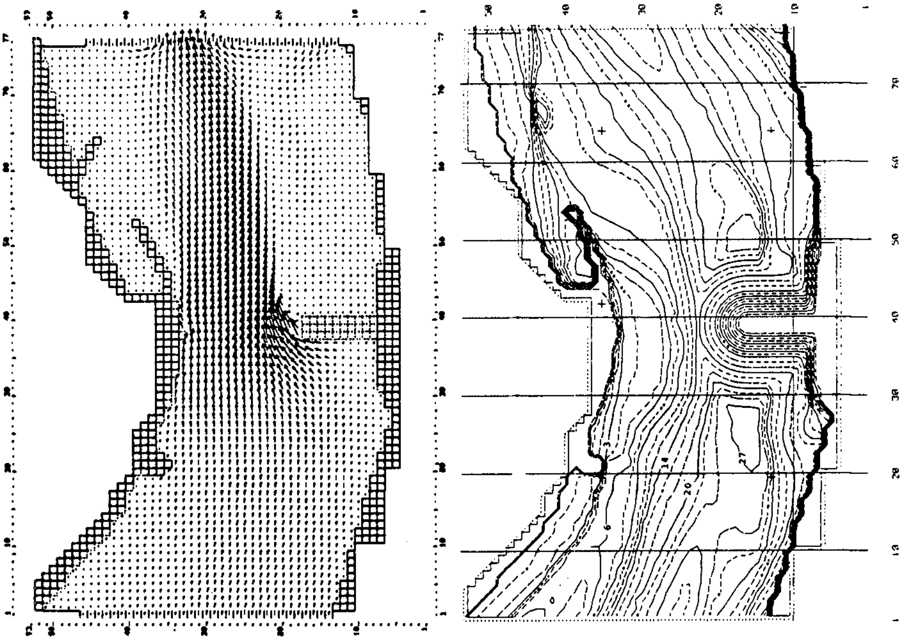


figure 6

Comparison between the physical scale model and the numerical test model results numerical model

Bathymetry



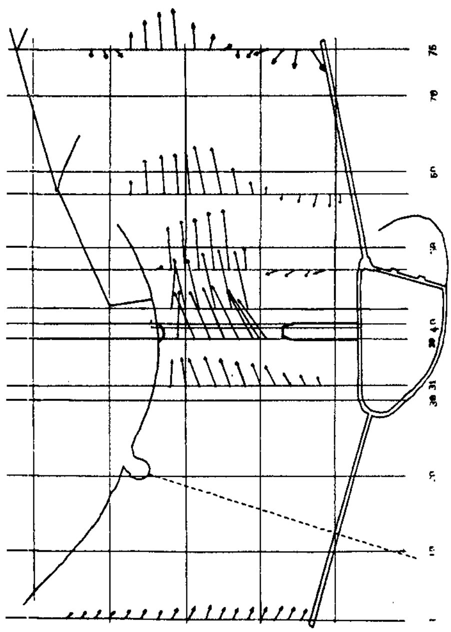


figure 7

Comparison between the physical scale model and the numerical test model

results physical scale model

The investigations with the model had two purposes:
- prediction of the flow conditions in the closure gap, the results being used as input for the calculation of sand losses during the sandfill operation and prediction of the flow along the bank of the island of Tholen, in order to prevent possible problems with the existing, rather, weak dykes;
- prediction of the discharge coefficient of the closure gap (as a function of construction stage), such data being used as input for the one dimensional model covering the entire estuary up to the North Sea.

Figure 8 shows one of the investigated building stages.
The closure operation was successfully performed in October 1986.

4.2. Krammer model
Figure 9 shows the situation at the northern compartmentation dam in July 1986. Two gaps are still open.
The model of the area has a grid size of 50 meters, a time step of 30 seconds and some 25000 active grid cells.
The boundary conditions of the model are generated by the overall one dimensional model of the Eastern Scheldt (see also section 4.1.).
In September 1986 the smallest gap in the dam was closed. In figure 10 the flow pattern at the smallest gap, calculated by the model is compared with prototype measurements.
Although the grid size of the model is rather large in relation to the width of the gully, the model was able to simulate the flow pattern quite well.

After the successful closure of this small gap in September 1986 and the completion of the southern compartmentation dam, described in section 4.1., only the gully called the Krammer is still open.
The closure of this gap is planned in April 1987. The planned building stages have been thoroughly investigated. An example of the situation to be expected is shown in figure 11, where the flow pattern is plotted during an average maximum flood tide, when 70% of the gap is closed.
Figure 12 shows the flow pattern during maximum eb tide and maximum flood tide in more detail.
In the remaining cross section of 3000 m2 the average velocity is 2,0 m/sec, but localy 2,75 m/sec will occur.

The described flow pattern with an average velocity of 2,0 m/sec is only possible if the tide in the Eastern Scheldt estuary could be reduced. This is planned to be done by partial closure of the gates of the storm surge barrier.
A large amount of investigation effort has been invested in selecting the tide reducing measures that would reduce the velocities in the closure gap and at the same time would minimise the damage to the ecology of the estuary.
Figure 13 shows the expected (reduced) water elevation in the Eastern Scheldt during the last days of the closure operation of the Krammer Gap.
After completion of the dam, the storm surge barrier will be opened again completely and the tide will be fully admitted to the estuary.

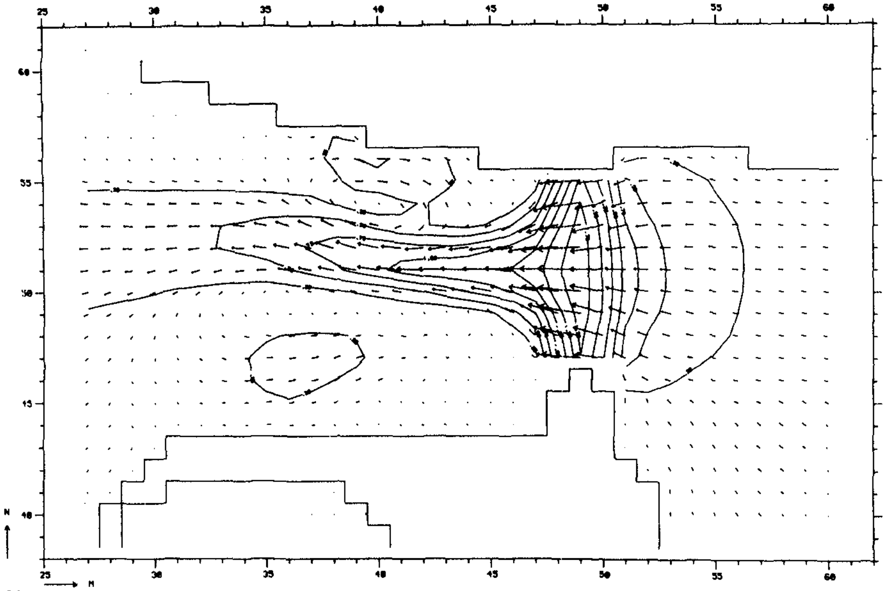


figure 8 One of the investigated building stages in the Tholense Gat model.

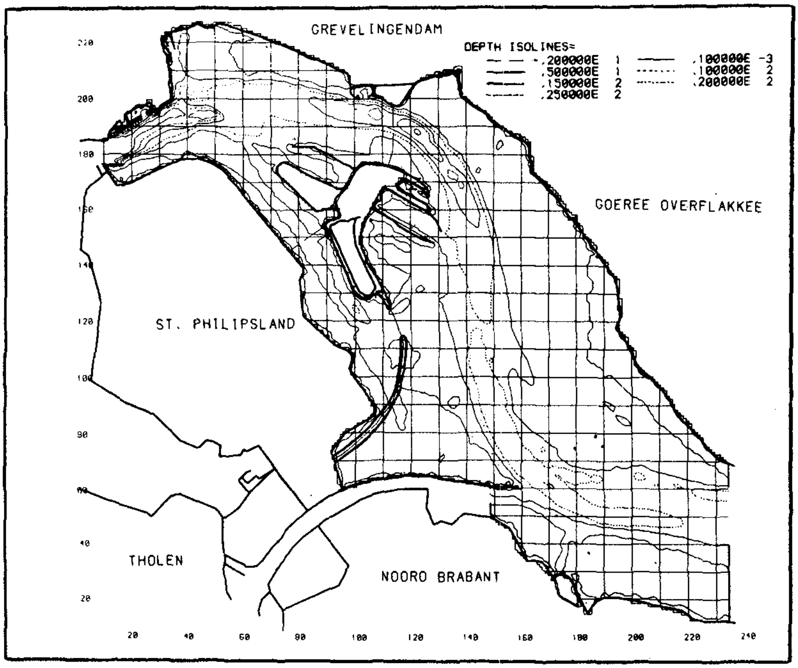


figure 9 Situation at the northern compartmentation dam in July 1986.

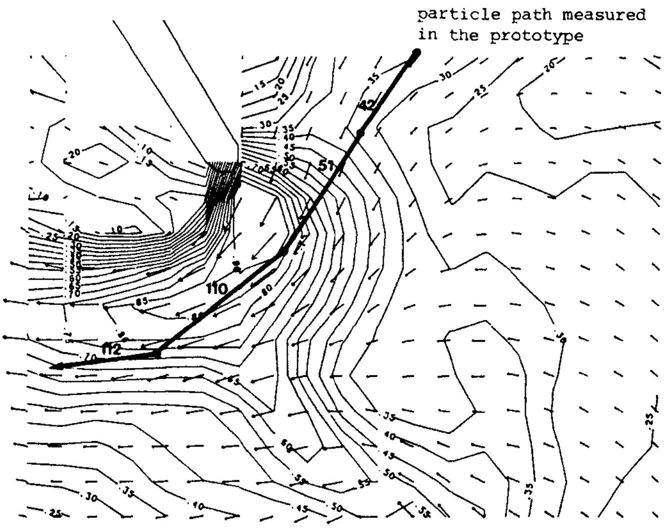


figure 10 Detail of the model of the area round the northern compartmentation dam, showing the comparison between prototype measurements and model calculations for the smallest gap, closed in September 1986.

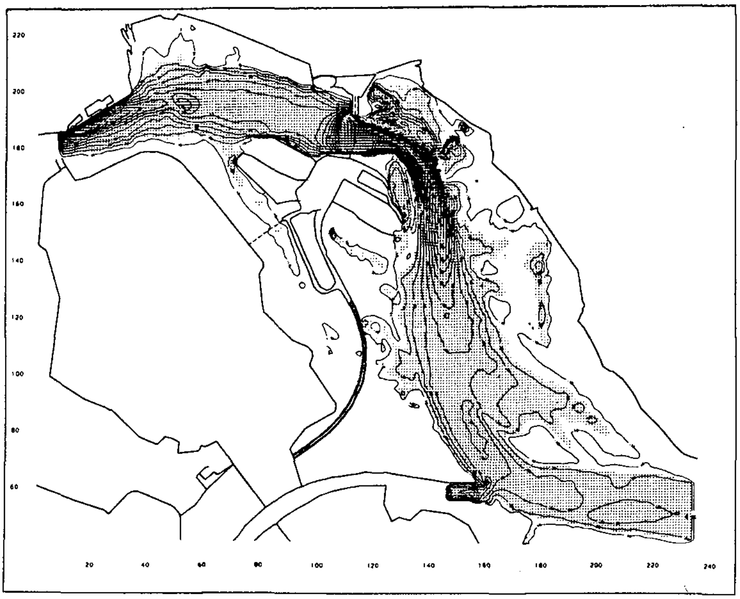


figure 11 One of the investigated building stages of the last gap in the northern compartmentation dam.

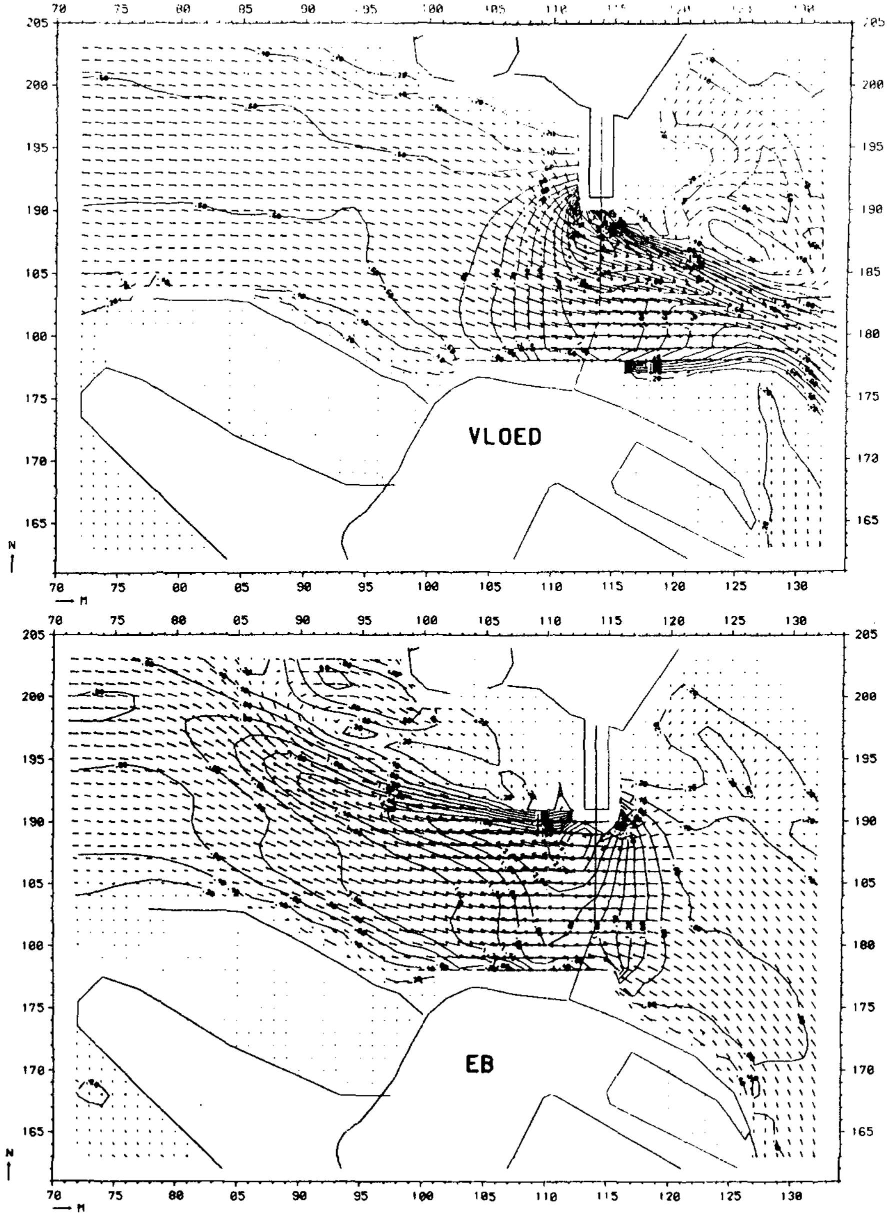


figure 12 Detailed calculated flow patterns during maximum eb tide and maximum flood tide.

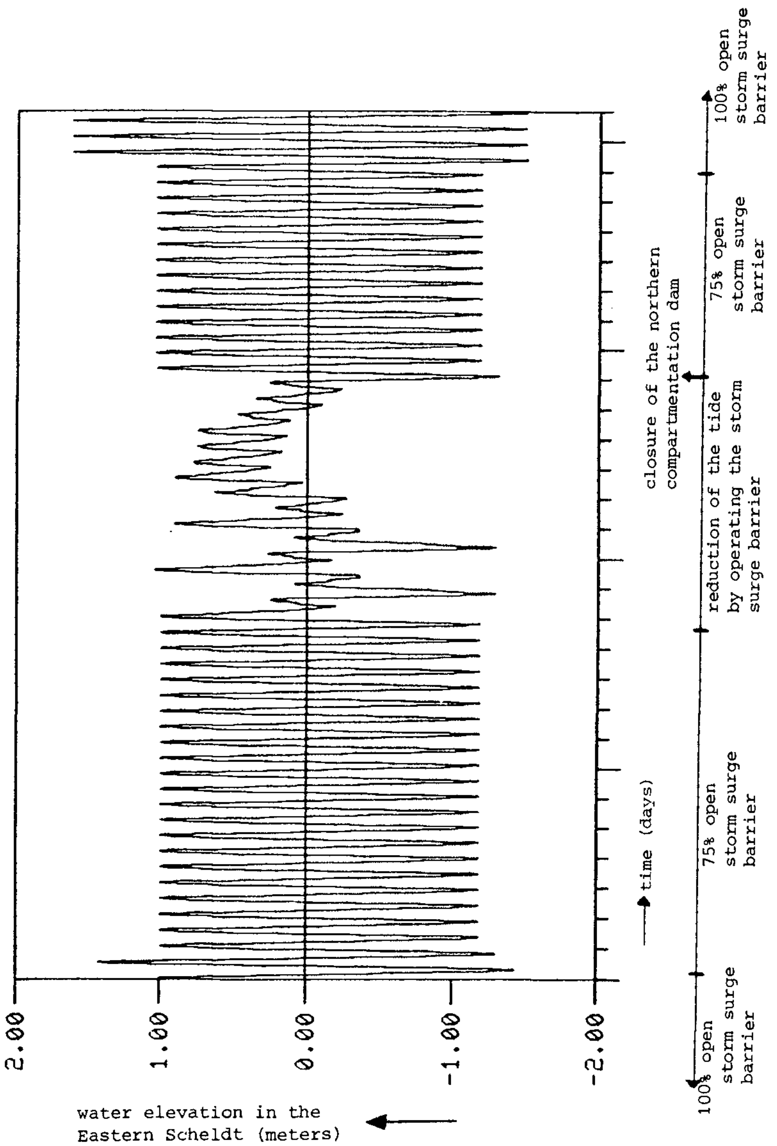


figure 13 Expected (reduced) water elevation in the Eastern Scheldt during the closure of the Krammer gully in the northern compartmentation dam.

5. Conclusions

Extensive tests with the WAQUA system, in comparison with prototype measurements and physical scale model results, have shown that the system is also reliable for small scale applications, provided that governing mechanisms are correctly simulated.
Models of sand closure building stages proved to be able to calculate the flow patterns accurately.
For the first time in the Netherlands, major closure operations were carried out without the use of physical scale models, but entirely based on calculations with numerical flow models.
The system proved to be a very useful engineering tool, accepted by and operated by civil engineers.

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