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A MODEL FOR PREDICTING DREDGING REQUIREMENT IN THE WESTERSCHELDE

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Abstract: A substantial annual dredging is required in the Westerschelde Estuary to maintain the shipping lane to the harbour of Antwerp. A key issue in considering a new enlargement of the navigation channel is the prediction of the required maintenance dredging as a function of the required depth of the navigation channel. Especially because the dredged sediments have to be disposed elsewhere in the estuary, this strongly influences both the morphology and the ecology of the estuary. This paper presents a new method for predicting the required maintenance dredging, based on the hybrid modelling approach of ESTMORF (Wang et al., 1998) and ASMITA (Stive et al., 1998). The model shows that not only the required channel depth but especially the associated surface area influences the amount of maintenance dredging. The model explains why a purely empirical method overestimates the dredging amount since the last enlargement of the navigation channel. First analysis and comparison with the field observations in the Westerschelde Estuary show that the model has the potential to become a predictive tool for dredging requirement, with a much better accuracy than the existing methods.

Key words: Westerschelde Estuary, Navigation, Dredging, Sedimentation

1. INTRODUCTION

1.1 BACKGROUND

The Westerschelde is the marine seaward part of the tide-dominated Schelde estuary which is located in the south western part of the Netherlands. The estuary provides natural habitats and access to the harbour of Antwerp, which is situated about 60 km landward from the mouth of the estuary. A substantial annual dredging, amounts to some 10 Mm^3 per year at present, is required to maintain the navigation channel.

Dredging activities in the Westerschelde for deepening and maintaining the navigation channel are concentrated on the so called sills, i.e. shallow areas at transition between channel bends (the channel crossings). The most up to date analysis of the historical dredging records is given by Kornman et al (2002). In the first years of the last century the total amount of dredging in the estuary is about 1 to 2 Mm^3 per year. In the 1960's this was already increased to about 4 Mm^3 at the sills and 0.5 Mm^3 in the other areas. The first significant enlargement (deepening and widening) of the navigation channel started in 1967 at the Sill of Bath and ended in 1978 at the Sill of Hansweert. The sills were deepened to a minimum depth of 14.5 m below NAP (Dutch ordnance level ≈ mean sea level) for the navigation channel. In the period 1978-1989 the maintenance dredging at the sills amounted to about 8 to 9 Mm^3 per year and in the other areas about 2.5 Mm^3 per year. In the period 1989-1997 this decreased at the sills to about 6.5 to 7 Mm^3 per year, whereas in the other areas it remained the same. From

July 1997 to July 1998 the second enlargement of the navigation channel was carried out, increasing the guarantied navigation depth to 16 m below NAP. In the period after this enlargement the maintenance dredging at the sills appears to remain at the level of about 6.5 to 7 Mm^3 per year, whereas in the other areas it increases to 4 Mm^3 per year.

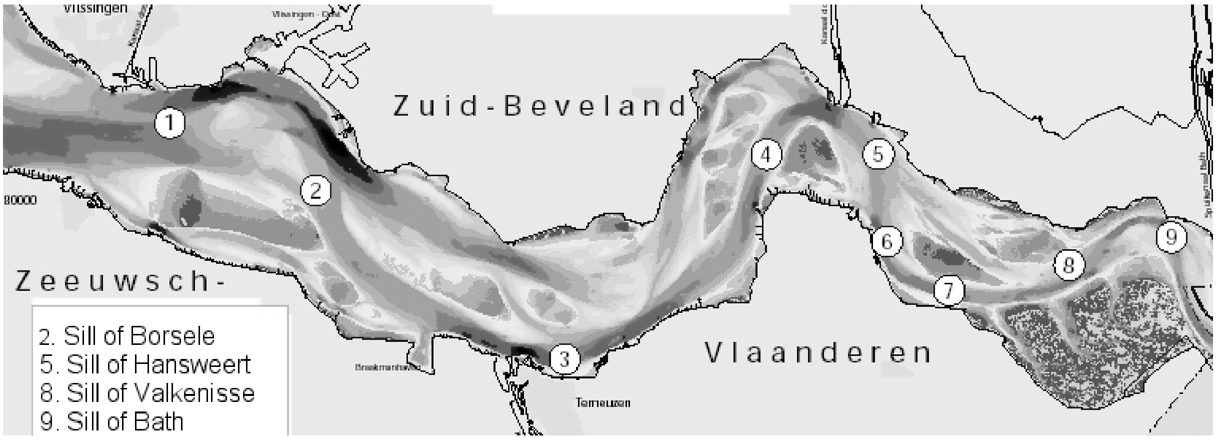

Fig. 1 Westerschelde and the dredging areas

At present the feasibility of new enlargement scenarios are being studied. A key issue in the feasibility study is the prediction of the required maintenance dredging as a function of the required depth of the navigation channel. Especially because dredged sediments have to be disposed elsewhere in the estuary, this strongly influences both the morphology and the ecology of the estuary (Winterwerp et al, 2001, Wang and Winterwerp, 2001).

1.2 PREVIOUS WORK

In the past the required maintenance dredging has been predicted using empirical relations between the dredged sediment volume and the required depth (Vroon et al, 1997). Figure 2 shows the results of such an analysis according to Allersma (1992). The historically observed maintenance dredging is plotted against the over depth at the sills. The line shown in the figure is derived using regression analysis. Prediction for of required maintenance dredging after new enlargement of the navigation channel is based on extrapolation. Based on such method the total maintenance dredging in the estuary after the second enlargement was predicted at about 16 Mm^3 per year. This considerably overestimates the observed maintenance dredging (10−12 Mm^3) since the last enlargement program. Sedimentation at the sills has also been studied using detailed 2D/3D models (Verbeek et al, 1999). Such detailed process-based models appear very useful to explain mechanisms that determine the sedimentation at sills. However, they cannot yet be used to predict the required maintenance dredging, because they still cannot simulate the sedimentation pattern at a sill with sufficient accuracy.

1.3 MODEL CONCEPT

In this chapter a simple model for the dredging requirement at a sill is derived. For this purpose the model principle as used in ESTMORF (Wang et al, 1998, 1999) and ASMITA (Stive et al, 1998, Stive and Wang, 2003) is used: A dredging area at a sill is considered as a single element. It is assumed that an equilibrium depth of the area exists, which is too small for navigation. Therefore an over depth is created by dredging. This over depth creates a sediment demand and has as consequence that sedimentation takes place in the area. The rate of sedimentation in the area will thus depend on the size of the area, the over depth, the capacity of sediment transport from the surrounding area and the vertical exchange rate in the area. The derivation of these dependences is as follows:

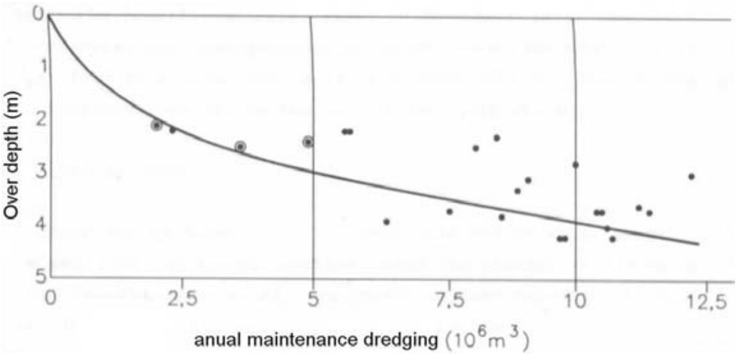

Fig. 2 Historical analysis of Allersma (1992)

2. DESCRIPTION OF THE MODEL

The mass-balance for the sediment in the water phase of the dredging area yields:

$$\delta(c_E - c) = w_s A(c - c_e) \tag{1}$$

Herein

δ = horizontal exchange coefficient (m^3/s),
c_E = sediment concentration in the surrounding environment,
c = sediment concentration in the area (-, volume bed / volume water),
w_s = vertical exchange coefficient (m/s),
A = size of the dredging area (m^2),
c_e = local equilibrium concentration(-).

The term at the left hand side of this equation represents the sediment transport from the surrounding environment to the dredging area by inter-tidal dispersion. The term on the right hand side represents sedimentation at the bed, i.e. the dredging requirement. The sediment concentration c in the area cannot be smaller than 0. Therefore the maximum dredging requirement in the area is equal to δc_E., as can be found by substituting c=0 at the left hand side of the equation.

The local equilibrium concentration in the dredging area is determined by the depth h and the equilibrium depth h_e:

$$c_e = c_E\left(\frac{h_e}{h}\right)^n \tag{2}$$

in which n is a constant. This relation implies that if there is no over depth the equilibrium concentration is equal to concentration in the surrounding and no sedimentation takes place in the area.

By solving the concentration c from Eq. (1) and combining with Eq. (2), the rate of sedimentation in the whole area, or the dredging requirement S, is derived as

$$S = w_s A(c - c_e) = \frac{w_s A\delta}{w_s A + \delta}(c_E - c_e) = \frac{w_s A\delta c_E}{w_s A + \delta}\left(1 - \left(\frac{h_e}{h}\right)^n\right) \tag{3}$$

This equation relates the dredging requirement to the characteristics of the area, characteristics of the surrounding, and parameters describing the sediment transport processes. The theoretical maximum dredging requirement δc_E and the equilibrium depth h_e are the unknowns in practise, and can therefore be considered as calibration parameters for the model.

2.1 FIRST ANALYSIS

In order to analyse its behaviour Eq. (3) is made dimensionless using the theoretical maxim dredging requirement δc_E:

$$\frac{S}{\delta c_E} = \left(\frac{\frac{w_s A}{\delta}}{1+\frac{w_s A}{\delta}} \right) \left(1 - \left(\frac{1}{1+\frac{\Delta h}{h_e}} \right)^n \right) \tag{4}$$

Herein Δh is the over depth:

$$\Delta h = h - h_e \tag{5}$$

There are two terms on the right hand side of Eq. (4): one for the influence of the size of the area and one for the influence of the relative over depth. Fig. 3 and Fig. 4 show respectively the influence of the size of the dredged area and that of the over depth on the dimensionless sedimentation rate. The product of the two terms is depicted in Fig.3, in the case that the size of the area A is proportional to the over depth, as an example according to

$$\frac{w_s A}{\delta} = 0.4 \frac{\Delta h}{h_e} \tag{6}$$

It is interesting to observe that the influence of an increase of the size of the area as well as of the over depth decreases as the variables become larger themselves (Fig.3 en Fig.4), but that the combined effect is a S- curve (Fig.5). For small over depth the required maintenance dredging increases more than linearly with the increase of the over depth. For larger values of the over depth the increase rate decreases and the dredging amount will never be larger than a limit when the over depth becomes very large.

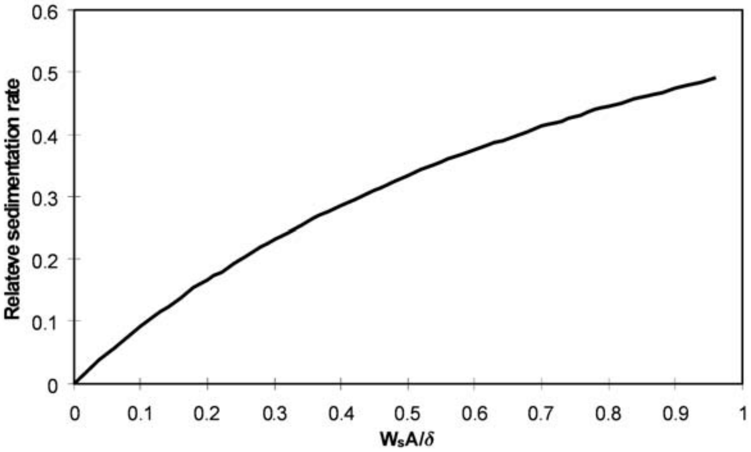

Fig. 3 Influence of the size of the area on the relative sedimentation rate.

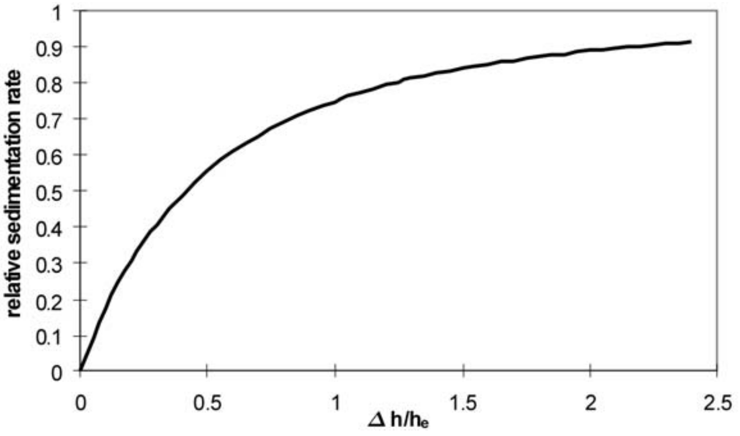

Fig. 4 Influence of the over depth (n=2) on the relative sedimentation rate.

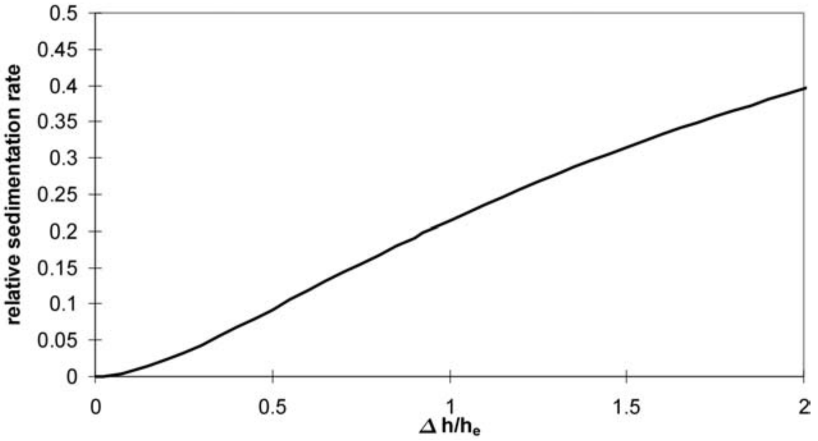

Fig. 5 Relative Dredging requirement as function of over depth if the size of the area is proportional to the over depth

In order to obtain an indication of the influences of the over depth and of the size of the area, estimations of the order of magnitude of the various parameters have to be made. Table 1 gives an overview for the four most important sills in the Westerschelde. This table will be explained in the next paragraphs. As mentioned earlier δ, c_E and the equilibrium depth h_e are the important unknowns which need to be estimated.

Table 1 Relative influence of over depth and size of the area on the dredging requirement, and a first estimate of the order of magnitude of the absolute dredging requirement *S* according to the model

Sill	*h* (m)	h$_e$ (m)	*A* (m^2)	$w_s A / \delta$	$\Delta h / h_e$	*S* (Mm3/yr) model	*S* (Mm3/yr) 1999-2001
Bath	16	8	945643	0.01	1.0	1.1	1.0
Valkenisse	16	8	835174	0.01	1.0	1.0	1.7
Hansweert	16	8	2297511	0.02	1.0	2.6	2.6
Borssele	16	10	597374	0.01	0.6	0.5	1.2

For the analyses of the influence of the size of the area use is made of the following values of parameters, conform the calibrated ESTMORF model for the Westerschelde:

w_s = 0.001 m/s
c_E = 0.00005
D = 1250 m^2/s (dispersion coefficient)

The horizontal exchange coefficient δ depends on the dispersion coefficient as follows:

$$\delta = \frac{OhD}{R} = \alpha h D \tag{7}$$

Herein

O = length of the contour of the dredging area (m),
R = a length scale representing the distance between the centre of the area and the surrounding (m),
h = the depth in the area to be maintained (m),
α = O/R (-), assumed to be constant.

In this first analysis the dredging areas are assumed to be circle shaped, so α is equal to 2π. For a maintained depth of NAP-16 m this results into a horizontal exchange coefficient δ of 117810 m^3/s. Combining this with the size *A* of the sill areas (Kornman et al, 2002), yields that the relative size of the area term, $(w_s A)/\delta$, varies between 0.01 and 0.02 (see Table 1). For such values the dredging requirement increases linearly with size of the area: for this range of the relative area the graph in Fig.3 is a straight line, and the slope of the line is about 0.98.

This agrees qualitatively well with the observations, especially at the sill of Hansweert after the first enlargement of the navigation channel in the early 1970's, as described by Kornman et al (2002). The increase of the maintenance dredging after that enlargement is especially due to the increase of the dredging area.

For the determination of the influence of the over depth an estimation of the equilibrium depth at the sills is required. Allersma (1992) argued that the equilibrium depth at the sills varies between NAP-8 m and NAP-10 m. Because the size of the channels increases in the seaward direction, the equilibrium depth of the sill of Borssele, in the western part of the Westerschelde, is probably larger than the equilibrium depth at the sills in the eastern part. The in this analysis used values for the equilibrium depth at each sill are summarized in Table 1. For a maintained depth of NAP-16 m this results into a relative over depth of 0.6 – 1.0 (see Table 1). For this range of the values the over depth has no more large influence on the sedimentation rate (see Fig.4). The slope of the line is decreases in this range from 0.5 to 0.3.

3. DISCUSSIONS AND CONCLUSIONS

In Table 1 the actual dredging amount at the four major sills in the Westerschelde Estuary in the period 1999-2001 is also shown. The predictions by the model appear to agree well with these observations. It should be remarked that no calibration of the model has been carried out. All the input parameters are based on the operational ESTMORF-model which is set up for the long-term morphological development of the whole estuary, and on the literature. Obviously the model has the potential to become a predictive model for the dredging requirement in the estuary, with a much better accuracy than the existing methods. For this purpose the model should be calibrated using all available data for each of the sills / dredging areas. Compared to the existing methods the model has two advantages. First, the model considers each individual dredging area separately instead of considering all dredging areas together. Second, the model is more based on physical principles rather than basing only on the field observations.

That the dredging requirement as function of the over depth shows a S-shape curve (Fig.5) explains why the existing methods overestimate the dredging requirement after the last enlargement of the navigation channel. Based on the historical data Allersma (1992) concluded that the dredging requirement is proportional to the power 2.2 of the over depth. This is probably because that the available data only concern the first deepening of the navigation channel. This means that the data in fact only represent the first part of the S-curve, showing the shape of a parabola.

It has been concluded that the changes in the dredging requirement at the sills is to a large extent determined by the changes in the size of the areas where dredging is required, and much less determined by the change of the over depth (Eq.4). This agree qualitatively well with the observations. Korman et al (2002) report that the sedimentation rate per unit of area at the sills does no more increase due to the last enlargement of the navigation channel since 1997. This suggests that the influence of the over depth is even less than the model has predicted. The reason of this can be that the over depth is less increased due to the enlargement of the navigation channel than it is assumed in the model. For a further deepening a larger area of the sill needs to be dredged. The natural equilibrium depth of the newly deepened area is larger than the old dredged area. Averaged over the whole area the increase of the over depth should be therefore smaller then the extra deepening. This justifies that the over depth at a sill / dredging area should be considered as a calibration parameter.

REFERENCES

Allersma, E., 1992, Analysis of the physical system of the Eastern part of the Westerschelde (in Dutch), WL | Delft Hydraulics, Report Z368.

Kornman, B.A. and Liek, G.J. and H. Schippers, 2002, Dredging and dumping in the Westerschelde Estuary, A new look at the maintenance dredging, National Institute of Coastal and Marine Management, Document RIKZ/AB/2002.840x (in Dutch).

Stive, M.J.F.;Capobianco, M., Wang, Z.B.; Ruol, P.; and Buijsman, M.C.,1998. Morphodynamics of a Tidal Lagoon and the Adjacent Coast, in Dronkers, J. and Scheffers, M.B.A.M. (ed.), Physics of estuaries and coastal seas, Balkema, Rotterdam, 1998, pp 397-407

Stive, M.J.F. and Z.B. Wang, 2003, Morphodynamic modelling of tidal basins and coastal inlets, To appear in *advances in coastal modelling.*

Verbeek, H., Wang, Z.B. & P.M.C. Thoolen, 1999, Secondary currents in estuarine morphodynamic modelling, a case-study of the Western Scheldt, IAHR symposium on River, Coastal and estuarine morphodynamics, Genova, Italy, 1999.

Vroon, J.H., C. Storm & J. Coosen (1997) *Westerschelde, stram of struis*, evaluation report of the OOSTWEST project concerning the Western Scheldt, National Institute of Coastal and Marine Management (in Dutch).

Wang, Z.B., Karssen, B., Fokkink, R.J. and Langerak, A., 1998. A dynamic/empirical model for long-term morphological development of estuaries, in Dronkers, J. and Scheffers, M.B.A.M. (ed.), Physics of estuaries and coastal seas, Balkema, Rotterdam, 1998, pp 279-286.

Wang, Z.B., A. Langerak, and R.J. Fokkink, 1999, Simulation of long-term morphological development in the Western Scheldt, IAHR symposium on River, Coastal and estuarine morphodynamics, Genova, Italy, 1999.

Wang, Z.B. and J.C. Winterwerp, 2001, Impact of dredging and dumping on the stability of ebb-flood channel systems, River, Coastal and Estuarine Morphodynamics Conference RCEM2001 (IAHR), Japan.

Winterwerp, J.C., Z.B. Wang, M.J.F. Stive, A. Arends, C. Jeuken, C. Kuijper and P.M.C. Thoolen, 2001, A new morphological schematization of the Western Scheldt Estuary, The Netherlands, River, Coastal and Estuarine Morphodynamics Conference RCEM2001 (IAHR), Japan.