CHAPTER 61

EXPERIENCE WITH MOVABLE BED TIDAL MODELS

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INTRODUCTION

A particular problem, of those arising in the economic development of estuary regions, concerns the maintenance and enlargement of navigation channels. The sediment transport plays an important role in connection with this problem. Though the hydrodynamical processes are today, with the help of mathematical procedures, fairly exactly grasped, there is still insufficient knowledge about the related transport processes, the formation of ripples and dunes and of long-term periodical morphological changes.

Nevertheless, the engineer wants information about sediment transport for his planning. A well-known aid is the movable bed hydraulic model, which has been technically developed to simulate the natural fluid-sediment interaction. Such models are not yet standard in hydraulic research institutes and furthermore, they are not easy to handle. This is probably due to a lack of suitable similarity criteria for insuring valid experimental results. However, there exist recently developed somewhat compromised similarity relationships, which can be used for distorted movable bed tidal models.

The experience gained with the movable bed model Elbe I at the Bundesanstalt für Wasserbau (BAW) in Hamburg provides an incentive for investigating special cases in other large tidal models of the German North-Sea coast. These models are presented in Fig. 1. From west to east:

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a)	Ems-model	Scales	1:500/100
b)	Jade-Weser-model	"	1:800/100
c)	Elbe-model I	"	1:800/100
d)	Elbe-model II	"	1:500/100
e)	Eider-model	"	1:250/50

The investigations involved morphological changes in areas with navigation channels, training structures, dumping places for dredged material, changes of water levels in connection with deepened channels, new high water dikes and influence of storm tides for models a) through d) and a damming up for model e) with regard to scour protection up-and downstream of the weir reach.

EQUATIONS AND ASPECTS

The following dimensionless parameters describe the sediment transport:

$$R_* = \frac{u_* . D}{\nu} \quad \text{(Reynolds-Number)} \qquad (1)$$

$$F_* = \frac{u_*^2}{\varrho' g D} \quad \text{(Froude-Number)} \qquad (2)$$

$$D_* = \left(\frac{\varrho' . g}{\nu^2}\right)^{1/3} . D = \left(\frac{R_*^2}{F_*}\right)^{1/3} \quad \text{(Sedimentological Diameter)} \qquad (3)$$

$$G_* = \frac{q_s'}{\varrho . u_*^3} \; ; \; g_* = \frac{q_s'}{\varrho_s . g . D . u_*} \quad \text{(Transport Numbers)} \qquad (4)$$

u_*	= shear velocity	$[L . T^{-1}]$
D	= characteristic grain diameter	$[L]$
ν	= kinematic viscosity	$[L^2 T^{-1}]$
ϱ, ϱ_s	= specific density of the fluid and bed material	$[M . L^{-3}]$
ϱ'	= relative specific density = $\frac{\varrho_s - \varrho}{\varrho}$	$[1]$
g	= gravitational acceleration	$[L . T^{-2}]$
q_s'	= specific sediment transport	$[dyn L^{-1} T^{-1}]$

$$(\Lambda) = (L, h, D, \varrho') \text{ (Comparison of prototype and model parameters)} \qquad (5)$$

These relationships are suitable for the description of various phenomena. One obtains a similarity function from the comparison of prototype-model parameters in equation 5, where the quantities L = length, h = depth, D = grain diameter and ϱ' = relative specific density provide the basis of the model. Since the estuaries of our coastline are considered to be of the "well-mixed" type, in which the salinity decreases uniformly from the sea mouth to the river, but where the fresh water and salt water are fairly well-mixed throughout the vertical, density effects are neglected in flows described by the similarity criteria.

The scale relations for movable bed models are extensively discussed in our paper submitted to the 13th Conference [5]. The scale relations are based on roughness conditions of the bed material considering different light weight materials. Gehrig's calculations in Fig. 2 [1] show good agreement with the empirically developed expression of Lacey and Inglis. This may serve for an initial assignment of model scales.

Due to the premise that model dunes should be geometrically similar to their counterparts in prototype, an extension of the time scale must be considered, mostly for distortions larger than 5. For the Elbe model I with a distortion of 8, the multiplier α , first estimated empirically and later on calculated, reflects the deviation from a "Froudian Model". Yalin also derived this in his paper presented at the 13th Conference [6]. He labeled his multiplier ξ .

The calculations for time extensions are based on the interaction between average stream velocity and sediment transport in preference to shear stress. Water level slope, water depth, grain diameter and grain density as well as kinematic viscosity of the fluid and roughness coefficients of the whole system are the main variables.

The idea to work with "Non-Froudian models" is not new. At the former "Preussische Versuchsanstalt"in Berlin where

Casey and Shields carried out their basic research, Krey developed a model technique for rivers with stationary uniform discharge. With the use of natural sand, from which the finest particles had been removed to avoid cohesive influence, an agreement with nature-like sediment transport was achieved with the aid of steeper slopes for model and water level ($\sim$ 1:600). In these cases the discharge steps must be calibrated in relation to different water-depths.

Prototype and model values of our estuaries are listed in Fig. 3, a graph after Krey: the dimensioned roughness coefficient K against a variation of the Reynolds-number. For u . R we set u_* . h (shear velocity times water depth). Following the ordinates to the parameter for channels with bed material of fine sands, the total roughness coefficients of the considered river sections can be estimated. From this the average flow velocity $u = \frac{u_* \cdot K}{g}$ is available both for the prototype and model. The comparison of these results show finally the deviation from the Froude law, as similarly shown in Yalin's interpretation. The too intensive mobility of the bed material in the model can be reduced with the time extension $\alpha = \frac{\lambda_u}{\sqrt{\lambda_y}}$.

The verification of prototype and model values with Yalin's criteria are presented in Fig. 4 [6]. On the left side in the Y/Ycr - X plane the presence of ripples on dunes would not be expected, when polystyrene is selected with a diameter larger or equal 2 mm. In the model, X or R_* according to Yalin must always be larger than 25. To achieve the similarity of dunes, prototype and model points should be both outside the shaded region in the X - Y plane on the right side. These assumptions are given for all models with distortions between 5 and 8. However, the necessary deviation from a "Froudian model" has an upper limit. Test results in the Elbe model I, with a distortion of 8, showed only practical α or ξ values of up to 1.5 for this relative long estuary with one tide generator. Beyond this limit the water level slope flattened during the last part of the ebb phase. Only short estuaries or sections with two-sided tide generation allow smaller extensions of more than 1.5. Therefore roughness coefficients given by the similarly reproduced bed deformations limit the scale of distortion. In Fig. 5, left graph A, the correlation between α and distortion n with different length scales λ_y is presented. Because the unshaded region is only available, the upper limit with α = 1.5 combined with a length scale 1:800 allows a distortion of n=8. This was selected for the Elbe model I with a resulting suitable vertical scale of 1:100.

However, it must be mentioned that the first empirically estimated time extension for this model with α = 1.4 was used throughout all tests. Adequate to lower distortions the necessary time extensions decreased. This leads to an approximation of the Froude law for distortions < 5. From this it is obvious that we sometimes have much trouble finding the effective artificial roughness which reproduces similar water level slopes in highly distorted models with fixed beds.

A further correlation of polystyrene grain diameter with Yalin's limitation of $X \geq 25$ in Fig. 5, right graph B, shows the small range outside of the shaded area. Fortunately we found polystyrene grains with a diameter of about 2 mm which satisfy these requirements.

Of special significance is the morphological time scale, i.e. the time necessary for equal changes of the morphology in prototype and model. The relationship of significant transport depends on the F_* values above the critical values, given in the Shields-diagram (Fig. 6).

Prototype and model values of our estuaries are noted and reveal the influence of grain diameter and density. A relative high mobility can be found in nature and a diminished one in the model, both caused by maximum velocities during the steepest rising or falling water in the flood or ebb phases.

Fig. 7 presents a variation of the Shields diagram with a correlation of the grain diameter versus grain Reynolds-number. Parameters are the grain Froude-number and grain

density. The natural sand, D = 0.4 mm, shows an F_* of 0.5. The available polystyrene with 2 mm diameter gives $F_* \sim 0.3$ (after calculations for the Elbe-model given in the appendix) and consequently a lower mobility.
In the model $F_* = 0.5$ requires a grain diameter of 1.0 mm but this would be outside of the limitation of $X = R_* > 25$ (right of the dashed vertical).

The morphological similarity can be expressed as a time relation, in which natural changes are reproducible in the model. Historical tests showed that model changes occur more rapidly than according to the time scale specified by Froude. Finally the morphological scale was found empirically to be 1:705, (2 minutes in the model to about one day in nature).

INDICATIONS TO THE MODEL CONSTRUCTION

Movable bed models should be set up in closed heatable halls to avoid large deviations in water-temperatures. It is recommended that the tidal region be built to include the total area of tidal influence, for only in this way can the effect of artificial structures be precisely eliminated. In considering a combination of a "fixed and movable model section", technical model simplifications are allowed in the fixed bed area, which then only has a secondary function. Fig. 8 depicts the Elbe model I, situated in a 40 x 112 m test hall. Various deviations from the natural course were necessary to optimally fit the model into the hall.

In addition to the usual equipment, test halls should have movable service bridges with which the entire surface area of the hall can be covered, so that all work and measurements can be carried out without having to step inside of the model (Fig. 9).

In addition to special constructions for tide generation, such as a steerable sector gate, exact quantitative water dispersion adequate to discharge cross-section and electronic optical tide curves reader, the areally acting irrigation and drainage system is especially important (Fig. 10).

This last installation is an essential tool for the whole success of the work. Other measuring installations shall not be described; they are generally well-known.

RESULTS

Historical morphological development investigations in the Elbe-model I showed good agreement between nature and model. The relation between alternating flow processes during a tide and the thereby established sediment transport can be, through proof of hydrodynamic similarity, better comprehended for the total estuary region in the model than in nature. Detailed descriptions of the first practical tests which have been carried out to prove the stabilization effect of a new main navigation channel north-west of Cuxhaven are given in the Proceedings of the 13th Conference.

According to Fig. 11, the minimum local silting distribution was found for test II with a tangential extension of the existing training wall. Prototype sounding control measurements verified the occurrence of advantageous developments for the stabilization.

A new method must be found for models to measure the spread of first dredged and later on dumped material. This is significant for the maintenance and deepening of main navigation channels.
Dumping fields in the outer Elbe with examples of several measuring points in Fig. 12 show that the dumped material was not brought back to the widened Center Channel. To measure the spreading, the artificial model sediment (polystyrene) serves itself as tracer. But single grains with 2 mm diameter can only bear radioactivity when a suitable element can be bound onto their surfaces. Therefore the element bromine was used, which could be bound chemically with polystyrene. The duration of the presented tests was 150 tides or about 33 hours in the model. This nearly corresponds to the 36 hour half-life of bromine. More details are described in our paper for the IAHR Congress in Istanbul 1973.

A large area bottom training was investigated in the Elbe model II. For this purpose a segment of the model was fitted with a movable bed. The similarity to nature was also very evident. The situation map in Fig. 13 shows the Elbe area between Brunsbüttel and Scheelenkuhlen (km 684-km 696). 8.5 million m^3 were to be dredged out of the river bed to build up the foreshore for industrial areas. The dredging fields, marked with I through IV, are outside of the main navigation channel, and the widening of the cross-section favours the hydraulic requirements. The discharge became more balanced, velocities showed more parallel directions and the bottom deformations flattened.

The results in Fig. 14 show for test 0 with the existing condition in the longitudinal profile a relatively unsteady formation of dunes with different elevations. Test 6 indicates the same length after the dredging with a more flattened bottom. These developments explain the interaction of the fluid-sediment movement and the effectiveness of training actions.

CONCLUSIONS

Movable bed tidal model techniques have developed substantially in the past few years. However, experimental results have been only sparsely published. Experience has shown that such models are very useful and that even with small construction changes a definite morphological development resulting from outside forces and bottom topography is demonstrated.

O'Brien's relations [2] between minimum flow area and tidal prism could be proved both by calculation and model tests. Fig. 15 presents a simplified calculation method in a metric system. Definite cross-sections of the German North Sea coast show similar proportions to estuaries of the Pacific coast. These relations have a special bearing on the enlargement of navigation channels.

Finally it should be stated that movable bed models have definite advantages over fixed bed models because there is a direct interaction between fluid motion and sediment transport processes.

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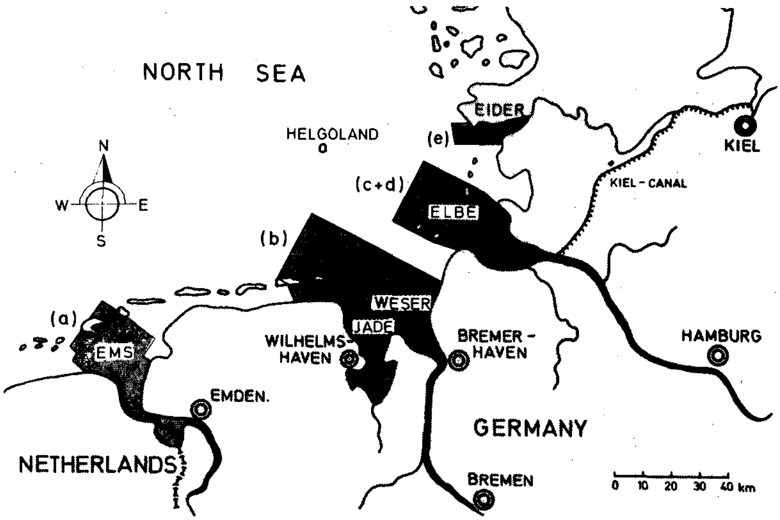


FIG. 1. - ESTUARY MODELS OF THE GERMAN NORTH-SEA COAST

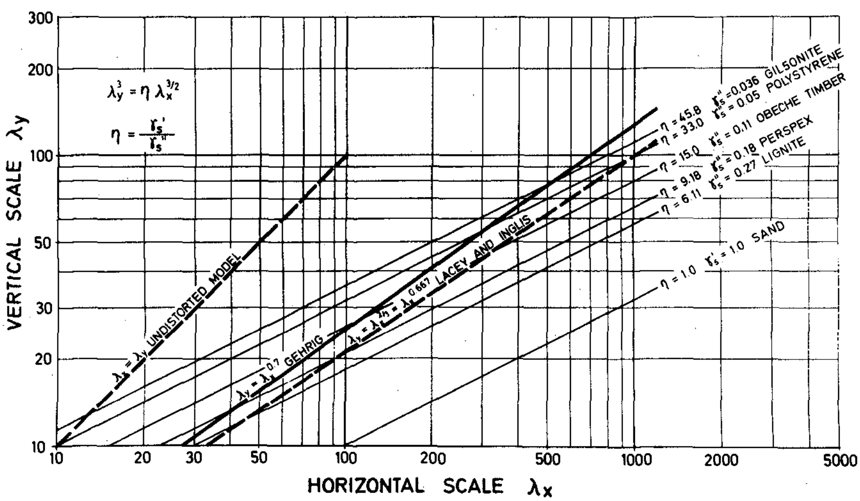


FIG. 2. - SCALE RELATIONS FOR MOVABLE BED MODELS (CONSIDERING ROUGHNESS) AFTER GEHRIG [1]

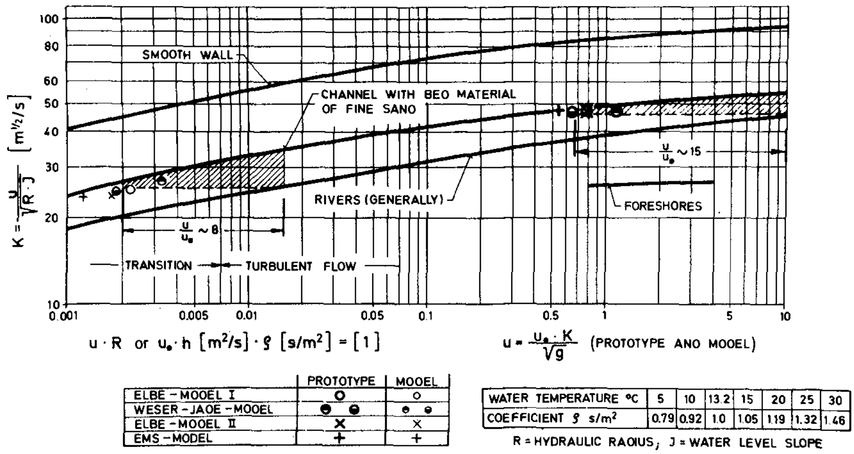


FIG.3. - ROUGHNESS COEFFICIENT K VERSUS KREY'S NUMBER u.R.ϱ OR NUMBER u.R. WHEN $\varrho \sim 1$ (WATER TEMPERATURE 13,2°C)

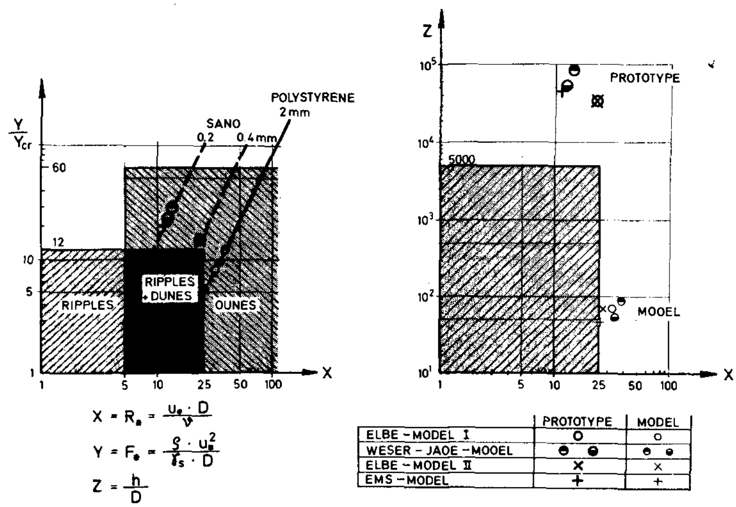


FIG.4. - YALIN'S CRITERIA ON THE GEOMETRICALLY SIMILAR REPRODUCTION OF DUNES IN A TIDAL MODEL WITH MOVABLE BED [6]

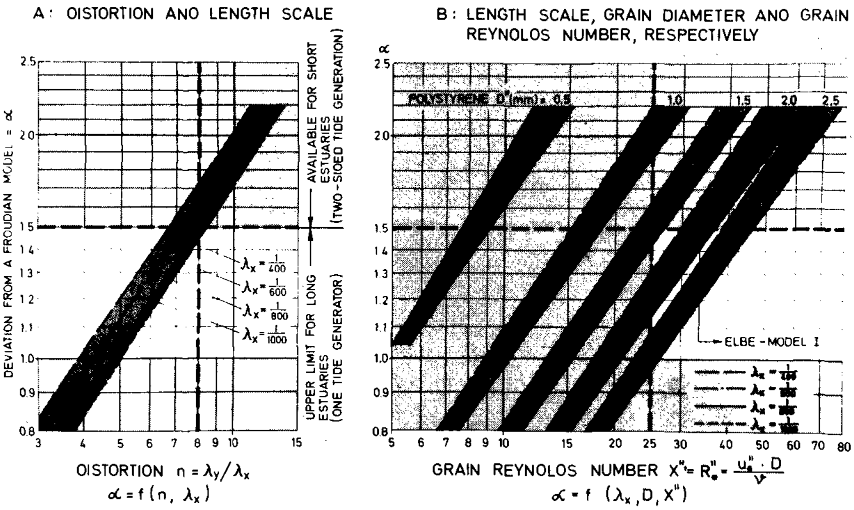
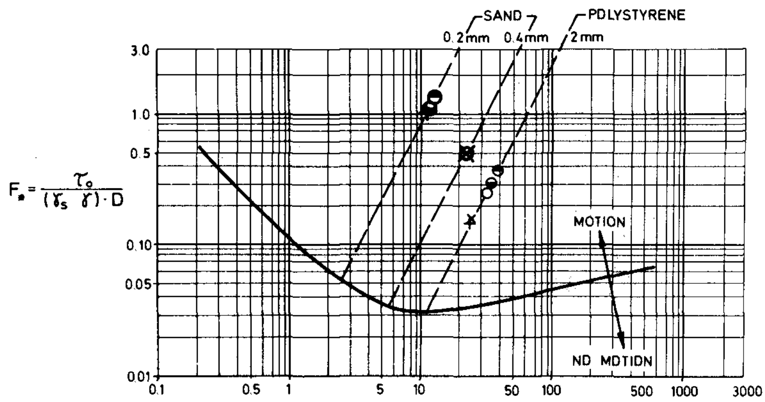


FIG.5. - CORRELATION OF THE DEVIATION FROM A FROUDIAN MODEL (EXAMPLE ELBE-ESTUARY, $u_*'' = 0.0575$ m/s)



	PROTOTYPE	MODEL
ELBE - MODEL I	○	○
WESER - JADE - MODEL	◒ ◒	◒ ◒
ELBE - MODEL II	×	×
EMS - MODEL	+	+

FIG.6. - SHIELDS-DIAGRAM, DIMENSIONLESS CRITICAL SHEAR STRESS VERSUS SHEAR REYNOLDS NUMBER

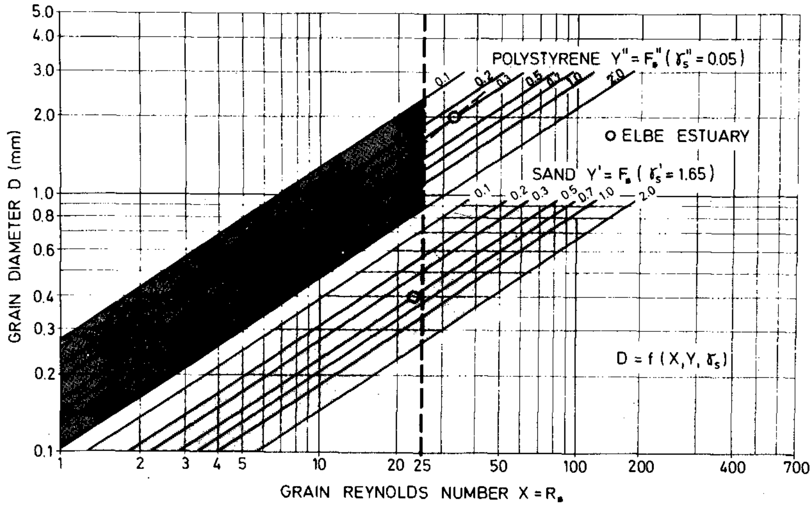


FIG.7. - CORRELATION OF THE GRAIN DIAMETER, GRAIN REYNOLDS NUMBER, GRAIN FROUDE NUMBER AND GRAIN DENSITY, RESPECTIVELY

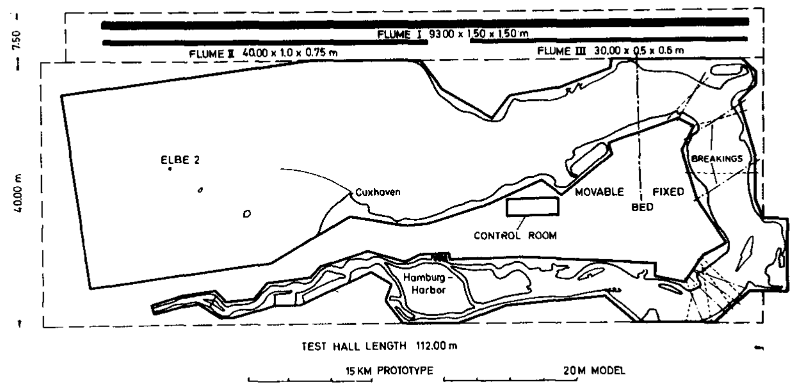


FIG.8. - SITUATION MAP OF THE HALL WITH THE ELBE-MODEL I

FIG.9. - SERVICE BRIDGES

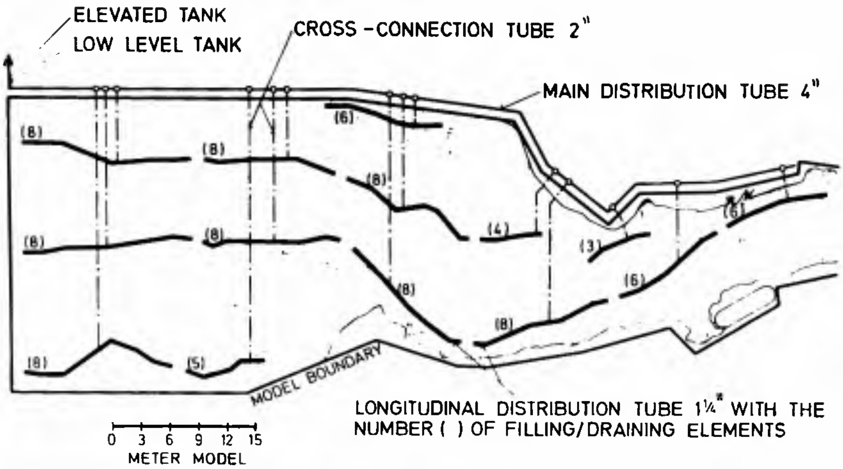


FIG.10. - IRRIGATION AND DRAINAGE SYSTEM

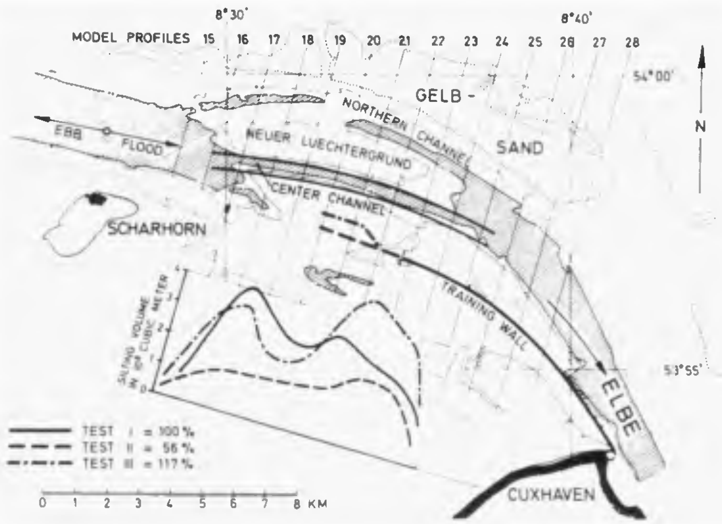


FIG. 11. - SCHEMES FOR THE TRAINING WALL EXTENSION, MEASURED SILTING RATES IN THE NEW "CENTER CHANNEL"

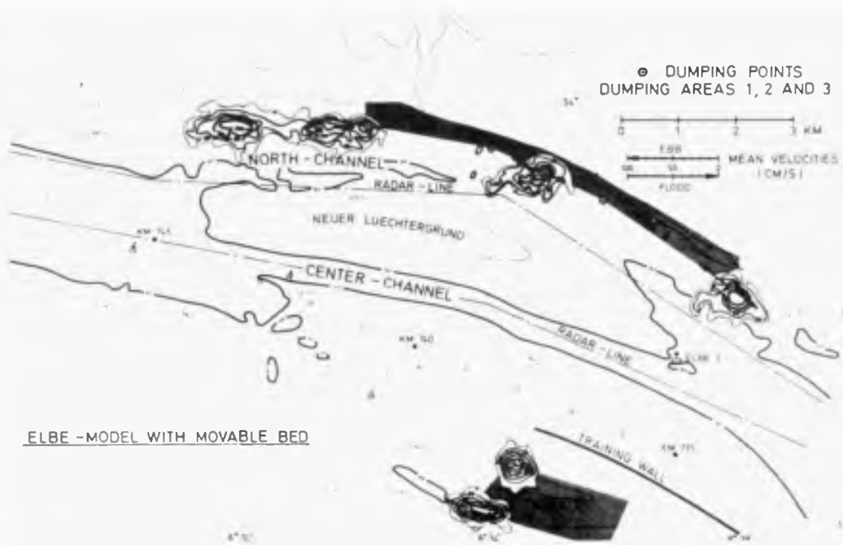


FIG. 12. - SPREADING OF DUMPED MATERIAL IN THE OUTER ELBE (MODEL TESTS WITH RADIOACTIVE TRACERS)

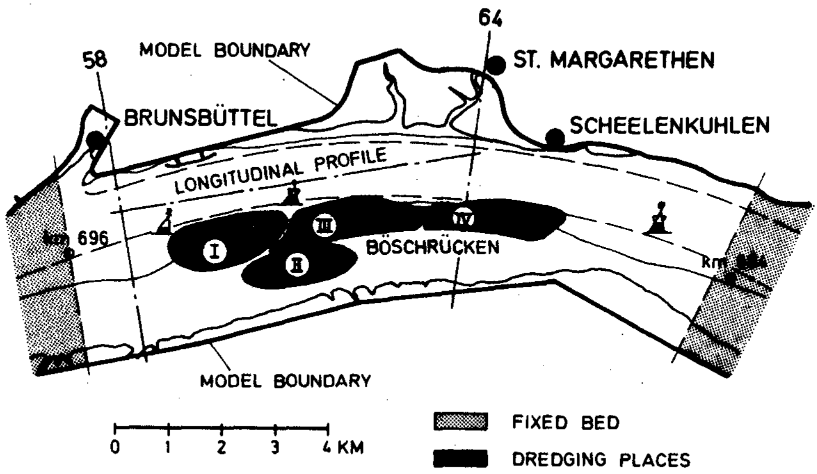


FIG. 13. - SITUATION MAP OF THE ELBE RIVER BETWEEN BRUNSBÜTTEL AND SCHEELENKUHLEN (km 684-km 696)

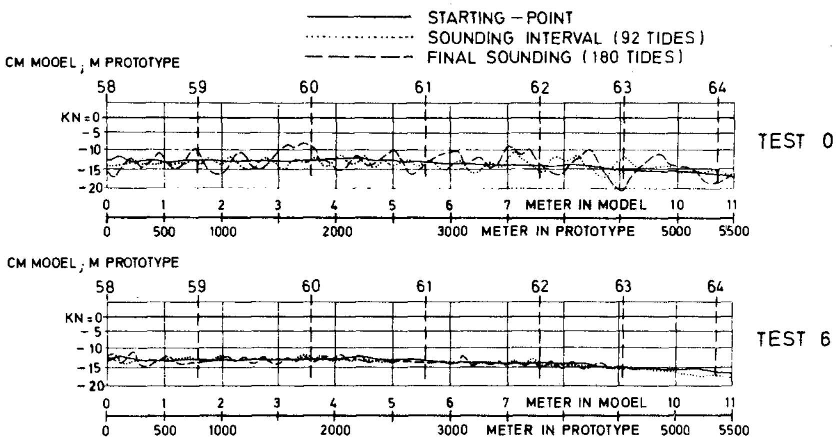


FIG. 14. - ELBE MODEL II, LONGITUDINAL PROFILE BETWEEN THE CROSS SECTIONS 58 - 64 (TESTS 0 AND 6)

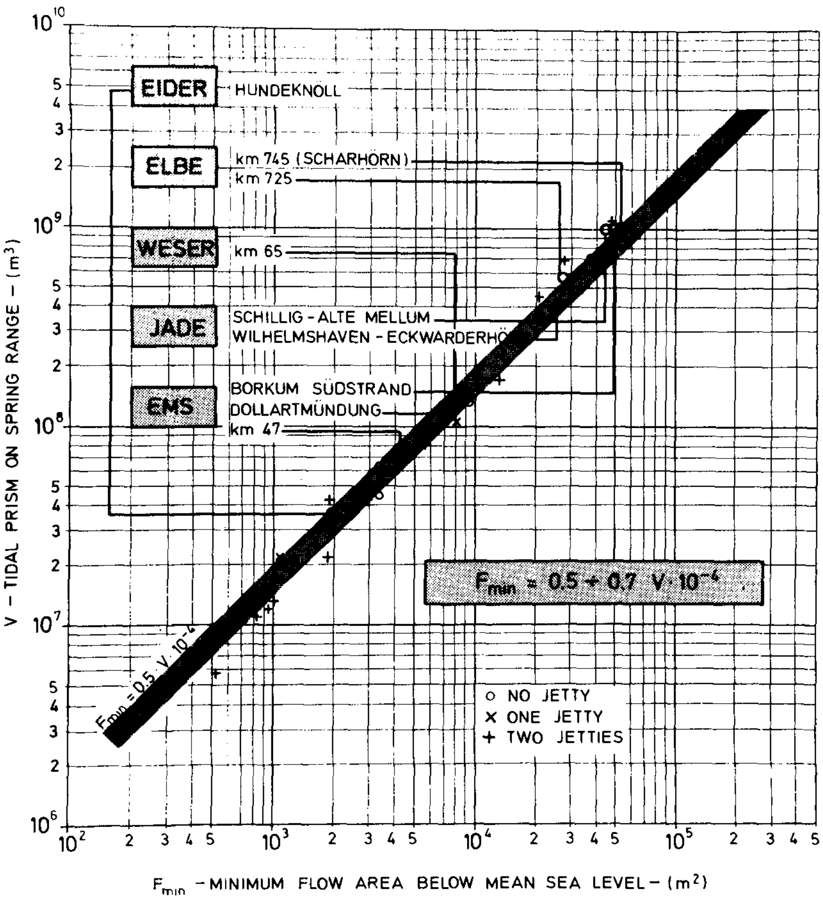


FIG. 15. - MINIMUM FLOW AREA AND TIDAL PRISM (AFTER O'BRIEN [2])

APPENDIX

CALCULATIONS FOR THE ELBE MODEL I WITH MOVABLE BED

$h' = 13.5\ m$
$D' = 0.4\ mm$
$L' = 28.3\ km$, $H = 0.7\ m$ $\}\ J' = 2.5 \cdot 10^{-5}$ between Brunsbuttel and Cuxhaven
$\gamma_s'/\gamma = 1.65$
$\nu = 10^{-6} m^2/s$; $g = 9.81\ m/s^2$; $\rho = \gamma/g = 101.94\ kp\,s^2/m^4$

Bed material in the model: Polystyrene $\gamma_s'' = 0.05$, $D'' = 2mm$

$\lambda_{\gamma s} = \frac{0.05}{1.65} = \frac{1}{33}$; $\lambda_D = \frac{0.002}{0.0004} = 5$

$\lambda_Y = \frac{1}{100}$ vertical scale relation

$\lambda_X = \frac{1}{800}$ length scale relation

$n = \frac{\lambda_Y}{\lambda_X} = 8$ distortion

$Z' = \frac{h'}{D'} = \frac{13.5}{0.0004} = 33750$

$Z'' = \frac{h''}{D''} = \frac{0.135}{0.002} = 67.5$

$\lambda_Z = \frac{67.5}{33750} = \frac{1}{500}$

$X' = \frac{u_*' \cdot D'}{\nu}$; $u_*' = \sqrt{\frac{\tau'}{\rho}}$; $\tau' = \gamma \cdot h' \cdot J' = 1000 \cdot 13.5 \cdot 2.5 \cdot 10^{-5} = 0.3375$

$u_*' = \sqrt{\frac{0.3375}{101.94}} = \underline{0.0575\ m/s}$

$X' = \frac{0.0575 \cdot 0.0004}{10^{-6}} = \underline{23}$ $\qquad Y_{cr}' = 0.035$ (Shields)

$Y' = \frac{101.94 \cdot 0.0575^2}{1650 \cdot 0.0004} = \underline{0.51}$ $\qquad Y'/Y_{cr}' = \frac{0.51}{0.035} = \underline{14.57}$

$X'' = \frac{u_*'' \cdot D''}{\nu}$; $u_*'' = \sqrt{\frac{\tau''}{\rho}}$; $\tau'' = \gamma \cdot h'' \cdot J'' = 1000 \cdot 0.135 \cdot 2 \cdot 10^{-4} = 0.027$

$u_*'' = \sqrt{\frac{0.027}{101.94}} = \underline{0.0163\ m/s}$

$X'' = \frac{0.0163 \cdot 0.002}{10^{-6}} = \underline{32.6}$ $\qquad Y_{cr}'' = 0.032$ (Shields)

$Y'' = \frac{101.94 \cdot 0.0163^2}{50 \cdot 0.002} = \underline{0.271}$ $\qquad Y''/Y_{cr}'' = \frac{0.271}{0.032} = \underline{8.47}$

$\lambda_X = \frac{32.6}{23.0} = 1.42$; $\lambda_Y = \frac{0.271}{0.51} = \frac{1}{1.88}$

$u_*' \cdot h' = 0.0575 \cdot 13.5 = 0.776$
$u_*'' \cdot h'' = 0.0163 \cdot 0.135 = 0.0022$
(Krey's number $u \cdot R \cdot \rho$ with $\rho = 1$; water temperature 13.2°C ; $R = h$)

Choose the roughness coefficient K from Krey's graph for channels with bed material of fine sand:

$K' = 47$; $K'' = 25$

$$\frac{u}{u_*} = \frac{K \cdot \sqrt{h \cdot J}}{\sqrt{\frac{\tau}{\rho}}} = \frac{K \cdot \sqrt{h} \cdot \sqrt{J} \cdot \sqrt{\gamma}}{\sqrt{\gamma} \cdot h \cdot J \cdot \sqrt{g}} = \frac{K}{\sqrt{g}}$$

Prototype : $u' = \frac{u_*' \cdot K'}{\sqrt{g}} = \frac{0.0575 \cdot 47}{3.14} = \underline{0.86\ m/s}$

Model : $u'' = \frac{u_*'' \cdot K''}{\sqrt{g}} = \frac{0.0163 \cdot 25}{3.14} = \underline{0.13\ m/s}$

$\lambda_u = \frac{u''}{u'} = \frac{0.13}{0.86} = 0.15$

Necessary time extension for the tide period after Froude

$$\alpha = \frac{\lambda_u}{\sqrt{\lambda_Y}} = \frac{0.15}{\sqrt{\frac{1}{100}}} = \underline{1.5}$$

[Calculations with the "Technical System": kp, m, s]