HEIGHT DISTRIBUTION OF ESTUARINE WAVES

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ABSTRACT

A field investigation program on waves was carried out in the Weser estuary, German Bight of the North Sea. Wave height and period distributions in this complicated wave climate can be approximated by a Rayleigh distribution. Empirical distributions of the wave heights characterise the different regions of the estuary. The presence of wave grouping as well as the group bounded long waves are shown in a few examples. The necessity of further investigations and analysis is highlighted.

1. INTRODUCTION

The necessity to gain more knowledge about the sea state has become increasingly important with growing demands, especially of the offshore industry, within the last few decades. Not only the needs for basic research work on wave dynamics but the necessity of field data and a fast evaluation of significant values derived even from fragmentary records or visual estimates is evident. This task seems to be simple when dealing ideally with straight shore lines and gradually decreasing water depths.

However, waves travelling from the open sea into shallow water areas of an estuary with a irregular topography and a pattern of deep channels, submerged bars, tidal flats and gullies are modified by shoaling, refraction, diffraction and even reflection processes. Combined with locally generated wind waves a very complex wave climate occurs, to which at a first glimpse hardly any of the existing theories or analysis procedures can be applied.

In 1975 a field investigation program was started in the Weser estuary which is part of the German Bight of the North Sea (Fig. 1). It was designed in order to gain information about the existing wave climate and therefore create a basis for the design of all coastal structures and the development of wave prediction methods.

The mouth of the river Weser opens into a V-shaped estuary with a width of approximately 2 km at its origin and more than 20 km at its transition to the open sea. The main channel divides into two branches in the inner wadden area where wave action is of minor importance for morphological stability. The first impact of waves is to be recognized

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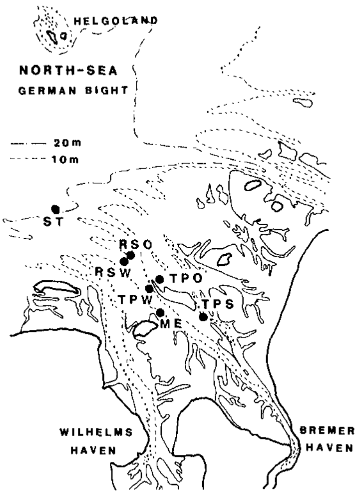


FIG. 1 WESER ESTUARY, GERMAN BIGHT, NORTH SEA
-LOCATIONS OF MEASUREMENTS-

at the edge of the wadden area. Then the major channel is again divided into two branches cutting through the reef region. In this area a strong littoral drift crosses the estuary and causes continuous shifting of bars and channels (1).

To be able to record conditions for typical regions of the estuary the wave recording stations were arranged in deep water (ST), in the reef region, at the edge of a deep channel (RSW), behind a submerged bar (RSO), in the wadden area in the main channel (TPW), in front of (TPO, ME) and behind (TPS) tidal flats.

The locations ST, RSW, RSO and TPW, the results of which are mostly being discussed in the following, were equipped with waverider buoys. Records of 20 min length of each station were stored on digital tape every 80 minutes. Wind measurements were taken on a centrally located lighthouse near RSW.

2. STATISTICAL ANALYSIS

The results of this investigation were to be used for different purposes, i.e. design of offshore and coastal structures and for wave prediction as a basis for the assignment of special ships (dredges, barges, etc.). Therefore, an extended analysis was performed on part of the data, which, among others, included spectral analysis, parameterization of multi-peak spectra and thereby separation of superimposed wave systems. Most of the results are presented in (2), (3) and (4). Since this procedure turned out to be very time-consuming and therefore costly, a simplified method was applied. By evaluating height and period distributions significant values could be defined. Knowledge about ratios or distributions of different wave parameters allows estimating significant values from a fragmentary record or visual observations. Measured values from a reference station can be transferred to different regions of the estuary.

2.1 Wave Height Histograms

Subsequently the zero-up-crossing wave heights of every record were checked for their possible correspondence with one of the customary theoretical distributions:

a. the normal (Gaussian) distribution (N)
b. the log-normal distribution (NL), which is mostly applied for very long time series (16)
c. the Rayleigh distribution (R)

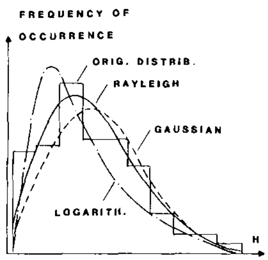


FIG. 2 WAVE HEIGHT DISTRIBUTION

The various possibilities in terms of histograms are shown in Fig. 2.

Fig. 3 shows the comparison for 20-min records of four stations. To find the best correspondence with a theoretical distribution the CHI^2 test, a stringent statistical method, was applied. To summarize the results of most of the 20-min time series obtained with wind coming from two prevailing sectors SW-NW and N-SE, Table 1 shows the percentage of records with a correspondence to the theoretical distributions (col. 2-4). The average probability of correspondence for the best fit (maximum percentage of records) is given in col. 5 whereas col. 6 shows the percentage of records without any theoretical fit. Finally, cols. 7 and 8 show the assignment of the records to periods of flood or ebb current. Percentages not adding up to 100% show that some of the records could not be assigned to either of the tidal phases. From this table it can be concluded that although there is some correspondence with the normal distribution the most likely theoretical one is the Rayleigh distribution. Others are negligible. Obviously the winds

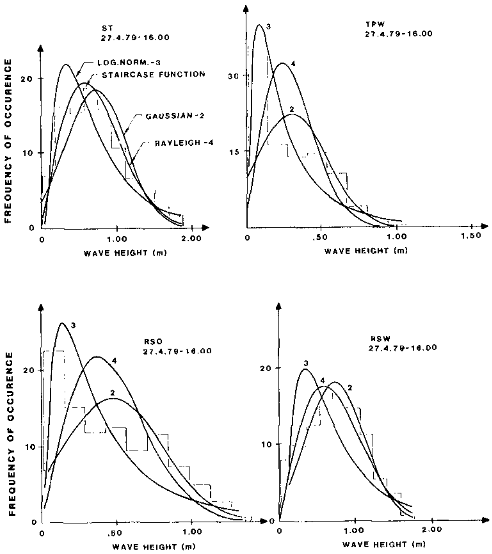


FIG. 3 HEIGHT DISTRIBUTION OF ESTUARINE WAVES

1	2	3	4	5	6	7	8
LOC.	PERC. OF REC. WITH CORRESPONDENCE TO (%)			PROBAB. OF BEST CORR. (%)	REC WITHOUT CORR. (%)	R (%)	
	N	NL	R			E	F
ST	11	-	48	14	61	28	62
	-	-	6	20	94	50	50
RSW	24	1	80	22	24	39	52
	42	1	82	29	15	42	58
RSO	22	1	64	23	37	50	50
	18	9	50	29	26	36	64
TPW	3	0	47	22	53	24	76
	7	2	37	33	61	27	73

TABLE 1 CORRESPONDENCE WITH THEORETICAL DISTRIBUTIONS
- WAVE HEIGHTS -

coming from the north-easterly sector show better results, but there is no evidence that deep water location-distributions (ST) have a better fit than those in shallower regions. It has to be mentioned that a percentage likelihood of 25% visually (Fig. 2) means a satisfactory correspondence of staircase function and theoretical function.

Tidal currents influence the height distributions especially at locations where tidal currents are concentrated in the main channel. The better correspondence can be found with currents and waves travelling in the same direction. The influence of currents on wave heights and periods has been discussed in (3).

3.2 Probability Distributions

Already in 1952 Longuet-Higgins (11) pointed out that for a narrow spectrum measured in deep water wave height distributions could be approximated by a Rayleigh distribution. In the meantime it has been mentioned by several authors that Rayleigh fits even broader spectra and is often valid for shallow water waves too. Since the Rayleigh distribution was derived on the basis of a narrow spectrum, it seems to be very likely that for a case of superposed wave systems this theoretical distribution must lie somewhere in between over- and underprediction due to the specific location of measurement. To evaluate this range, typical series of measurements taken either during flood or ebb tide were compared with the theoretical cumulative proportional probability

$$p(\eta) = 1 - e^{\frac{-\pi}{4}\eta\alpha} \qquad \text{with} \quad \eta = \frac{H}{\overline{H}}$$

where the wave height H is normalized with respect to the average wave height $\overline{H}$. In case of a Rayleigh distribution α=2.

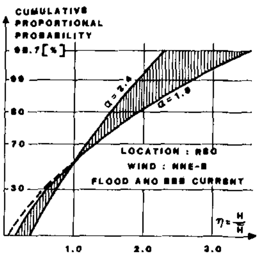


FIG. 4 WAVE HEIGHT DISTRIBUTION

$$p\left(\frac{H}{\overline{H}}\right) = 1 - e - \frac{\pi}{4}\left(\frac{H}{\overline{H}}\right)^{\alpha}$$

It appeared that the cuves ranging in between the boundaries of Fig. 4 were not very smooth and intersected especially in times of changing tide (flood to ebb current and vice versa). However, typical values for the exponent α could be assigned to the various locations of the estuary. Table 2 summarizes the results.

CUMULATIVE PROPORTIONAL PROBABILITY:	$p(\eta) = 1 - e^{-\frac{\pi}{4}\eta^{\alpha}}$	$\eta = \frac{H}{\bar{H}} = \frac{H}{H_{AVE}}$
OPEN SEA (LOC. ST):	$\alpha_F = 2.0$ $\alpha_E = 1.9$	
REEF REGION (LOC. RSW):	$\alpha_F = 2.2$ $\alpha_E = 1.95$	
REEF REGION (LOC. RSO): (SIT. LEE OF REEF)	$\alpha_F = 1.95$ $\alpha_E = 1.85$	
TIDAL FLATS (LOC. TPW/TPO): (SIT. IN A TIDAL GULLY)	$\alpha_F = 1.8$ $\alpha_E = 1.7$	

TABLE 2
PROBABILITY EXPONENTS α FOR DIFFERENT REGIONS OF THE WESER ESTUARY
F = FLOOD CURRENT E = EBB CURRENT

It appears that the exponents for flood currents (waves propagating with current) are bigger than the values for ebb conditions (waves propagating against currents). This was only different in a few cases with very strong southerly winds.

Based on these relationships and on the statistics which Longuet-Higgins (11) derived from the Rayleigh distribution or on an approximation of that given by Schüttrumpf (20), relationships between various wave height parameters like H_{MAX}, $H_{1/10}$, $H_{1/3}$ and H_{AVE} can be calculated using the number of waves in a record. According to this the following values were obtained as an average for the whole estuary:

$$H_{1/3}/H_{AVE} = 1.62$$
$$H_{MAX}/H_{1/3} = 1.88$$

2.3 Wave Periods

A comparable analysis was performed on the wave periods too.

1	2	3	4	5	6	7	8
LOC.	PERC. OF REC. WITH CORRESPONDENCE TO (%)			PROBAB. OF BEST CORR. (%)	REC WITHOUT CORR. (%)	R (%)	
	N	NL	R			E	F
ST	21	-	43	20	54	52	48
	8	-	28	13	70	73	27
RSW	45	9	66	26	20	45	55
	6	15	67	21	27	50	50
RSO	30	5	57	21	34	48	52
	18	13	51	22	33	45	55
TPW	10	23	46	21	36	39	61
	-	37	30	18	42	46	54
1	2	3	4	5	6	7	8

TABLE 3 CORRESPONDENCE WITH THEORETICAL DISTRIBUTIONS - WAVE PERIODS

Table 3 shows the comparison of the results of the same four locations in the estuary as given in Table 1. It appears again that the probability of the correspondence with a Rayleigh distribution is higher than others. Although the results seem to be comparable with those from height distributions, the scattering of cumulative probability curves did not allow an assignment of typical distributions to the different regions of the estuary which could lead to the calculation of maximum values of wave periods. During a storm tide in the inner estuary the significant wave period was measured to exceed

$$T_{1/3} > 15 \text{ s}$$

and the maximum value reached

$$T_{MAX} = 18.2 \text{ s}$$

These values were obtained by wave gauges and could not be verified by waverider recordings. The limitation of the waverider buoy for long period waves is a distinct disadvantage for respective investigations.

3. LONG WAVE ANALYSIS

3.1 Grouping of Waves

In recent years it has become more and more accepted that, especially in shallow water, waves tend to form groups which heights exceed a specified wave height, i.e. $H_{1/3}$ or H_{AVE}. The concentration of energy in wave groups could be critical for structures especially if the frequencies involved lie within the range of the characteristic or eigenfrequency of the structure. Ships or other floating structures can respond in a resonant rise. Investigations of grouping phenomena for the Weser estuary using the number of consecutive waves with a height $H_i > H_s$ have been performed by Barthel (2) and for other regions in the North Sea by Siefert (21) and Rye (17). All those seemed to match suggestions by Goda (10) based on theoretical considerations. Descriptions of wave grouping using the envelope of a time series of water surface elevations were given by Nolte and Hsu (14). This method, which simply connects peaks and troughs to indicate the presence of groups, seems to be a rather rough interpretation. Regarding the concentration of energy in a wave group, Funke and Mansard (8) presented the SIWEH-function (SIWEH = Smoothed Instantaneous Wave Energy History). This function

$$E(t) = \frac{1}{T_P} \int_{\tau=-T_P}^{T_P} \eta^2(t+\tau) \cdot Q_1(\tau) d\tau \qquad \text{for } T_p \leq t \leq T_n - T_p$$

where T_n = length of the finite wave record
T_P = peak period of the spectrum
$Q_1(\tau)$ = smoothing window which acts as a low pass filter

describes the distribution of energy along the time axis with energy defined as the square of water surface elevations.

The description of the groupiness of a time series of the sea state is given by the dimensionless groupiness factor

$$GF = \frac{\sqrt{m_{0\varepsilon}}}{m_0}$$

where $m_{0\varepsilon}$ = zeroth moment of the SIWEH spectral density
m_0 = zeroth moment of the short wave spectrum.

This factor describes the standard deviation of the instantaneous wave energy about its mean. GF=.9 indicates a highly grouped sea state. GF-values up to 1.1 have been recorded. Typical values range between .5 and .8. Other important factors are the group repetition period, the length of the group and the variation of the group repetition period. A description of groupiness in terms of the SIWEH spectral density is given in Funke and Mansard (8).

In order to define grouping properties of estuarine waves a preliminary analysis using the SIWEH-function and calculating the groupiness factor was applied on a limited number of records. Fig. 5

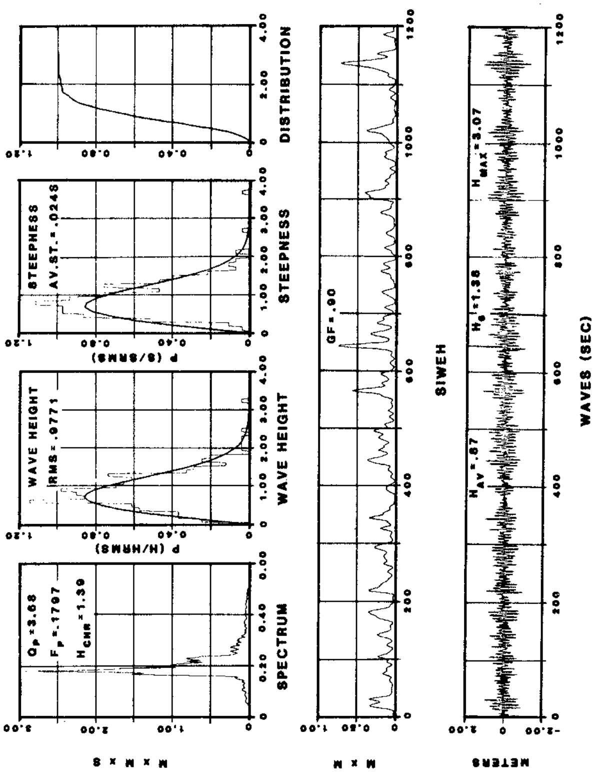


FIG.5 WESER DATA ANALYSIS - LOC. ST 23.4.80 - 17.40

shows an example of the results of the general analysis procedure. This time series recorded at location ST in relatively deep water at wind velocities of 12 m/s already shows distinct wave groups with a high groupiness factor of GF = .9. Wave heights as well as steepness fit visually quite well to the theoretical (Rayleigh) distribution. The variance spectral density shows a single peak spectrum with some energy contents in the low frequency region.

In Fig. 6 different wave parameters are plotted versus time for three locations in the estuary for one recorded long time series

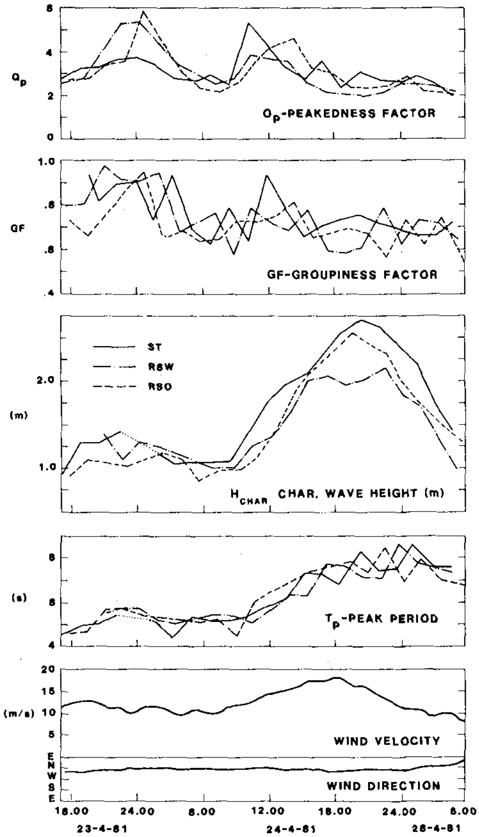
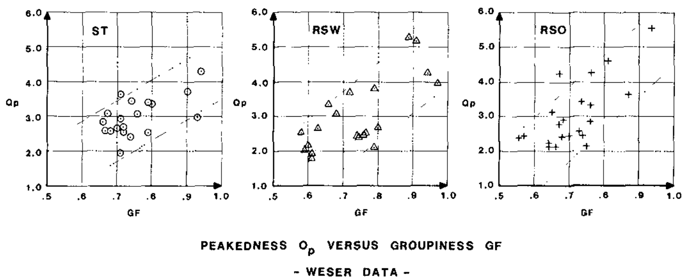


Fig. 6 WAVE PARAMETERS Q_P, GF, H_{CHAR} T_P
WESER ESTUARY-ST-23.-25.4.81

available for this analysis. While characteristic wave heights and peak periods follow increasing and decreasing wind velocities nicely, it seems that the groupiness factor GF varies without any correlation to wind and other wave parameters. However, the time variations of the peakedness factor

$$Q_P = \frac{2}{m_0} \int_0^{\infty} f[S(f)]^2 \, df$$

which was introduced by Goda (9) seem to coincide somewhat with those of the groupiness factor GF. Both parameters grow with increasing wind up to a certain extent and then decrease again which agrees with observations of Rye (7) as far as the formation of groups is concerned. Though wave group formations were found to be more pronounced for a narrow, sharply peaked spectrum (Rye (18), Goda (10)), an interdependency of Q_P and GF could neither be detected in model studies (a synthesised spectrum can keep its shape for different groupiness factors) nor in the analysis of prototype data (13) so far. Spectral peakedness factors Q_P are plotted versus groupiness factors GF in Fig. 7 for the three locations under discussion. In spite of the scatter a distinct trend seems to indicate a relationship. The correlation coefficients are Rxy = 0.75-.78. However, this phenomenon has to be investigated for more records under different conditions.



GROUPINESS FACTOR (FUNKE & MANSARD , 1979)	$GF = \sqrt{m_{05}}/m_0$
PEAKEDNESS FACTOR (GODA , 1970)	$Q_p = \frac{2}{m_0^2} \int_0^{\infty} f(S(f))^2 df$

Fig. 7 PEAKEDNESS Q_P VERSUS GROUPINESS GF
- WESER DATA -

4.2 Bounded Long Waves

Due to radiation stress, wave groups generate a group bounded long wave. This long wave typically appears as a setdown under the group and a setup in between the groups (Fig. 8) as shown by Longuet-Higgins and Steward (12) for groups of regular waves. As these long waves can

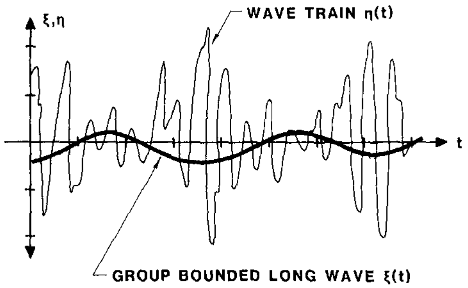


Fig. 8 GROUP BOUNDED LONG WAVES
- DIAGRAMMATIC SKETCH -

excite slow drift oscillations of moored structures and travelling ships or cause harbour resonance, their detection in a record, or rather in the spectrum, is of major importance. Unfortunately, many of the customary wave measuring devices are not capable of picking up these low frequency elevations among the short waves. The commonly used waverider buoy attenuates the output for frequencies below .1 Hz so that a compensation function has to be used. Somewhere between .06 and .05 Hz the instrument fails to record low frequencies. In order to estimate the amount of long wave energy present in prototype data recorded by similar instruments the long wave energy or long wave surface elevations have to be calculated. Bowers (6) and Dean and Sharma (7) used the Laplace-equation to define these second order waves. Another definition, based on the momentum equations, has been given by Ottesen-Hansen (15).

The various long wave components are computed using the Fourier coefficients of the primary wave train. Basically, each pair of frequencies resp. Fourier coefficients generates a long wave contribution. Hence the second order surface elevation becomes

$$\zeta_{nm}(t) = G_{nm}(f,\Delta f)\,[(a_n a_m + b_n b_m)\cos(\Delta\omega_{nm}t) + (a_m b_n - a_n b_m)\sin(\Delta\omega_{nm}t)]$$

with G_{nm} being the transfer function given by Ottesen-Hansen (15) and discussed by Sand (19).

4.3 Long Waves in Natural Wave Trains

As mentioned before, low frequency oscillations can be dangerous for floating structures. Especially vessels travelling in confined channels of an estuary with a limited water depth could be affected by groups of higher waves as well as by the group bounded long wave dependent on its height and repetition period. In order to get an idea about possible amplitudes and periods of these long waves, two 20-minute records were analysed with respect to long wave energy contents.

The following analysis procedure was used:

a. Fourier analysis is performed on the prototype wave train after application of a band pass filter.

b. All Fourier components for frequencies smaller than a given lower cut-off frequency and all components with an amplitude smaller than a given threshold are set equal to zero.

c. Fourier components of the bounded long wave are computed using the equations of Ottesen-Hansen (15) and Sand (19).

d. Inverse Fourier-transform is applied.

e. Superposition of short and bounded long wave train.

f. Spectral analysis.

g. Zero-crossing analysis on short and long wave train.

The program used for this purpose was developed in the Hydraulics Laboratory of the National Research Council Canada.

Fig. 9 shows the results of a record, obtained at location RSO (water depth = 8.0 m), with a groupiness factor GF = .90. The bounded long wave which is superimposed to the short wave train shows a distinct setdown under the wave groups. Spectral analysis was performed on the original wave train as well as on the superposed wave train (original + calculated bounded long wave). The encircled part in the spectrum on the right hand side was enlarged to show the difference in the low frequency part of the spectrum. From this it can be concluded that the energy contents in the low frequency part is considerably increased by taking the bounded long wave into account. This becomes more obvious by comparing the RMS-values, which were calculated separately for a certain low frequency range, where RMS_M refers to the measured and RMS_C to the superposed wave train. Zero-crossing analysis on both the measured wave train and the calculated bounded long wave yield the wave parameters $\overline{H} \triangleq H_{AVE}$, H_S and H_{MAX} as well as the mean period of the bounded long wave. Under the given conditions already a long wave with maximum height of .17 m and a mean period of 36 s can appear.

Since prototype records with more severe conditions were not at hand for this analysis, a wave train measured off the coast of Newfoundland, Canada, was applied to a water depth found at loc. ST in the Weser estuary. Wave heights and periods of comparable order of magnitude have been recorded at this location before.

Fig. 10 shows the results of the above mentioned analysis on this wave train with a groupiness factor of GF = .94. It appears again, that the superposition with the calculated bounded long wave adds a considerable amount of energy in the low frequency part of the spectrum indicated by the RMS-values which have been calculated only up to .05 Hz. A long wave with a mean wave height of .37 m and a maximum of .65 m

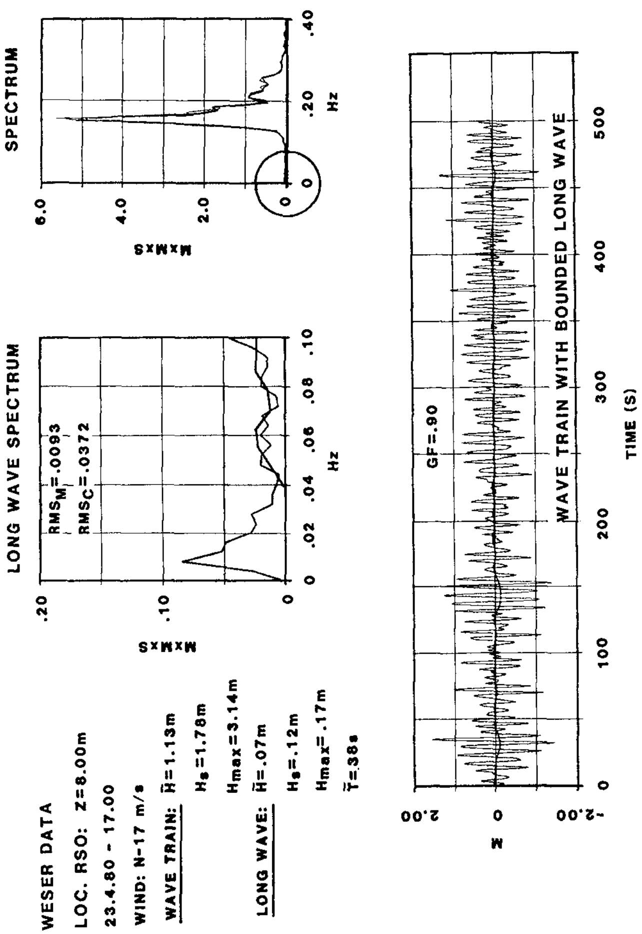


FIG.9 BOUNDED LONG WAVES IN NATURAL WAVE TRAINS

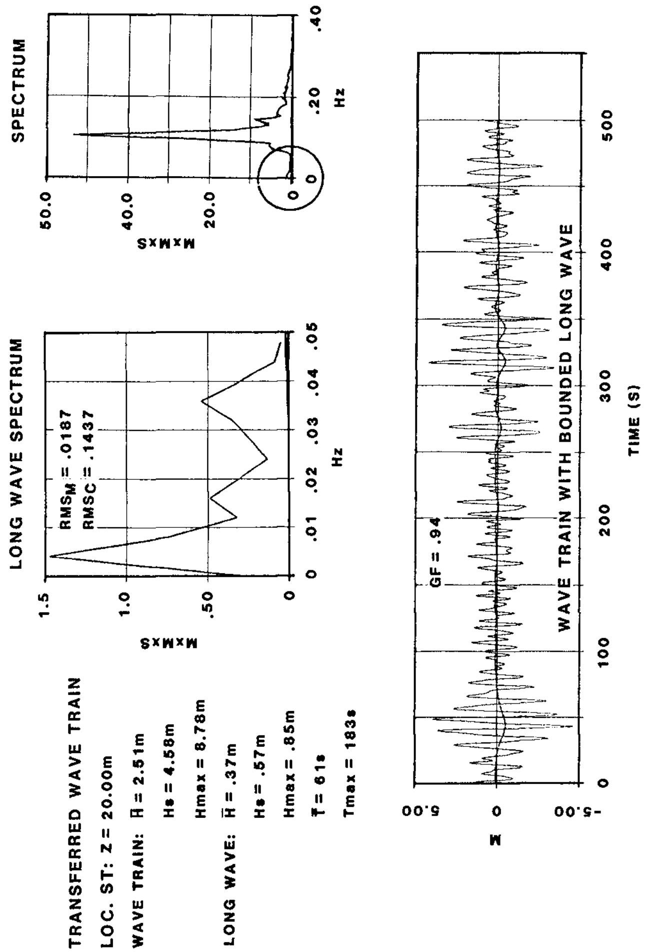


FIG.10 BOUNDED LONG WAVES IN NATURAL WAVE TRAINS

is present under these wave conditions. The mean period is 61 s whereas the maximum period goes up to 183 s. Typically these long waves tend to be stable and travel with the group velocity as long as the group is not attenuated, i.e. by breaking. According to model studies which have recently been done in the Hydraulics Laboratory of the National Research Council of Canada (5), it is very likely that these long waves are partly reflected on shoals. However, in deep channels they will propagate and penetrate into the inner estuary.

It is not yet known to what extent these long waves can affect the motion of travelling vessels. However, it has to be expected that, especially in confined shipping channels with a restricted water depth, a sudden increase of the draught or rather decrease of available water depth connected with grouped wave impact and in addition to squat, can lead to dangerous situations.

Analysis of all available records obtained in critical areas with respect to long wave activity is recommended.

5. CONCLUSIONS

Extended statistical analysis was performed on prototype data obtained in the Weser Estuary mostly with waverider buoys. Height and period distributions of 20-minute records were checked for their correspondence with theoretical distributions. The results permitted the following observations:

- Height and period distributions more likely follow a Rayleigh distribution than others.

- Modified empirical height distributions related to the Rayleigh distribution could be assigned to different regions of the estuary permitting the evaluation of different wave height parameters.

Further analysis using the SIWEH-function (8) and calculation of second order waves highlighted the presence of wave grouping in estuarine waves and the group bounded long waves. The findings suggest that

- in spite of a complex wave climate, grouping can be detected in this area,

- the spectral peakedness seems to be correlated to the groupiness factor,

- the group bounded long wave component, which has not been recorded, can be found and re-established by special analysis techniques.

Further research has to be performed on the long wave problem, including long wave statistics after analysis of all available data. In an additional project the influence of these long waves on travelling vessels ought to be investigated.

6. ACKNOWLEDGEMENTS

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