CHAPTER 223

Hydraulic Aspects of the construction of the Eastern Scheldt Storm Surge Barrier

Jan Konter[1] and Leo Klatter[2]

1. Abstract

The paper gives an overview of the results of the evaluation studies of the hydraulic aspects of the construction of the Eastern Scheldt Storm Surge Barrier. Subjects discussed are: methods used, design filosophy, results of flow modelling, stability of rubble stone structures, local scour and morphology.

2. Introduction

The Eastern Scheldt Storm-Surge-Barrier has been built across the three main tidal channels in the mouth of the Eastern Scheldt, from North to South respectively Hammen, Schaar and Roompot (see figure 1).

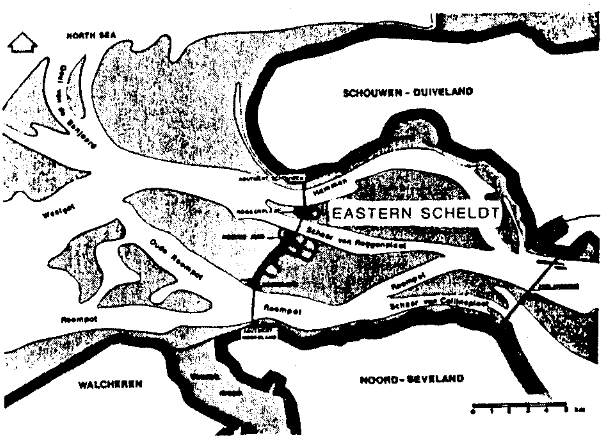
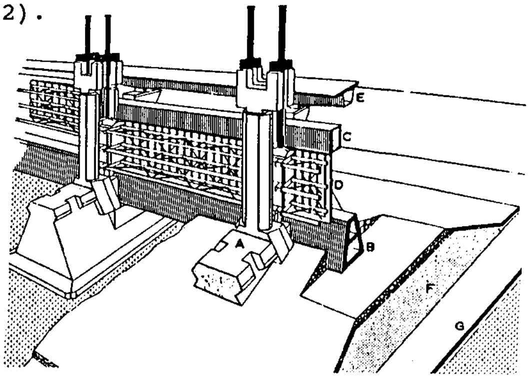


Figure 1: Location of the Storm-Surge-Barrier in the mouth of the Eastern Scheldt

[1,2] Rijkswaterstaat, Construction Division, Hydraulic Branch, P.O. Box 20.000, 3502 LA Utrecht

The three barrier sections are interconnected by dams, that have been constructed upon the shallow tidal flats between the main channels. The construction of the barrier took place in the original channels, without a building pit. This construction method was chosen to minimize the effect of the construction activities on the tidal movements. To enable such a construction method, prefabricated elements were used when and where possible. The original seabed served as a foundation. After soil improvement and compaction the sand-bed was covered with large prefabricated mattresses 41 m wide and 200 m long. Upon the filter mattresses the piers were placed (see figure 2).



A pier
B sill beam
C upper beam
D gate
E girder bridge
F sill
G filtermat

Figure 2: Elements of the Eastern Scheldt Barrier

The piers were packed by a rubble sill, that was built up in layers. A concrete sill beam and upper beam frame the actual flow opening, which can be closed by a gate. This gate is operated by hydraulic cylinders which were placed on top of the piers. The entire structure was assembled under open sea conditions. The construction activities took place simultaneously in the three channels.
The type of the structure, ass well as the construction method inflicted a number of hydraulic problems that had to be solved:
- flow problems
- stability of rubble stone and bottom protection
- local scour at the borders of the bottom protection
- morphology of the mouth of the Eastern Scheldt
- environmental aspects.

3. Set up of the Investigation

The construction of the Barrier often resulted in conflicting interests, e.g.

- the time schedule of the work favoured finishing one channel after another, but this was unacceptable for morphological reasons.
- Closing already installed gates, created favourable working conditions in the vicinity of the Barrier, but closing of some gates may create problems at locations were the gates were not closed, with the stability of stones and bottom protection. The complete closure of one channel was also not allowed for morphological and environmental reasons.

This indicates that numerous possible geometries of the Barrier under construction were possible, each with its own complex flow pattern. Therefore a flexible prediction system for the flow conditions was necessary. This could be accomplished by choosing a selected number of hydraulic parameters as "load" parameters and to relate the "strength" of the item considered (e.g. stability of stones) to the selected "load" parameter. The selected hydraulic parameters fulfill two important criteria:

1. It can be predicted with reasonable accuracy
2. It governs the process to the hydraulic problem. In other words there must be an unique relation between this hydraulic parameter and the strength.

In table 1 some examples are given of the flow parameters that were used as "governing hydraulic parameters" for the hydraulic problems encountered.

aspect	hydraulic parameter
environmental aspects	tidal difference Y
morphology at the mouth of the Eastern Scheldt	Δh_s
stability of rubble sill: - during construction - at final situation	 q/A Δh
hydrodynamic loads on the larg structural elements (piers, sill beams, upper beams, gates) during positioning	q/A
stability of bed protection	Δh
scour	Q

Table 1

To represent the flow conditions in the vicinity of the Barrier the following basic hydraulic parameters were selected

Q = discharge through a main channel (m^3/s)
Δh = head difference over the Barrier (m)

Δh_s = difference in water level between two main channels (m)
q/A = average velocity at the axis of the Barrier, defined as discharge per barrier section divided by the wet cross section (m^3/s)
Y = tidal difference in Yerseke (selected harbour in the Eastern Scheldt).

With this approach the flow parameters that had to be predicted (Q, Δh, Δh_s, q/A and Y), depended only on the global geometry of the Barrier under construction (expressed as μA).
Details of the flow pattern are not important for the behaviour of these parameters. In general these parameters can be predicted by a one dimensional flow model, eventually combined with a resistance model to get q/A (See figure 3).
The prediction of the wave characteristics can be done in the same way with a wave model. Basic flow parameters and wave characteristics are the boundary conditions for the structure and the input for eventually necessary three-dimensional scale models.

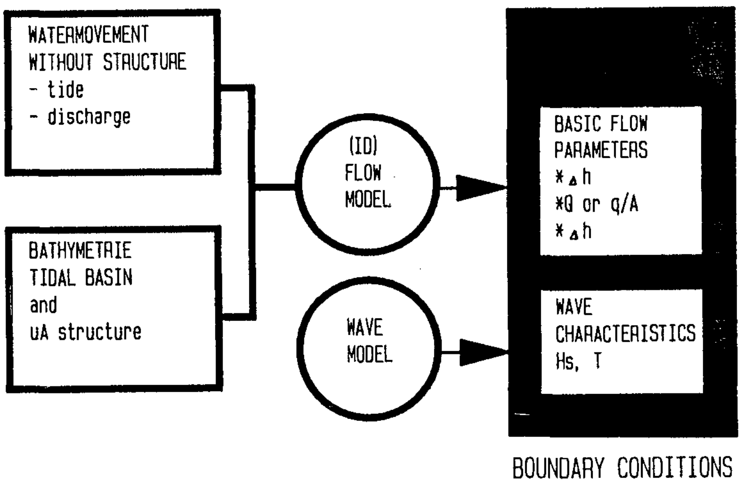


Figure 3: determination of boundary conditions

The next step is to find the "load-strength" relations, or the relation between the basic flow parameters and the design problems. It is strongly recommended to select a model that can express the strength in the same way as the loads (See figure 4) for example:

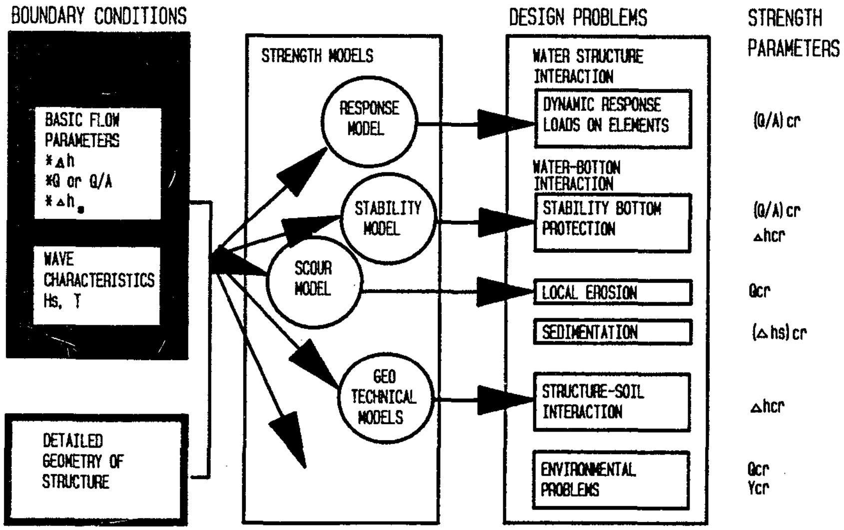


Figure 4: "load-strength" relations

Δh_{cr} and $(q/A)_{cr}$ are for example the critical values of Δh and Q/A at which the strength is not enough anymore (movement of stones, or to much erosion, etc.).
In this way insight can be obtained in the interaction between the different hydraulic aspects, and with this insight the optimal solution for the conflicting hydraulic problems can be found.
Beside this, expressing the loads and strength in the same parameter is necessary for probabilistic calculations.
It is noticed that as input for the strength models the detailed geometry of the structure is necessary.
Therefore a three-dimensional model is necessary, in which the geometry of the structure can be reproduced correctly. The most reliable way to study the "load-strength" relation is the use of physical scale models.
Also for the Eastern-Scheldt Barrier studies, a lot of attempts were made to find the "load-strength" relation by mathematical models. A reliable mathematical model for the complex three-dimensional interaction between structure-structure element bottom and water movement needs still a lot of effort and time before the same accuracy can be reached as a physical (scale) model. The mathematical model, gave more insight in the "black-box" of the physical scale model, but for most of the design purposes of the Barrier the results of the scale models were used.
A combination of relatively simple 1D or 2D-mathematical

models (finding the boundary conditions or "loads") and 3D scale models (finding the "load-strength" relations) proved to be the optimum tool.

4. Results

The approach described in section 2 proved to be very successful. The selected governing parameters made an integration of all items possible, and in most cases an optimal solution could be found between the conflicting interests.
A continuous evaluation of field experience during the construction period served as a check on the relations that were used. By means of the experience gained, the reliability of the predictions could be improved significantly.
After completion on the Barrier, it was decided to perform evaluation studies on the main hydraulic aspects of the construction (flow modelling, stability of rubble stone and bottom protection, local scour and morphology). In this evaluation study was looked at the accuracy of the used models, not from a scientific point of view, but as a design tool.

4.1 flow modelling (Klatter et al, 1986, 1989)

A comparison between (tidal) scale models an numerical models showed that overall tidal models can be safely substituted by numerical models, either one - or two dimensional (vertically averaged). The choice between one dimensional and two dimensional depends on the geometry of the estuary and type and extend of the results that are needed, e.g.
- a one dimensional model can predict Q, Δh, Δh_s and Y
- a two dimensional model can also predict the horizontal velocity distribution.

A detailed scale model is strictly needed if three-dimensional phenomena play a significant role. For large structures, such as the Eastern-Scheldt Barrier, the combination of a numerical model and detailed scale models will provide an optimal design tool.
The correct reproduction of the hydraulic characteristics of the Barrier was vitally important for the application of all models, both numerical and scale models. The hydraulic characteristics of the Barrier could be simulated correctly in a two-dimensional (depth-average) numerical model by using the discharge coefficients, determined from flume tests on representative sections of the structure.
For use in a one-dimensional numerical model, an overall

discharge coefficient had to be used. This discharge coefficient must be determined from either a scale model of the entire structure or through a two-dimensional numerical model combined with flume tests.

Verification of the models was of major importance, since the basic design parameters (Q, Δh) were determined with these models. The verification procedure was set up in such a way that each step in the forecast procedure was checked systematically. In this way not only the final results of the forecast system (predicted design parameters) were evaluated, but also the models as individual elements in the forecast system.
In this paper only a summary of the results of the verifications is presented for the following items:
- discharge in the main channel Q
- head difference over the Barrier Δh.

<u>Discharge in the main channel Q</u>

The measured discharges were compared with hindcast of the tidal motion during the respective day of measurements. The results of this comparison were used to determine the need of a re-calibration of the 1D-model, especially for the discharge coefficients of the barrier.

The experience gained by the verification was that, as the construction of the Barrier progressed, the discharge characteristics of the Barrier more and more dominated the tidal flow in the estuary. The influence of the overall discharge coefficient became more important than the schematization of the Eastern Scheldt itself.
Additionally a verification was performed of the predicted design values of the discharge at maximum (ebb/flood) flow Qmax. This was done by transforming the measured Qmax to the corresponding value at average tidal conditions. The results of the verifications, both for design values and hindcast of the discharge at maximum flow are summarized in table 2.
Table 2 gives the average and standard deviation of the difference between measurement and forecast (in %)

relative deviation	design values Q_{max}				hindcast Q_{max}			
	max. ebb		max. flood		max. ebb		max. flood	
[%]	mean	σ	mean	σ	mean	σ	mean	σ
Roompot	-1.5	6.2	4.1	4.8	1.5	5.4	3.1	4.7
Schaar	-5.3	10.2	2.5	11.3	-2.7	3.9	4.4	5.0
Hammen	2.6	9.6	3.8	5.6	-2.4	6.4	-2.4	3.3
Total	-1.6	8.9	3.5	7.5	-2.1	5.1	1.7	5.2
Overall	mean=0.9% σ = 8.5%				mean=-0.2% σ = 5.4%			

Table 2: Results of verification Q_{max} 1D-model IMPLIC

The conclusions from the results presented in Table 2 are:

- The model errors mostly had a random character.
- The errors in the hindcasts were less than in the design values.
- The accuracy of the initial calibration of 10% (maximum error) had also been achieved with the hindcast ($2\ \sigma \approx 10\%$).

In figure 5 the predicted design values of the mean velocity between two piers Q/A have been plotted against the measured values. In this figure low velocities corresponded to early construction stages and high velocities to later stages. The overall error in the Q/A forecast proved to be 12.4% (σ/μ), against 15% that was assessed before hand.

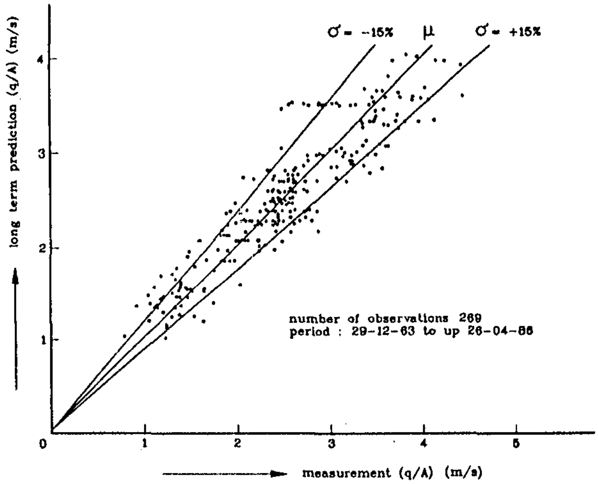


Figure 5: Results of the verification of the velocity forecasts at the location of the barrier.

Head difference across the Barrier Δh

The use of the parameter Δh depended strongly on the narrowing of the channel, and thus of the construction stage of the Barrier. Δh increased from lest than 0.2 m in early construction stages to over 1.0 m in te later stages (overage tide conditions).

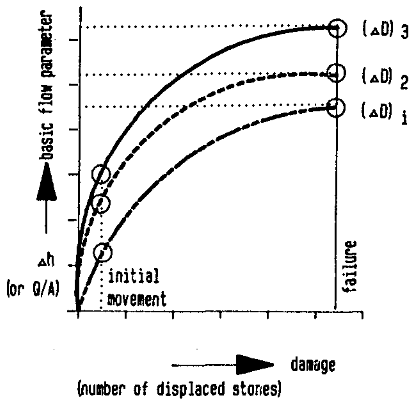
The accuracy, in which this parameter could be predicted turned out to be 10% to 20% (narrowing of the channel with more than 75%). Once experience was gained with a specific geometry of the barrier re-calibration diminished the errors in Δh computation with 5% to 10%.

4.2 Stability of rubble sill and bottom protection

Prediction of the stability of the rubble sill and several types of bottom protections at structures like the Storm-Surge-Barrier is only possible in a scale model based on Froudes law of similarity (see De Groot et al, 1984 and Konter et al, 1988).

The scale rules for a stability model are rather simple. The geometry of the structure and the dimensions of the bottom protection must be reproduced on the same linear length scale. Beside this the density and shape of the stones or blocks in the model must be the same as in nature. It can be shown that also stiffness and water-permeability can be reproduced correctly.
In general, it proved to be possible to build in all the relevant strength properties of stones and other types of bottom protections in a Froude model. With such a model the "load-strength" relation can be determined very well. However, a close interaction between modeler, designer and contractor during the whole test-program proved to be important.
The influences of changes in geometry, changes in the stone-size during construction, inaccuracies in the layer thickness due to the construction method must be investigated. Also the bed-roughness of the subsoil may have a great influence on the stability, especially in case of a filter layer directly laying on a (smooth) geotextile. All these aspects have to be incorporated in the test-program.

A result of a test series is given in figure 6.



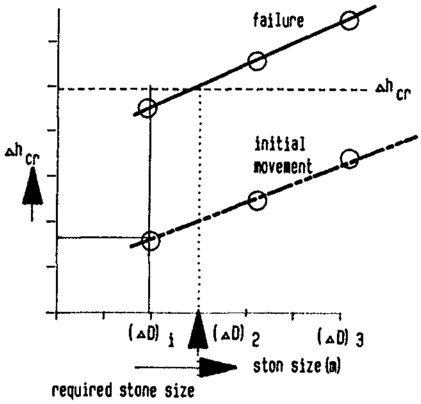


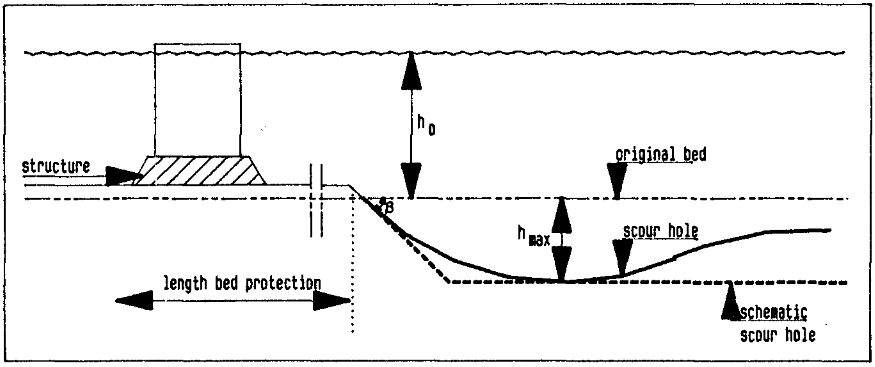
Figure 6a: Test result   Figure 6b: Design graphs

Figure 6a gives the relation between basic flow parameter and the number of displaced stones, for three different stone sizes. It is recommended to test the whole range of the flow parameter because in some cases, unexpected changes occurred in the vertical flow pattern and therefore also in the relation between flow parameter and damage. The damage is also a function of the exposure time. A representative exposure time for extreme conditions has to be defined. With this exposure time figure 6a gives for each tested stone-size the critical value of the flow parameter for initial movement and failure, which can be plotted in figure 6b. The require stone size can be found, comparing figure 6b with the boundary conditions.

For the Eastern-Scheldt Barrier tests had been done in scale models with length scales varying between N_L=80 and N_L=13.
Also a test in nature with coloured stones placed on the bottom protection has been carried out. The results of these tests, were in agreement with each other, if taken into account all the aspects (different exposure time, stone size diameter, geometry).

<u>4.3. Local scour</u> (Konter et al, 1986)

A method has been developed to predict the scour development in time, during the several construction stages of the Barrier. This method is based on a systematic investigation, which has resulted in the following empirical relations (see figure 7).



$$t_1 = \frac{330.\ \Delta^{1.7}\ .h_0^{\,2}}{(\alpha U-U_{cr})^{4.3}} \quad (1) \quad \text{and} \quad \frac{h_{max}}{ho} = \frac{t}{t_1}^{P} \quad (2)$$

Figure 7: Empirical relations for local scour

in which:

Δ	=	relative density of the bed material under water	(-)
t	=	time	(hours)
t_1	=	time in which h_{max} = ho	(hours)
U	=	current velocity (= Q/A_{tota} or q/A)	m/s
U_{cr}	=	critical velocity for initiation of bottom material	m/s
α	=	geometry parameter, depending on the geometry of the structure (construction stage)	
p	=	coefficient (in two dimensional flow conditions p=0.4) in three dimensional flow conditions p = varying between 0.2 and 0.6 depending on the water-depth.	

The time scale of the scouring phenomenon can be deduced from relation (2).

$$n_t = n_1^{2} \cdot n_\Delta^{1.7} \cdot n_{(\alpha u - ucr)}^{-4.3}$$

The values of α and p are the same in model and nature. For a particular construction stage $h_{max}(t)$ can be measured in a scale model, in which the geometry is represented on length scale. The values of α and p can be determined with this model tests and the relations mentioned above.
In nature the values of α, U, U_{cr} and Δ are known, so the time scale is known, and the development in time can be determined. The influence of unsteady flow and upstream sand transport can be introduced (see Konter et al, 1986).

Relation (2) indicates that the erosion capacity depends mainly on the scour rate parameter αU. It proved to be important to investigate the value of αU for each specific construction stage

Figure 8 gives a direct insight in the construction stages with maximum erosion. The maximum scour rate occurs downstream the part of the Barrier at which the sill beams have not yet been placed. Downstream the already placed sill beams αU has a lower value, which can be seen in figure 8, when placing the sill beams in one channel is completed. The translation of αU to $h_{max}(t)$ can be made using the relations mentioned above.
It has been proved by the scour development in nature (see Konter et al, 1986) that there is a reasonable similarity between model and nature for construction stages with αU values greater than 3.0. For situations with αU-values lower than 3.0 the scour development is

strongly depending on the (often) uncertain amounts of cohesive parts in the bottom material and the upstream sand transport.In such situations the prediction method can only give an upper limit of the scour development in time 0.3 m in a month).
The model tests can also give insight in the steepness of the upstream slopes for a specific geometry (construction stage).

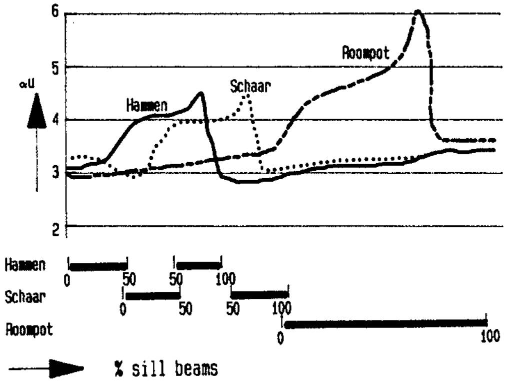


Figure 8: The values of αU (flood) during placing of the the sill beams

It showed that vortices with vertical axes cause very steep slopes (in model) and therefore relatively dangerous for the geo-technical stability of the bottom protection. These dangerous geometries configuration with (partly closed gates in a channel) were avoided and therefore no evaluation in nature was possible.

The method mentioned can also be applied for situations without a bottom protection, and gives a very accurate prediction of the time development of local scour (high values of αU).

4.4 Morphology (Bliek et al, 1986)

During the construction of the Barrier, the three main channels were unequally constricted. This might cause water-level differences between the main channels, with increasing flow velocities and therefore unacceptable developments in the morphology. Even short cut channels could be initated or deepened. One of the dangers of short cut channels is the progressive erosion that might occur.

- the initial increase of flow velocities could result in erosion on the shoal
- the deepening of the shoal due to erosion could reduce its flow resistance and cause an extra increase in velocities, with an increase erosion rate and so on

- finally, there may be a significant change in the main channel system in the mouth of the estuary, with its influence on the design parameters (Q and Δh) of the channels
- change in the design parameters have its influence on the other hydraulic aspects (stability bottom protection, scour).

Short cut channels cannot be compared with main tidal channels where, in general, an increase in flow velocities, will cause a widening of the profile and a reduction of the flow until a new equilibrium is reached. The approach to study the effects of short cut channels is presented in fig. 9.

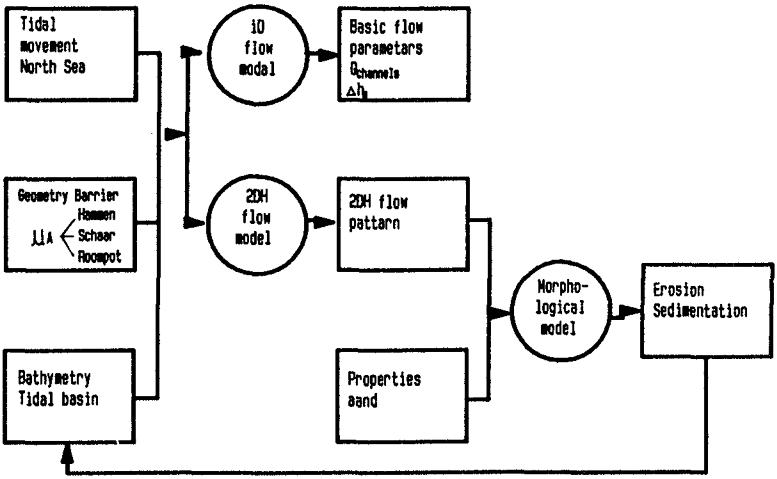


Figure 9: Set up morphological investigation

- investigation of the change of the governing load parameters Δh_s for the different geometries of the Barrier by means of a 1D-model, from which the critical construction stages can be derived
- calculation of the flow pattern for a selected number of critical construction stages by a 2DH-model
- quantifying the erosion under extreme conditions and what's most important the consequences of an extreme erosion on the basic flow parameters (that means other hydraulic aspects).

This approach proved to be very successful, also because the used mathematical models appeared to be applicable and reliable.

5. Conclusions

* For large hydraulic structures a combination of scale models and numerical models will provide optimal results, in general:
  - 1D or 2DH numerical models to predict the boundary conditions
  - 3D scale models to find the "load-strength"relations.
* To ensure optimal use of hydraulic research results, a careful selection of "governing" hydraulic parameters is very important.
  Both the "loads" and the "strength" have to be expressed in these parameters.
* A scale model based on Froudes law on similarity can solve almost all hydraulic problems at hydraulic structures. In general a correct reproduction of the flow pattern is more important than a correct reproduction of all the stability parameters.

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