CHAPTER 119

TWO-DIMENSIONAL STABILITY ANALYSIS OF TIDAL BASINS AND TIDAL FLATS OF LARGER EXTENT

by

Eberhard Renger [+)]

Abstract

Stability studies of natural tidal basin system demand a regime-oriented analysis and a characteristic quantification of the morphological values. Hence it was necessary to create relative form parameterization dependent on the location by means of a two-dimensional system of natural coordinates (z =elevation, s = gully length coordinate).

The underlying logic for the determination of the equilibrium of the tidal basins and tidal flats is as follows:
When the continuity equation for non-steady flow at any cross-section (s_i , z_i) of a tidal basin, within the mean tidal range is applied, a dimensionless relationship between horizontal and vertical cross-sections (A and F) and tide-generated mean velocities of current (±u) and tidal rise and fall (± v) can be derived with an accuracy of more than 90 %:

$$\frac{u}{v} \cong \frac{A}{F}$$

The analysis of the term on the right-hand side of this equation showed a characteristic vertical distribution of the relationship for all investigated tidal basins of the German Bight and look rather similar. The reference values of the corresponding relationships depend on the area of the tidal basin (E) at MHW and the mean tidal range (H).

The influence of the horizontal extent has been elaborated by varying the line of intersection systematically along the gully-length-coordinate (s). In addition it was possible to point out the differences between the characteristics of stable and (well-known) non-stable conditions by means of a two-dimensional analysis of the dammed-off tidal river EIDER/German Bight.

The relations derived may prove to be useful in the planning of future constructions and even in understanding and influencing the disadvantageous changes in running systems.

[+)] Dr. Ing. E. Renger, Senior Research Engineer, Landesamt für Wasserhaushalt und Küsten, Kiel, Germany, Head of Teilprojekt B3, Sonderforschungsbereich 79, Technical University, Hannover

Introduction

Stability conditions of tidal basins and tidal flats have been mainly observed from natural systems of minimum morphological change. Some well-known basic relationships between morphological and hydrological components have been empirically derived by making wider comparisons of similar systems.. As a fundamental result several investigations have pointed out the most important equilibrium relationships between the cross-sectional area of a tidal basin inlet and the associated tidal prism or the area of the tidal basin (see Ref.).

However, the entrance is only one particular part of a tidal basin or estuary. Cross-sections and tidal prisms schow a characteristic variation during tidal rise and fall (z) and along the gully axis (s). As a consequence, and in addition to earlier stability investigations, the local distribution and the relationship between horizontal (s) and vertical (z) components of the system have to be taken into account.

The present paper concerns a two-dimensional analysis which has been elaborated in order to obtain basic informations about the forecasting-modelling of morphological change, i.e. the proof of stability and the calculation of sand balances.

Because of the complicated interactions within these "tidal basins with movable bed" attention is focussed on the following three aspects which in author's view are the most instructive with the knowledge that is available to us at the moment:

1. The method of analysis
2. The comparison of the derived form parameters due to stability conditions
3. The proof of instability and time-dependent change of the representative form parameters by means of the regime of the EIDER, a tidal river in the inner German Bight.

It is hoped that the relations derived may prove to be usefull in the planning of future constructions and even in unterstanding and influencing the disadvantageous changes in running systems.

Basic assumptions and analysis

In contrast to the results of former investigations carried out by various authors, this investigation had to elaborate a two-dimensional approach to quantifying the tidal-hydrodynamic and morphological characteristics of the system as a whole. Therefore natural coordinates were assumed within the area of the tidal basin both vertically (z = elevation) and horizontally (s = gully length coordinate).

The horizontal and vertical cross-sections (A and F) were measured and calculated from the maps at a scale of 1 : 10 000. They were mainly analized within the mean tidal range for the 6 different tidal basins at the seaward boundary at the bar with the help of computers (Fig.3). It must emphatically be pointed out that a comparision of tidal basins as a whole can only be successful if they are taken as a physiographic unit within the seaward boundary at the bar! RENGER, (5,7)

The physical behaviour of the tidal wave within the basin may be easily described by the continuity equation for non-steady flow.

$$u = \frac{\tilde{A}}{\tilde{F}} \cdot \frac{dh}{dt} \qquad (1)$$

On the right-hand side of Fig. 1 there is a schematical cross-section over a plan view.

In this elementary tidal basin (section)

- the inflow volume ($Q \cdot dt$) equals the increase of the tidal volume ($\tilde{A} \cdot dh$) and
- the flow (Q) equals the term ($\tilde{F} \cdot u$).
- The mean velocity of tidal rise and fall (dh/dt) is substituted by (v) - as seen on the left hand side of Fig. 1.

When these basic equations are combined the mean current velocity (u) in the cross-section ($\tilde{F}$) is derived within a good accuracy as

$$u = \frac{\tilde{A}}{\tilde{F}} \cdot v \qquad (2)$$

When this equation is transformed into a dimensionless expression, the hydrodynamical components are separated from the morphological ones (Fig. 2)

$$\frac{u}{v} = \underbrace{\frac{\tilde{A}}{\tilde{F}}}_{\text{hydrological}} = \underbrace{\frac{A}{F}}_{\text{morphological}} \qquad (3)$$

As the values depend exactly on three variables of space and time f (z,s,t) a restriction on two variables of space is very useful in this first approach. Thus the term on the right-hand side of this equation was preferred for analysis. In addition the morphological system shows an integrating character from the morphogenetic point of view because of its much greater inertia of change.

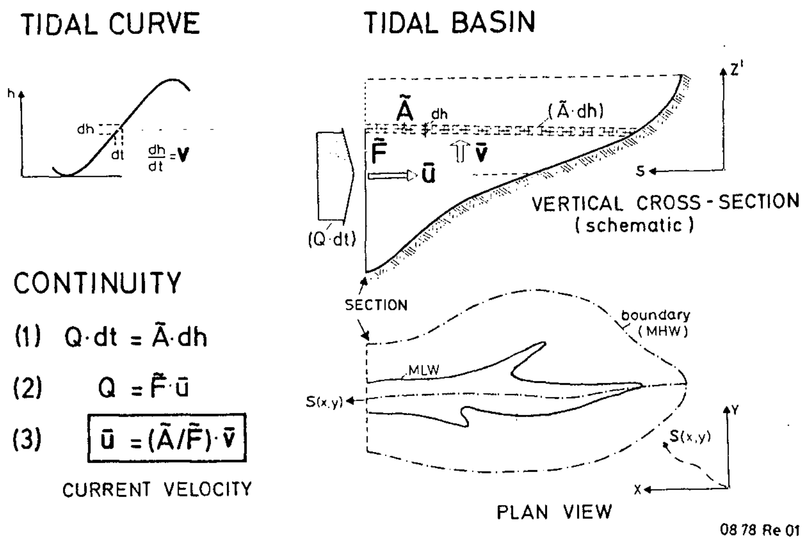

TIDAL CURVE
TIDAL BASIN
h
dh
dt
dh/dt = V
Ã
dh
(Ã·dh)
F̃
V̄
ū
(Q·dt)
Z'
S
VERTICAL CROSS-SECTION
(schematic)
CONTINUITY
(1) Q·dt = Ã·dh
(2) Q = F̃·ū
(3) ū = (Ã/F̃)·V̄
CURRENT VELOCITY
SECTION
boundary
(MHW)
MLW
S(x,y)
Y
X
PLAN VIEW
08 78 Re 01

Fig. 1

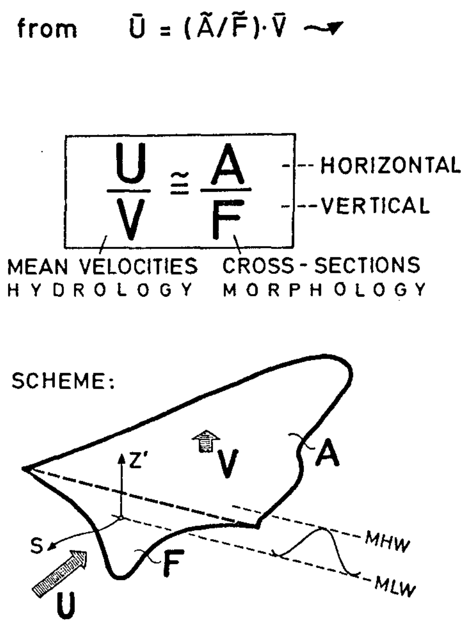

from Ū = (Ã/F̃)·V̄
U/V ≅ A/F
HORIZONTAL
VERTICAL
MEAN VELOCITIES
HYDROLOGY
CROSS-SECTIONS
MORPHOLOGY
SCHEME:
Z'
V
A
S
F
MHW
MLW
U
08 78 Re 02

Fig. 2

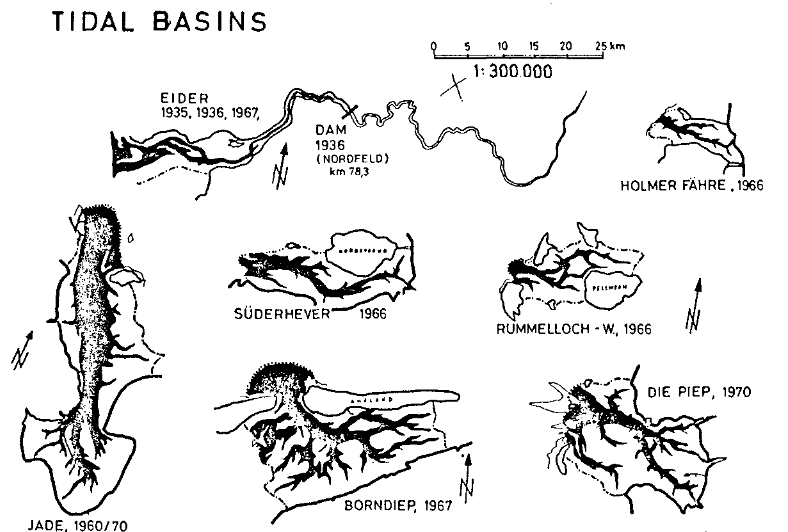

TIDAL BASINS
0 5 10 15 20 25 km
1: 300 000
EIDER
1935, 1936, 1967,
DAM
1936
(NORDFELD)
km 78,3
HOLMER FÄHRE, 1966
SÜDERHEVER 1966
RUMMELLOCH - W., 1966
DIE PIEP, 1970
BORNDIEP, 1967
JADE, 1960/70
0878 Re 03

Fig. 3

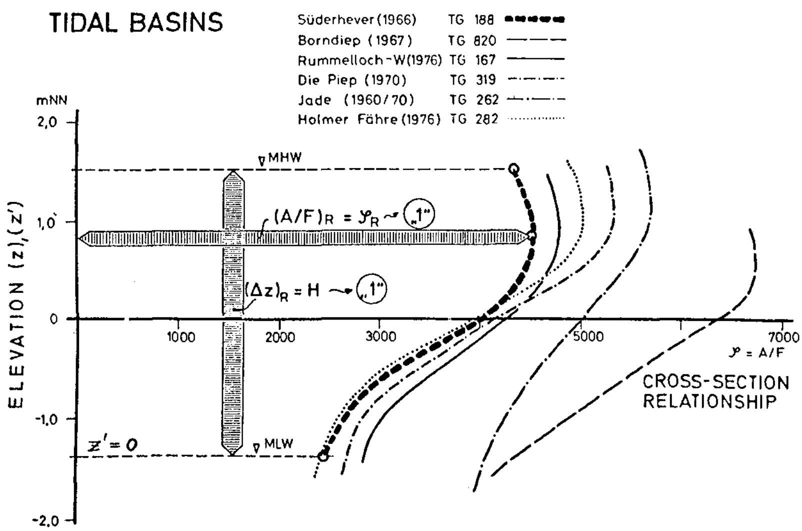

TIDAL BASINS
Süderhever (1966) TG 188
Borndiep (1967) TG 820
Rummelloch-W (1976) TG 167
Die Piep (1970) TG 319
Jade (1960/70) TG 262
Holmer Fähre (1976) TG 282
mNN
2,0
1,0
0
-1,0
-2,0
ELEVATION (z),(z')
MHW
MLW
(A/F)R = 𝒫R ~ „1"
(Δz)R = H ~ „1"
z' = 0
1000
2000
3000
5000
7000
𝒫 = A/F
CROSS-SECTION RELATIONSHIP
0878 Re 04

Fig. 4

One-dimensional comparison of tidal basins as a unit (E_σ)

The vertical distribution of the corresponding relationships (A/F) are shown in Fig. 4.

As a first result it can be pointed out that

- the curves show a charakteristic distribution in the vertical and look rather similar,
- the (A/F) varies from about 2,500 at MLW up to 7,000 and more at MHW, and that
- there is an optimum near MHW, which has to be pointed out for future analysis.

In order to make the systems comparable the distribution functions were made uniform in both variables. Therefore the vertical component (z) was shifted to MLW (z') and related to the mean tidal range (H), with (ζ = z'/H). (4)

The abscissa (A/F = $\mathcal{F}$) was related to the optimum value of ($\mathcal{F}$), with

$\mathcal{F}^* = [(A/F)/(A/F)_R]$. (5)

This dimensionless relationship

$$\mathcal{F}^* = f(\zeta) \qquad (6)$$

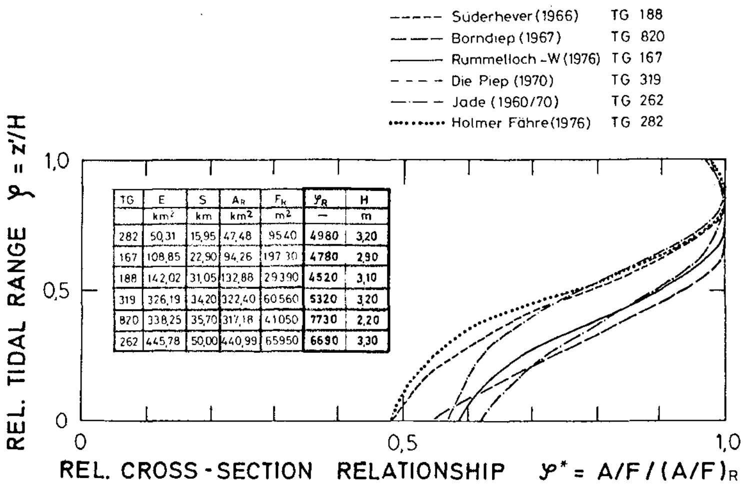
is used as a basic relationship for every further comparison (see Fig. 5).

The following 4 parameters are of main interest for the stability analysis:

- the vertical distribution curve ($\mathcal{F}^*(\zeta)$)
- the range of the ($\mathcal{F}_R$)
- the range of the corresponding (A_R) (meaning a "measuring area" for modelling purposes)
- the mean tidal range (H)

As a first result of this investigation about morphological similarity it was posible to work out some significant attributes:

- The vertical distribution-curve ($\mathcal{F}^*(\zeta)$) shows a rather uniform characteristic,
- The ($\mathcal{F}_R$) (at the optimum) was found to have an average value of about 5,200 for the inner German Bight with a mean tidal range of about 3 m (cf. table on Fig. 5 and upper graph of Fig. 10).
- One investigated tidal basin of an area with a smaller mean tidal range of about 2,2 m (Borndiep, The Netherlands) showed a <u>greater</u> $\mathcal{F}_R$ -value.
- The A_R-value was found mearly to be almost equal with the area of the tidal basin (E) at MHW-level.



TG	E	S	A_R	F_K	φ_R	H
	km²	km	km²	m²	—	m
282	50,31	15,95	47,48	9540	4980	3,20
167	108,85	22,90	94,26	19730	4780	2,90
188	142,02	31,05	132,88	29390	4520	3,10
319	326,19	34,20	322,40	60560	5320	3,20
820	338,25	35,70	317,18	41050	7730	2,20
262	445,78	50,00	440,99	65950	6690	3,30

Fig. 5

0878 Re 05

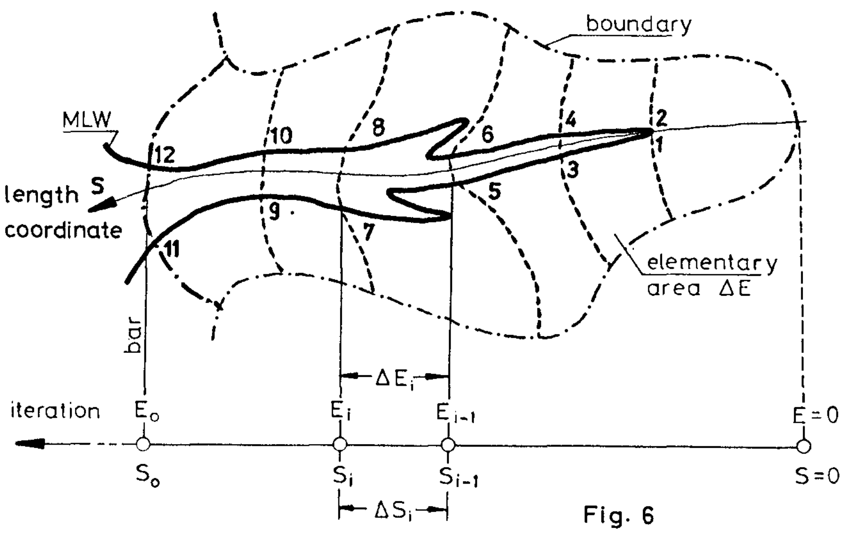


Fig. 6

Two-dimensional comparison of tidal basins within the physiographical unit (E_0)

In order to ascertain the horizontal variation of the relationships within the tidal basins, the sections were iteratively varied along the gully axis (see Fig. 6); in other words:
the A(z) becomes an increasing variable due to the gully-length coordinate (s) (Ref. 7). Precisely the procedure of analysis was carried out at every section as explained before.

The vertical variation ($\wp^*(\Upsilon)$) due to the gully length (s) of three investigates tidal basins of very different size and type is shown in the next three graphs (Figs. 7,8,9).

Fig.	Tidal basin	Area at MHW (E_0)	Mean tidal range (H)
7	Süderhever, 1966	142 km^2	3,0 m
8	Born-diep (NL)1967	320 km^2	2,2 m
9	Jade-Estuary 1960/70	446 km^2	3,3 m

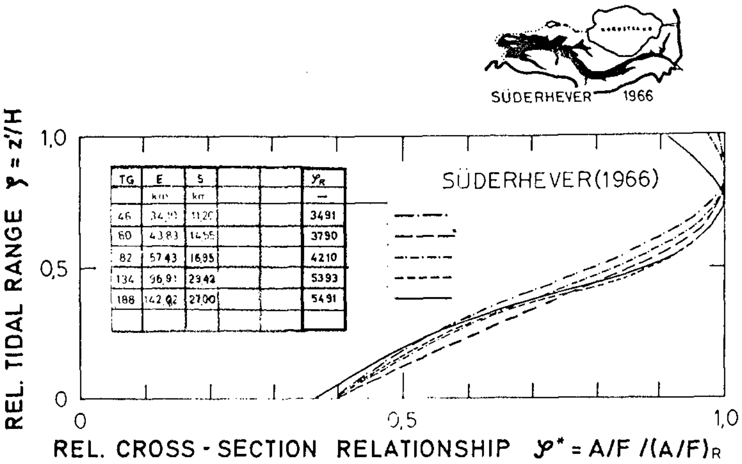
One most important result is that in every example the set of curves look rather similar and the curves always coincide very well.

The horizontal variation of the morphological characteristics only shows differences in the $\wp_R$-value. The dimensionless reference parameter seems to depend mainly on the mean tidal range (Fig. 10). On the one hand it is dependent on the order of the tidal range in general and on the other hand it seems to increase due to the decreasing tidal range along the gully length coordinate from land to sea.

The proof of instability

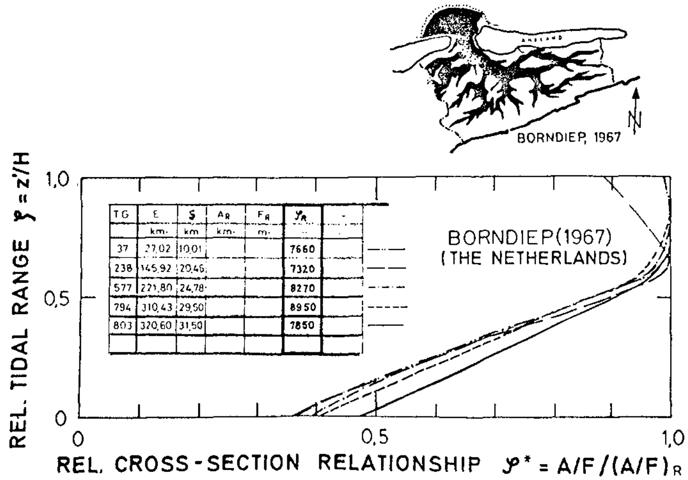
Referring to the last graphs on Fig. 10 we find some irregularities and deviations which may be of different origins, such as:

- methodical errors or mistakes
- influence of simplification (2 variables of space)
- individual attributes of the system that are not covered by the approach
- or even a certain degree of instability.



TG	E	S			φ_R
	km	km			—
46	34,90	11,20			3491
60	43,83	14,55			3790
82	57,43	16,95			4210
134	96,91	23,42			5393
188	142,02	27,00			5491

Fig. 7



TG	E	S	A_R	F_R	φ_R	-
	km	km	km	m		
37	27,02	10,01			7660	
238	145,92	20,46			7320	
577	221,80	24,78			8270	
794	310,43	29,50			8950	
803	320,60	31,50			7850	

Fig. 8

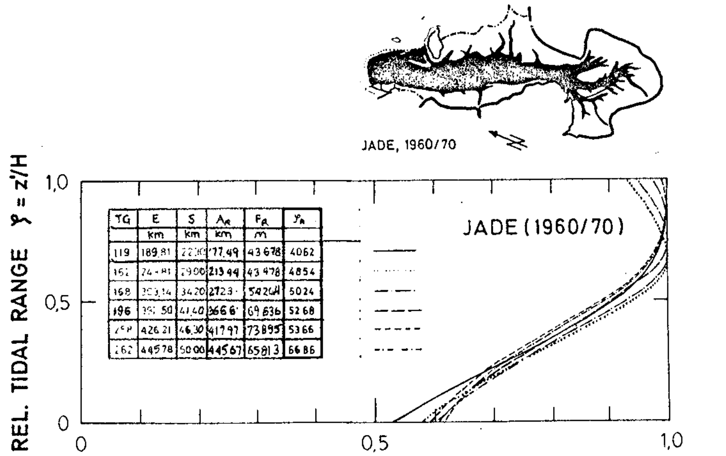

JADE, 1960/70
JADE (1960/70)
REL. TIDAL RANGE φ = z'/H
1,0
0,5
0
0
0,5
1,0
REL. CROSS-SECTION RELATIONSHIP φ^* = A/F/(A/F)R
TG | E km | S km | AR km | FR m | φ_R
119 | 189,81 | 77,49 | 43 678 | 4062
213 44 | 43 478 | 4854
3420 | 5024
196 | 41,40 | 69 636 | 5268
426 21 | 46,30 | 41797 | 73895 | 5366
44578 | 5000 | 44567 | 65813 | 6686
0878 Re 08

Fig. 9

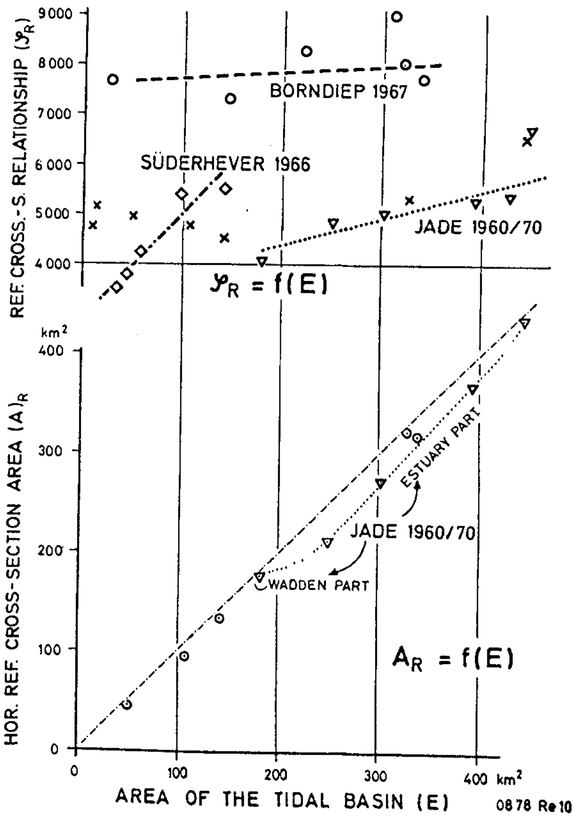

REF. CROSS.-S. RELATIONSHIP (φ_R)
9000
8000
7000
6000
5000
4000
BORNDIEP 1967
SÜDERHEVER 1966
JADE 1960/70
φ_R = f(E)
km²
400
300
200
100
0
HOR. REF. CROSS-SECTION AREA (A)R
ESTUARY PART
JADE 1960/70
WADDEN PART
AR = f(E)
0
100
200
300
400 km²
AREA OF THE TIDAL BASIN (E)
0878 Re10

Fig. 10

However, this is an open question at the present, and the deviations must be analized systematically by future investigations.

For these reasons we have to appreciate all the more the measurements of a tidal regime in the nature of which the non stability is well-known from its time-dependent change in the past towards an equilibrium state. The change of the characteristic form parameters are to be proved by the tidal river EIDER in the inner German Bight, which was dammed off at km 78 in 1936 (note the black part on Fig. 11.)
To get some idea about the change of the regime during the following 30 years the very heavy accumulation of about 50 Mio m^3 of silt has been observed outside the barrage over an area of about 25 km^2 and 30 km length.

In the lower part of the graph 3 time-stages of the investigated change of the regime are shown schematically (1935, 1936 and 1967). As an example the three time-stages are pointed out for the selected profiles nos. 78 and 115 at km 10 and km 20 in front of the barrage which are to be discussed subsequently in the next two graphs (Figs. 12 and 13).

The related (A/F)-distribution $\varphi^*(\xi)$ is mearly the same just before and just after the damming off in 1935 and 1936 as can be shown on both profiles. But in contrast, the $\varphi^*(\xi)$-curve of the situation 31 years later in 1967 after the heavy accumulation mentioned above is not quite similar.

The corresponding φ_R -distribution due to the length-coordinate (s) is given in the next graph (Fig. 14). It is surprising to find that the φ_R -values of the non-influenced tidal river EIDER as a constant almost exactly the same as the average value of about 5,200 that was analized from tidal basins, although the $\varphi^*(\xi)$-curve was very different.

At the second time-stage just after the damming-off the reference values were found to be drastically diminished, as can be seen from the dotted line near the abscissa. Within the next 31 years the values had increased slowly towards the original level of 5,200 due to the accumulation of silt that had taken place.

At the moment we are not quite sure about the degree of non-stability (instability) because the type of the tidal basin has changed too much. But for other reasons a certain accumulation in consequence of the damming-off is still to be expected.

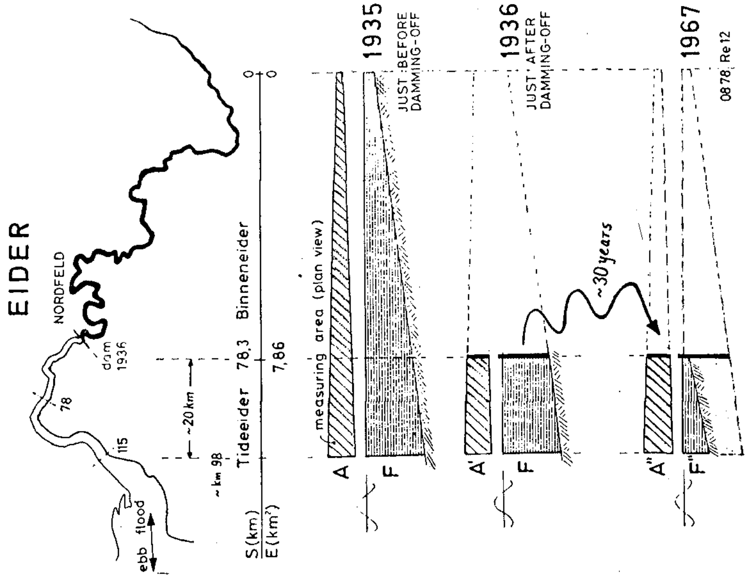
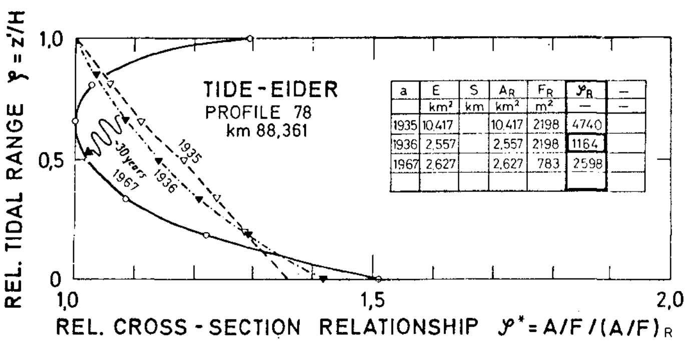
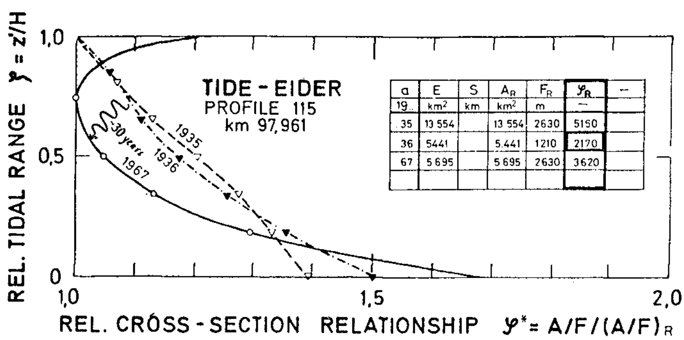


Fig. 11



a	E	S	A_R	F_R	φ_R	—
	km²	km	km²	m²	—	—
1935	10,417		10,417	2198	4740	
1936	2,557		2,557	2198	1164	
1967	2,627		2,627	783	2598	

Fig. 12



a	E	S	A_R	F_R	φ_R	—
19..	km²	km	km²	m	—	
35	13 554		13 554	2630	5150	
36	5441		5.441	1210	2170	
67	5 695		5 695	2630	3620	

Fig. 13

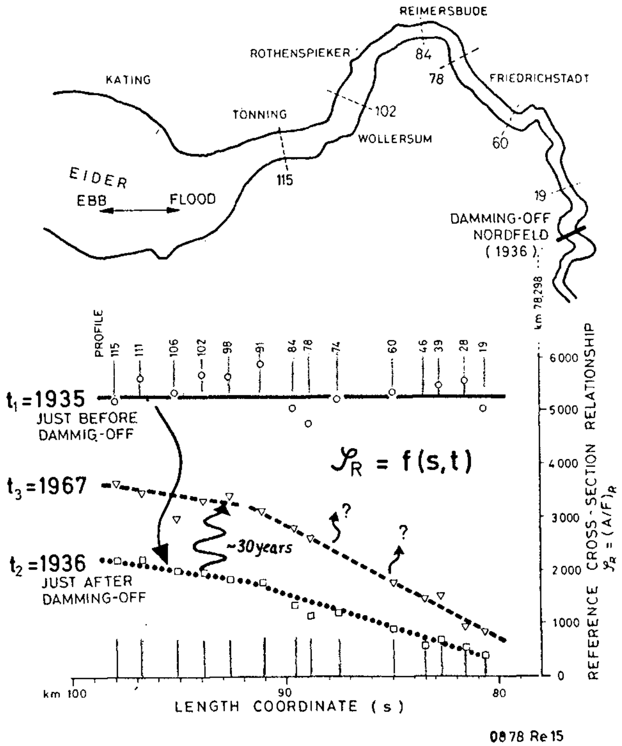

REIMERSBUDE
ROTHENSPIEKER
KATING
FRIEDRICHSTADT
TÖNNING
102
WOLLERSUM
EIDER
EBB
FLOOD
DAMMING-OFF
NORDFELD
(1936)
km 78,298
PROFILE
t_1=1935
JUST BEFORE
DAMMIG-OFF
$\mathcal{S}_R$ = f(s,t)
t_3=1967
~30years
t_2=1936
JUST AFTER
DAMMING-OFF
REFERENCE CROSS-SECTION RELATIONSHIP
$\mathcal{S}_R = (A/F)_R$
LENGTH COORDINATE (s)
0878 Re 15

Fig. 14

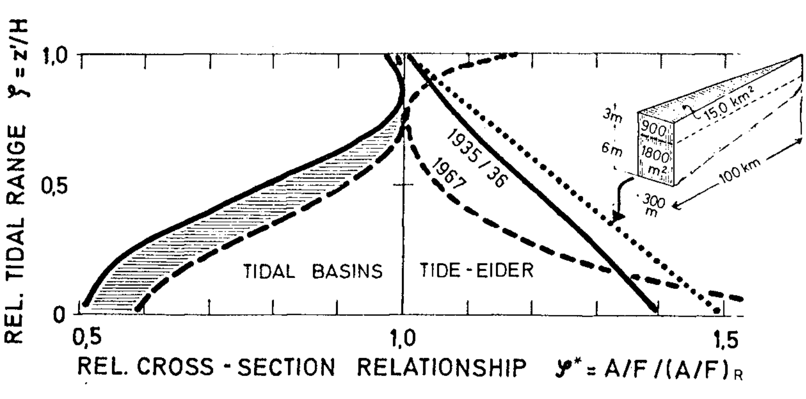

REL. TIDAL RANGE $\zeta = z'/H$
1935/36
1967
TIDAL BASINS
TIDE - EIDER
15,0 km²
900
1800
m²
100 km
300 m
REL. CROSS - SECTION RELATIONSHIP $\mathcal{S}^* = A/F/(A/F)_R$

Fig. 15

Conclusions

Morphological change of tidal regimes is, to be precise, dependent on four variables:

- 3 variables of space and
- 1 variable of time

In addition complicated boundary conditions of the regime have to be covered. As a consequence a certain simplification due to the approach and a certain selection of parameters as well as a drastic data reduction is necessary and even possible.

In order to apply the method, morphological data (maps) in particular, as well as mean tidal conditions, must be known. The extensive quantity of data can only be handled with the help of computers, as has been pointed out in earlier publications.

Because of open boundary conditions in tidal flats, stability criteria must specified by further systematic investigations, and with reference to the boundary conditions. The universal application of these investigations to other tidal basin systems may result in similar equilibrium characteristics.

At the momant there are only a few results, and these have only exemplary significance. But these first results promise to be a good tool in stability analysis and forecasting modelling of tidal flats and tidal basins due to man-made influences on the regime.

Acknowledgements

This study is part of the Research Project "Morphological Analysis of Tidal Basins" which is carried out in the Special Research Center 79 of the Technical University of Hannover. The research upon which this paper is based was supported by the Deutsche Forschungsgemeinschaft which is greatfully acknowledged by the author.

Morphological data was provided by various coastal administrations of Germany, The Netherlands, Danmark and Great Britain. Special thanks are due to my colleagues Dipl.-Ing. H. Messal and R. Dieckmann who were always available for help and discussion.

References

1) BRUUN, P., GERRITSEN, M.: Stability of Coastal Inlets. Journal of the waterways and Harbors Division. Proc. of the ASCE WW3, May 1958

2) HENSEN, W.: Ausbau der seewärtigen Zufahrten zu den deutschen Nordseehäfen, Hansa Nr. 15, 1971

3) O'BRIEN, M.P.: Equilibrium Flow Areas of Inlets on Sandy Coasts. Journal of Waterways and Harbors Div. Proc. of the ASCE. Vol. 15, No. WWI, Feb. 1969

4) RENGER, E., PARTENSKY, H.-W.: Stability Criteria for Tidal Basins. Proc. 14th Int. Conf. on Coastal Engineering, 1974

5) RENGER, E.: Quantitative Analyse der Morphologie von Watteinzugsgebieten und Tidebecken. Mitteilungen des Franzius-Instituts für Wasserbau und Küsteningenieurwesen der TU Hannover, H. 43, 1976

6) RENGER, E.: Grundzüge der Analyse und Berechnung der Morphologie von Watteinzugsgebieten und Tidebecken. Mitteilungen des Franzius-Instituts für Wasserbau und Küsteningenieurwesen der TU Hannover, H. 44, 1976

7) RENGER, E.: Quantitative Geomorphological Analysis of Erosional Topography with Respect to the Morphology of Tidal Basins. XVII Int. Conf. Ass. for Hydr. Res. 1977

8) RODLOFF, W.: Über Wattwasserläufe. Mitteilungen des Franzius-Instituts für Grund- und Wasserbau der TU Hannover, H. 34, 1970

9) VOLLMERS, H., GIESE, E.: On the Reproduction of morphological Changes in a Coastal Model with movable Bed, Proc. XVI. IAHR Congress, Sao Paulo, Vol. I., 1975

10) WALTHER, Fr.: Zusammenhänge zwischen der Größe der ostfriesischen Seegaten mit ihren Wattgebieten sowie den Gezeiten und Strömungen. Forschungsstelle Norderney der Niedersächsischen Wasserwirtschaftsverwaltung, Jahresbericht 1971, Band 23, 1972