CHAPTER 141

ELBE TIDAL MODEL WITH MOVABLE BED

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ABSTRACT

The Bundesanstalt für Wasserbau (BAW) was charged to investigate an estuary tidal model of the Elbe-river (North Sea). The model, fitted with a movable bed, serves for special research with regard to suitable actions for the enlargement and maintenance of the main navigable channel in the sea area.

Because in tidal estuaries the interaction of fluid and solid material is extremely unknown, the investigation was undertaken to find out the arising morphological changes, only caused by tidal currents, considering structure or dredging works present or planned in prototype. The procedure seems advantageous and a better way as speculative interpretations of sediment movements, derived from flow velocities in a fixed bed model.

The horizontal scale of the model is 1:800, the vertical scale 1:100. After basic considerations as similarity, hydrology, morphology, respectively, specifications of the modelling technique are given and finally some test results are discussed.

SIMILARITY CONSIDERATIONS

In general the sediment transport in open channels cannot be described for models only by the Froude law, because

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the perfect rough area of the resistance number is rarely available. Therefore it seems necessary to make compromises between the similarity laws of Froude and Reynolds.

The specific sediment transport can be expressed as

$$q_s' = f(\varrho, \varrho', g, \nu, D, w, u_*)$$

whereby $$u_* = \sqrt{g.h.I_e}$$

It denotes:

ϱ, ϱ_s	= specific density of the fluid and bed material	$[ML^{-3}]$
ϱ'	= relative specific density = $\frac{\varrho_s - \varrho}{\varrho}$	$[1]$
g	= gravitational acceleration	$[LT^{-2}]$
ν	= kinematic viscosity	$[L^2T^{-1}]$
w	= fall velocity of the grain in resting water	$[LT^{-1}]$
u_*	= shear velocity	$[LT^{-1}]$
h	= water depth	$[L]$
D	= characteristic grain diameter	$[L]$
I_e	= energy gradient	$[1]$
q_s'	= specific sediment transport	$[dynL^{-1}T^{-1}]$
κ	= Karman constant	$[1]$

Dimensionless parameters can be formed with these characteristic values:

Reynolds numbers:

$$R_* = \frac{u_* \cdot D}{\nu}; \quad R_w = \frac{w \cdot D}{\nu}$$

Froude numbers:

$$F_* = \frac{u_*^2}{\varrho' g D}; \quad F_w = \frac{w^2}{\varrho' g D}$$

Sedimentological diameter:

$$D_* = \left(\frac{\varrho' g}{\nu^2}\right)^{1/3} D = \left(\frac{R_*^2}{F_*}\right)^{1/3} = \left(\frac{R_w^2}{F_w}\right)^{1/3}$$

Transport numbers:

$$G_* = \frac{q_s'}{\varrho\, u_*^3}; \quad g_* = \frac{q_s'}{\varrho_s\, g\, D\, u_*}$$

The term $Z = \frac{w}{\kappa\, u_*}$ shows advantageous the distribution of grains transported in suspension.

It has been found out that the numbers F and R have their special significations for the outline of transport occurrences. Gehrig [1] has developed similarity relations by comparison of these numbers for model and prototype. These relations allow the estimation of horizontal and vertical model scales as well as details of material constants D and ϱ'. Conditions therefore are:
The model must be distorted and the resistance number is in the range of $R_* < 70$.

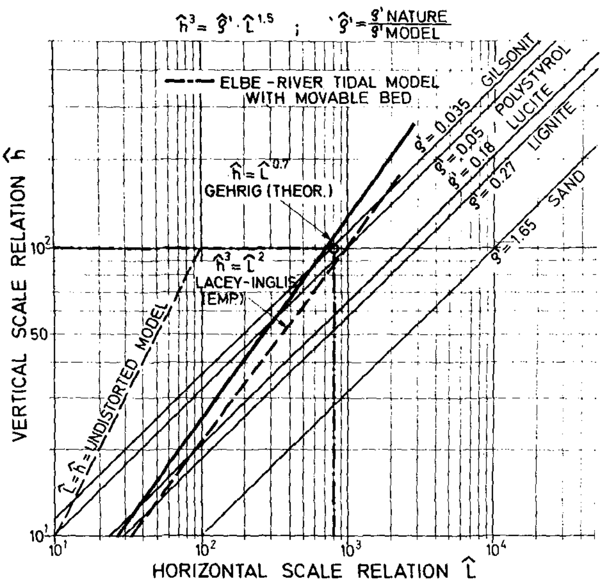

Fig. 1 Scale relations for movable bed models [1]

The starting equations are:

$$R_* = \frac{\sqrt{g\ h_N\ I_{eN}}\ D_N}{\nu_N} = \frac{\sqrt{g\ h_N\ K\ I_{eN}}\ D_N}{\sqrt{\hat{h}_N}\ \nu_N\ \hat{D}}$$

$$F_* = \frac{g\ h_N\ I_{eN}}{\varrho'_N\ g\ D} = \frac{g\ h_N\ I_{eN}\ K\ \hat{D}\ \hat{\varrho}'}{\varrho'_N\ g\ \hat{h}\ D}$$

The symbol $(\wedge)$ denotes the reverse values of the similarity scale, $K = \frac{\hat{L}}{\hat{h}}$ is the similarity relationship of the distortion. Two terms can be derived from these definitions:

$$(\wedge)\ h^3 = L^{1.5}\, \varsigma' \qquad (1)$$

$$(\wedge)\ D^3 = \varsigma'^{-1} \qquad (2)$$

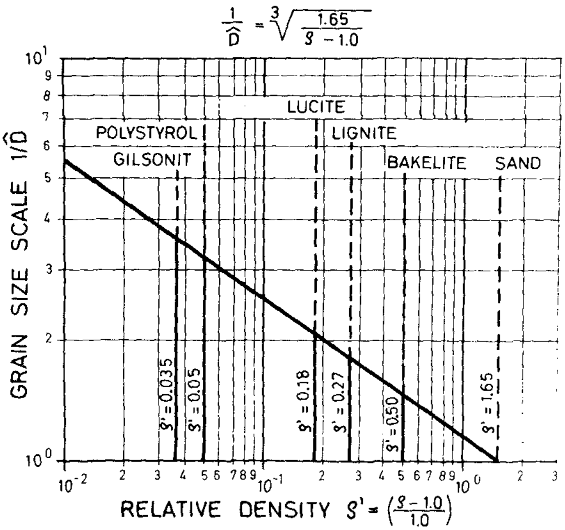

Fig. 2 Scale relations between density and grain diameter of the model bed material [1]

The Fig. 1 and 2 show the graphs of these equations. Suitable scale relations can be determined.

The following principles should be taken into consideration:

a) The horizontal relationship $\hat{L}$ of the model depends on the available area.

b) The vertical relationship $\hat{h}$ depends on the accuracy for the determination of the water levels.

c) Distortion and model discharge affect $\hat{L}$ and $\hat{h}$.

d) $\hat{D}$ and $\hat{S}'$ will be determined adequate to available or buyable material.

e) In tidal models, the time scale for morphological changes can only be found empirically. (Historical tests).

HYDROLOGICAL AND MORPHOLOGICAL INFORMATIONS

The boundaries in the sea part of the tidal model (Fig. 3) were chosen with great accuracy after previous historical investigations [2]. The inlet contains special constructions for the adjustment of the tide wave generation. Flow velocities, flow directions and water-level slopes show good agreements between model and prototype for a great range of different tidal waves after adjustment.

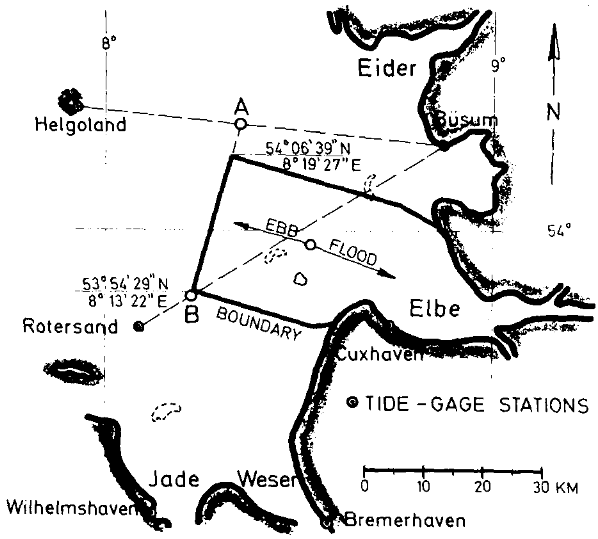

Fig. 3 Boundaries of the model in the sea area

Series of mean tides in the model did not satisfy natural occurrences. Therefore a month's cycle with 57 different tides was used with half monthly unequality between neap tide and spring tide (Fig. 4).

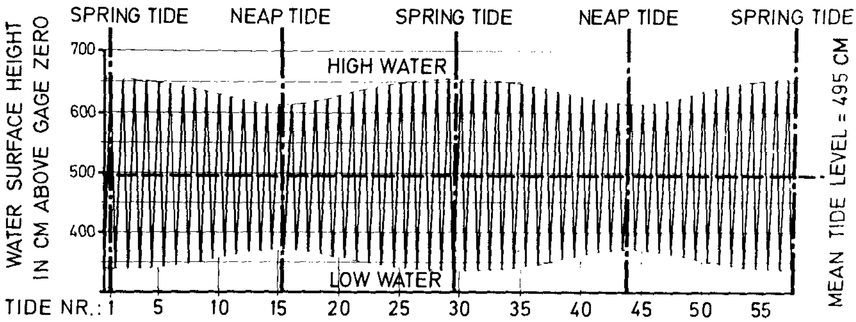

Fig. 4 Mean monthly tide curves (Cuxhaven)

The chosen scales for the model, required a very mobile bed material with a specific density of 1.05 g/ccm(gram per cubic centimeter). The material has a uniform grain diameter (D$\sim$2 mm) and forms itself a good roughness under flow conditions. Because investigations will last several years, material should not change its characteristic. The plastic material POLYSTYROL satisfies requirements, but this material is very expensive. With a layer of about 10 cm, 120 000 kp (kilopond) were needed. The water-repellent property can be reduced by additives. In general, morphological changes observed in situ and model have been found in good agreement when the tide period in the model was modified.

Density currents and the coriolis acceleration are hardly to realize in distorted models with movable beds, here they were neglected, nevertheless the flow parameter are in good agreement.

MODEL CONSTRUCTION

The model was built from the mentioned boundary in the sea area up to the extreme point of the tidal influence at the weir Geesthacht. The length in axis is about 170 km. Hamburg, the main harbour of West Germany, has a distance of about 100 km from Cuxhaven at the river mouth (Fig. 5).

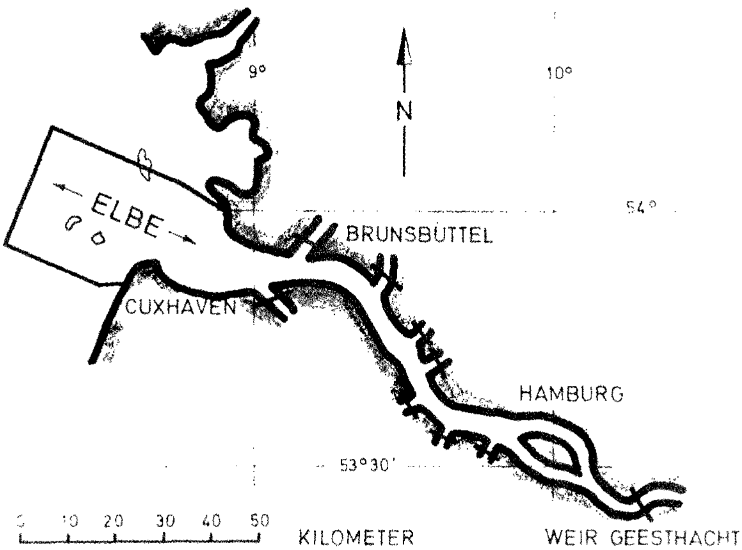

Fig. 5 The Elbe-River from the sea up to the extreme point of tidal influence (weir Geesthacht)

Besides special constructions for tide generation with a steerable sector gate, eleven adjustable pressure pipes, distributed over the width of the inlet (30 m), serves for exact quantitative water dispersion adequate to discharge cross-section. Before test runs the movable bed was moulded by placed tin profiles (later on removed), which are based on a step-like substructure of concrete (Fig. 6).

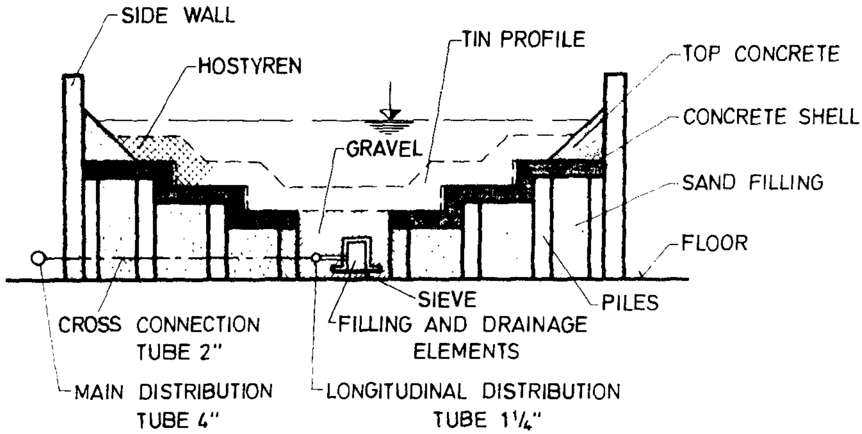

Fig. 6 Model cross-section for the movable bed part (schematical)

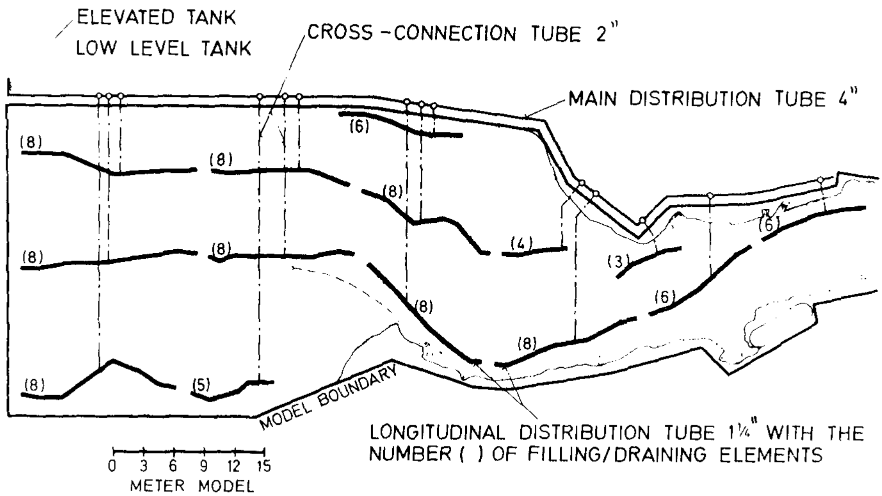

Fig. 7 Distribution system for irrigation and draining

The model has a square dimensional acting irrigation and drainage system, so that morphology cannot be destroyed during filling and draining (Fig. 7). Measurements and observations are possible from mobile bridges [3].

ELECTRONIC INSTRUMENTS

An electronic optical system reads tide curves, recorded on an endless tape as theoretical values. Vibrating points, system Delft, with remote control are installed as effective value for tide generation and as water-level gages. Steering and recording of data occurs in a central control station. Furthermore the following measurements are practicable (likewise by remote control): water-level slopes, velocities, measured with micro-propellers, flow directions, and the sounding of morphology with an optic-electrical system mounted on a float (Fig. 8). This instrument can be applied to a water-depth of 32 cm below a necessary cover height of 10 cm.

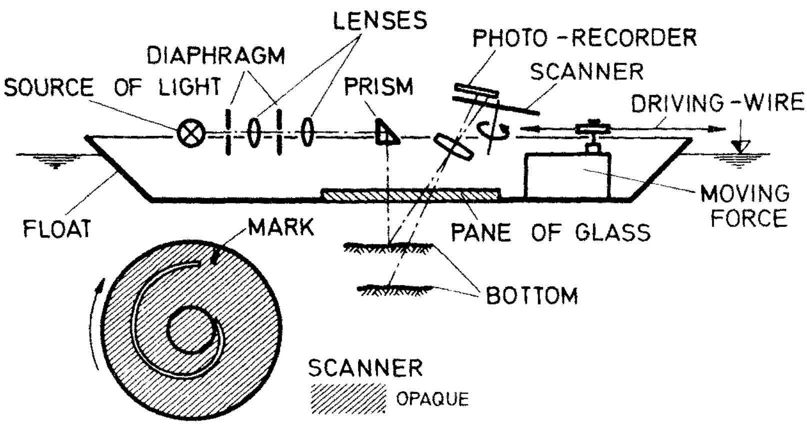

Fig. 8 Optic-electrical recording instrument for morphological sounding

This must be considered for the construction of the inlet. The profile sounding was realized after dark, because the influence of foreign light is extremely high.

SIMILARITY CONTROL

The verification of similarity occurs in two steps:

a) Dynamical similarity

b) Morphological similarity

To a. Test results of water-levels, flow velocities and flow directions as well as flood and ebb durations were compared between model and prototype. Therefore the Froude law was stated. The model area, later on fitted with a movable bed, was provided with a quasi fixed sand bed but with artificial formed surface roughness. All occurrences are in good agreement, as an example may serve the presentation of different measured tide curves (Fig. 9).

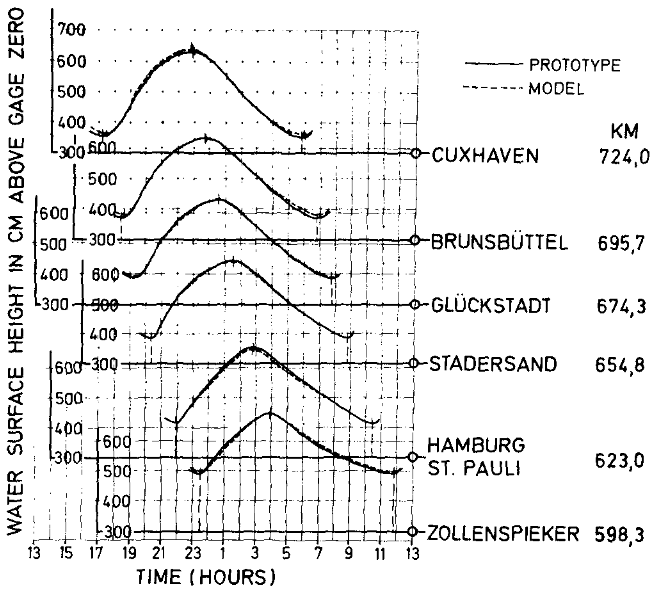

Fig. 9 Comparison of tide curves in model and prototype

To b. The morphological similarity can be expressed as a time relation, in which natural bed changes are reproducable in the model. Therefore historical tests were used in steps from 1910 to 1970. The tide period, derived from Froude, must be enlarged with a factor 1.4 to get favourable values for roughness and bed deformations. Finally the morphological time scale was found out with 1/705; (one day in nature is about two minutes in model).

FIRST PRACTICAL MODEL TESTS

The first tests have been carried out to prove the stabilization effect of a new main navigation channel, following natural canal development tendencies north-west of Cuxhaven.

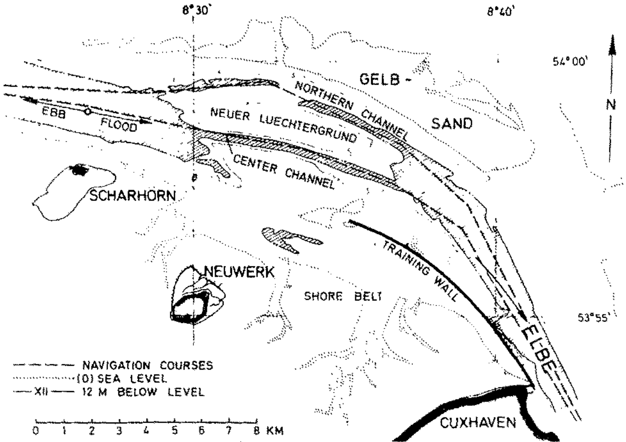

Fig. 10 Part of the Elbe-river estuary (north-west of Cuxhaven, 1969)

Till to-day sailing and arriving ships used two channels, the "Center Channel" and the "Northern Channel" (Fig. 10). It is designed to widen and deepen the "Center Channel"for the whole traffic and especially for bigger ships. In the past decades the existing bipartition of the navigation channels leads to highly unstable conditions by different flood and ebb current directions and from this, likewise difficulties occur for navigation. With the completion of a 9.25 km long training wall in the sea area 1968 (Fig.10), stabilization effects can be observed but the two navigation channels are still too flat. The new scheme for the widening of the "Center Channel" includes an additional extension of the training wall (about 3 km lengthening) and therefore two plans should be investigated in comparison with the existing wall length.

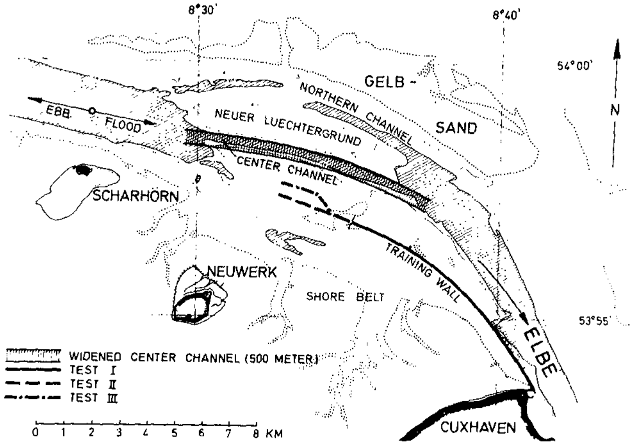

Fig. 11 Schemes of the training wall extension

In Fig. 11 denotes test I the existing length of the training wall, test II a tangential extension and test III an extension in a break off form, respectively. The existing longitudinal shape of the wall is given in Fig. 12. The wall is a riprap construction on fascine mattresses.

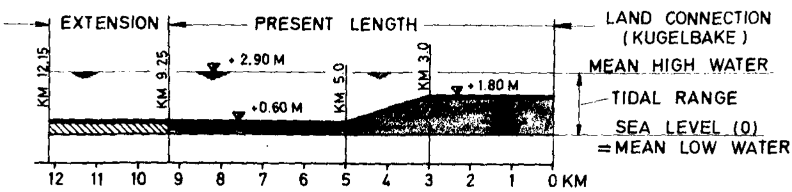

Fig. 12 Longitudinal section of the training wall with slope details

The new widened and deepened "Center Channel" (500 m width, 12 m depth below sea level), was considered as present in the model when the tests started. Each test lasted 186 hours in the model, what corresponds to a natural extrapolation time of 15 years in prototype. The measured silting rate at the end of this time, inside of the new dredged channel, was reduced to a year's rate and specified in per cent (Test I = 100 %).

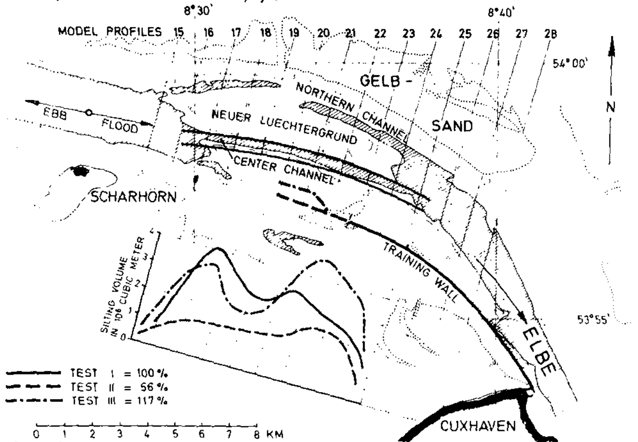

Fig. 13 Test results of the measured silting rate in the new "Center Channel" in relation to the training wall extension

The results given in Fig. 13 in per cent and with their local distribution, show a minimum rate for test lI with the tangential extension. This is clearly more advantageous as the breaking form in test III with 117 %. In this case the break off form catches more material and compensates the training wall extension.

For test I with the existing training wall length the silting rate of the "Center Channel" was measured with 1.475 million cubic meter per year (model volume multiplied with model scales and devided through the number of test run years), for a channel width of 500 m. As a possible chance to compare dredging rates between model and prototype may serve Fig. 14.

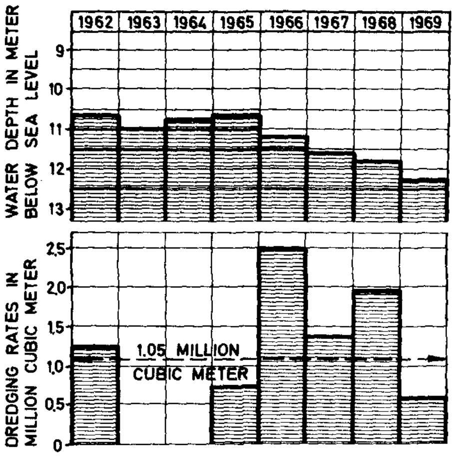

Fig. 14 Development of the mean water depth in relation to the dredging rates in prototype

The prototype informations show a mean dredging rate (1962-1969) of 1.05 million cubic meter per year for the mean channel width of 350 m. With the extension factor for the width of 500/350 = 1.43, this rate will be enlarged to 1.5 million cubic meter, similar as the rate, calculated from the model. This agreement is actual surprising but it is better to look not only at quantitative but more at qualitative results. However, the facts of these tests show obviously the possibility to minor the dredging rate in the "Center Channel" by extension of the training wall in form of test II.

The complex shoaling occurrences are outlined in Fig. 15. The different shoaling directions known in prototype and well simulated in the model too, are produced from diverging flood and ebb current directions. Resultant flow directions, noted for several measuring points, explain the relationship between sediment transport and flow directions and demonstrate the difficulties for the stabilization of the navigation channel.

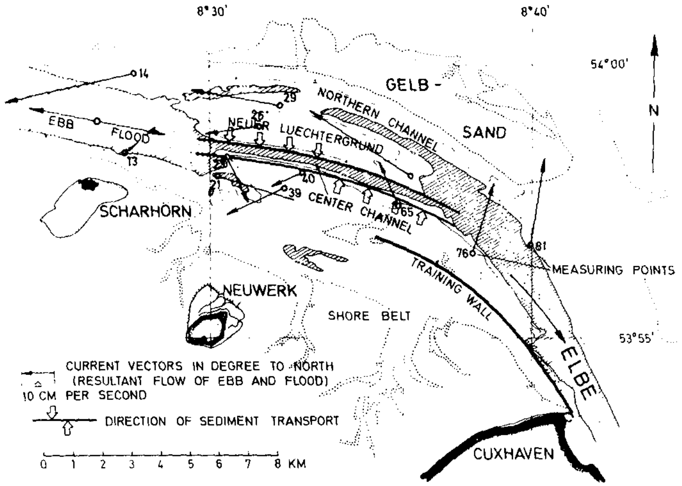

Fig. 15 Shoaling dynamic in the "Center Channel" area

Further testing sections considered changed position runs of the "Center Channel". Details are given in Fig. 16. The measured silting rates are also given in per cent with respect to test I. The training wall has here the extension of about 3 km with a total length now of 12.25 km for all variants (IV to VI).

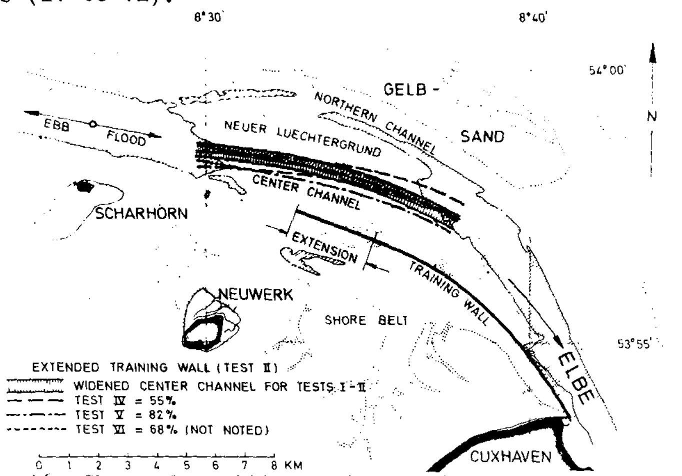

Fig. 16 Changed positions of the "Center Channel"

The results show, that a small turn of the "Center Channel" against clockwise direction (test IV), gives nearly the same per cent number as in test II (55 % to 56 %). However, in this case the navigation course is not advantageous.

Test V deals with a small approach of the "Center Channel" in direction to the training wall, but the shoaling rate increases (82 %). In Test VI a mixing of the "Center Channel" runs IV and V decreases again the shoaling rate (68 %). First of all, the tests to find out the optimum position showed the extreme sensibility of the movable bed and the influence on small constructional changes. On the other hand one can see that the natural developed channel, now stabilized by the training wall, is obviously the optimum channel course.

CONCLUSIONS

The presented study on a tidal model with a movable bed points out the successful reproduction of morphological occurrences in a tidal estuary. The valuation of the different construction plans of the training wall extension shows an optimum for the tangential lengthening (Test II), that means a minimum dredging rate for the "Center Channel", as the main navigation channel in the Elbe-river estuary. It is to mention that the measured quantitative shoaling rates were only used as a qualitative comparison basis. We know that it is impossible to reproduce all natural phenomena complex in a model, but in some instances, these models are a valuable help for the estimation of constructional or dredging works in coastal areas.

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