CHAPTER 221

CROSS-SECTIONAL STABILITY OF ESTUARY CHANNELS IN THE NETHERLANDS

BY
F. Gerritsen[1], H. de Jong[2], A. Langerak[3]

ABSTRACT

In this paper, stability characteristics of tidal channels of the Western Scheldt and of the Wadden Sea are compared.
The Western Scheldt is a major estuary in the southern part of the country and is the only remaining open sea-arm in that area after construction of the Delta Project. The Wadden Sea is situated in the northern part of the country and the inlets form the connection between the North Sea and the Wadden Sea.
Stability parameters used for the comparison are the maximum discharge, Q_{max}, the Flood Volume FV (of Tidal Prism) and the mean tidal velocty, .
It appeares that linear trends can be established between the cross-section and the various stability parameters, for each of the two systems, but that the regressionrelationship is not the same.

Attempts have been made to develop a universal relationship by introducing a dimensionless stability parameter, in which the dominating hydraulic characteristics are combined. The results are interesting but further research is required to refine this method. The established morphological relationships can be used to predict the changes in channel equilibrium when external changes in the estuary system are introduced. For the Western Scheldt the one-dimensional numerical tidal model IMPLIC will be combined with distinct morphological relationships for the estuary to be used as a predictive tool for the new equilibrium situation created by dredging works.

1 Professort of Ocean Engineering, University of Hawaïï, Honolulu
2 Reseacher, Rijkswaterstaat, Tidal Waters Division, Middelburg
3 Project Engineer, Rijkswaterstaat, Tidal Waters Division, Middelburg, The Netherlands

1.Introduction

During recent years the interest in morphological behavior of estuarine channels has significantly increased. There is a distinct need to predict the morphogical changes in a system after man-made works have been carried out. Among the latter are the dredging of navigation channels and the construction of guide dams to maintain channel depth. Another important reason for the rising interest is the prediction of the effect of sea level rise on the estuarine system on a longer time scale.

Examples of man-made interventions in The Netherlands are the development of the New Waterway leading to the Port of Rotterdam, the dreding operations in the Western Scheldt and the construction of coastal protection works in and near the Texel Inlet (see Figure 1).

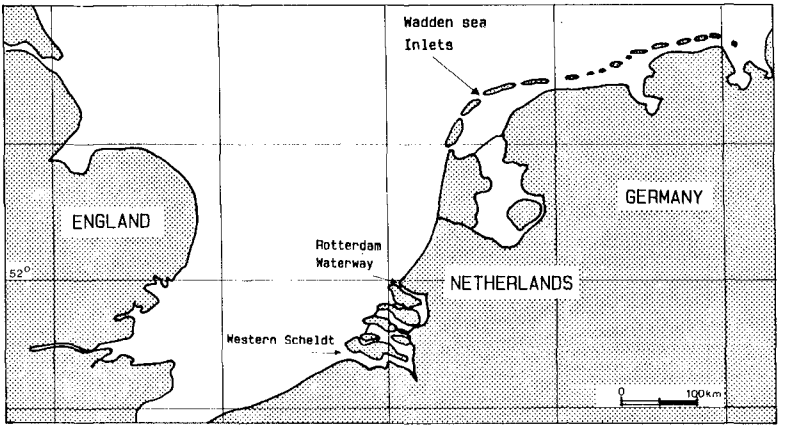


Figure 1. Inlets on the Dutch coast.

The study of morphological behaviour of hydraulic systems such as estuary channels and tidal inlets can follow two different lines of approach. In the first the governing hydraulic equations are combined with equations for the movement of sediment and for the conservation of the mass of sediment. Up to present this avenue has not led to satisfactory results mainly because of uncertainties in the transport equation for the sediments. The second approach is to combine hydraulic calculations with appropriate morphological relationships between channel dimensions and tidal flow.

Detailed studies of the Western Scheldt as a whole and of the Wadden inlet systems (including the channels in the flood tidal delta) have shown that a number of morphological relationships are well defined and consistent so that they can be used as predictive tools to predict future equilibrium. A combination of these relationship (one of them) with a tidal numerical model is seen to be of great significance for future morphological studies.

The objective of this study is to compare cross-sectional stability criteria for the Western Scheldt Estuary and the Wadden Inlets. As stability parameters we will use the

maximum discharge (Qmax),the flood volume (FV), the stability shearstress s and the mean tidal velocity, v. In addition a dimensionless stability parameter will be introduced to account for the influence of different hydraulic characteristics on the stability relationship. Finally the one-dimensional numerical model IMPLIC will be used in combination with distinct stability relationship as a predictive tool for morphological development.

2.Regression Analysis

In this section regression relationships for the selected parameters will be discussed for both the Western Scheldt and the Wadden Inlets and conclusions will be drawn regarding the usefulness of these parameters as stability indicators.

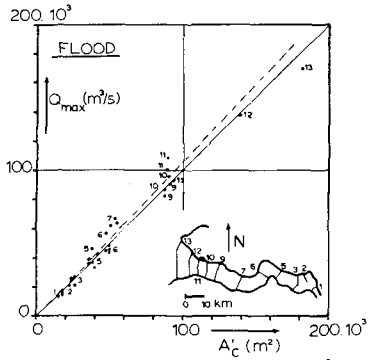
Western Scheldt

In previous studies (Gerritsen and De Jong, 1984,1985) it has been suggested that the maximum discharge Q_{max} may well be related to the cross-sectional profile A^1_c, which is the cross-section of the channel below the tide level, at which the maximum discharge occurs.
In this paper characteristic tidal parameters are related to the mean tide. Although in some cases the mean springtide condition may be a better criterion for stability analysis (because bedforming conditions are likely to be associated with springtide) for our study area this difference appears not to be significant. The relevant stability relationships for the Western Scheldt are shown in Figures 2 to 5 (incl.).

The Western Scheldt is a well mixed estuary; the contributing river Scheldt originates in the southern part of Belgium with a mean discharge of 105 m^3/s,
which is small compared to the maximum tidal discharges in various locations along the estuary itself. Although the river discharge is small, it creates a density gradient along the estuary and has a minor effect on the vertical velocity distribution.
However, in the stability analysis no significant influence has been detected from the river discharge or density gradient.

Figures 2 to 4 show the various transects across the Western Scheldt, numbered 1 through 13 (location 13 at the mouth). The dots in the graphs numbered 1-13, correspond with the transects shown in the Figures.
Figure 2 shows the regression between Q_{max} and A_c^1 for flood flow. The dotted line represents the computed regression relationship. For the calculation of this line the cross-sections 12 and 13, which show a somewhat deviating behaviour, have been excluded. This deviating behaviour is also visible in other graphs (see Figures 3 and 4) and can be explained by the effect of wave action on the stability relationships. The presence of waves affects the shearstress near the bottom and thereby affects the stability relationship.

The remaining cross-sections 1 through 11 are grouped around the mean regression line, but some distinct deviations are also noticeable, such as for cross-sections 7 and 11. In these locations the estuary is narrower than would be expected from the overall trend due to bank stabilization works and the profiles are consequently somewhat deeper and



.Figure 2. Regression between Q_{max} and A_c^1 for cross-sections in the Western Scheldt (flood conditions, mean tide).

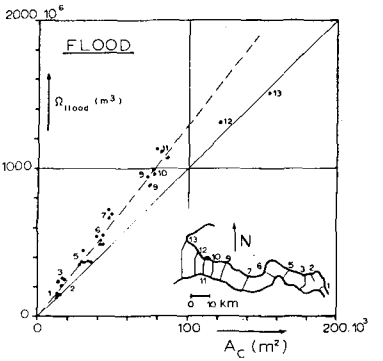


Figure 3. Regression between Ω and Ac for cross-sections in the Western Scheldt (fllod conditions, mean tide).

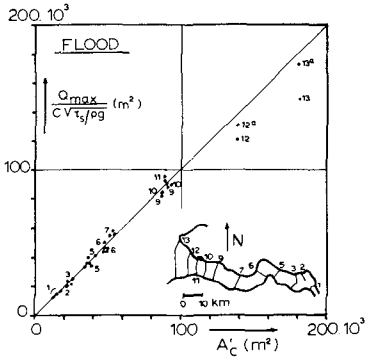


Figure 4. Regression between $Q_{max}/C\sqrt{\tau_s/\rho g}$ and A_c^1 for cross-sections inthe Western Scheldt and constant value of τ_s related to mean tide (flood conditions).

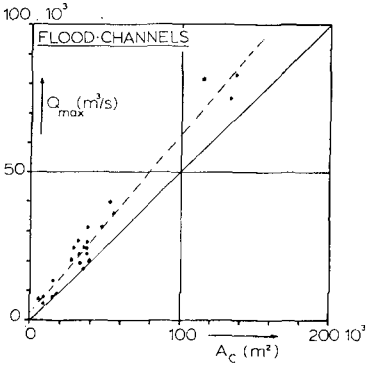


Figure 5. Regression between Q_{max} and A_c for flood channels in the Western Scheldt (mean tide).

the velocities somewhat higher than in the other profiles, for which the width is not controlled.

The relationship between Flood Volume FV (Tidel Prisma) and cross-sectional area Ac (taken below M.S.L.) is shown in Figure 3.

Cross-sections 12 and 13 again deviate from the regression curve (because of wave action), but the profiles 7 and 11 now fall into place. The correlation coefficient is slightly higher than for the relationship between Q_{max} and A_c^1.

The third regression relationship of interest is that between $Q_{max}/C\sqrt{\tau_s/\rho g}$ and A_c^1, in which τ_s represents the stability shear converted to mean tide conditions) and C is Chézy coefficient. The mean fluid density is ρ and the acceleration of gravity is denoted by g.

In this analysis the stability shear stress τ_s selected in such way that the regression line makes an angle of 45 with both axis. The two transcets 12 and 13 again show a deviating behaviour.

Corrections for the influence of waves can be made by considering the effect of waves on the sediment transport by currents. For this correction use is made of the Bijker

formulation (Bijker, 1967) and the method for this is discussed in Gerritsen and De Jong, 1984. This correction changes the points 12 and 13 to 12a and 13a, which is a significant improvement in the overall relationship.

An estuary like the Western Scheldt is characterized by the existence of flood and ebb channels, in which the flood respectively the ebb dominates.
Figure 5 shows the relationship between Q_{max} and A_c for the typical flood channels. It appears that a high correlation occurs, but it is also evident that the slope of the line is somewhat steeper than in the similar relationship of Figure 2.
A steeper line indicates that maximum velocities (average over profile) are higher for the channels than for the entire cross-section between banks, which is to be expected.

Wadden Inlets

The Wadden Inlets connect the North Sea with a shallow inland sea, called the Wadden Sea (fig. 6). In the early part of this century the Wadden Sea was in open connection with a large but shallow sea, the Zuiderzee, between Noord-Holland and Friesland and the other eastern provinces. The constuction of the Zuiderzee enclosing dam, which was accomplished between 1928 and 1932, affected a significant change in the tidal characteristics and flow conditions of the remaining Wadden Sea. The body of water south of the dam is now called IJssel Lake. A small amount of fresh water is discharged from the lake into the Wadden Sea through sluices in the dam. The effect of this freshwater flow on the larger discharge rates in the Wadden Inlets is considered negligible.

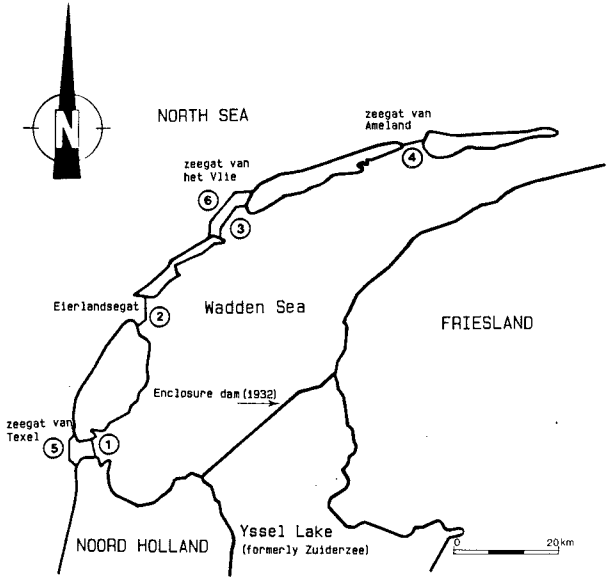


Figure 6. Dutch Wadden Sea (Western part) and Tidal Inlets.

One of the consequences of the closing has been a significant increase in Q_{max} in the Texel Inlet (cross-sections 1 and 5, Figure 6), which resulted in a strong morphological adjustment (first a reduction followed by an enlargement) of the channel cross-section. Although some parts of the Wadden Sea itself may not have reached a new equilibrium it is found that the Wadden Inlets have reached a condition with a new equilibrium.

In the following some of the prevalent stability relationships will be discussed.
Figure 7 shows the relationship (regression) for all the inlet cross-sections shown in Figure 6. Again we will notice that cross-sections 5 and 6, which are exposed to the open North Sea and are affected by wave action, show a deviating behaviour. The regression line for sections 1-4 shows a high correlation
($r = 0.960$). It is to be noted that the cross-sections 1 through 4 have widely different cross-sections and depths. The Q_{max}/A_c^1 value (which represents

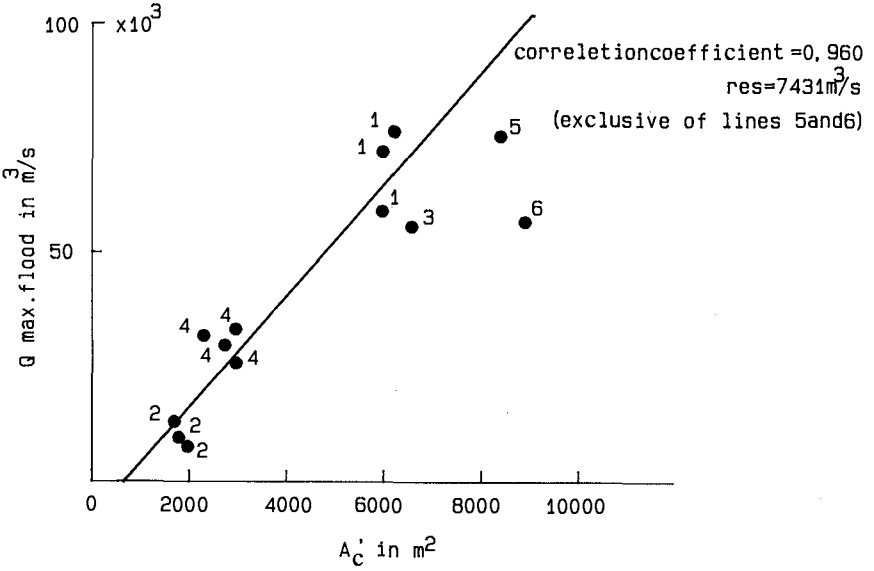


Figure 7. Regression between Q_{max} and A_c^1 for Wadden Inlets (flood conditions, mean tide).

the average maximum velocity) is not the same for all profiles but increases with the size of cross-section. The regression line consequently does not pass through zero, which is an important characteristic of this relationship.
Figure 8 shows the regression between the flood volume (FV) and the area A_c. The solid line represents the calculated regression line for all sections, exclusive 5 and 6 (which are affected by wave action), whereas the dashed line represents the corresponding line for the Western Scheldt cross-sections (excluding profiles 12 and 13). It appears that the values for the Eyerlandse Gat, E, (section 2) somewhat deviate from the line, but that the other inlets fit the general relationship well.
It is to be noted that the Eyerlandse Gat is a relatively shallow part of the Wadden Sea

in which the depth of the major channels is much less than that of the other parts. The above suggests that a smaller depth corresponds to a lower maximum velocity, which would plot the points for cross-section E (or 2) below the average regression line.

A comparison between the solid and the dotted line shows that the trends for the two systems, the Western Scheldt and the Wadden Sea, are somewhat different.
The suspected effect of velocity on the plottings in Figure 8 is proven by plotting the value of the tide average velocity against the hydraulic radius R (Figure 9). In the data points information for the Wadden Inlets as well as for the Western Scheldt is included. The trend is clear and convincing: the hydraulic radius (or depth) plays a significant role on the velocity , which translates into effects on Q_{max} and FV as well. The data points of the Eyerlandse Gat (E) now fit well in the overall relationship of Figure 9, as do the values for the Western Scheldt (W).

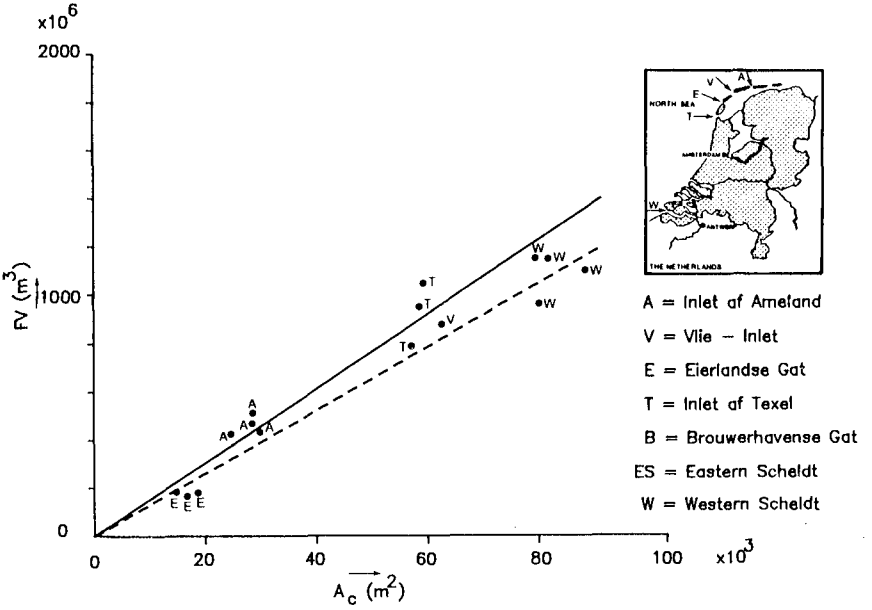


Figure 8. Regression between FV (Ω) and A_c for Wadden Inlets and compared with relationship for Western Scheldt.

It may be concluded that the difference in hydraulic radius (or depth) is one of the principal reasons why regression relationships show deviating trends.
Figure 9 presents important information to calculate and predict the expected behaviour. The relationship between A and Ω (FV) may be adjusted by the dependency on R (or h). Using the data of Figure 8 we may express that relationship between and R by:

$$\bar{V} = \alpha R^{\beta} \qquad (1)$$

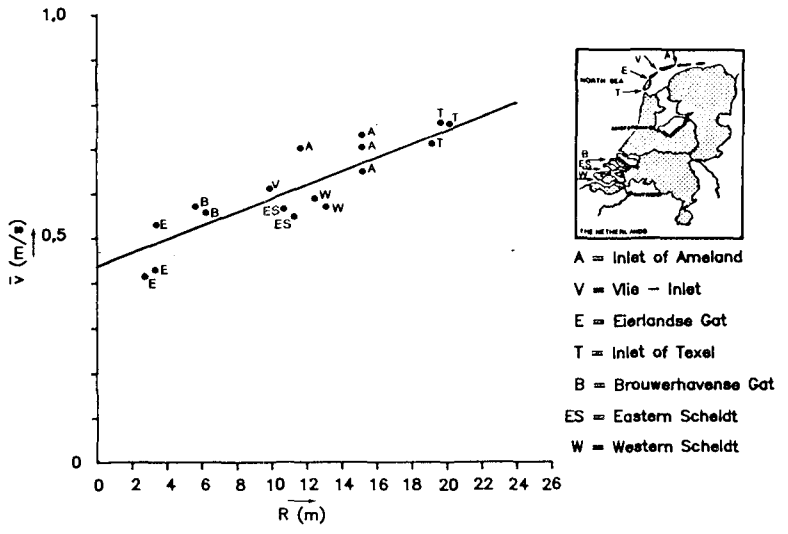


Figure 9. Relationship between v and R for Dutch inlets.

Figure 9 provides the data to calculate the values of α and β : $\alpha = 0.353$ and $\beta = 0.25$
From the relationship between v and Ω or (FV)

$$\bar{v} = \frac{2\Omega}{A_c T} = \alpha R^{\beta} \qquad A_c = \frac{2\Omega}{T\alpha R^{\beta}} \tag{2}$$

Substituting the experimental values of α and β, and taking a semi-diurnal tide, we have:

$$A_c = 1.269 \times 10^{-4} \frac{\Omega}{R^{0.25}} \tag{3}$$

This relation shows an influence of R on the dependency between A_c and Ω
In a relatively wide and shallow estuary the hydraulic radius R is almost equal to the mean depth h; equation (3) then develops into:

$$A_c = 1.269 \times 10^{-4} \frac{\Omega}{h^{0.25}} \tag{4a}$$

For relatively deep channels R is retained. Writing $R = \frac{A}{P}$ where p is the wetted perimeter, equation (3) develops into

$$A_c = (7.64 \times 10^{-4})\, p^{0.2}\, \Omega^{0.8} \tag{4b}$$

In shallow channels p ≈ b, so that

$$A_c = (7.64 \times 10^{-4})\, b^{0.2}\, \Omega^{0.8} \tag{4c}$$

which equation reminds us of the early O'Brien equation with power 0.85.

The equations 4a through 4c express the influence of the form of the cross-section (wide and shallow versus deep and narrow) on the relationship between A_c and Ω.
In the Western Scheldt overall depths in the various channels vary between 9 and 11 m, thus the effect of depth on the relationship between Ac and will be small.
Exceptions are Transects 7 and 11, where the mean depth is over 15 m and for which a small deviation from the overall trend can be expected.

3. Dimensionless stability parameter

A philosophical discussion on stability problems in tidal inlets and estuaries reveals that hydraulic and sedimentological characteristics play a role in the total stability equation (see Bruun and Gerritsen, 1959, Bruun, 1978).
The following parameters may be considered:

Hydraulic Characteristics
Mean tidal velocity, $\bar{v}$
Hydraulic radius, (or average depth) R
Bottom roughness, k
Chezy coefficient, C
Wave action, H_s
Density of water (sea and estuary), ρ

Sedimentological characteristics
Diameter bottom materiaal, D_{50} and D_{90}.
Density of sediment, ρ_s
Concentration of sediment, $\bar{c}$
Littoral drift, M

Unfortunately field data do usually not contain a significant range of the various parameters which allow the determination of the influence of these various parameters on the stability problem.
The inlets and estuary under consideration all have for instance a large $\frac{Q_{max}}{M}$ ratio, meaning that tidal flow by passing, if it occurs, is prevalent. The one exception may be the Eyerlandse Gat which has a smaller tidal prisms.
With these large tidal flows it is thus expected that the rate of littoral drift does not significantly affect the stability relationships. If water density differences are neglected and the effect of wave action is eliminated (by excluding the profiles exposed to strong wave action) the following parameters remain as essential to the problem:
Relationship between Q_{max} and gross rate littoral drift, M
Diameters of bottom material D_{50}, D_{90}

Chezy coefficient C
Relative density of sediment $\Delta = \frac{\rho_s - \rho}{\rho}$
Ripple effect on sediment (μ)
Depth of channel (h)

It is of interest to formulate a dimensionless parameter, in which the above characteristics are grouped together, either directly or indirectly.
One approach is to consider the similarity between the natural conditions and those in a hydraulic model with movable bed. The design of a movable bed model is based on the condition that the transport scale (the ratio in which sediments in the field and in the model are transported) must be invariant. Only then will a movable bed model give a correct representation of the field conditions to be simulated. In a tidal inlet or estuary channel stability is associated with the condition that

$$\frac{\partial q_s}{\partial s} = 0 \tag{5}$$

Only then a stable cross- section can be expected. This condition represents a self similarity condition comparable to the one for a moveable bed model.
In order to determine what type of relationship provides such (self) similarity a distinction is made between two conditions: one in which the bedload transport dominates and another one, in which the sediment transport in suspension provides the larger portion of the sediment transport. We will consider bed load predominance here. If bedload may be obtained from Bijker (1967) he finds that for the invariance of the transport scale the following condition must be met:

$$n_v = \left(\frac{n_D n_\Delta}{n_\mu}\right)^{1/2} n_C \tag{6}$$

in which scale relationships are identified by n and

$$\frac{V}{\left(\frac{\Delta D}{\mu}\right)^{1/2} C} = \text{Const.} \tag{7}$$

The velocity V in the above expression refers to the time averaged velocity v, as well as to the maximum velocity Vmax. The value of the constant will consequently differ for these two characteristic velocities.
In the present analysis we will use the value and the corresponding constant we identify with A_1:

$$\frac{\bar{V}}{\left(\frac{\Delta D}{\mu}\right)^{1/2} C} = A_1 \tag{8}$$

In the above expressions 6 - 8 , C represents the Chezy coefficient and μ the ripple coefficient, which expresses the ratio between the bottom shear stress acting on the grain and the total bottom shear stress in the channel where is calculated from

$$\mu = \left(\frac{C_{D90}}{C}\right)^{3/2} \tag{9}$$

in which C_{D90} represents the Chezy coefficient corresponding to the grain size D_{90}.

Using data from the Western Scheldt the values of A_1 have been calculated and are plotted against A_c in Figure 10. The average value of the calculated data points is $A_1 = 0.37$.

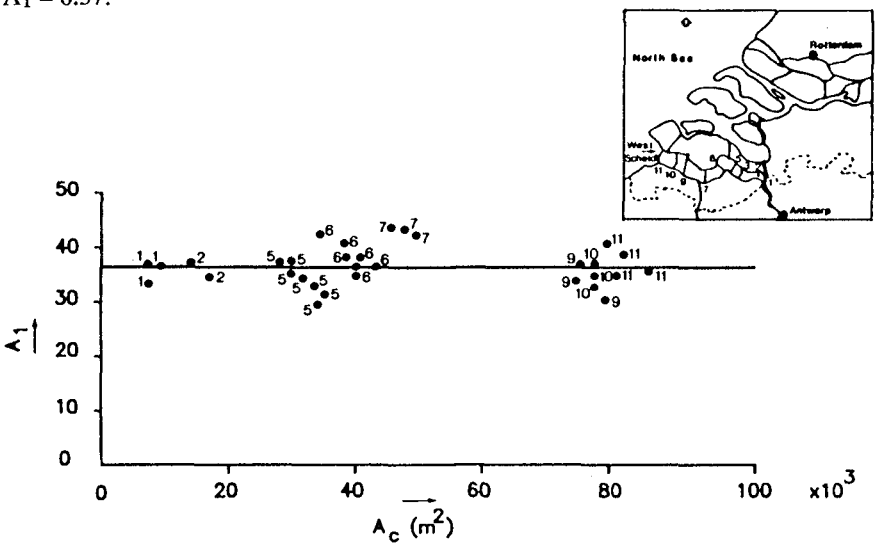


Figure 10. Dimensionless parameter A_1 versus cross-section A_c for Western Scheldt.

In a similar way values of A1 are calculated for the Wadden Inlets and for the channel system inside the Vlie Inlet. Values of A1 for the Wadden Inlets were respectively:
All inlets (incl. 5, 6) $A_1 = 0.43$
Channels $A_1 = 0.40$
It is concluded that with the present formulation the objective of finding a universal constant that fits all data is not met.
However, a certain amount of precaution is warranted. The determination of the values of A_1 includes the use of hydraulic parameters (μ and C) which have values, that may deviate from the calculated ones, because of lack of precise formulation for the values of these parameters.
It may also be true that the conditions that underlie the basis for A1 (predominant bedload transport) are not as they were assumed and that suspended transport plays a more dominant role in the process than assumed.
Further analysis will be required to clarify this uncertainty.

It is of interest to confront the condition expressed in equation (7) with the validity of the assumption that the stability shear stress may constitute a stability parameter.

Equation 7 may be converted to:

$$\frac{\mu \tau_s}{(\rho_s - \rho) g D_{50}} = \text{Const.} = A_2 \qquad (10)$$

It is concluded that a constant value of s is not in agreement with a constant value of A2 , but that the stability condition requires

$$\frac{\tau_s}{(\rho_s - \rho) g D_{50}/\mu} = \text{const.} \tag{11}$$

4.Computer Simulation

The use of morphological stability relationships in computer simulation of these processes is based on the use of an appropriate numerical model (for hydraulic calculations) and an additional morphologieal submodel to be incorporated in the numerical scheme.

In the Western Scheldt the numerical hydraulic model IMPLIC, which is a one-dimensional tidal model, provides an efficient basis for the calculations.

In order to find out whether or not the present schematization for the IMPLIC model is accurate enough to allow formulation of stability relationships, model data have been used to verify the possible use of stability relationships in the model. Figure 11 shows the present channel system of the Western Scheldt and Figure 12 the corresponding set of interconnected channels that form the IMPLIC model.

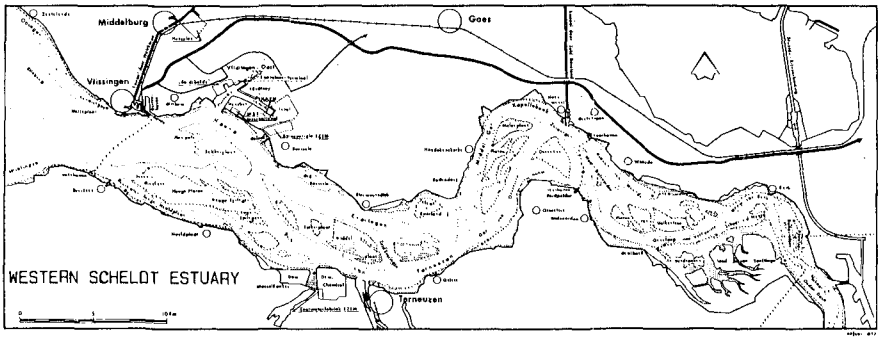


Figure 11. Western Scheldt Estuary.

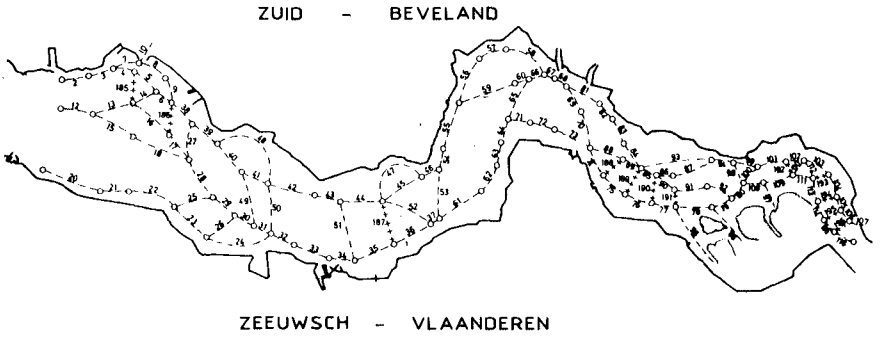


Figure 12. Schematization of Western Scheldt for IMPLIC model.

It appears that the schematization of the model is accurate enough to allow the establishment of morphological relationships from the model data.
That the present model has the capabilities to be used in conjunction with predescribed stability relationship to calculate stability conditions after technical changes have been made in the system.

The procedures of computation are in an iterative mode. After a change has been made in the system, (which is in equilibrium) tidal calculations are made with IMPLIC to determine the changes in discharge. In general the system will be out of equilibrium after the change is made and will turn back to a new equilibrium. An example is the deepening of a navigatonal channel by dredging, which has been the case in the Western Scheldt.

Suppose the increase in cross-section from a dredging operation equals ΔA.
Depending on the extent of the dredging operation tidal velocities in the system will change (usually decrease) after the dredging and the system will develop into a new equilibrium. In the computations cross-sections are adjusted gradually until a new equilibrium stage is obtained, in which the morphological parameter which is selected for the computations, corresponds with the adjusted cross-section.

Morphological adjustment usually develops in an exponential way as a function of time. This corresponds with the assumption

$$\frac{\partial A}{\partial t} = -\lambda \Delta A = -\lambda (A - A_o) \tag{12}$$

in which Ao represents the equilibrium cross-section and a time scale factor. If Ai is the initial cross-section immediately after dredging integration gives

$$\frac{A - A_o}{A_i - A_o} = e^{-\lambda t} \tag{13}$$

The coefficient determines the time scale of the process. An estimate for the value of can be obtaimed from the gradient of sediment transport that has been induced into the system.
The continuity equetion for sediment transport can be written in the form

$$\frac{\partial A}{\partial t} + \frac{\partial \bar{Q}_s}{\partial s} = 0 \tag{14}$$

In which Q_s is the mean rate of sediment transport through the cross-section over a tidal cycle.
Using equation 12 thus leads to:

$$\frac{\partial A}{\partial t} = -\frac{\partial \bar{Q}_s}{\partial s} = -\lambda (A - A_o) \tag{15}$$

$$\lambda = \frac{\partial \bar{Q}_s}{\partial s} / A - A_o \tag{16}$$

$$\lambda i = \left(\frac{\partial \bar{Q}_s}{\partial s}\right)_i / A_i - A_o \tag{17}$$

Where the index i denotes the initial condition after dredging.
The value $\partial \bar{Q}_s / \partial s$ can be calculated using an appropriate formulation for sediment transport from which λ can be calculated.

5. Conclusions and recommendations

1 Both for the Western Scheldt Estuary and for the Wadden Inlets morphological relationships have been established that provide a valuable tool for morphodynamic analysis.
2. Morphological relationships can be established for entire cross-sections, but also for separate flood or ebb channels, if the corresponding flood flow or ebb flow is taken as the relevant parameter.
3. The hydraulic radius or mean depth appears to be a significant scaling parameter in comparing large and small tidal inlets. The established relationship between v and R can be used to modify the relationship between Ac and , taking the effect of depth into account.
4. The introduction of a dimensionless parameter is intended to make morphological relationships independent of grain size, material density mean depth and channel roughness.
   A first approach is promising but needs further work.
5. Morphological relationships can be used in combination of a numerical tidal model. The model IMPLIC has been selected to be used for the Western Scheldt.

6. Selected References

1.Bruun, P. and F. Gerritsen (1960): 'Stability of Coastal Inlets'. Elsevier Scientific Publishing Co., Amsterdam, Oxford, New York.
2.Bruun, P. (1978). 'Stability of Tidal Inlets, Theory and Engineering'. Elsevier Scientifie Publishing Co., Amsterdam, Oxford, New York.
3.Bijker, E.W. (1976): 'Some Considerations About Scales for Coastel Models with Movable Bed'. Doctoral Dissertation, Delft Technological University.
4.De Jong, H. and F. Gerritsen (1984): 'Stability Parameters of the Western Scheldt Estuary'. I.C.C.E., 1984, Houston.
5.Gerritsen, F. and H. de Jong (1985):'Stabiliteit van doorstroomprofielen in het Waddengebied'. Rijkswaterstaat, The Netherlands, Nota WWKZ-84.V016.
6.Kreeke, J. v.d. and J.A.C. Haring (1979): 'Equilibrium Flow Areas in the Rhine-Meuse Delta'. Coastal Engineering, 3, 97-111. Elsevier Scientific Publishing Co., Amsterdam.