CHAPTER 59

Analysis of Storm Tide Waves

by

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ABSTRACT

First results of a wave investigation program in the Outer Weser (German Bight of the North Sea) point out, that under storm conditions higher waves than computed by the normal prediction methods are possible in the exterior estuary. In the interior estuary higher waves occur mainly as a sort of swell. The influence of bad weather conditions on the probability of runs of waves with $H^* > H_{1/3}$ is shown in two examples in comparison with a theoretical investigation.

INTRODUCTION

The importance and necessity of field investigations as far as waves are concerned has been underlined by experts again and again. Though there were several investigations in the deep water of the North Sea, in the wadden area and on sandy shores of islands one cant' find hardly any in estuaries. There are given computation and prediction methods for straight shores with parallel contours or islands and shores with concentric circular contours, but there is hardly any example for shores, bars and sand-banks with deep channels between them and another bar following a few kilometers behind (11). The knowledge of the often very complicated wave systems in an estuary, i.e. the correlation of water level, tidal currents, waves, orbital currents and morphological changes leads to an estimation of the effect of waves on structures and morphology (1) in the distinct regions of an estuary and vice versa. For this reason a field investigation program was started in 1975, which is carried out by the Wasser- und Schiffahrtsamt Bremerhaven, an office of the Federal Waterways Administration, and is supported by the Federal Ministry of Research and Technology. FIG. 1 shows a part of the Weser estuary with the locations ST, RSO, RSW, TPO and TPW. The following investigations are planned on this locations in detail:

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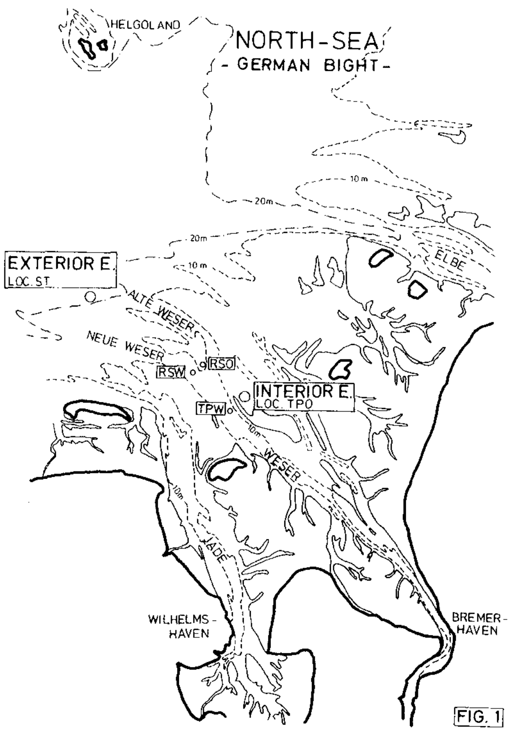


FIG. 1

a. alteration of significant data of waves entering the estuary

b. distribution of wave energy behind reefs and bars

c. influence of waves on the morphological shape of the bottom and - vice versa - the influence of morphology on the waves

d. determination of design data for all structures

e. influence of waves on the assignment of ships and particularly of long-period-waves on the lurch of deep-drawing ships with a small keel-clearance.

STORM TIDE WAVES

On the 3rd of January, 1976, the wind in the German Bight grew from 16 m/s to nearly 30 m/s (Beaufort 11). The direction changed from 175° (S) to 295° (WNW). The water level at gauge ALTE WESER ros e to NPH + 9.10 m, while the mean Low Water (MLW) is NPH + 6.32 m.

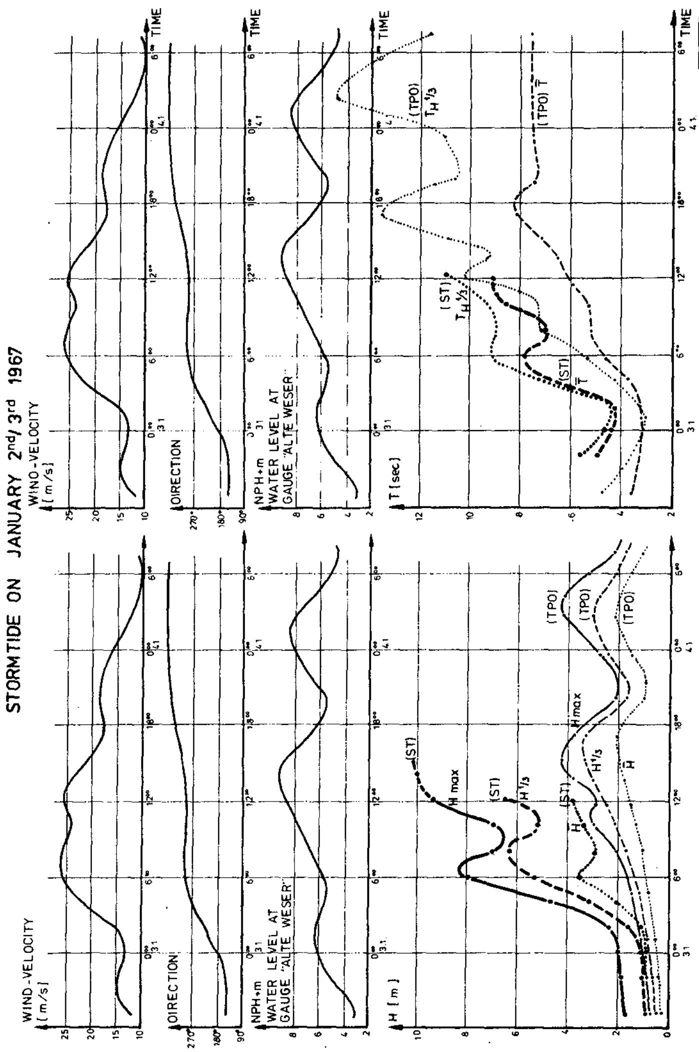

STORMTIDE ON JANUARY 2nd/3rd 1967
WIND-VELOCITY [m/s]
DIRECTION
NPH+m WATER LEVEL AT GAUGE 'ALTE WESER'
H [m]
T [sec]
TIME
H max
H 1/3
H̄
(ST)
(TPO)
$T_{H 1/3}$
$\overline{T}$

FIG. 2

Though the wave buoys and gauges were not yet installed completely we succeeded in gaining some data at the locations ST and TPO. A third wave gauge failed by collision with a drifting ship.

Loc. ST lies at a water depth of about 22m. It is to record the waves coming from the open sea and produces prototype data for the exterior estuary. Loc. TPO lies in front of a sand-bank at about 4m water depth and represents the interior estuary.

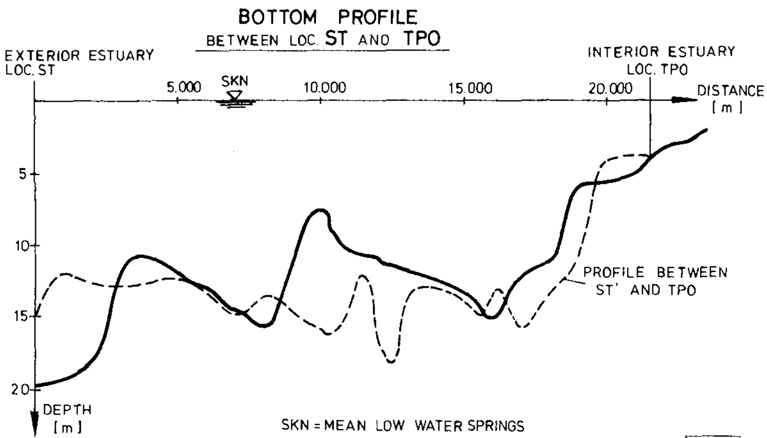


FIG. 3

In FIG. 2 the measured values are plotted as a function of time. You can see the mean and significant wave height $\bar{H}$ and H 1/3 in the exterior e. growing with increasing wind-velocity very quickly and becoming smaller with decreasing wind-velocity. Unfortunately the recorder broke down at 3.oo p.m. because the measuring range wasn't expected to be so wide. The mean and significant periods $\bar{T}$ and T 1/3 show nearly the same attitude dependent on wind-velocity.
With a time-lag of about two hours the mean and significant wave heights $\bar{H}$ and H 1/3 come to their maximum values in the interior estuary. A second peak was registrated on the 4th of January at about 3.oo a.m. It is obvious that in this case the height follows the water depth during a decreasing wind-velocity. Striking is the strong increase of the periods $T_{H\ 1/3}$ in the interior estuary up to values of 16 sec. But I'll come back to this phenomenon later on.

ALTERATION OF HEIGHTS AS A FUNCTION OF WIND - VELOCITY AND WATER DEPTH

As there had been a lot of measurements in the meantime, the slope of wave height, wind-velocity and water depth for this region could be investigated more thoroughly. For this purpose records at an almost coincident water level or wind velocity were combined. FIG. 4 shows, that in the interior estuary the correlation between $\bar{H}$ respectively $H_{1/3}$ and the water depth (r= o.85 - o.87) is much better than in the exterior (r= o.46 - o.52).

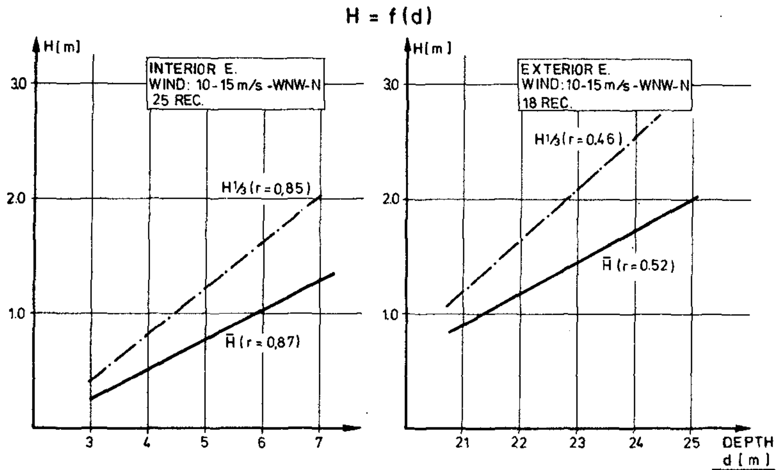


FIG. 4

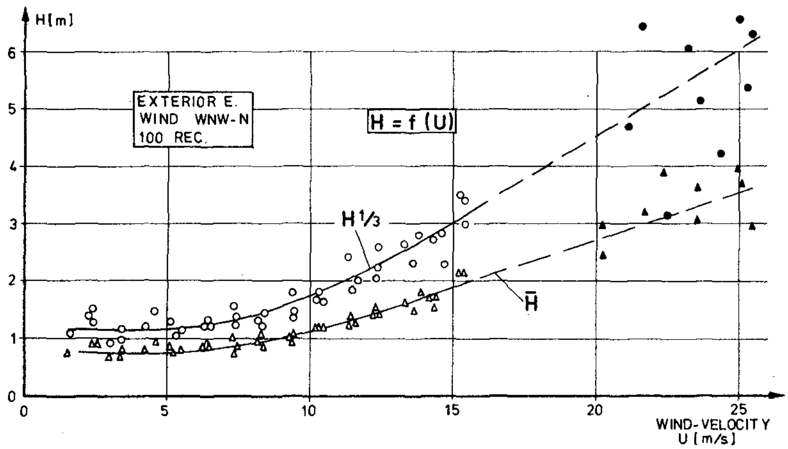
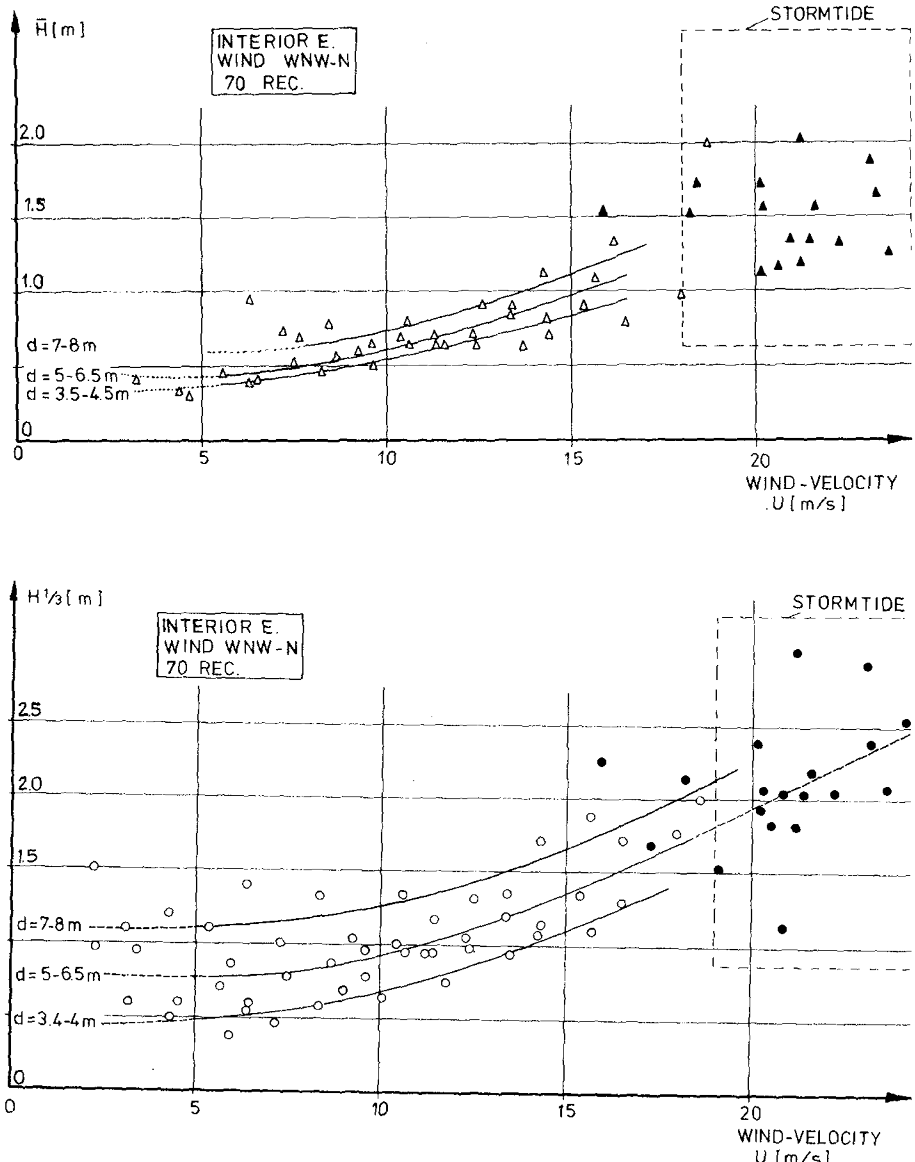


FIG. 5

FIG. 5 shows a good correlation between heights and wind-velocity for the exterior e. as it is to be found in literature --- mostly as a linear slope. The values obtained in the storm tide (U=2o - 25 m/s) fit this drawing.



H = f (U)

FIG. 6

In FIG. 6 the same values for the interior e. are plotted, split into single graphs for $\bar{H}$ and $H_{1/3}$. In this case the values can be clearly arranged in groups with different water depths, showing that the depth-dependency is more important than in the exterior estuary.

ALTERATION OF WAVE PERIOD AND STEEPNESS

An astonishing fact gave the strong increase of the wave periods in the interior during the storm tide. The significant period $T_{1/3}$ came up to more than 15 s. The evaluation of more data in this field gave the latest findings, that waves in extraordinary weather conditions occur mainly as swell in this region. With the simplified assumption, that

$$L = \bar{T}^2$$

a mean wave length of 80 m is to be found, which may have a dangerous influence on deep-drawing ships in a narrow channel.

One should believe that - similar to a tidal wave - waves coming from the open sea into an estuary become steeper and shorter by shoaling, refraction and diffraction. Just the opposite seems to be true in this case. After evaluating a lot of additional records it could be pointed out, that as a general principle periods become longer during the penetration of waves into this estuary, though there are deep channels between the shoals. The local wind influence seems to be of subordinate importance.
FIG. 7 shows the alteration of the significant wave period $T_{1/3}$ and the so called steepness factor

$$s = \frac{\bar{H}}{g \cdot \bar{T}^2}$$

for two groups of waves with different height.

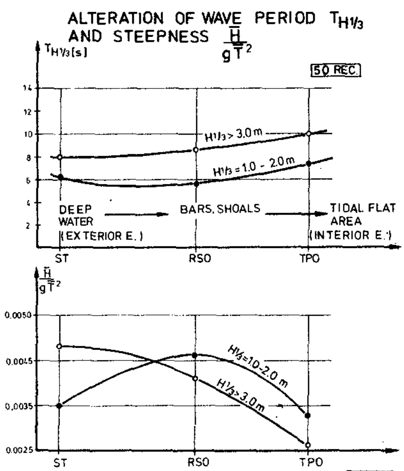


FIG. 7

You can see that the periods increase and the steepness factor becomes small with decreasing water depth, i.e. while the waves approach the interior estuary. The same phenomenon was detected by SIEFERT (1o) with measurements in the wadden sea of the Outer Elbe. (Loc. RSO in this case lies on a bar where breaking of waves occurs at a smaller water depth (Fig. 7).

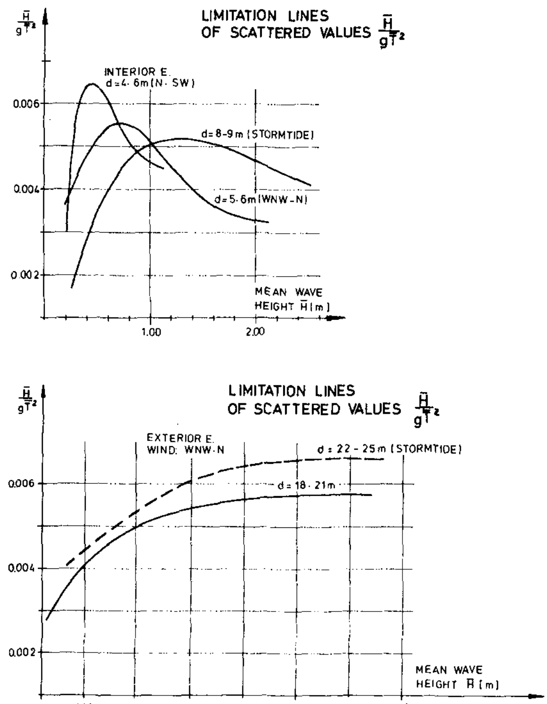


FIG. 8

The increasing period of waves penetrating the interior estuary necessarily reduces the steepness factor s with a constant or decreasing height. While in the exterior estuary during a high wind velocity and water depth (that is for example during a storm tide) the steepness increases and comes to a constant value (limitation line of the scattered values of $s = \frac{\bar{H}}{g\,\bar{T}^2}$);

the scattering of values with a larger water depth in the interior e. is wider, the maximum values however are smaller. The values for a different wind-direction are plotted in comparison to show the irritability of wave climate against the different factors of influence. Obviously the steepness in the interior e. decreases with increasing mean wave height, dependent on wind-direction and therefore the fetch-length too. This fact seems to be important for the design criteria of structures.

Alteration of wave parameters

FIG. 9 shows the mean period $\overline{T}$ as a function of the mean wave height $\overline{H}$. Apart from the differences between the interior and exterior e. on normal conditions one can see, that a storm tide causes a considerable alteration of wave characteristics. By this chance it becomes obvious that abnormal wind conditions evoke shorter periods and steeper waves in the exterior, while in the interior just the opposite is true.

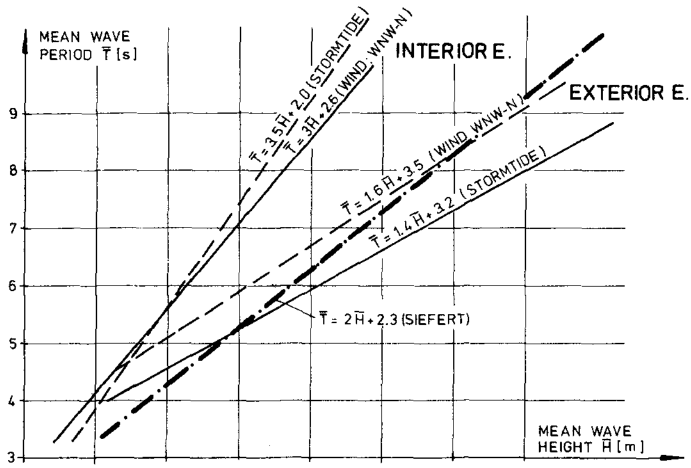


FIG. 9

FIG. 1o shows the mean ratio of periods and height in the interior and exterior e. during normal and storm conditions.

TABLE 1 (FIG. 1o)

WAVE HEIGHT

		$\overline{H}$ / $H_{1/3}$ / $H_{1/10}$ / H_{max}
INTERIOR ESTUARY	AVERAGED VALUES FROM 1oo RECORDS:	1 / 1.47 / 1.75 / 1.98
	STORM TIDE VALUES: (44 REC)	1 / 1.55 / 1.85 / 1.89
EXTERIOR ESTUARY	AVERAGED VALUES FROM 1oo RECORDS:	1 / 1.5o / 1.86 / 2.14
	STORM TIDE VALUES: (16 REC)	1 / 1.55 / 1.95 / 2.3o

WAVE PERIOD

		$\bar{T}$	$T_{H1/3}$	$T_{H1/1o}$	T_{Hmax}
INTERIOR ESTUARY	AVERAGED VALUES FROM 1oo RECORDS:	1	1.27	1.3o	1.29
	STORM TIDE VALUES: (44 REC)	1	1.46	2.21	1.34
EXTERIOR ESTUARY	AVERAGED VALUES FROM 1oo RECORDS:	1	1.12	1.12	1.57
	STORM TIDE VALUES: (16 REC)	1	1.11	1.o9	1.o8

In afew words:

Interior: The ratio of the mean to the sign. periods increases at a storm tide very much. That is a hint to the transformation into swell. The ratio of the height doesn't change so much; maximum height decreases.

Exterior: Wave periods become smaller, the waves therefore become steeper. The ratio of mean to significant respektively maximum height increases. These results fit the frame of the words said before.

MAXIMUM WAVE HEIGHT

Because in the Outer Weser no investigations in the wave field had been carried out for a long period, the results of the storm-tide records were astonishing and startling at the same time, especially because the high wind-velocities had had only a short-time-occurence and the direction had changed permanently. After Mc Cowan a theoretical maximum wave height (for deep water) H_{max} = o.78 d =~19 m (d_m = 24 m) is possible. But waves with higher wind-velocities in the German Bight with its limited water depth are to be considered as shallow water waves and therefore wall turbulence friction takes effekt in addition to the free turbulence friction. Wave energy and height are reduced by this. DRAPER (3) has predicted (for this region of the North Sea) a maximum wave height of 17 m under conditions of a 5o-year-design storm with a duration of 12 hours.

If you consider a design storm with

wind-velocity: U = 4o m/s
duration: t = 5 hours
fetch-length: F = 25o km
effective f.-l-: w = 15o km

different prediction methods for the German Bight result in a significant wave height of

$$H_{1/3} = 7.o - 1o.5 \text{ m } (8).$$

With the revised prediction method of BRETSCHNEIDER (2) for shallow water under the above mentioned conditions a significant wave height of

$H_{1/3}$ = 6.7o m was evaluated for the exterior e.

and with the ratio of

$$\frac{H_{max}}{H_{1/3}} = \left(145 \frac{g \cdot d}{U^2}\right)^{0.1} \pm 10\ \% \quad (2)$$

a maximum wave height of 10.0 m is possible.

ROLL (6) deducts a maximum wave height up to 8.0 m from observations on lightships. During the storm tide of January 3rd a significant wave height of

$H_{1/3}$ =6.72 m was registrated in

the exterior estuary until the instrument failed. The max. wave height, which could be read in the incomplete record, was

10.0 m (end of registration width).

According to the steepness of the wave and its incomplete period one could estimate its height of about

12 - 13 m.

The maximum height in the interior estuary can hardly be predicted by well-known methods, because the ratio of

$$\frac{H_{max}}{d} = f\ (d,\ \text{topography}),$$

which is a function of water depth and sorounding topography (10), is very complicated in this area.
The highest possible propagating wave is after KISHI (5)

$H_{max} = 0.9\ d$ for $d < 0.1\ L$

$H_{max} = 0.146\ d$ for $d > 0.4\ L$

(with a parabolic change between the two boarders)

For normal waves with $L = \bar{T}^2$:

$H_{max} = 0.9\ d$ for $d < 0.1\ T_{H_{max}}^2$

$H_{max} = 0.146\ T_{H_{max}}^2$ for $d > 0.4\ T_{H_{max}}^2$

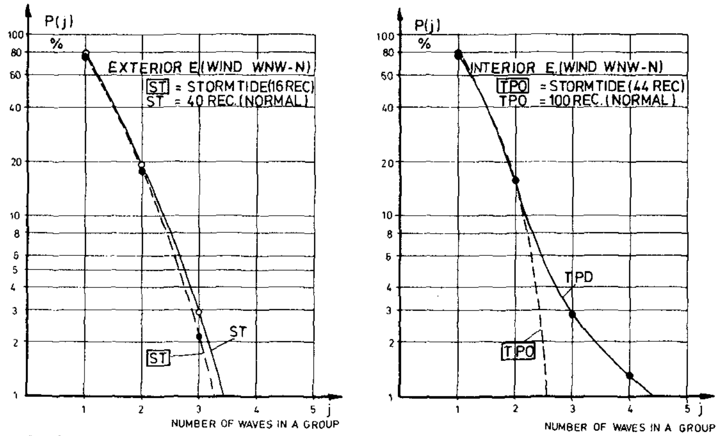
and with the given ratio of mean to significant period $\bar{T}/T_{H\,1/3}$ respectively max. period $\bar{T}/T_{H_{max}}$ the max. height becomes

$H_{max} = 0.9\ d$ for $d < 0.18\ \bar{T}^2$

$H_{max} = 0.26\ T^2$ for $d > 0.72\ \bar{T}^2$

The theoretical max. height H_{max} = 8.4 m for gentle slopes.

The comparison between normal and storm conditions in FIG. 12 turns out, that with the investigated wind-directions a higher probability of consecutive waves $H^* > H_{1/3}$ is not to be found. Its obvious that in the interior e. shorter runs of waves occur under bad weather conditions. This seems to be important for the design of all structures in this area.



PROBABILITY OF WAVE GROUP FORMATION, WAVES GREATER THAN $H_{1/3}$

FIG. 12

CONCLUSIONS:

The results of the relatively short measurements during the storm tide in comparison with records under more normal conditions can be comprised as follows:

a) The wave heights in the exterior e. are mostly wind-dependent, while the local wind-influence in the interior e. is subordinate to the water depth.

b) After wind-velocities more than 15-20m/s the higher waves in the interior e. occur with long periods changing to a sort of swell. Therefore there is a certain danger for deep-drawing ships,which has to be investigated more thoroughly. Max. wave heights are influenced by the reefs and bars in front of the interior e. and are reduced at a rate of about 50 - 60 %.

c) The max. heights in the exterior e. came up to a value of more than 10.0 m already in a short storm. Heights of more than 15.0 m are not impossible.

d) The wave parameters change with a different range in unusual weather conditions according to the above mentioned facts.

e) Runs of waves with $H^* > H_{1/3}$ don't occur more often under bad weather conditions than normally. In the exterior e. the distribution fits a theoretical one; in shallower water it is nearly the same as in the adjacent area of the Outer Elbe.

In the present investigations the influence of tidal currents upon

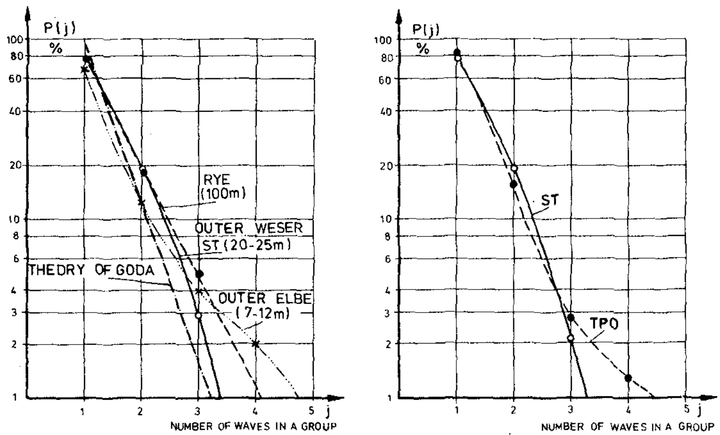
According to the measurements in question this height cannot be found in the interior estuary, because a considerable transformation of energy occurs on the reefs and bars. During the storm tide the measured max. wave height read

$$H_{max} = 4.05 \text{ m with a period of } 18.2 \text{ s.}$$

Later on we gained records after two hours with wind from WNW with 2o m/s, in which the max. height was 3.5 m with a period of 12s.

CONSECUTIVE HIGH WAVES

In addition to the highest water level and max. or significant wave height a certain dynamic strain by vibration or perhaps resonance caused by a run of waves of certain height can be important for the design of structures in coastal areas. Because of the unexpected high waves it was of great interest, to analyse the records of the storm tide and those under normal conditions in this regard. The problem has already been treated numerically by GODA (197o) (4) for wide spectra. Evaluations of field data under storm conditions were done by RYE (1975) (7). SIEFERT (1976) (9) determined the probability of consecutive high waves for an adjacent area of the Outer Elbe with its wadden sea. A comparison of the results is plotted in FIG. 11.



PROBABILITY OF WAVE GROUP FORMATION, WAVES GREATER THAN H1/3

FIG. 11

The drawing in semi-logarithmic scale shows, that the probability of groups of waves greater than the significant wave height $H_{1/3}$ in the exterior estuary best fits the theory of GODA (4). In the computation of 4o records there was no run of more than 3 consecutive waves. The probability in the interior e. shows a good correspondence with the results in the Outer Elbe.

the wave parameters has been neglected. It will be the task for the next time to find out this influence by measurements for distinct regions of the Weser estuary.

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