CHAPTER 200

FLOW DEPENDENCY OF BOTTOMSTRESSES IN TIDAL MODELS

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In modeling studies the bottomstress parameter may not be taken as a constant for making predictions. This is particularly true when large changes are being made in the water bodies. Engineering judgement is than necessary as studies to a relation between the bottomstress parameter and tidal flow velocity are not conclusive.

Introduction to the project

In 1976 the Netherlands Rijkswaterstaat embarked on constructing the final stage of the Deltaplan with the Eastern Scheldt-project. Three structures had to be built: a 3 kilometer long stormsurge barrier in the mouth of the estuary - to be closed during storms - and two so-called compartimentation dams (fig. 1). The dams, which created a lake in part of the estuary, had to provide (a) a tide-free shipping lane from the city of Antwerp to the river Rhine, and b) storage of fresh water flowing into the estuary. The latter was necessary to maintain high salinity in the estuary without large fluctuations for the ecological system as the stormsurge barrier reduced the tidal currents and thus the mixing.

The Deltaplan as a whole (fig. 2) enhanced the protection from the stormsurges in the Rhine-Meuse delta. The plan comprised closure of all estuary branches except for the New Waterway, which is the shipping lane to Rotterdam, and the Western Scheldt, which is the shipping lane to Antwerp. In 1976, the Deltaplan was completed except

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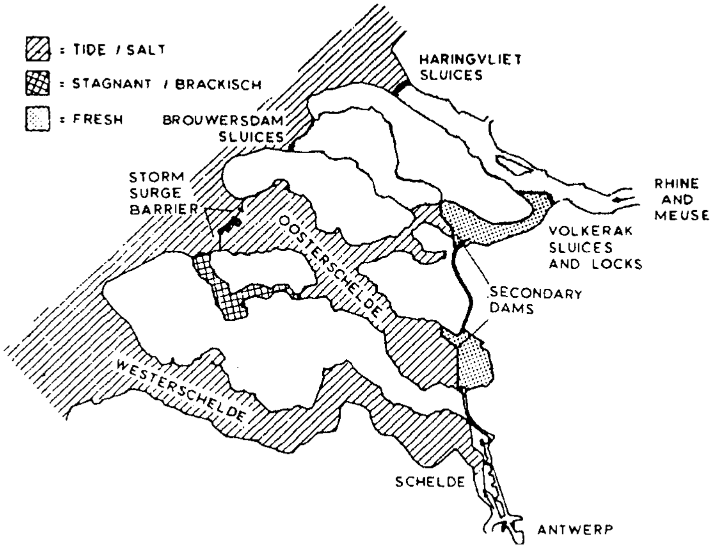


Fig. 1 Overview of the Eastern Scheldt project with location of the Stormsurge Barrier and Compartimentation Dams.

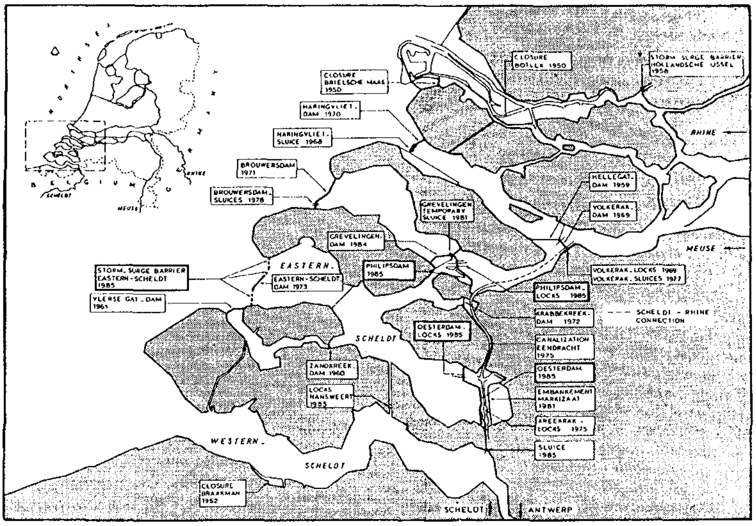


Fig. 2 View of the Deltaplan, including the Eastern Scheldt project.

for the most difficult part, namely the construction of the stormsurge barrier and the compartimentation dams in the Eastern Scheldt.

Function of the models

Large hydraulic engineering projects like the construction of the stormsurge barrier and the compartimentation dams require reliable short term predictions of the weather and of the currents and waterlevels. The predictions are needed to schedule and adjust the progress of the construction. Predictions over longer periods are also required to evaluate different options in the design and the construction methods.

The contract between the government and the construction-consortium for the project contained a clause which required the Rijkswaterstaat to provide the consortium with accurate tide and surge predictions. If the predictions deviated from observed values by a certain amount, extra payments were due for expected damages. As a result, the required accuracy of the models was high. The waterlevels had to be predicted within 5% of the observed values on an average, and currents had to be predicted within 10% of the observed values on an average. The prediction period ranged from 24 hrs.- for predictions of the combined tide and surge - to 4 yrs., the latter for predictions of tide only.

For the short term predictions, a one-dimensional model was used. This model was based on the numerical solution of the St. Venant-equations (fig. 3). For the long term predictions of tidal heights and currents, the one-dimensional model was also used, as the computation time on a HP1000-A was only one minute for every 24 hrs. real time. However, for the prediction of current distributions and intensities to be used in the design and construction planning, the one-dimensional model had insufficient resolution and a family of depth averaged two-dimensional models (fig. 4) was used with a spatial solution ranging from 45 m. for the detail models to 400 m. for the overview model. Some of the high resolution simulations required 20 hours on a main frame computer.

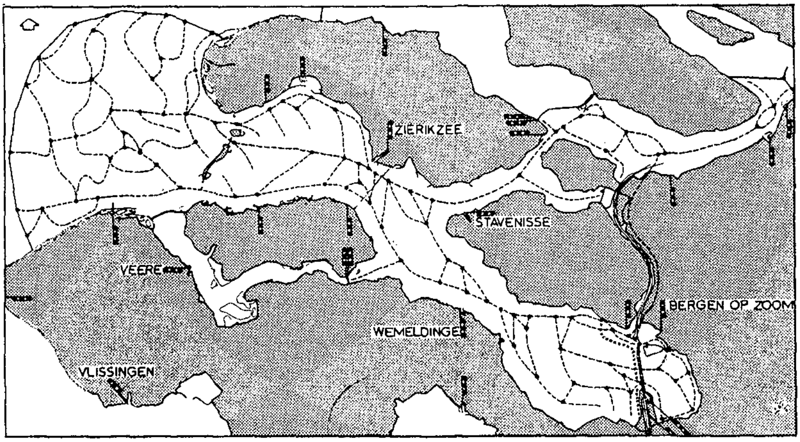


Fig. 3 One-dimensional tidal model used to make long and short term predictions.

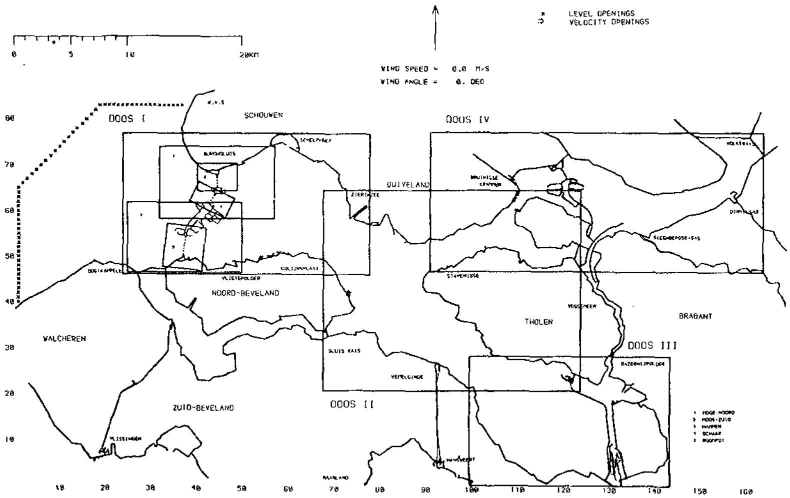


Fig. 4 Two-dimensional tidal models used in the evaluation of the design and construction methods.

In the beginning of the planning and execution of the project, hydraulic scale models were used together with numerical models. But after comparing hydraulic scale model results and numerical model results with observed data it was shown that numerical model results were more accurate (Leendertse 1984). As a numerical model was also more flexible and cost-effective, during the final construction phases of the project the design, the preparation and the actual construction depended completely on the use of numerical models.

Importance of the bottomstress representation

To fulfill the requirements of accuracy, all aspects of the models like the boundary conditions, bottom-schematisation and friction factors were carefully reviewed. A large number of experiments were made in a two-dimensional model of the estuary (Leendertse, 1988) to investigate the effects of the advection term approximation in the hydrodynamic equations and to investigate the comparative importance of the timestep size, the gridsize, the depth accuracy, the roughness estimates, and the horizontal momentum exchange. Similar experiments were made for the one-dimensional model.
From these experiments, it was concluded that the depth approximation, the boundary conditions and the bottomstress coëfficients were the most significant factors to obtain accurate predictions. For the depth approximation about a man-year's effort was expended to present the geometry of the estuary with high accuracy in the models. For the depth approximation, extensive use was made of computer programs which accessed the huge bathymetric data files. To verify the accuracy of the approximation, graphs were prepared with the depth in every cross-section of the model in comparison with the data of the bathymetric files. For the boundary conditions, a new technique was developed for estimating boundary tide levels from existing waterlevel recording stations in the vicinity of the boundary. A high accuracy of the estimates of these boundary conditions was obtained, but it appeared more expedient to measure the waterlevels at the model seaward boundary by installing off-shore recording stations and transmitting the data to the computer which made

all the predictions. For verification purposes of the one-dimensional model, measurements of levels and currents were made at many locations in the estuary and these were also available on-line for verification.

The bottomstress parameters were found by adjusting the model for existing conditions. After making verification simulations, a project review indicated that all required standards were met for the existing conditions. However, as the flow conditions in the estuary would change due to the construction of the barrier and the dams, it was to be expected that the bottomstress parameters would change also. Thus for the long term predictions, considerable uncertainty was introduced particularly as the tidal amplification in the estuary is very sensitive to the bottomstress.

Bedforms and tidal systems

If significant changes in a hydraulic system of an estuary with a sandbottom are made, then such changes have an impact on the bedform. However, little is known about bedform changes in estuaries. This is in contrast to rivers where estimates are available on the impact of discharge changes on the bedform and the frictional losses. For estuaries where the changes in flow are much more rapid such estimates are not yet possible as the research directed toward establishing relations between flow and bottomstress is not conclusive. However, a relationship between flow and bottom roughness for quasi stationary systems can, under certain conditions, be used to obtain an insight in the behaviour of the bedform and bottomstress in an estuary.

The key parameter in this case is the bed response time to hydraulic changes. The bed-response time will be short if the bottom consists of loose packed fine sands and the currents are strong. The bed is then easily erodable and new bedforms appear in a matter of hours. In such a case, the relationships for quasi stationary flow can be expected to be applicable. However, if the bottom consists of densely packed sands or consists of coarse sands or gravel, the development of new bedforms can be a matter of months. In the first case, with loose packed fine sands and relatively strong currents, the tidal currents will have a direct one to one relationship with the bedform and the full cycle of bedforms depicted in Fig. 5 might be seen during a springtide/neaptide cycle or even during one tidal cycle. In the second case, the tidal currents have an impact on bedforms, but the extent of the changes can not yet be predicted.

The Eastern Scheldt estuary resembles more or less to the first case as it consists for a large part of the fine (D50 is 300 mu or less) loose packed sands and the currents are strong. Thus, we may expect a "rapid" response to changes in the hydraulic system.

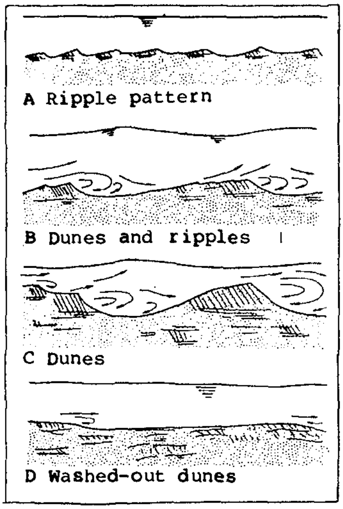
Effect of the stormsurge barrier on bottomstress parameters

An extensive analysis of field data and a very extensive modeling effort permitted an accurate prediction of the modification of the tidal amplification in the Eastern Scheldt due to the construction of the stormsurge barrier.

Part of the modification was due to the obstruction of the flow by the barrier, in part it was due to modification of the bottomstress. In engineering investigations, it is common to assume that the bottomstress parameters are invariant, but before the barrier was constructed, it was noted from comparisons of one- and two-dimensional model results with observed tidal heights and currents that the bottomstress parameters depended on the flow conditions during previous tidal cycles. For example, if the model was adjusted for average tide conditions then the computation of a springtide would show too much tidal amplification and computations for neaptide would underestimate the tidal heights (Leendertse 1988).

To analyze the phenomena, the amplification of the tide in the estuary was determined from observations at two stations. One station was located at the seaward extremity of the estuary, the other far inland. The tidal amplification was determined by cross-spectral analysis from records of about 100 hours during springtide, during neaptide, and during average tide. The tidal amplification of the semi-diurnal tide appeared strongly dependent on the tidal heights.

For example, during neaptide amplification is 1.31, but during springtide the amplification is only 1.17. The phase lag is also influenced by the tidal amplification.



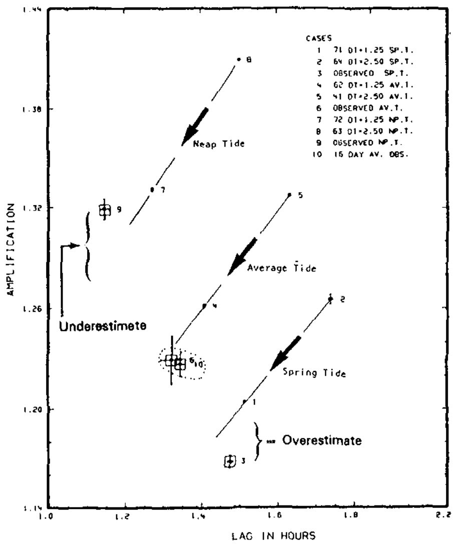


Fig. 5 Various bedforms at increasing velocity.

Fig. 6 Computed and observed amplification and phase lag of the semi-durinal tide over the estuary.

The amplification and phase-shift of the tide in a model may depend on one hand on the resolution in space and time of such a model and on the other hand on the bottomstress parameters such as the Chézy- or Manning's-value found during calibration of the model. In the numerical experiments with a two-dimensional model the three mentioned tide conditions were simulated and the tidal amplifications were determined by cross-spectral analysis. Two sets of experiments were performed, one with a time-step of 1.25 min. and the other with a time-step of 2.5 min.

As in numerical models, the time-step influences the propagation speed and amplitude of the tide, the two sets of experiments deter mined the influence of the resolution in time upon the results. The results of the analysis are summarized in fig. 6. The arrows in the graph show the effect of the reduction of the time-step. Increased resolution brings the amplification of tide in the model within the confidence band of the observations of the average tide, but this is not the case for the simulations of the springtide and the neaptide.

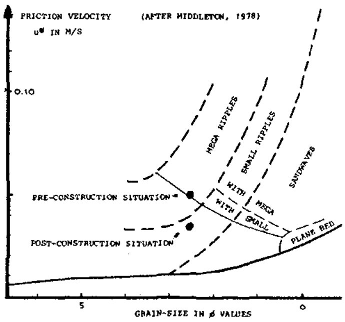


Fig. 7 Bedforms during the pre-construction and the post-construction period.

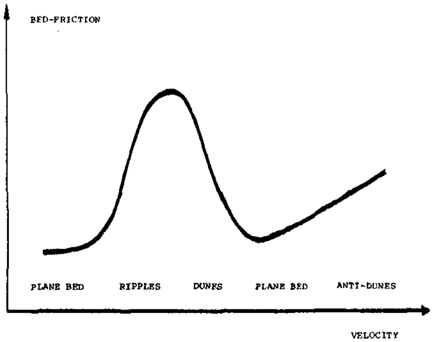


Fig. 8 Bedforms and their impact on bed friction.

From the experiments with the two-dimensional model and similar ex- periments with the one-dimensional model, it was concluded that the magnitude of the tidal flow reduction due to the barrier had to be taken into account in determining the bottomstress parameter. The impact of the structure as a whole on the hydraulic system was con siderable as a decrease of the tidal currents at least to 70% of the original value was predicted; thus not only needs the bottomstress parameter to be adjusted for neap- and springtide, but also for the long term predictions.

From literature for stationary systems, it was evident that the bed forms for fine sands like in the Eastern Scheldt (D50 is 200 mu) would vary with the flow speed according to the following ranges:

- flat bed 0,00 to 0,40 m/s
- bed with small ripples 0,40 to 0,70 m/s
- bed with mega-ripples or dunes 0,70 to 3,00 m/s

The friction is deemed to vary accordingly and a literature study indicated that the bedform with the highest bottomfriction is centered around the transition from mega-ripples to small ripples.

If the Eastern Scheldt would be a stationary system or a system with a very short response time, the bedforms before the construction should be a transition from mega-ripples to small ripples (fig. 7). Side looking sonar surveys showed indeed small ripples on top of mega-ripples as the dominant bedform in the non-stationary Eastern Scheldt.

As this bedform has the highest bedfriction (fig. 8), lower frictions could be expected when the construction proceeded. The tidal velocities during construction would drop at least to 70% of their original value, leading to a predominant bedform with small ripples and thus a smaller bedfriction.

Two different approaches were used to predict the modification of the bottomstress parameter. In the first approach, the Chézy-coëfficient in the numerical model was adjusted for neaptide and for springtide and a relation was established between the Chézy-coëfficient and the tidal range. The next step was to extrapolate the available data on the neaptide/springtide cycle to the future situation after the construction of the stormsurge barrier. We assumed a linear relation between the tides and the change in bedfriction and so an extrapolation was made for the future situation with lower tidal amplitudes, lower velocities and thus a lower bedfriction. A 12% higher Chézy-value (12% lower bedfriction factor) based on this analysis was expected.

For the second approach to predict the modification of the bottom-stress parameter, we used the results of experiments in a sand flume of the Delft Hydraulics Laboratory. The Netherlands Rijkswaterstaat had commissioned the Laboratory to study the interaction between sand and flowing water. The studies resulted in a relation between velocity and bedfriction for stationary systems at different grain sizes. The results (Van Rijn 1982) are depicted on a prototype scale in fig. 9.

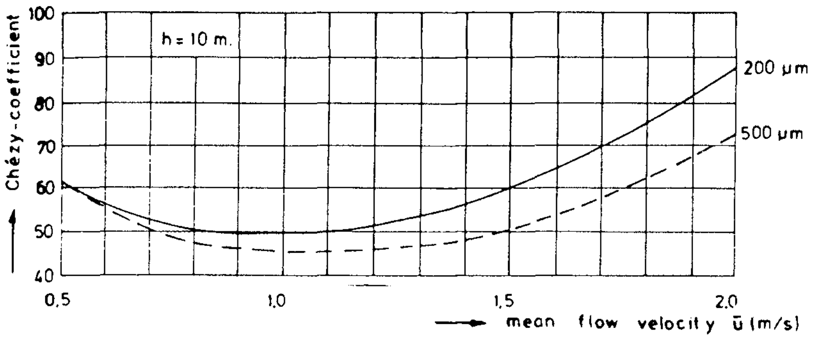


Fig. 9 Relation between the velocity and the Chézy-value in a flume at constant velocity for two grainsizes.

As fine and loose packed sands are present in the Eastern Scheldt, we assumed the bed-response time of this estuary to be short and certainly shorter than the construction time of the barrier. The results of the flume investigation indicated that the velocities which were present before the construction would generate mega-dunes with small ripples, and these were indeed present. As from numerical model studies, the tidal changes after construction were as a first estimate known, we could derive from fig. 9 that the Chézy-values would increase by 10 to 12%.

As both approaches indicated about the same increase, we estimated that a 10 to 12% higher Chézy-value was to be expected after the construction of the stormsurge barrier. This modification was then used for the post-construction predictions. After the barrier was constructed, a comparison was made again between observed tidal heights and currents and those obtained from the one- and two-dimensional models.

The agreement was excellent and this confirmed that the Chézy-value had indeed increased by 12% because of the construction of the bar rier. We found it somewhat remarkable to achieve such a good esti mate, because predicting changes in morphology is still more an art than a science.

Effect of dam construction on bottomstress parameters

The two dams near the inland extremities of the estuary were con structed to form two lakes (Fig. 1). These two lakes were connected by a ship channel. The dams were not constructed at about the same time, but the tidal openings in the dams were closed in sequence.

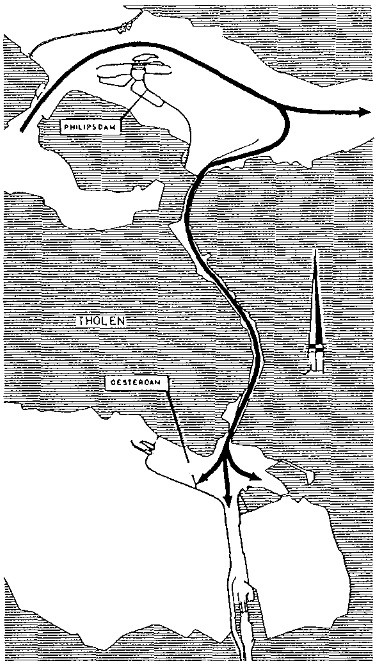


Fig.10 Flooding of the (southern) lake via the adjoining ship-channel.

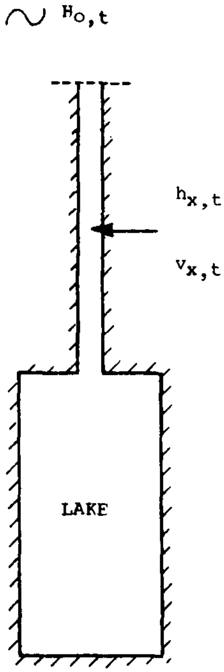


Fig.11 Schematic representation of the southern lake and the adjoining channel.

First the opening in the southern dam was closed and about a half year later the remaining opening in the northern dam was closed. Before the dam construction and also before the openings in the dams were closed, the tidal amplitudes and phases were about the same at the northern and southern end of the channel. As the surface area of the channel is fairly small, the tide generated only weak currents in the channel. During flood, water flowed southward in the northern part of the channel and northward in the southern part. Near the middle currents were very weak and variable (slack). This rather unusual situation precluded estimation of the bottomstress parameter with adjusted numerical models.

It was to be expected that after closure of the southern dam, the tidal flow in the channel would change very significantly. The area behind the southern dam would then receive its ebb and flood waters through the channel (Fig. 10). To predict the currents in the channel and the tidal heights in the area behind the southern dam for the condition with one dam closed, a series of model experiments were made. In the simulations the same bottomstress parameter as in other tidal channels with similar bottom material and currents was used, but shortly after the closure of the southern dam, it appeared that the measured currents were about 20% larger than predicted. Apparently, the bedfriction in the channel was reduced significantly. These high currents introduced erosion at several locations and required the installation of more revetments and bottom protection devices then originally expected. The high currents impeded shipping also.

After the closure, the tidal system consisted of a basin connected by a narrow channel to the tidal waters at the northern end of the channel (Fig. 11). In the channel, the velocities would reach their maximum value about 10 minutes after high water or low water slack and the maximum velocity remained constant until 10 minutes before the next change of tide.

Further analysis indicated that the tidal flows (maximum velocities) and the bedform were in a weak unstable equilibrium. If the maximum velocities increase temporarily because of a passing storm, then the bottom roughness could be reduced slightly by a feed back system as depicted in fig. 12 and in following tidal cycles higher velocities could occur. If the relation between bedform (flow resistance) and maximum velocities was taken into account in the analysis, it appeared that the velocities would increase gradually untill the velocities would exceed 1,65 m/s.

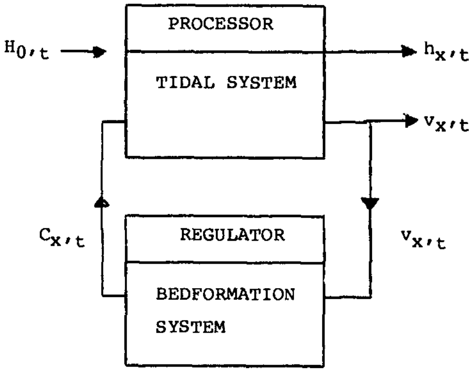


Fig. 12 The ship channel depicted as a control system

If then an increase would occur by a storm, the bottom roughness might be reduced significantly and the velocities would become very high. However, a stable equilibrium would finally be attained with maximum velocities of 2.0 m/s. From measurements in the channel just before the closure of the northern dam, it appeared that the maximum velocities were 1.60 m/s. This just below the critical transition.

Fortunately, the very high velocities of 2,0 m/s were not observed. It is not clear if the gradual increase had not reached the critical transition of about 1,65 m/s or that the relations used in the analysis where not valid. For example the analysis used a relation between velocity and bottomstress obtained from data which show considerable deviations from the mean. Also the sediment of the channel

contained some clay, thus the bottom material was not exactly the same as used in the analysis. Furthermore, the installation of revetments and bottom protection, which all have rough surfaces,might have increased the flow resistance locally.
A significant change in an estuary due to a temporarily unstable flow/bedform equilibrium can not often be observed. However, it is expected that such temporarily unstable bedform conditions are occurring quite often in estuaries. The instabilities are, however, mostly not obvious as the changes in the tidal system occur gradu ally. The "unstable" system than adapts itself by increased sedimentation or erosion till a new equilibrium is reached. The occurrance of such events may by the way be one reason for the deviations be tween observed and computed water levels and currents of a well adjusted model.

Conclusions

In modeling studies, the bottom stress parameter may not be taken as a constant for making predictions. This is particularly true when large changes are being made in the water bodies that are modeled.

References

Leendertse, J.J., "Verification of a model of the Eastern Scheldt"; The Randcorporation; R-3108-NETH; april 1984.

Leendertse, J.J., "A summary of experiments with a model of the Eastern Scheldt"; The Randcorporation;R-3611-NETH; juni 1988.

Van Rhijn, L.C., "The Prediction of Bedforms, Alluvial Roughness and Sediment Transport"; The Delft Hydraulics Laboratory; S 487; oktober 1982.