CHAPTER 57

STORM SURGE PREDICTION IN TIDAL RIVERS: A NEW CONCEPTION

by Winfried Siefert*)

INTRODUCTION

The heights of extreme storm surges in the North Sea rise up to 4 or 5 m above mean high tide. Warning services are established along the coast, mainly based on empirical connections between weather and tide data. A lot of wrong announcements are given especially for places up the tidal rivers. This can become disasterous for a lot of modern, highly sensitive harbour facilities.

Thus storm surges are the famous plagues of the southern North Sea coast. Moreover, the "ten plagues of Germany" occurred during the last 16 years.

So recently a new conception for storm surge prediction in tidal rivers was developed - with the result of a lot of new understandings of tidal dynamics in rivers (SIEFERT, 1968). We investigated about 130 storm surges, hindcasting all of them and forecasting about 20 of them, and analysed their behaviour in tidal rivers. Now we are able to forecast the upstream heights and even the shape of the surge curve in the Elbe with an accuracy of ± 2 dm, 6 hours in advance. In order to do this, informa-

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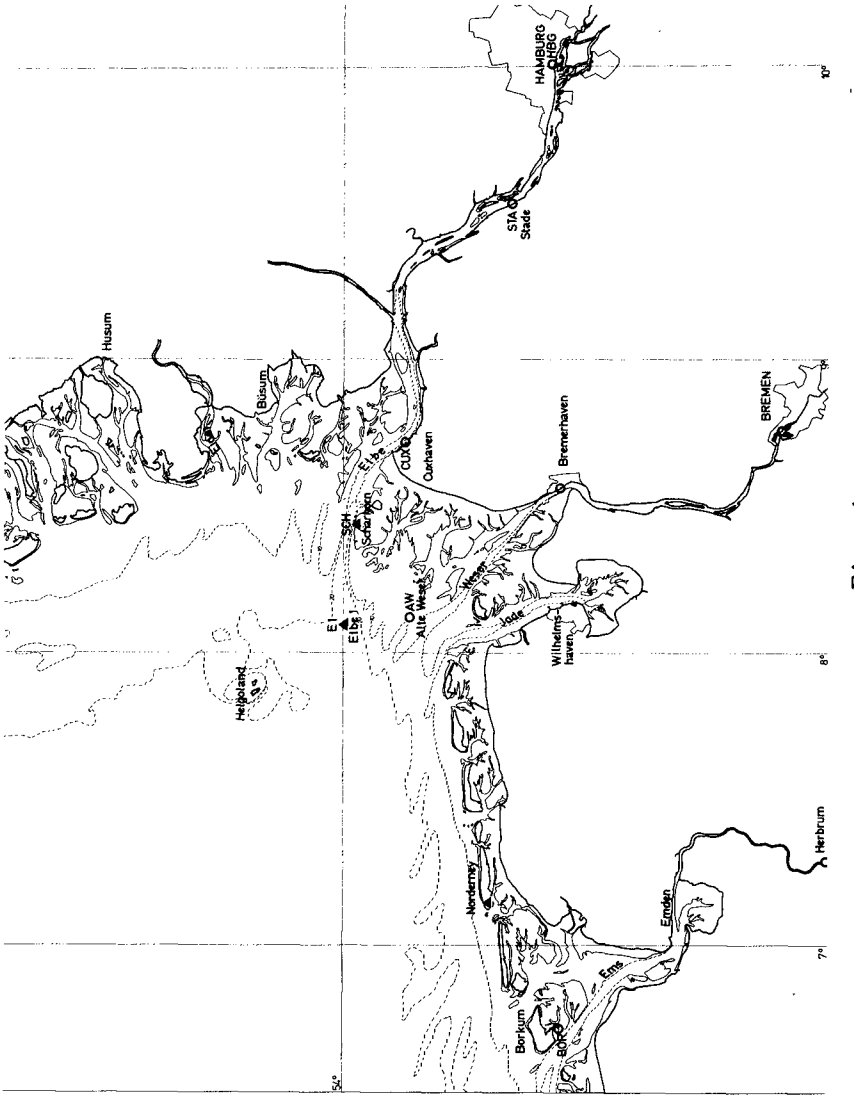
HAMBURG
OHBG
STA
Stade
Husum
Büsum
CUX
Cuxhaven
Bremerhaven
BREMEN
SCH
Scharhörn
Elbe 1
Elbe 2
OAW
Alte Weser
Weser
Jade
Wilhelms-haven
Helgoland
Norderney
Herbrum
Emden
Ems
Borkum
BORK
10°
8°
7°
54°

Fig. 1

tions about the boundary values are necessary. We tried to obtain informations from the stations on fig. 1 (circles = tide gauges, triangles = weather stations). It turned out that for a sufficiently exact prediction for the Elbe region data from Borkum (tide), Cuxhaven (tide) and Scharhörn (wind) are necessary.

CONCEPTION

The new conception for understanding the dynamics of storm surges in rivers and for developing a reliable warning system is very simple: Storm surge behaviour in a river is treated as a problem of combination of boundary values and eigenvalues. To solve these problems mathematically, a lot of differential equations have to be treated. This is not yet sufficiently possible. It can easier be solved in a hydraulic model (including all eigenvalues) with variation of the boundary values. This was done for the Elbe (for 200 river-km), with special respect to Hamburg, and thereafter transferred to other rivers (fig. 2).

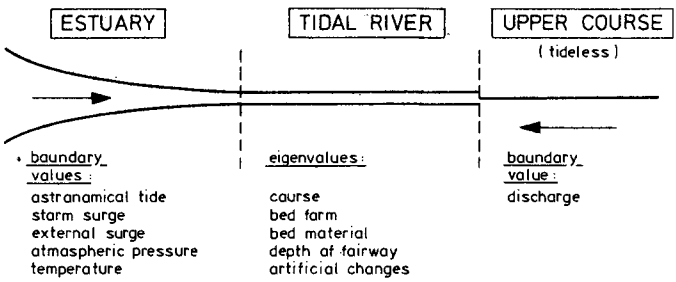

Fig. 2

It turned out that all other than astronomic influences result in a special, individual surge curve in the estuary. So we have to consider as seaward boundary values only two curves: the (more or less regular) tide curve and the (irregular) surge curve. These have to be combined with the eigenvalues by tide-river-dynamics. The latter can be considered constant during individual storm events. They are mainly changed by man (deepening and widening of fairway, course corrections, new dyke lines, weirs, dams, sluices etc.) and so are varying through the decades. The upper boundary value (discharge) can also be treated as constant during a surge.

The identification of the seaward boundary values is done by separation of the astronomical or (in first-order approximation for this area) of the mean tide wave and the surge wave (fig. 3):

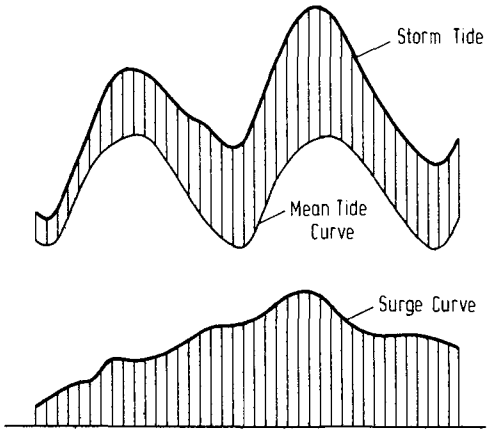

Fig. 3

The surge curve is characterized by 5 parameters as shown in fig. 4. After these treatments we investigated how these curves behave, when they proceed in a river, and especially, how they interact.

CHARACTERISTIC SYSTEM NUMBER

Correlations between storm tide heights of different gauges along a tidal river show no significant coherences. For interpretation of tidal dynamics it is necessary to take into account the complete curves.

HARLEMAN and LEE (1969) give some methods for the solution of tidal propagation in estuaries. The harmonic solution of the linear function equation for the tidal elevation at any x and t

$$\eta = \frac{\eta_{oH}}{2} \cdot e^{-\frac{\delta x}{2}} \cdot (e^{\mu x} \cos(\sigma t + kx) + e^{-\mu x} \cos(\sigma t - kx))$$

contains the amplitude attenuation coefficient μ. The authors computed the damping parameter μx for the Delaware estuary. So did PARTENSCKY and BARG (1977) for the rivers Elbe, Weser, Ems and St. Lawrence.

Using μ and the variation of the damping parameter $\frac{d\mu x}{dx}$, the simple equation for wave propagation in shallow water could be modified to

$$c = S \cdot \sqrt{g \cdot d^*}$$

with g = acceleration of gravity
d^* = representative water depth in a river

It turned out that the characteristic system number S of a river can be computed as

$$S = \sqrt{\frac{1}{\mu} \cdot \frac{d\mu x}{dx}}$$

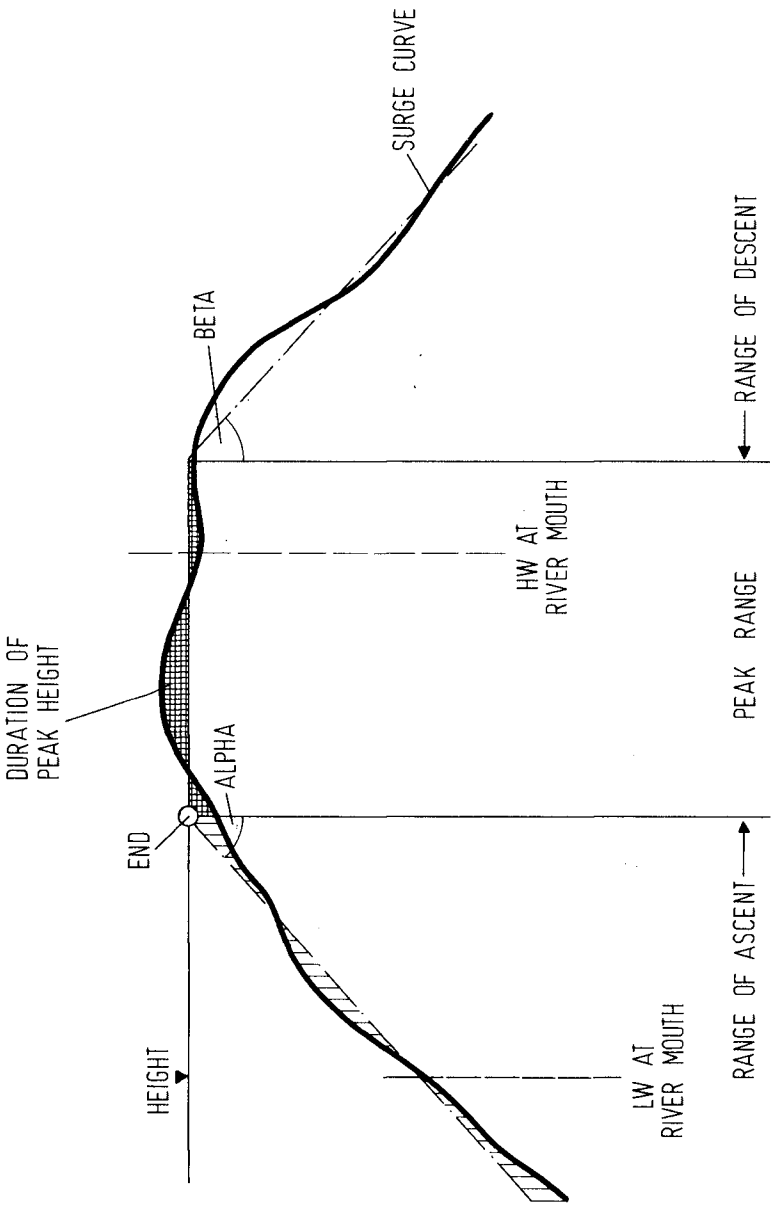

Fig. 4
Storm Surge Parameters

The values vary from 0.56 for the Elbe to 1.11 for the Delaware (SIEFERT, 1978). It changes with time, i.e. with secular changes in the river as were mentioned before.

Computations of a lot of tides and storm surges showed that the "representative water depth" d^* in a river is characterized by the depth of the fairway d_F. This fact is best proved in rivers with a distinct fairway of a certain length, as the tide and storm surge dynamics are the more concentrated at the fairway the deeper it is, relative to the rest of the cross-section.

So the equation

$$c = \sqrt{\frac{1}{\mu} \cdot \frac{d\mu x}{dx}} \cdot \sqrt{g \cdot d_F}$$

shows that c is a function of d_F alone only as long as μ and $\frac{d\mu x}{dx}$ are constant. It can be started from the principle that they are during the time of a storm tide.

LONG WAVE INTERACTIONS

If that is so, the so-called pick-a-back-effect during propagation of tide and surge waves in a river results in special interactions as shown in fig. 5. Thereby it

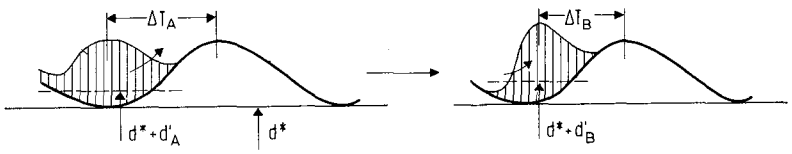

Fig. 5

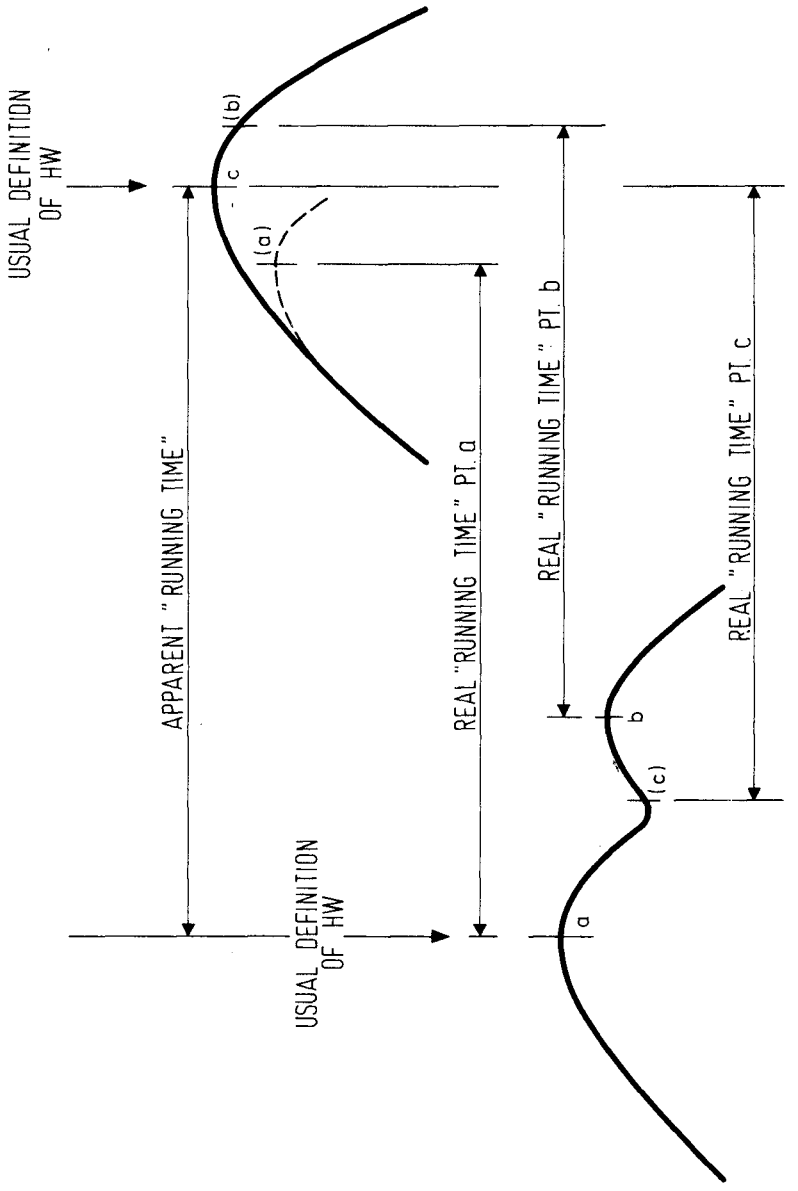

Fig. 6
Example Shape Variation of Tide Curves Between two Locations

becomes very difficult to identify real and comparable peak heights and peak velocity differences between two locations (fig. 6).

The interactions result in differing propagation velocities not only of the surge, but also of the tide waves. This may be illustrated by the shape of the surge curves on fig. 7. They occurred on Jan. 3, 1976 during the highest storm tide ever registered in the Elbe. The comparison of the shapes

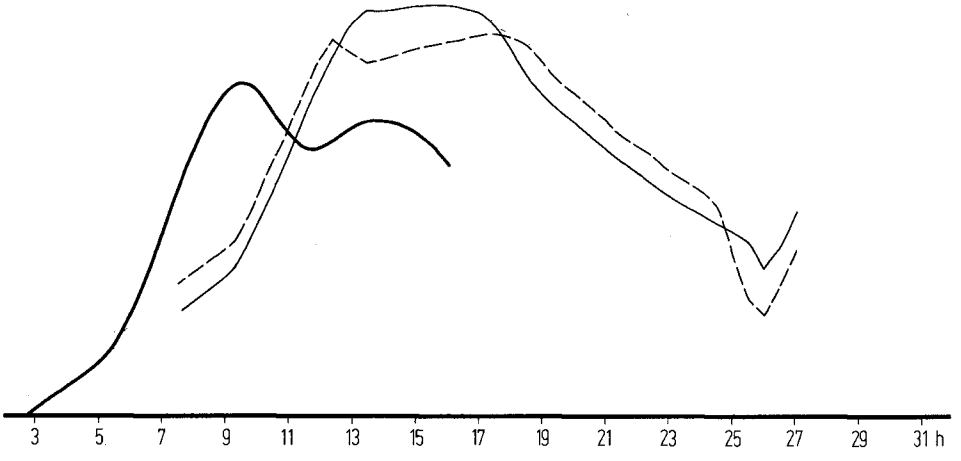

Fig. 7

Thick solid line: surge wave in Cuxhaven
Thin solid line : surge wave in Hamburg (101 km upstream), evaluated under the hypothesis of undisturbed tide wave propagation
Dashed line : surge wave in Hamburg, evaluated under the hypothesis that tide wave propagation from C. to H. lasted 3 h instead of (normal) 4 h

give the hint that tide waves must run a lot faster than usual. As only small alterations of the surge curves are to be expected, best fit shifts have to be found. (This is one of the first results of an extensive computer investigation that is still in progress.)

ACCURACY OF PREDICTIONS

At the moment the "Hamburger Sturmflut-Warndienst" (WADI) is working on the basis of data from Borkum and Cuxhaven (tides) and Scharhörn (wind), fig. 1 . The evaluation is based on the parametrisation of the surge curve as indicated on fig. 4 . This allows predictions of the storm tide maximum in Hamburg 6 to 8 h in advance with an accuracy of

± 25 cm in height
± 30 min. in time.

All values scatter within these borders.
Note: The results were not only obtained by hindcoasts, but also by about 20 forecasts since 1976.

As soon as the quantitative effects of interaction dynamics will be physically understood, they will be taken as a new basis for predictions of complete storm tide developments in tidal rivers.

DEVELOPMENT OF STORM TIDE HEIGHTS SINCE 1900

The analysis of more than 130 storm tides proved to give a suitable data collection to answer the question, why the heights of storm tides in tidal rivers of the southern North Sea increased so remarkably during the last decades. It is often presumed that this development is an effect of river improvements in Ems, Weser, and Elbe respectively.

For the purpose of finding the real reason, mean heights of high storm surges - each mean height representing about 4 to 12 events in a decade - were calculated. Their heights above mean high water level (MHW) varied considerably, with a resultant increase of about 80 cm from 1900 to 1975 (fig. 8). But variations as well as total increase in Hamburg can be explained by changes of surge curve parameters in Cuxhaven (101 km downstream). On fig. 8 only the influences of ALPHA and HEIGHT (see fig. 4) are taken into account. That yields to the conclusion that the increase in surge heights in Hamburg is almost completely an effect of higher surge curves in the Elbe estuary, i.e. an effect of stronger wind in a critical direction.

REFERENCES

HARLEMAN, D.R.F. LEE, C.H.: The Computation of Tides and Currents in Estuaries and Canals. Mass. Inst. of Techn., Hydrodyn. Lab., Techn. Bull. No. 16; Cambridge, Mass. 1969

PARTENSCKY, H.-E. BARG, G.: Energy Dissipation in Tidal Estuaries. Proc. 15th ICCE, ASCE, New York, N.Y. 1977

SIEFERT, W.: Sturmflutvorhersage für den Tidebereich der Elbe aus dem Verlauf der Windstaukurve in Cuxhaven. Mitt. Franzius-Inst., Techn. Univ. Hannover, Vol. 30, 1968

SIEFERT, W.: Über das Sturmflutgeschehen in Tideflüssen. Mitt. Leichtweiß-Inst., Techn. Univ. Braunschweig, Vol. 63 1978

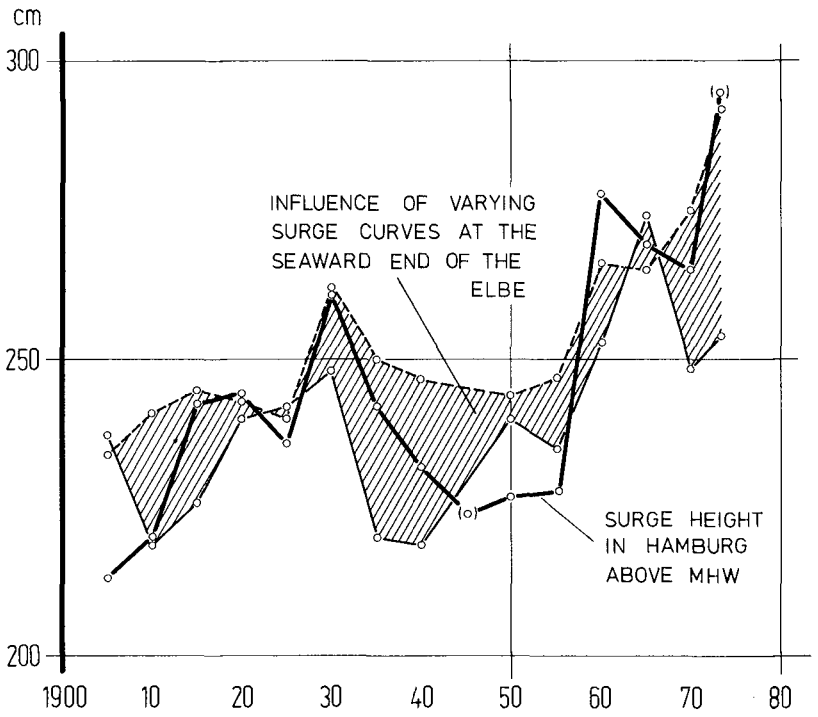

Fig. 8

Development of Mean Heights of High Storm Surges in Hamburg, Compared with Development of Surge Curve Parameters in Cuxhaven