CHAPTER 10

WAVE INVESTIGATIONS IN SHALLOW WATER

Dr -Ing. Winfried Siefert

Strom- und Hafenbau Hamburg
Forschungsgruppe Neuwerk, Cuxhaven, Germany

Abstract

Examination of the significant heights of zero-crossing waves in the Elbe Estuary has yielded two noteworthy results: 1 In the deeper water of the estuary, the value of the quotient relating the significant and the mean wave heights is larger than on the bordering tidal flat. 2. The value of this function is dependent on the height of the waves; on the tidal flat this dependency is considerably more sensative than in deeper water. With increasing wave height the value of significant wave height divided by mean height becomes smaller

The propagation direction of waves moving onto the tidal flat is contingent upon the position of intertidal channels Such channels sharply reduce the possible propagation directions The waves nearly always move up-channel regardless of the wind direction

It is possible to derive special wave period and wave height distributions representing the conditions in very shallow water

I. Introduction

As part of a general research program investigating the hydrologic, hydrodynamic and morphologic characteristics and changes in the Elbe Estuary, wave measurements are carried out (Laucht, 1968, and Fig 1). Few recordings - at least in Germany - have been made of waves in the nearshore zone, consequently, no data was available for the Elbe Estuary at the beginning of this program Only a minimal amount of information on wave behavior in morphologically complex nearshore areas is found in the literature (Koele and de Bruyn, 1964; Wiegel, 1964, US Army, 1966). It was therefore necessary to tailor an investigation program to fit these special conditions

Concurrent wave measurements have been made at 6 stations, and in 1970 an additional 7 stations on the tidal flat will be added. Of the present 6 stations, 3 are located on the edge of the Elbe channel in water depths from 5 to 10 m, and 3 are located on the tidal flat in depths of less than 2 m (Fig. 2) Expanded records of 2 to 5 minute duration are recorded at preset intervals, following the Wemelsfelder principal. The results presented here are based primarily on the "Hundebalje" station located between the dune island Scharhorn and the island of Neuwerk on the "high tidal flat" bordering an intertidal channel system At mean high tide the water reaches a depth of 1 5 m at this point.

II. Interpretation of Wave Records

A Significant Wave Values

Expanded records from the various stations give only wave height and period and thereby only part of the significant wave characteristics which must also include wavelength, wave propagation direction and velocity The latter items can be obtained from radar and aerial photographs, however, these techniques don't yield the height and period (Siefert, 1969) An attempt is presently being made to combine aerial photo analysis with wave gauge records to bring together the height, frequency and directional spectrums

Following currently accepted methods, the records were analyzed for the mean values $\bar{H}$ and $\bar{T}$ of the zero-crossing waves as well as $H_{1/3}$, $TH_{1/3}$, and $H_{1/10}$. From these values, the ratios $C_{1/3}$, $C_{1/10}$, etc were calculated

It is commonly believed that wave parameters such as the mean or significant wave height are of somewhat limited use However, even in an area with extreme depth variations, these values still serve to give the engineer a relatively good picture of the waves Therefore, for preliminary work the calculation of spectrums can be omitted in favor of using the significant wave values For construction planning, characteristics such as mean, significant and maximum wave heights and periods are more useful than spectrum analyses.

In the investigation area it is common to have several wave systems coming from different directions converging and overlapping one another. These systems can have quite different heights and periods depending on their origin and age A typical Gaussian distribution, as found in the theoretical treatment of Cartwright and Longuet-Higgins, or a Rayleigh distribution for a very narrow wave spectrum, are seldom present (Koele and de Bruyn, 1964). When several systems overlap it becomes impossible to measure a mean wave-length or height of each system The high degree of scattering in the wave values precludes analytical treatment of data from this area until the mathematics of non-linear superposition is developed to a point where the spectrum can be calculated for shallow water (Wiegel, 1969).

In spite of these restrictions, the measured wave heights yield some interesting facts regarding the changes that take place in waves as they move into shallow water

B. Integration of the Dominant Wind Values

The values $\overline{H}$ and $\overline{T}$ from the wave records were classified according to wind velocity and direction The wind parameters prevailing during the 6 to 12 hour period preceding the measurement were categorized into various wind sectors (Schrader, 1968) For wind directions from SW to N, the waves from the open sea are responsible for the waves in the channels and on the tidal flat. For these directions, the wind conditions prevailing outside the tidal flat area (Scharhornriff station, Fig. 2) must be considered. The division of the land wind directions (N to SW) is based solely upon the topography near the recording station In Fig 3, therefore, the wind sectors at the Scharhornriff station apply to the entire investigation area, whereas the sectors at the Hundebalje station apply only to records from this station.

Aerial photographic analysis of the wave-length changes as waves move into shallower water showed that classic wave theory could not be applied in this topographically complex region (Siefert, 1969). As a result, the attempt has been made to work with the changes in wave height as the waves progress into shallower water.

III Waves in Shallow Water

A Comparison of Significant Wave Values in Deep and Shallow Water

In order to achieve a reliable shallow water - deep water comparison, over 500 records from the 6 recording stations were analyzed for both mean and significant wave values using the zero-crossing method. This amounted to a comparison of the tidal flat readings (from the Scharhorn-West, Scharhorn-Süd and Hundebalje stations) with the deeper water results (from the Scharhornriff, Scharhorn-Nord and Luchtergrund stations (see Fig. 2)).

Wave Parameter	Tidal Flat	8 m Water Depth
$C_\tau = \frac{T_{H_{1/3}}}{\bar{T}}$	1.11	1.30
$C_{1/3} = \frac{H_{1/3}{}^{*)}}{\bar{H}}$	1 49	1.52
$C_{1/10} = \frac{H_{1/10}}{\bar{H}}$	1.76	1.90
$\frac{H_{1/10}}{H_{1/3}}$	1.18	1 24

*) see Figure 4

All of the values show a tendency toward uniformity as the waves reach shallower water, ie , $H_{1/10}$ and $H_{1/3}$ become somewhat smaller in relation to the mean wave height. This is caused by a form of "sorting" in which the highest waves, which control the values of $H_{1/10}$ and $H_{1/3}$ in deeper water, are removed from the spectrum in shallower water. Therefore it is understandable that the ratio $C_{1/10}$ should become smaller faster than the ratio

$C_{1/3}$ The change in the wave spectrum is also clearly seen in the decreasing values of C_{τ} on the tidal flat

So one can not rely on having constant wave ratios in the coastal area This applies to the wave heights as well as the periods. The value of $C_{\tau} = \frac{T_{H_{1/3}}}{\overline{T}}$ for the deeper Elbe Estuary, as well as off the Dutch coast (Svasek, 1969), is 1 30, whereas on the tidal flat the value drops to 1 11 This lower figure corresponds well to the 1.10 calculated by Sibul (1955) for shallow water in a wind-wave channel (see Wiegel, 1964).

A further point should be mentioned which apparently is frequently overlooked in the evaluation of zero-crossing waves As Fig. 4 shows, using a deep water station (Scharhornriff) and a tidal flat station (Hundebalje) as examples, the ratio $C_{1/3} = \frac{H_{1/3}}{\overline{H}}$ is dependent not only on location but also on the mean wave height H. Higher waves produce a more uniform wave spectrum; on the tidal flat the uniformity is achieved more quickly than in deeper water.

Variances in the directional spectrum of the waves as they reach the tidal flat are shown in Fig. 5 where the main wave systems seen in two series of aerial photographs are presented (see also Siefert, 1969). In the inner portion of the Elbe Estuary, nearly all wave directions can be developed depending upon the wind However, this multiplicity of propagation directions is almost instantly reduced as the waves enter the tidal channels. The illustration shows propagation directions from WNW and E, a difference of 120° in the deep Elbe channel This difference is reduced to 30° in the Hundebalje channel. This would seem to indicate that waves always move up-channel on the tidal flat regardless of wind direction

B. Distributions of Wave Periods and Wave Heights

Everyone is aware of the large scattering in the relation of mean wave heights and periods, especially under the influence of complex topography and tidal conditions. Furtheron it is known that the heights and periods of individual waves seem to be nearly without any relation The only facts that become clear are that the highest wave in a spectrum does not belong to the longest period and that the longest period belongs to a wave of about mean height. Therefore it is useful to split further investigations into analyzing separate period and height distributions

Fig. 6 gives some characteristic period spectra in the form of cumulative distributions of the ratio of individual and mean periods in Gaussian paper. The comparison gives an interesting result: The distributions of Bretschneider and Putz are not the same, but similar, and both are derived for deep water waves. The spectra in the Elbe channel and the adjacent breaker zone (3 to 12 m) as well as those on the tidal flats (1 to 3 m) are different from those. The period spectrum of the waves obviously becomes wider with decreasing water depth. So it seems that the well-known theoretical Rayleigh-distribution is characteristic only for waves in very shallow water. The analytical variation of this distribution is possible by raising the factor "2" in the formula of the Rayleigh-distribution with increasing water depth.

Opposite developments can be noticed with the wave heights To the usually used Rayleigh-distribution after Longuet-Higgins there belongs a value $C_{1/3} = 1.60$. Many authors found that this value is not always constant (see Wiegel, 1964). Investigations in the Elbe estuary show that the mean value is less than 1 60 and that the quotient becomes smaller with increasing wave height, but not at any point with the same rate (Fig. 4). The cumulative distributions of the wave heights in Fig. 7 give characteristic curves for every $C_{1/3}$. As $C_{1/3}$ decreases with increasing mean wave height, the wave height spectrum then must become narrower. This apparent relationship between the width of the spectrum and $C_{1/3}$ can be expressed as a relation between the factor φ in the formula of the wave height distribution

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

and $C_{1/3}$:

$C_{1/3}$	1,35	1,40	1,45	1,50	1,55	1,60	1,65
φ	2,94	2,70	2,50	2,32	2,15	2,00	1,86

This relation is valid up to 99 8% and more. The following progress of the curves in Fig. 7 to a finite value indicates the influence of water depth, as there must be a maximum wave height even with the propability zero.

For a certain mean wave height in a certain place on the tidal flat, one can get the value of $C_{1/3}$ by Fig. 4, and further on Fig. 7 gives the complete wave height distribution in dependence on $C_{1/3}$.

Summarizing the investigations it can be stated that the <u>period spectrum</u> of waves progressing into shallow water becomes <u>wider</u> while at the same time the <u>height spectrum</u> becomes <u>narrower</u>. This fact has to be considered during further investigations, but we hope to find some general characteristics that may be applied to similar areas elsewhere.

C Wave Heights on the Tidal Flat

Tidal conditions result in the wave height on a tidal flat being controlled by the water level, ie., the tidal phase In addition to the tidal fluctuations, the water level is strongly influenced by wind thereby yielding complex relationships:

a) Wave height as a function of wind and water level
b) Water level as a function of wind

Some considerations may illustrate this double dependency of wave height on wind. When a constant water level is present (or in water deep enough to make such fluctuations insignificant) relationships can be established between wave height and wind. The Hundebalje station serves as a good example to show the influence of the wind on the water level. In the German Bight, and particularly near the coast, strong SW to N (sea) winds result in an accumulation of water and therefore increased mean tidal levels; NE to S (land) winds drive the water away from the coast and result in lower water levels. Because wave height is dependent on wind velocity and water level, higher waves can form on the tidal flat under sea wind conditions In contrast, land winds produce an increase in wave height coupled with a lowering of the water level The wave height can increase only as long as the first effect remains larger than the second; further increases in wind velocity will result in a decrease in wave height. It is therefore possible that hurricane force winds from some directions will produce no waves at all on the tidal flat if it falls dry.

This relatively simple hypothesis could be varified on the basis of one year's measurements at the Hundebalje station The events during land wind conditions could be particularly well defined during a long east wind period

Figure 8 shows the mean wave height $\bar{H}$ in relation to the wind velocity from various sectors for three water levels (HW + 1 m, HW, HW - 0.5 m). As would be expected, the individual values are scattered. For clarity only the lines of highest $\bar{H}$ are shown. It can be seen that during periods of land winds from sectors 1 to 3 (346^{o} to 210^{o}) the waves never reach an $\bar{H}$ of over 37 cm on the tidal flat. For a ratio between significant and mean wave height of $\frac{H_{1/3}}{\bar{H}} = 1.46$ (Fig. 4) the significant wave height for this location during N to SW winds is

$$H_{1/3} = 54 \text{ cm.}$$

From Figure 8 it can be seen that the highest waves do not develop when the water level (at a wind velocity of 19 to 22 m/sec) reaches the HW level (1.9 m), but rather a level some 20 cm lower. Thus, with a water depth of 1.7 m, mean wave heights up to 37 cm can be expected.

The maximum possible wave height is also of particular interest. The maximum height will develop under westerly winds when both wave height and water depth are increasing. It is too early to set an absolute height limit based on only one year's measurements, particularly when these include relatively few storm-wind periods. During W to NNW wind (sector 6, Fig 3) with Beaufort force 10 (about 27 m/sec) waves with a mean height of 60 cm were recorded. The significant wave height was 85 cm. The recording is being continued.

The dependency of wave propagation direction on water depth is shown in the fact that the highest waves on the tidal flat develop during W to NNW wind (sector 6). During these times the Hundebalje recording station on the tidal flat lies directly in the wind shadow of the island of Scharhörn (Fig 3). The fetch of about 1.5 km over water depths from 0 to 1 9 m is not sufficient to generate mean wave heights of over 50 cm. The relationship in Fig. 9 between wave height on the tidal flat (Hundebalje) and in about 8 m depth off the tidal flat (Lüchtergrund) shows that the highest waves are recorded <u>on</u> the flat at the times when the highest waves <u>off</u> the flat are recorded (sector 6, 268° - 354°).

It should again be stressed that the results obtained from the Hundebalje station apply only to its immediate area. The station was placed on a tidal channel in order to measure waves by their ingress on the tidal flat. On the higher parts of the flat away from channels, other conditions prevail which result in smaller waves. The wave spectrum on the tidal flat exhibits extreme local variations.

IV. List of Symbols

$C_{1/3}$	Ratio of Wave heights $\frac{H_{1/3}}{\overline{H}}$
$C_{1/10}$	Ratio of Wave heights $\frac{H_{1/10}}{\overline{H}}$
C_{τ}	Ratio of Wave periods $\frac{T_{H_{1/3}}}{\overline{T}}$
$\overline{H}$	Mean height of the zero-crossing waves
$\overline{H}_{max}$	Maximum from number of mean wave heights
$H_{1/3}$	Significant wave height = average height of the highest one-third of the zero-crossing waves
$H_{1/10}$	Average height of the highest one-tenth of the zero-crossing waves
HW	Mean high tide
$\overline{T}$	Mean period of the zero-crossing waves
$T_{H_{1/3}}$	Mean period of the highest one-third of the zero-crossing waves (i.e. the significant waves)

V References

Koele, L.A. and de Bruyn, P.A.: Statistical Distribution of Wave Heights in Correlation with Energy Spectrum and Water Depth. Proceedings, 9th Conference on Coastal Engineering, 1964

Laucht, H.: Ursachen und Ziele der Hamburger Küstenforschung an der Elbmündung. Hamburger Küstenforschung, Heft 1, 1968

Schrader, J.P.: Kennzeichnende Seegangsgroßen für drei Meßpunkte in der Elbmündung. Hamburger Küstenforschung, Heft 4, 1968

Siefert, W.: Seegangsbestimmung mit Radar und nach Luftbildern. Hamburger Küstenforschung, Heft 7, 1969

Svasek, J.N.: Statistical Evaluation of Wave Conditions in a Deltaic Area. Proceedings, Symposium Research on Wave Action, Delft, Holland, 1969

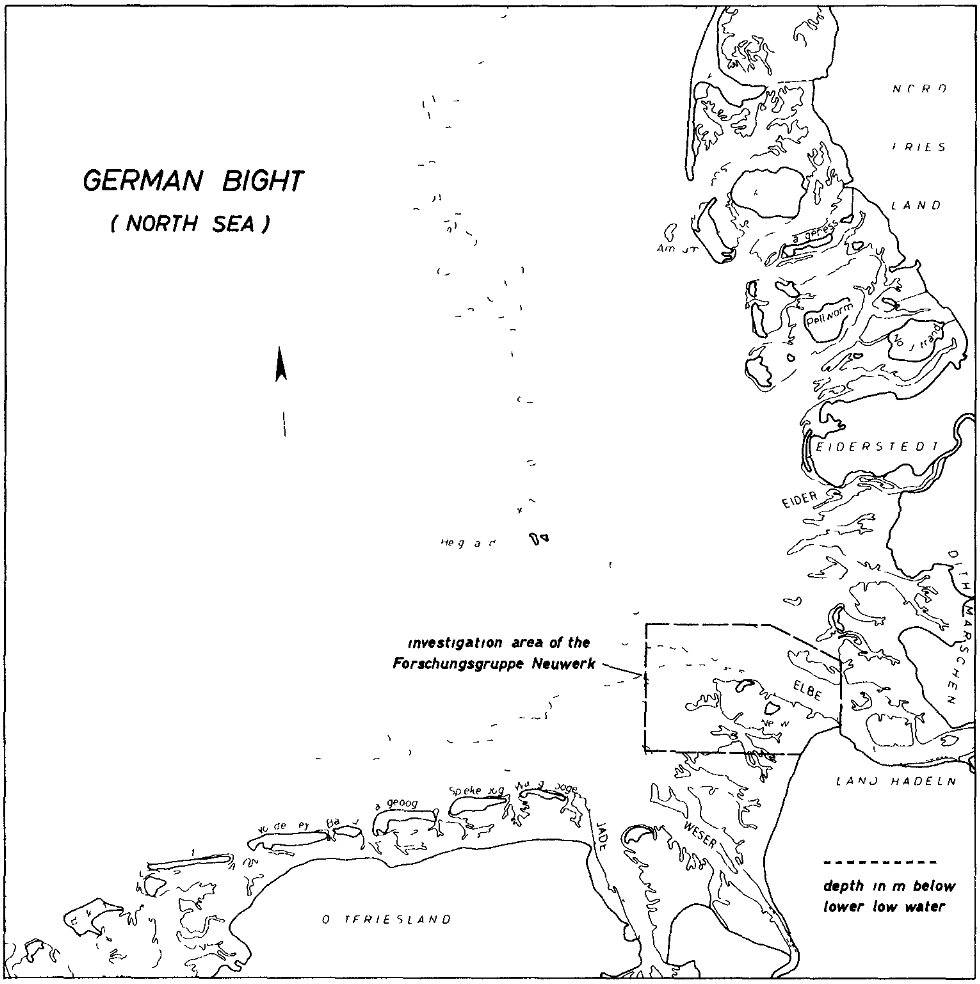
U.S. Army Coastal Engineering Research Center: Shore Protection, Planning and Design. Technical Report No. 4, 1966

Wiegel, R.L.: Oceanographical Engineering. Prentice-Hall Inc., Englewood Cliffs, N.J. 1964

Wiegel, R.L.: Waves and their Effects on Pile-Supported Structures Proceedings, Symposium Research on Wave Action, Delft, Holland, 1969

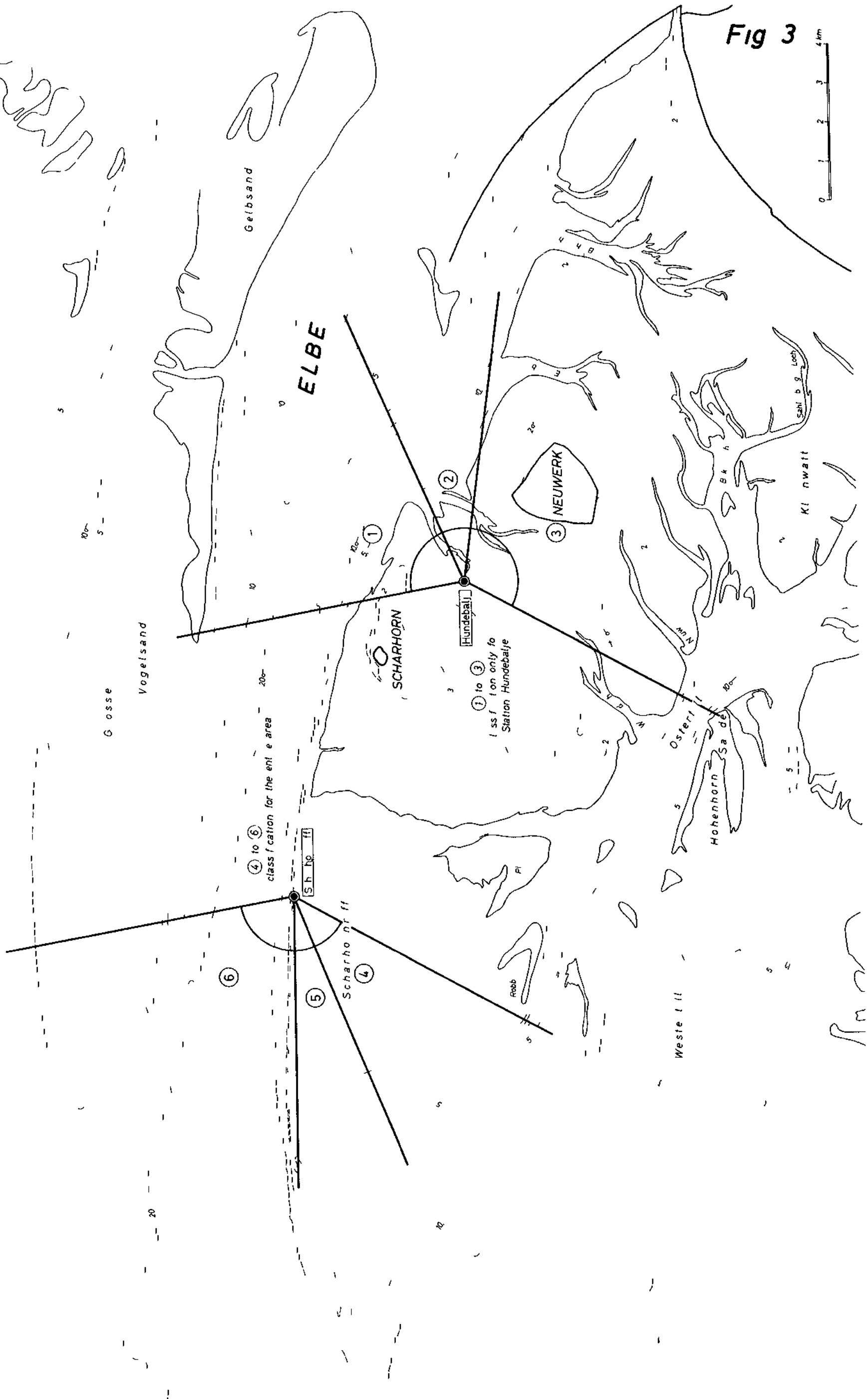
Fig 1

German Bight
with Jnvestigation Area of the Forschungsgruppe Neuwerk




Wave Jnvestigaton
in the Elbe Estuary
recording stations
edge of the area investigated
by aerial photos
Cuxhaven
ELBE
NEUWERK
SCHARHORN
Luechte grund
Scharhorn West
Scharhornriff
Vogelsand
Gelbs d
Robben
edge of the
ae al photos

Fig 2



Classification of Wind Directions for Station Hundebalje

Fig 4

Quotient of Significant Wave Height $H_{1/3}$ and Mean Wave Height $\bar{H}$ versus $\bar{H}$

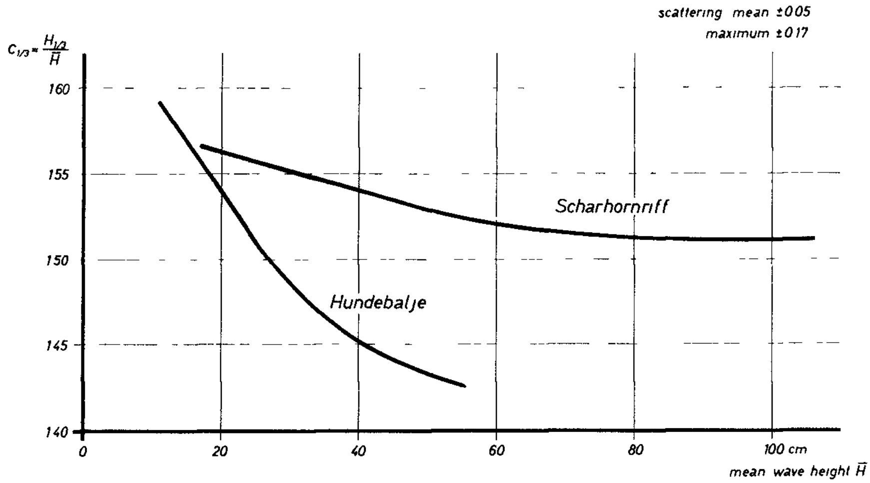


Fig. 5

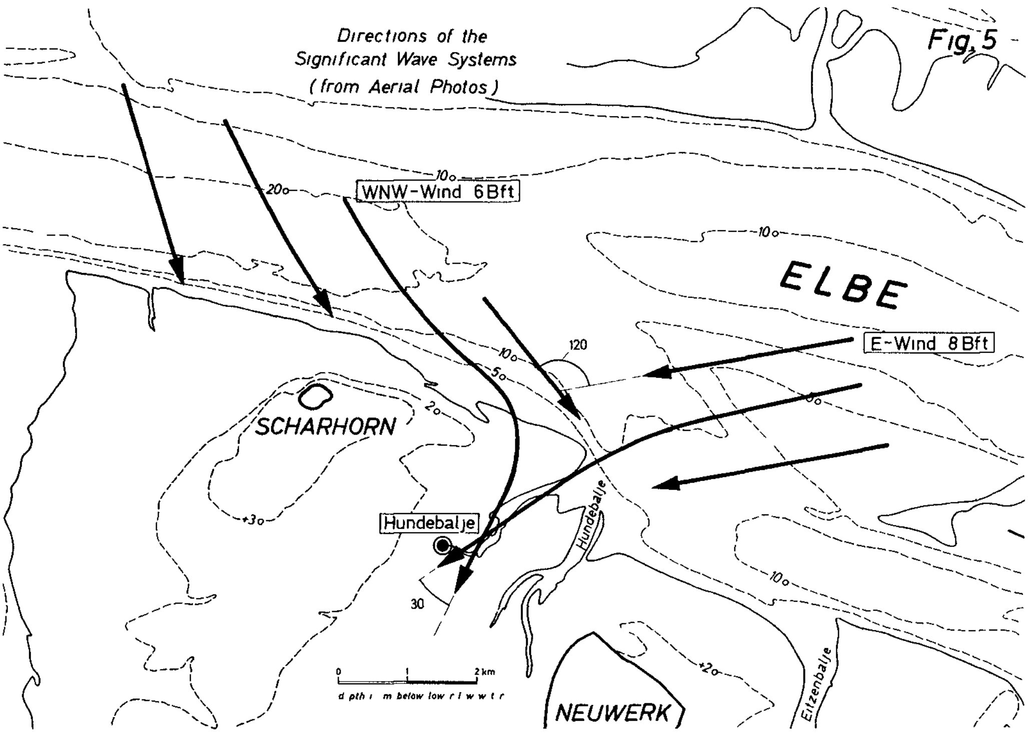
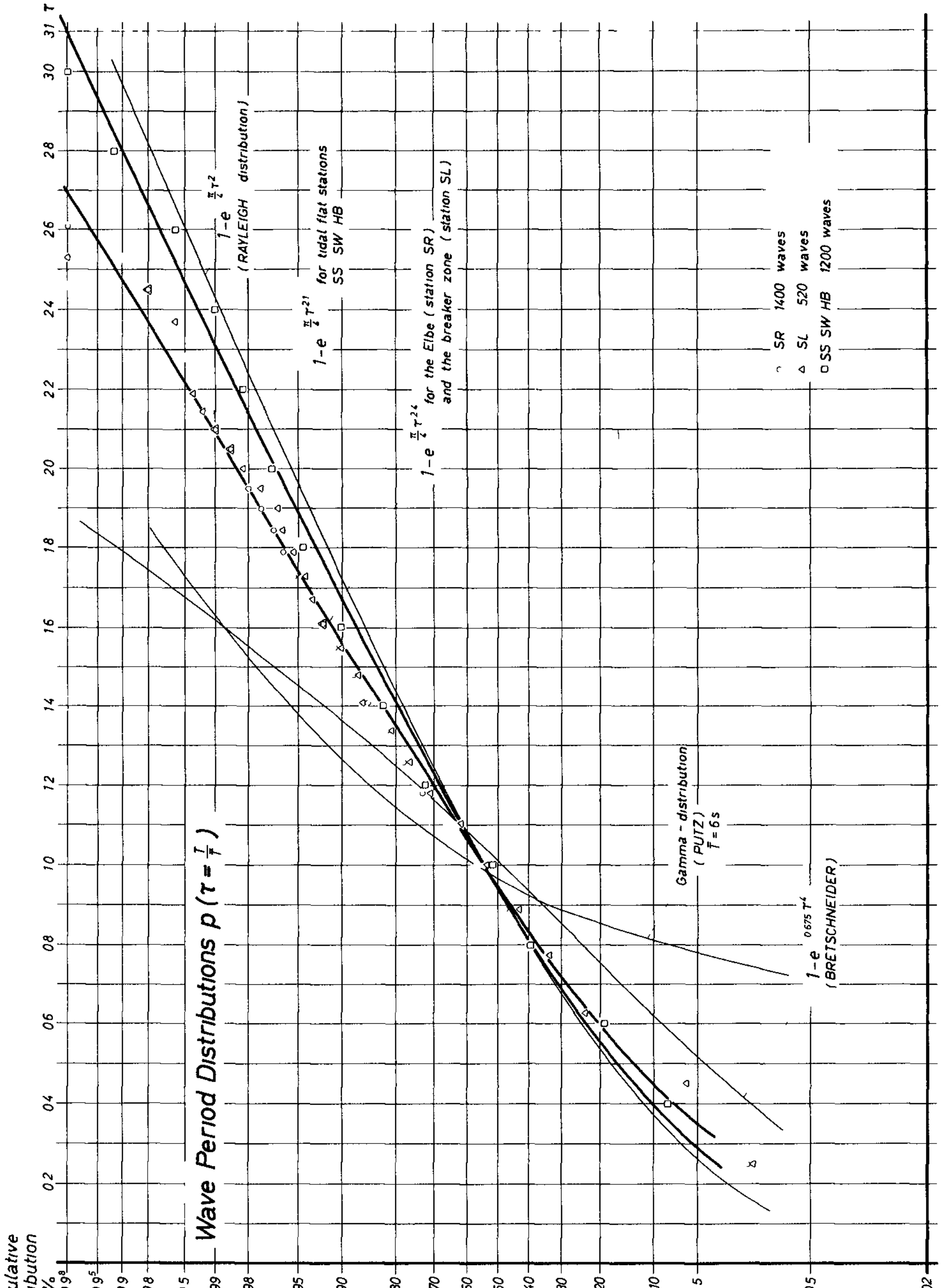
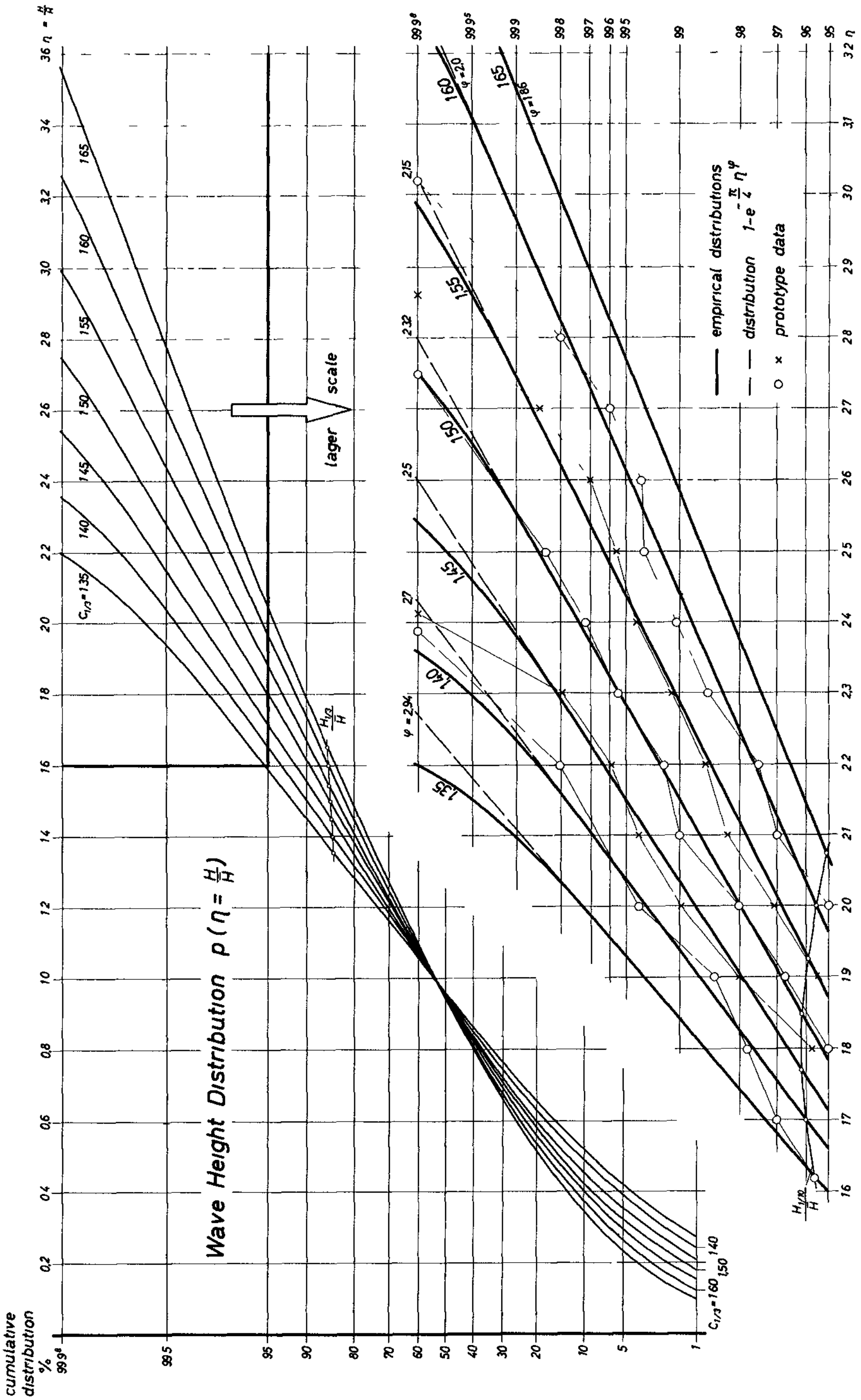


Fig 6



Wave Period Distributions p (τ = T/T̄)
cumulative distribution %
(RAYLEIGH distribution)
for tidal flat stations SS SW HB
for the Elbe (station SR) and the breaker zone (station SL)
Gamma - distribution (PUTZ) T̄ = 6s
(BRETSCHNEIDER)
SR 1400 waves
SL 520 waves
SS SW HB 1200 waves

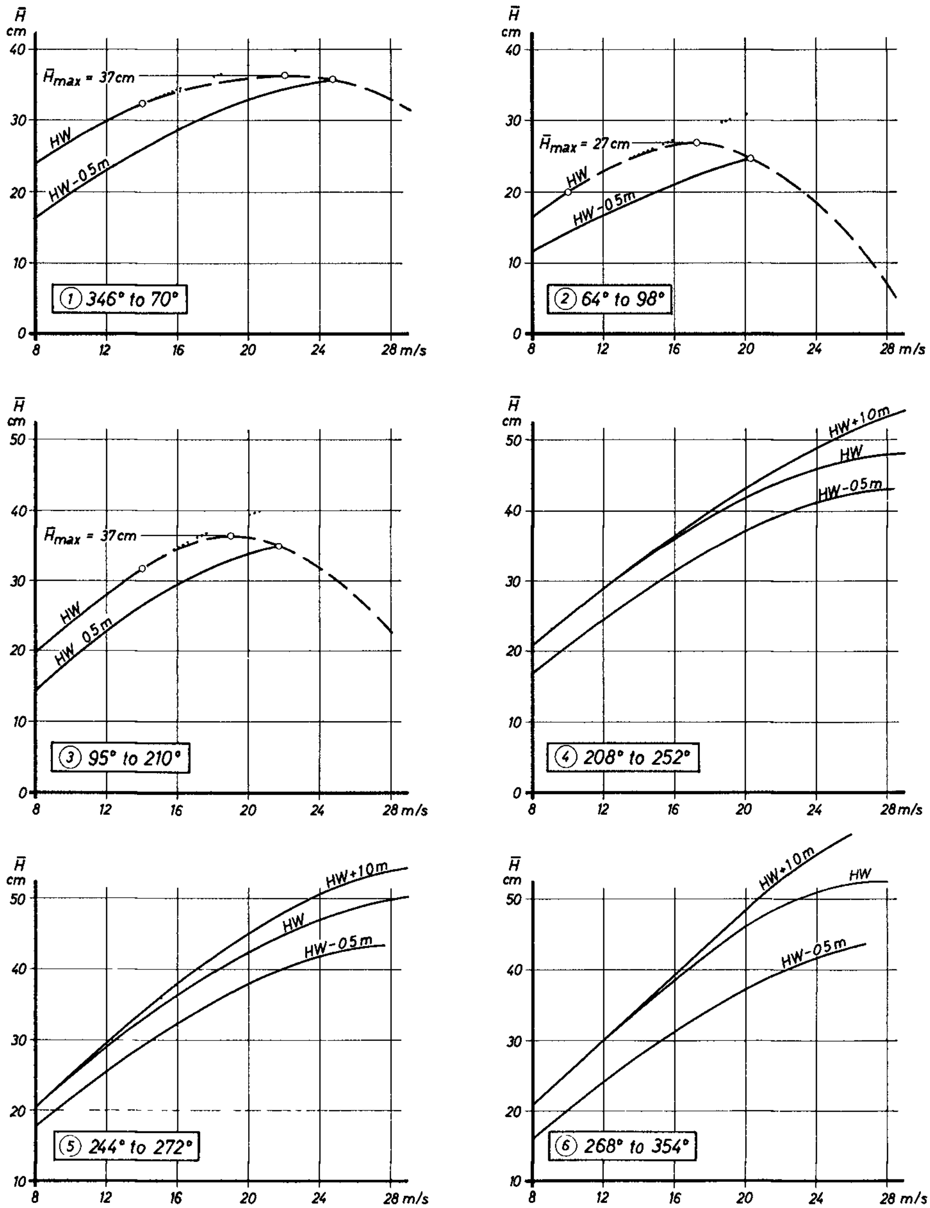
Fig 7



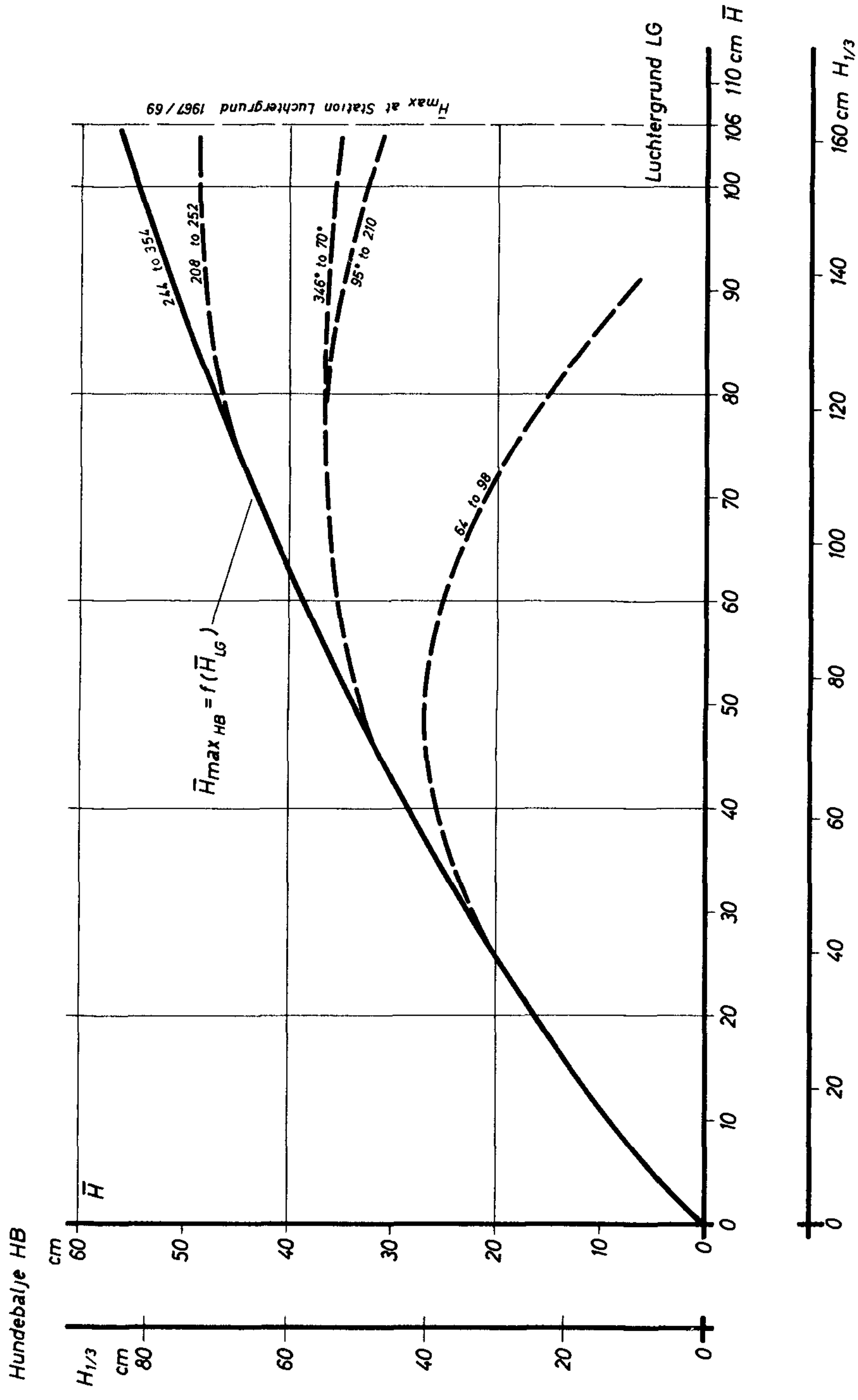
Wave Height Distribution p (η = H/H̄)
cumulative distribution %
36 η = H/H̄
lager scale
empirical distributions
distribution 1-e^{-π/4 η^φ}
prototype data
C1/3=135
C1/3=160
H1/3/H̄
H1/10/H̄
φ=2.0
φ=1.86
φ=2.94

Fig 8

Station Hundebalje
Relation between Wave Heights and Wind
(Depth of Water 1 9m at HW)



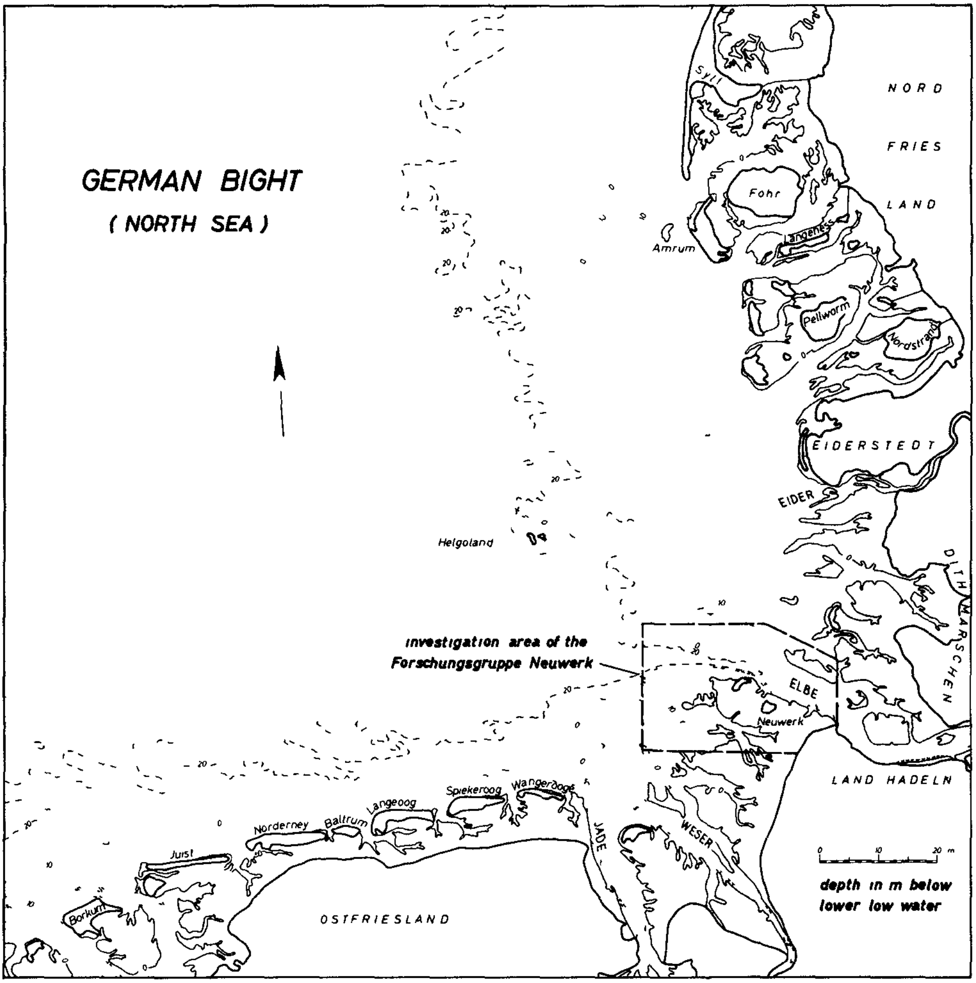
Fig



Relationship between Mean Wave Heights at Station Hundebalje for Different Wave Directions and Wave Heights in Deep Water (Station Luchtergrund)

Fig 1

German Bight
with Jnvestigation Area of the Forschungsgruppe Neuwerk



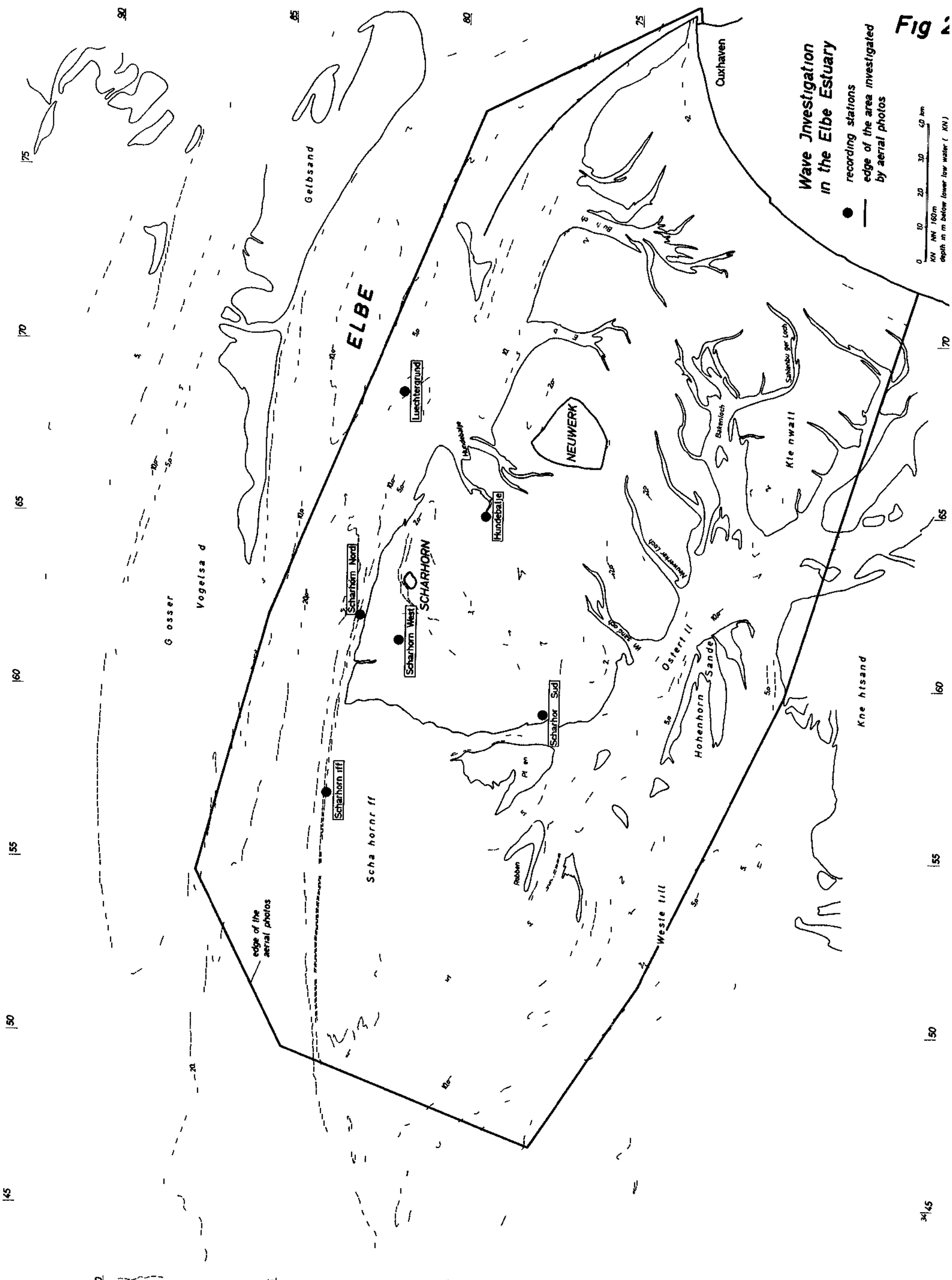
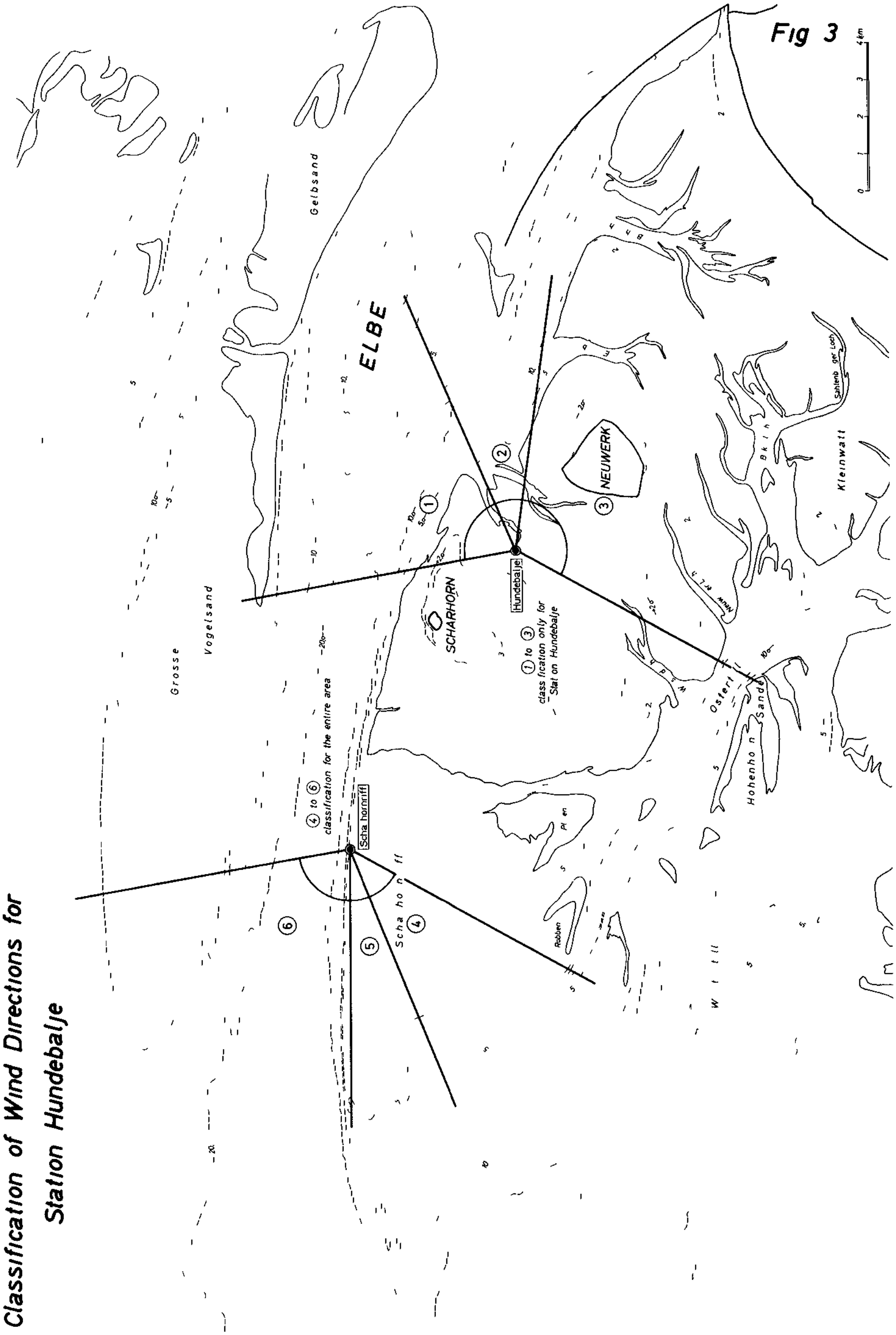

Wave Investigation
in the Elbe Estuary
recording stations
edge of the area investigated
by aerial photos
Cuxhaven
ELBE
NEUWERK
SCHARHORN
Luechtergrund
Hundebalje
Scharhorn Nord
Scharhorn West
Scharhorn Sud
edge of the
aerial photos
Gelbsand
Baken loch
Hohenhorn Sande

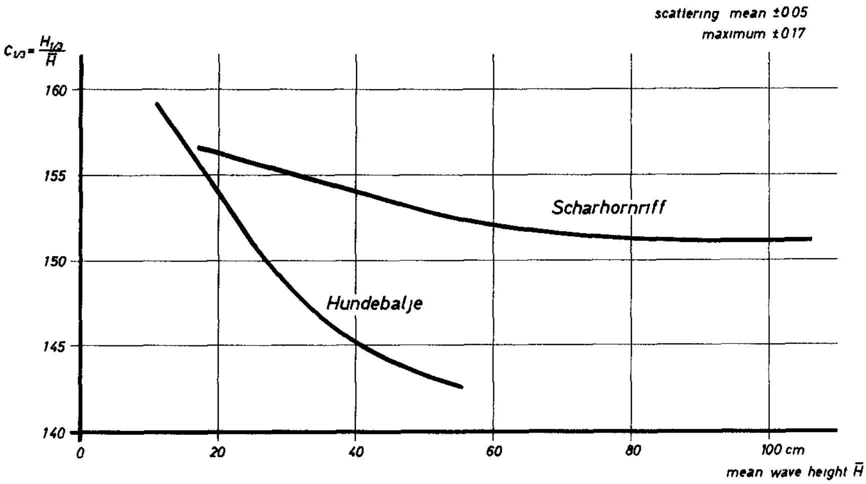
Fig 2



Classification of Wind Directions for Station Hundebalje

Fig 4

Quotient of Significant Wave Height $H_{1/3}$ and Mean Wave Height $\bar{H}$ versus $\bar{H}$



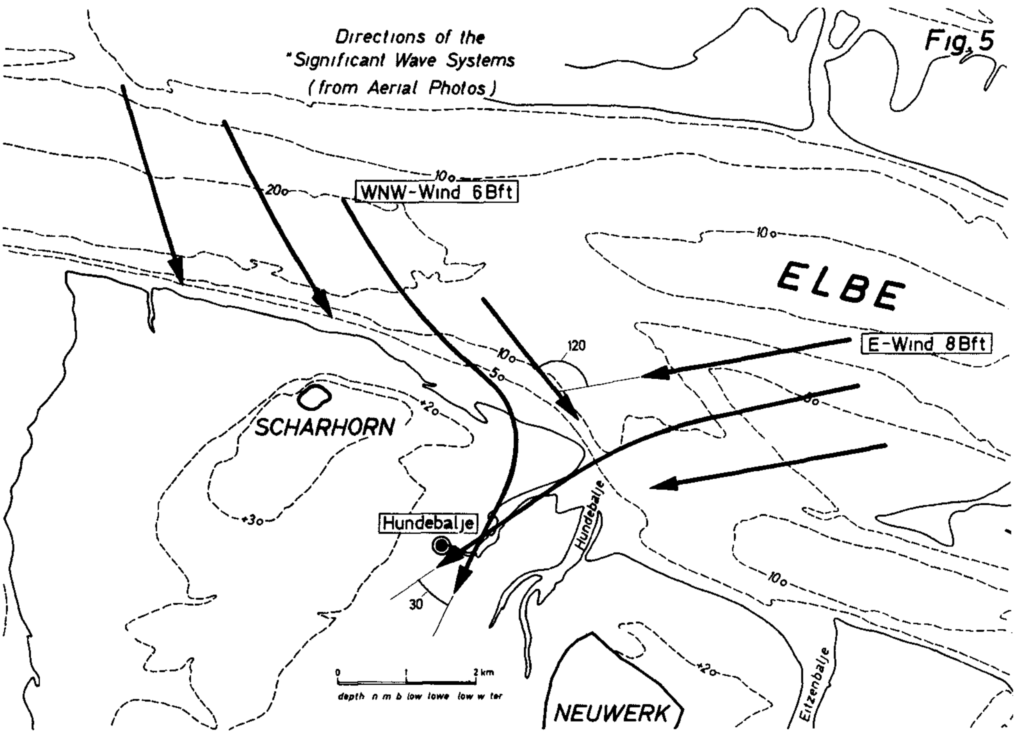
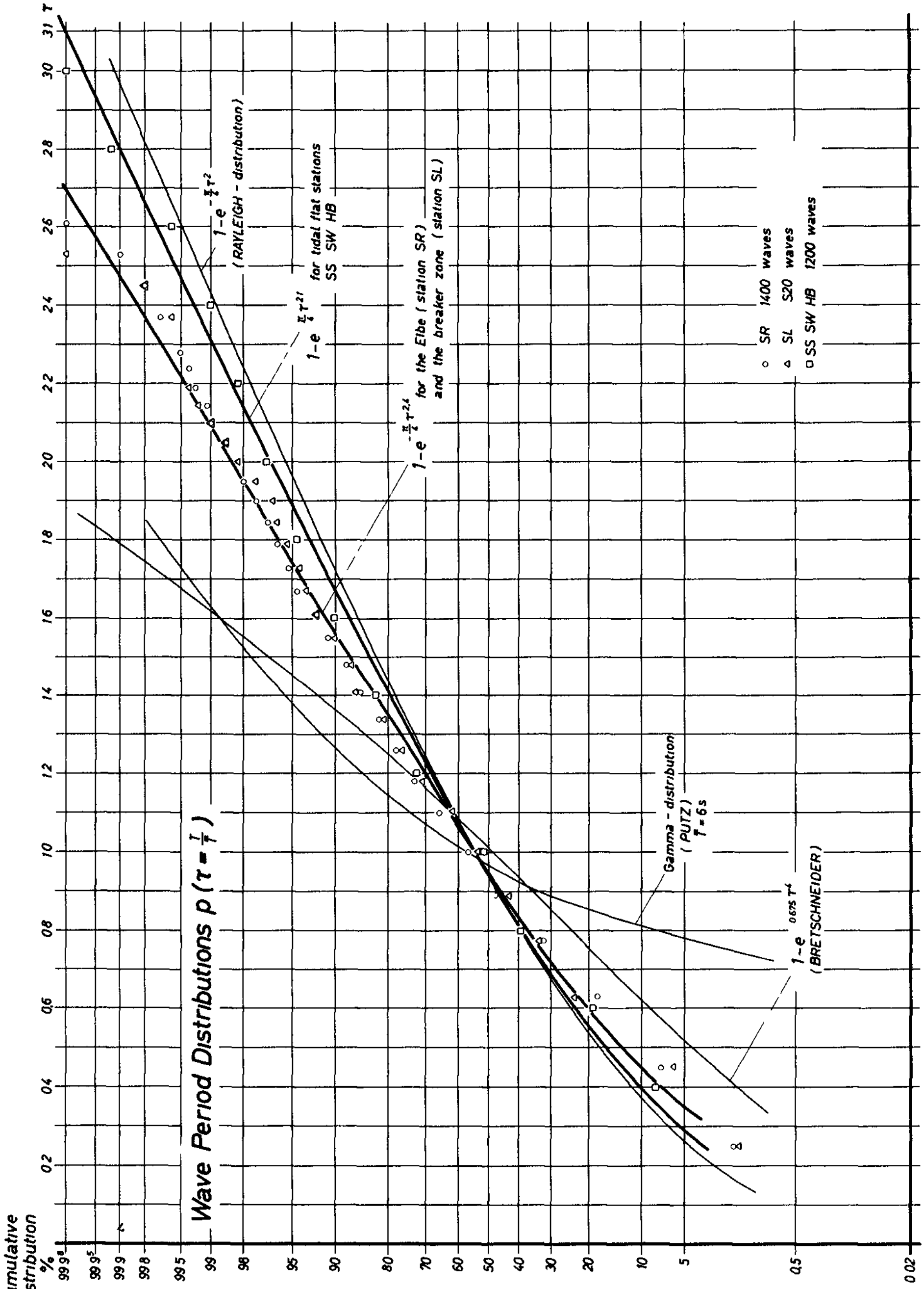
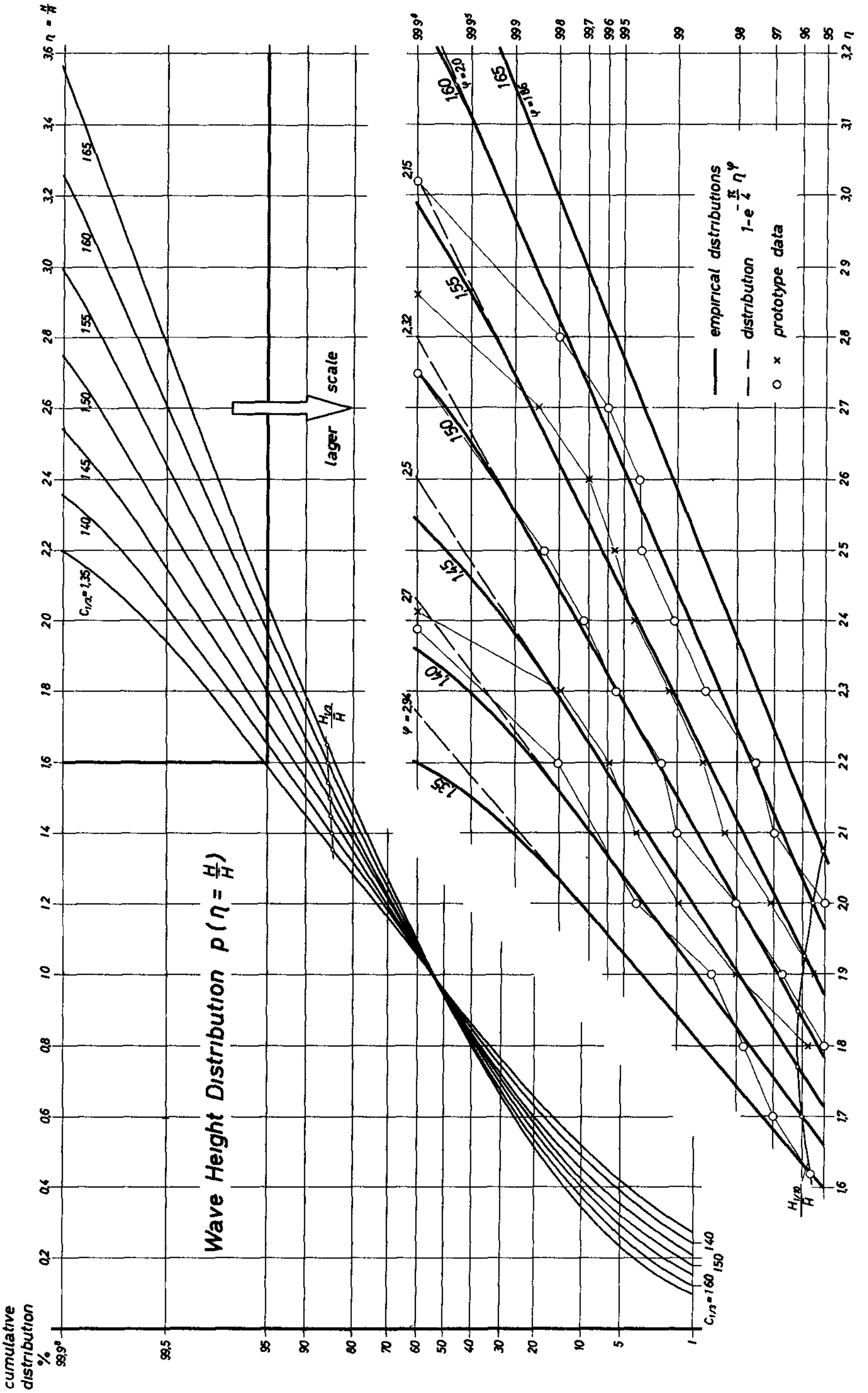


Fig 6



Wave Period Distributions p (τ = T/T̄)
cumulative distribution %
(RAYLEIGH - distribution)
for tidal flat stations SS SW HB
for the Elbe (station SR) and the breaker zone (station SL)
SR 1400 waves
SL 520 waves
SS SW HB 1200 waves
Gamma - distribution (PUTZ) T̄ = 6s
(BRETSCHNEIDER)

Fig 7

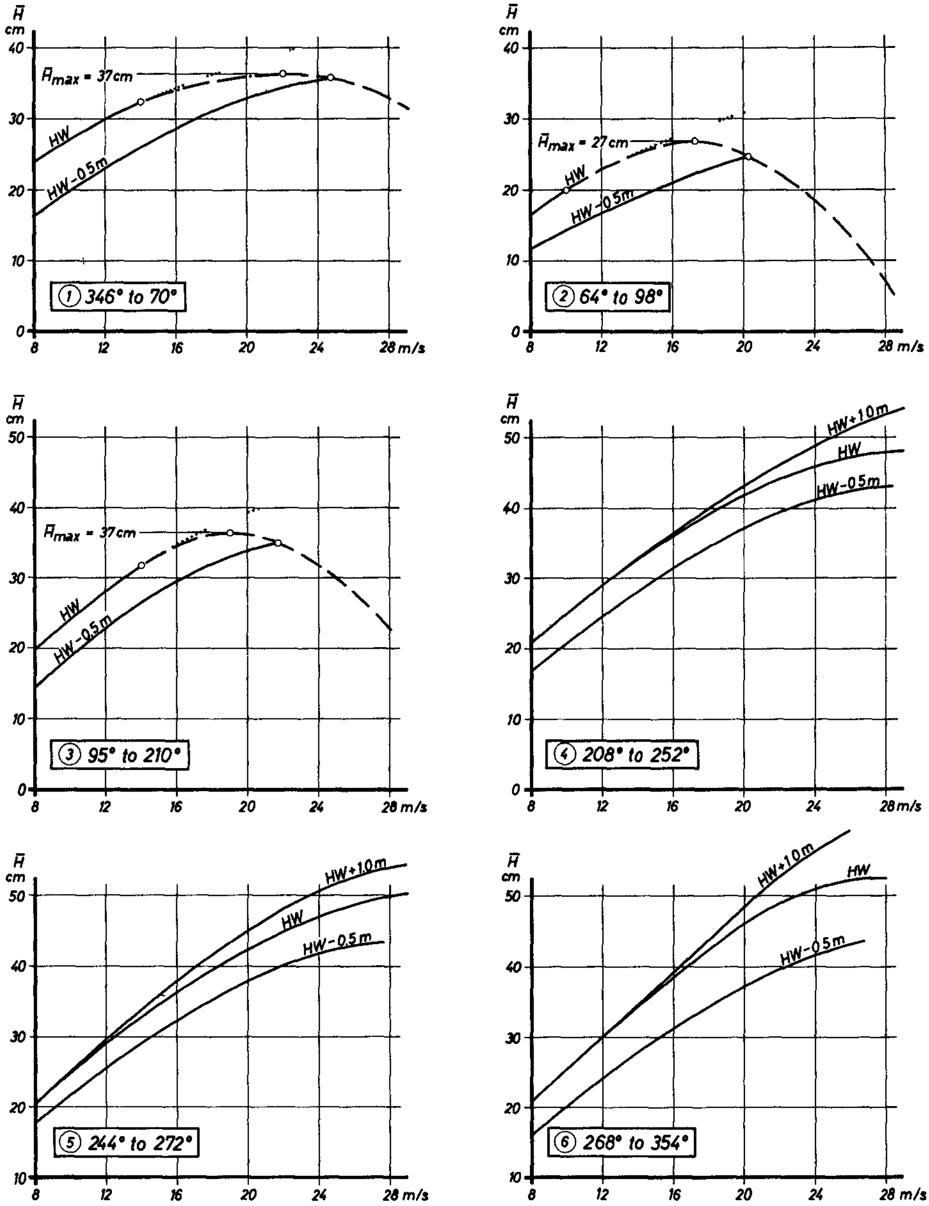


Wave Height Distribution p (η = H/H̄)
cumulative distribution %
lager scale
empirical distributions
distribution 1-e^{-π/4 η^φ}
prototype data

Fig 8

Station Hundebalje
Relation between Wave Heights and Wind

(Depth of Water 1 9m at HW)



Fig

Relationship between Mean Wave Heights at Station Hundebalje for Different Wave Directions and Wave Heights in Deep Water (Station Luchtergrund)