WAVE CLIMATE STUDY
In THE REGION OF THE EAST FRISIAN ISLANDS AND COAST

by Hanz Dieter Niemeyer [1])

1. The investigation area and research aims

The East Frisian Islands and Coast - located at the southern border of the North-Sea - are significantly characterized by a chain of off-shore islands which are separated from the mainland by wide spread tidal flats (FIG.1). Between the islands there are small and deep tidal inlets with strong currents, through which the tidal volume covering the flats is streaming in and out, with a tidal range of about 2,5 m.

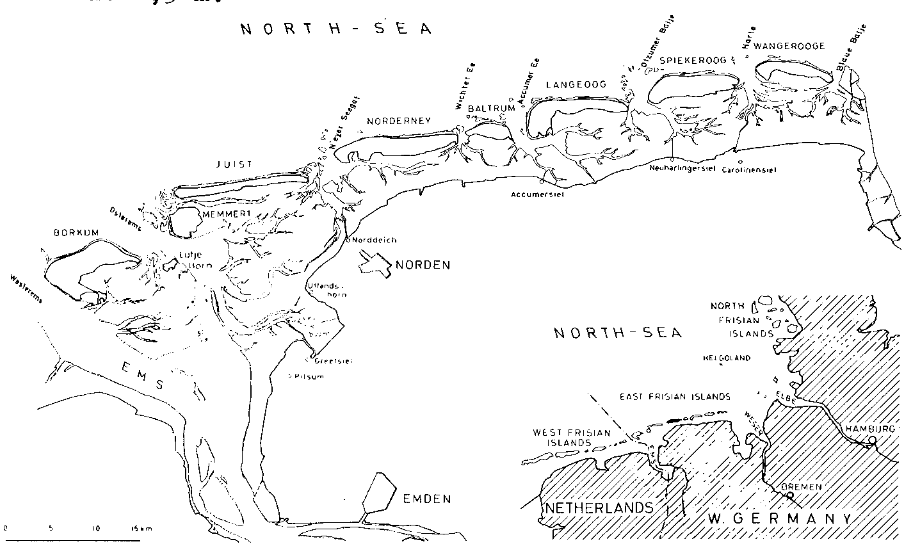

Fig. 1: The East Frisian Islands and Coast

Seaward the tidal inlets are enclosed by an arched chain of separated shoals ranging from the eastern part of one island to the northwestern one of the other island. During the occurence of high wave conditions these chains have the effect of closed bars where an intensive wave energy dissipation is forced by limited water depth.

Compelled by economic reasons the special research area was restricted to the zone around the tidal inlet Norderneyer Seegat (FIG.2) which significantly represents the

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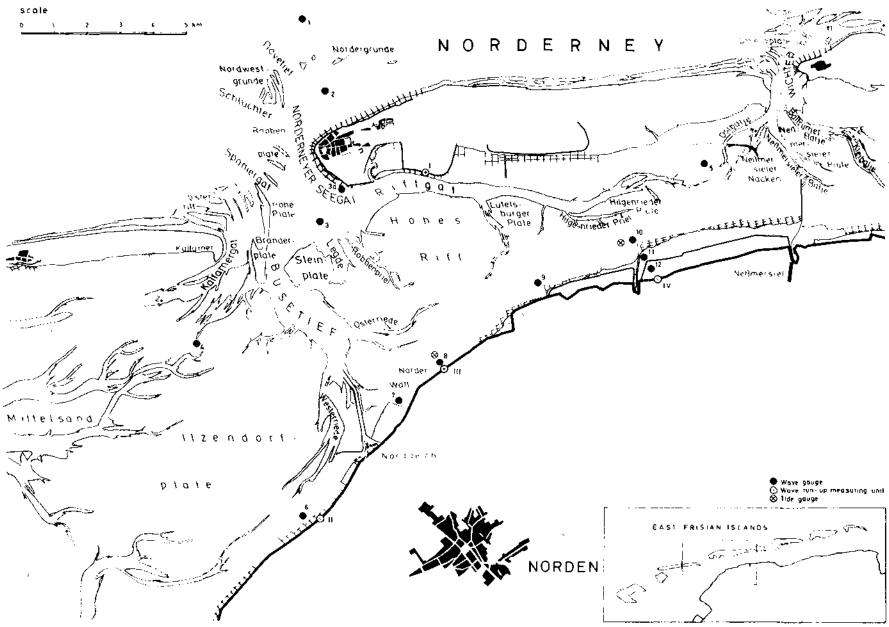

Fig. 2: Research Area and Measuring Net

main hydrographic and morphological features of the whole region of the East Frisian Islands and Coast.

There a measuring net of 13 wave measurement stations and also four wave run-up gauges inserted on sea dykes was erected (FIG.2). The spatial distribution of the wave measurement stations allows to record the changes in wave climate from the open sea to the mainland coast. The conception of the measuring net has therefore been orientated at the morphological features of the region in order to obtain data of their influences on waves propagating from the open sea to the mainland coast (LUCK + NIEMEYER 1977).

The main research aims of the wave measurement program are:

1. Derivation of a computable relationship, allowing the estimation of wave action in the seaward region of the East Frisian Islands and Coast as a function of wind conditions
2. Analysis of wave energy dissipation due to wave breaking on the bar
3. Determination of wave damping on the tidal flats
4. Establishment of design parameters for protection structures in function of wave action and wave loads in respect of the morphological and structural boundary conditions

In the on hand paper the first results of the study are presented, mainly referring to the changes of the heights of waves travelling from the open sea to the mainland coast.

2. Wave generation factors

The range of wind directions being most important for wave generation with respect to the research area extends from W to NNE (FIG.3). The length of fetch is great enough in consideration of the restricted water depth to establish a fully arisen sea within a few hours. Waves generated by winds from these directions are the only important for design conditions.

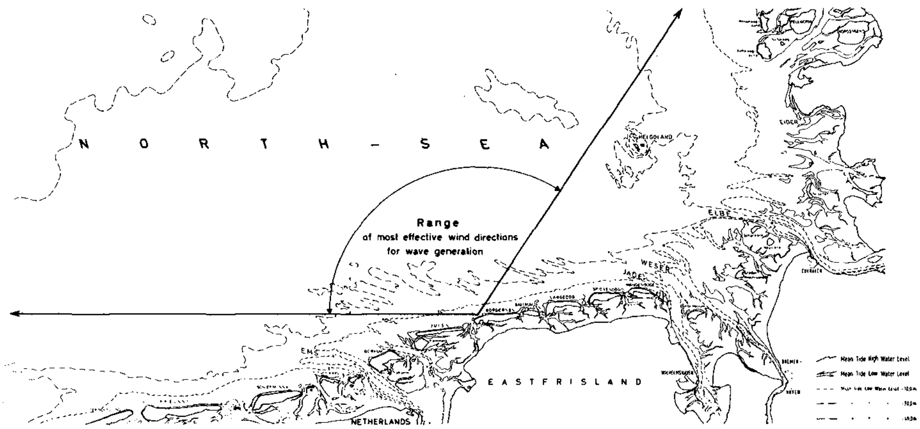

Fig. 3: Wave Generating Area

The hydrographical features of the generation area led to the conclusion that waves generated by normal high wind speeds within this range of directions should not differ in their order of magnitude.

The first investigations therefore were carried out in order to get a quantitative description of the interaction between wind velocity and wave height.

Linear regression analysis clearly shows that there is a rather high correlation between the significant wave height and the mean wind speed prevailing the last six hours before starting the wave measurements (FIG.4). In order to get dimensionally correct equations the significant wave height is plotted versus the ratio of chosen wind speed squared and gravitational acceleration.

But field data better meet a power curve fit for the same parameters than linear regression (FIG.5). The best accom-

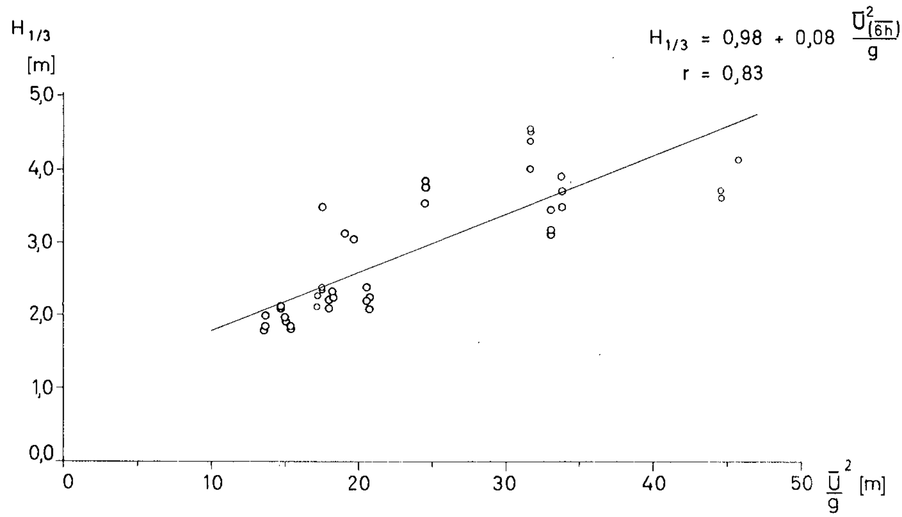

Fig. 4: Linear Regression of $H_{1/3}$ and $\frac{\bar{U}^2(\overline{6h})}{g}$

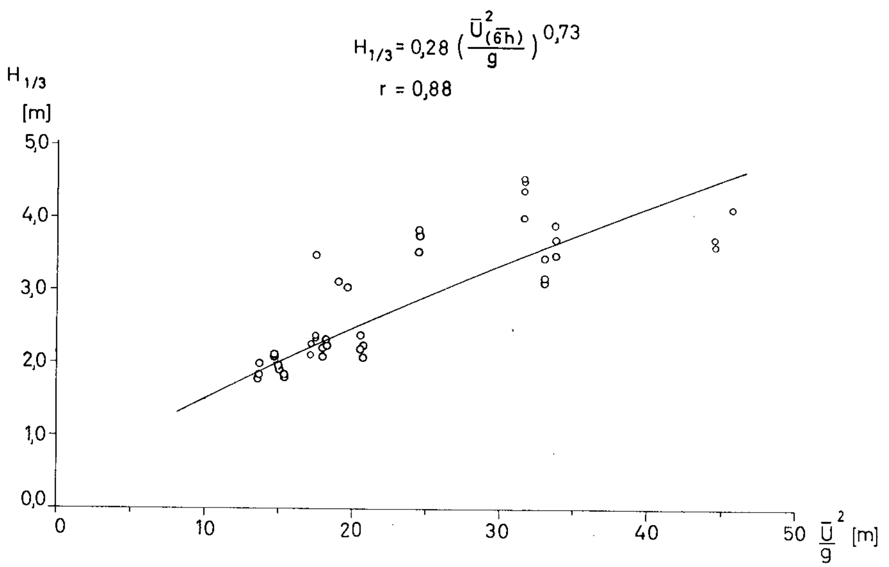

Fig. 5: Power Curve Fit for $H_{1/3}$ and $\frac{\bar{U}^2(\overline{6h})}{g}$

odation of data and the computed equation could be reached for a power curve fit using the mean wind velocity for the last three hours before starting the wave measurements (FIG.6). Exactly as for the significant wave height there is a high correlation between maximum wave height and mean wind speed on the same boundary conditions (FIG.7).

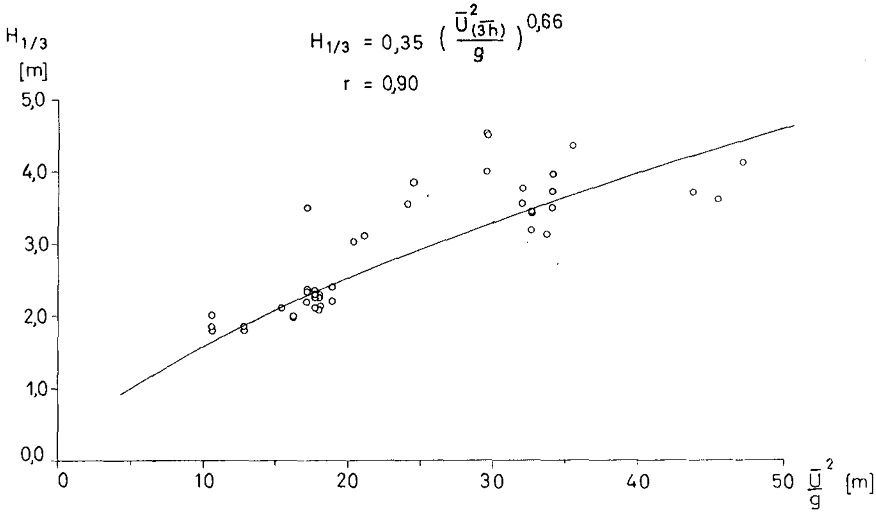

Fig. 6: Power Curve Fit for $H_{1/3}$ and $\frac{\bar{U}^2_{(\overline{3h})}}{g}$

These results show that the last three hours of the prevailing wind speed are the most important for the height of the occuring waves in the investigation area.

When comparing these results with the investigations of SCHÜTTRUMPF (1973) for the southern North Sea which are based on the hindcasting method of BRETSCHNEIDER (1954, 1957) it seems to be that for higher wind speeds than those measured during this research period a longer wind duration must be taken into consideration. Equally the influence of the distinct wind directions from W to NNE could increase on those conditions because then with the growing fetch length needed for the occurence of a fully arisen sea even small differences in the hydrographical features become more important for wave generation.

But the obtained results meet well enough the requirements for the estimation of wave conditions in the seaward region of the research area by forecasting or hindcasting techniques.

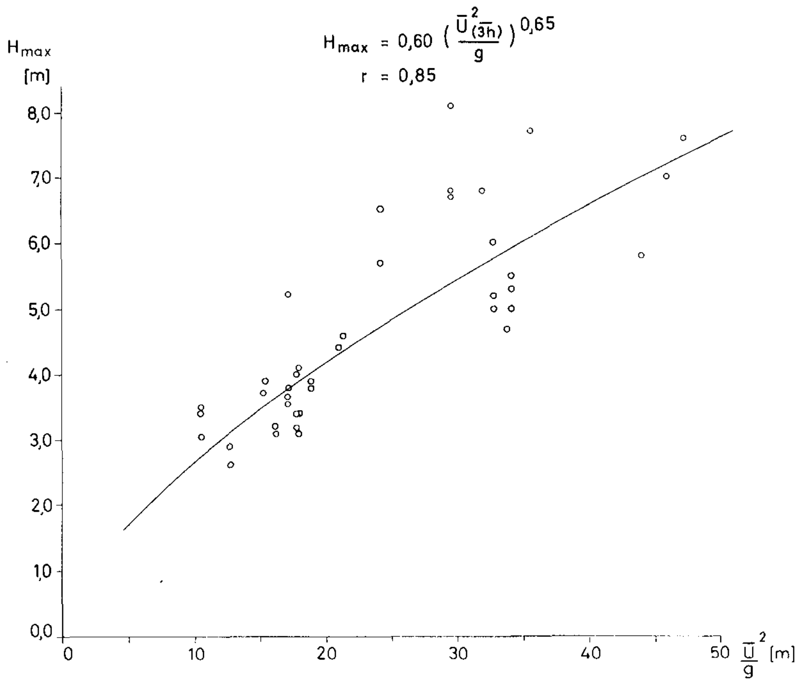

Fig. 7: Power Curve Fit for H_{max} and $\frac{\bar{U}^2_{(\overline{3h})}}{g}$

3. Wave energy dissipation due to wave breaking on the bar

The incoming waves reach the bar seaward of the tidal inlet Norderneyer Seegat and the northwestern shore of the island of Norderney. There the limited water depth induces the breaking of the higher waves. During high wave conditions the bar could be distinguished as a ring of white foam on which nearly all waves are broken ranging from the eastern end of the island of Juist around the tidal inlet Norderneyer Seegat and the northwestern shore of the island of Norderney.

It can be seen on aerial photographs that there is a significant difference between the western and the eastern part of the bar in respect of the height and areal extension of the shoals (FIG.8).

The analysis of data verifies that these different morphological features condition a distinct form of surf processes leading to a locally diverse form of wave energy dissipation in a quantitative und qualitative manner: The

Fig. 8: Aerial Photograph of the Bar Enclosing the Tidal Inlet Norderneyer Seegat and the Northwestern Shore of the Island of Norderney

waves which pass the bar in front of the northwestern shore of the island of Norderney are higher than those passing the part in front of the tidal inlet Norderneyer Seegat.

In the eastern part the water depth of the bar has a great influence on the height of waves recorded landward of the bar. There is a rather satisfactory correlation between significant wave height measured at station 2 and water depth (FIG.9). But the correlation coefficient is not high enough to believe that there is not any other important influence, because the graph indicates that waves of a different height can occur in the same water depth.

In order to describe wave energy dissipation on the bar it is useful to take into account not only the wave heights recorded seaward of the bar but also the water depth on the bar itself. As it is very difficult to define a concrete water depth on the bar it is replaced by the actual mean height of tide water level occuring during a measuring period.

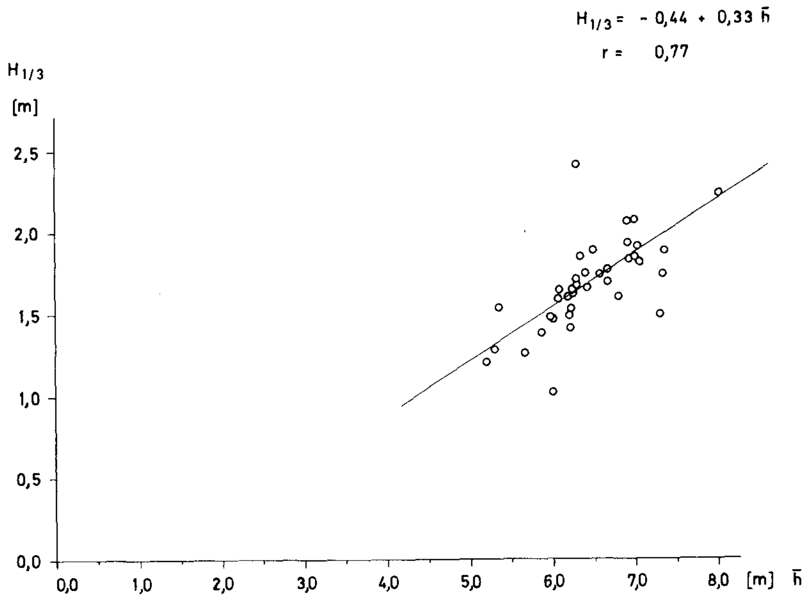

Fig. 9: Relation of Significant Wave Height and Water Depth at Station 2

In the eastern part of the bar in front of the northwestern shore of the island of Norderney wave energy dissipation can be described by the ratio of wave heights landward and seaward of the bar. It is dependent on the wave heights seawardly recorded in relation to the height of the tide water level:

$$\frac{H_{II}}{H_I} = f\left(\frac{H_I}{W_{PN}}\right) \qquad (1)$$

Explanatory in figures 10 and 11 wave energy dissipation is shown for the significant and maximum wave height. Data are best met by an exponential curve fit which is well proved by the high correlation coefficients (FIG. 10 and 11).

This result allows the determination of wave heights in front of the northwestern shore of the island of Norderney for a certain tide water level and wave heights seaward of the bar which can be easily estimated by the developped forecasting formulas.

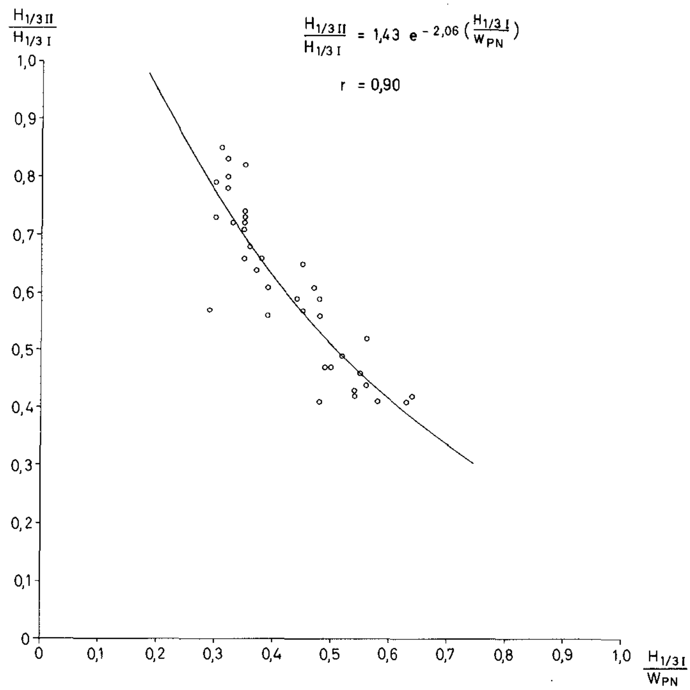

Fig. 10: Damping of Significant Wave Height on the Eastern Part of the Bar

These findings furthermore indicate the important protective function of the bar for the northwestern shore of the island. As the wave heights increase more considerably than the tide water levels during the occurence of storm tides, wave energy dissipation increases as well.

On the western part of the bar seawardly enclosing the tidal inlet Norderneyer Seegat the water depth in respect of incoming wave heights is much smaller than in the eastern part. As additionally the areal extension of the shoals is much larger than in the eastern part the important influences for surf processes and the connected wave energy dissipation differ as well.

Wave height damping on this part of the bar is only dependent on the incoming wave heights but not on the changing water depths on the bar.

There is a linear relationship between the wave heights seaward of the bar and the difference to those landward of the bar which could be proved by regression analysis for the significant and maximum wave height. The data fit the

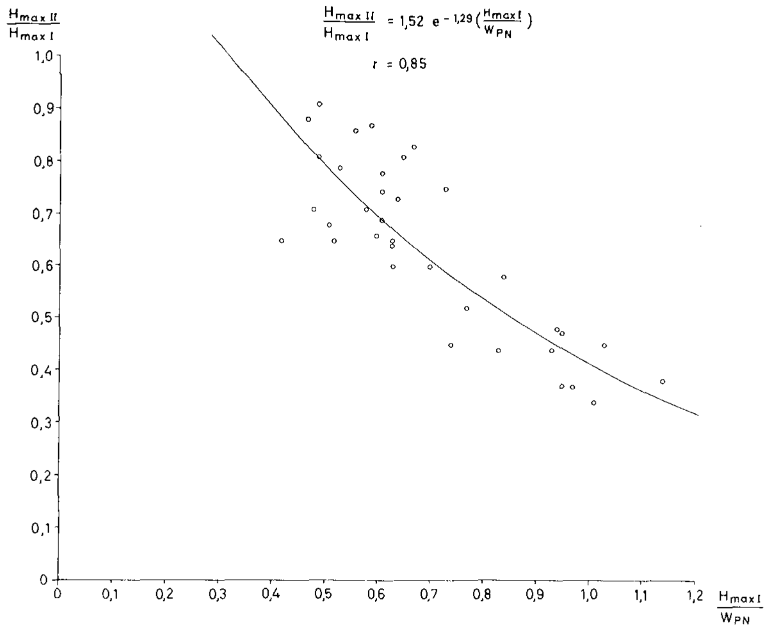

Fig. **11**: Damping of Maximum Wave Height on the Eastern Part of the Bar

computed equation nearly precisely which is as well proved by the very high correlation coefficients (FIG.12 and 13).

The decreasement of wave energy in front of the tidal inlet is of great importance for the wave conditions on the tidal flats and the wave loads on the dykes on the mainland coast. In this respect the part of the bar enclosing the tidal inlet has an essential protective function for the mainland coast.

The intensive wave energy dissipation on the bar is easily demonstrated by the ratio of maximum wave height to water depth recordered at the two stations landward of the bar. Its value is always much smaller than that necessary for shallow water wave breaking

$$H_b = h_b \tag{2}$$

which has been established by FÜHRBÖTER (1974) and SIEFERT (1974) by field measurements in shallow water regions. In this case the orders of magnitude are as follows:

$$H_{max\ II} \leq 0,57\ h \tag{3}$$

$$H_{max\ III} \leq 0,39\ h \tag{4}$$

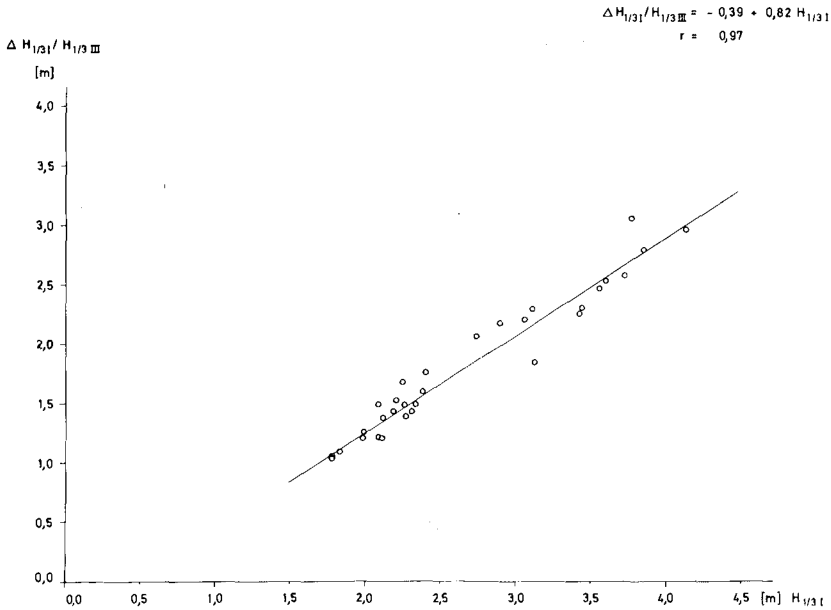

Fig. 12: Damping of Significant Wave Height on the Western Part of the Bar

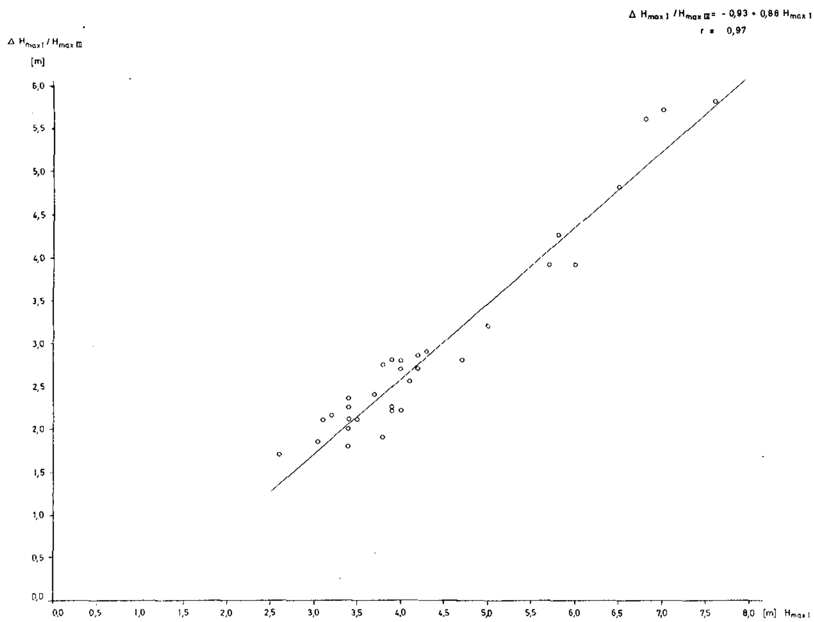

Fig. 13: Damping of Maximum Wave Height on the Western Part of the Bar

Landward of the bar wave breaking due to limited water depth cannot therefore occur before the new generated waves reach the shore of the island or the dykes on the mainland coast (FIG.14).

Fig. 14: Wave Breaking on the Bar in front of the North-western Shore of the Island of Norderney

4. Wave height damping on the tidal flats

While the waves passing the eastern part of the bar attack the northwestern shore of the island of Norderney, those which are generated after breaking on the eastern part spread out over the tidal flats. Though they are not high enough to be broken because of the limited water depth a certain wave damping on the tidal flats could be observed. It must be explained as a combined superposing effect of bottom friction, refraction, diffraction and shoaling.

The damping of maximum wave height from the inner part of the tidal inlet can be described as a function of itself in relation to the water depth at the end of the travel distance (FIG.15). One gets a more complicated expression for the damping of the significant wave height (FIG.15), but the influence of water depth can be distinguished too.

The intensity of wave height damping on the tidal flats can be described by another example:

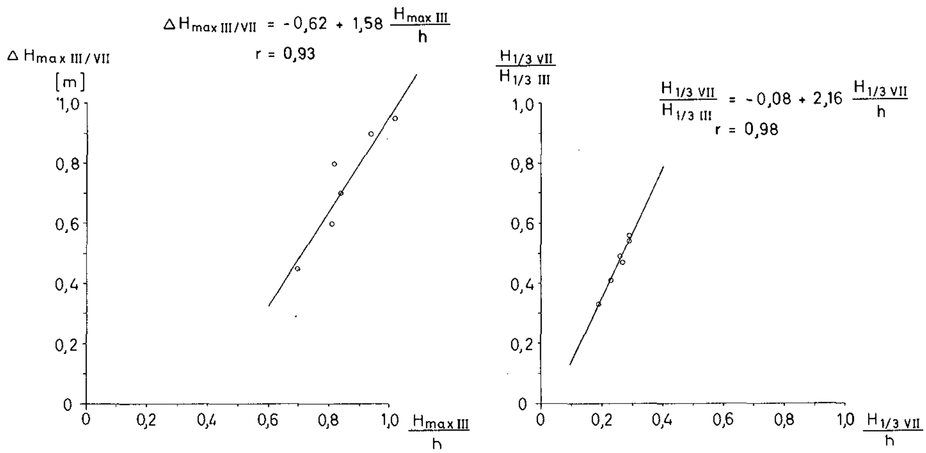

Fig. 15: Wave Height Damping on the Tidal Flats

The comparison between the ratio of maximum wave height and water depth at the two stations with a different distance to the tidal inlet shows that there is a nearly continuous damping of maximum wave height with respect to water depth and travel distance (FIG.16). Considering the growing heights of flats with increasing distance from the tidal inlet in connection with the constant ratio of wave height and water depth it is possible to come to the conclusion that there is a well-balanced dynamic equilibrium between the morphological configuration of the flats and the local wave climate.

But this result includes another important fact, because one wave measuring station is situated in front of a dyke without foreland the other on a dyke foreland. The obtained ratio of wave height and water depth is significant for flats without any wave breaking according to the investigation of SIEFERT (1974) in the southwestern region of the Elbe estuary. Regarding both results the up to now generally accepted theory of an intensive wave damping due to wave breaking on dyke forelands must be abandoned.

Regarding the topography of the research area it seems to be that the existence of dyke forelands is even a consequence of the local low wave energy.

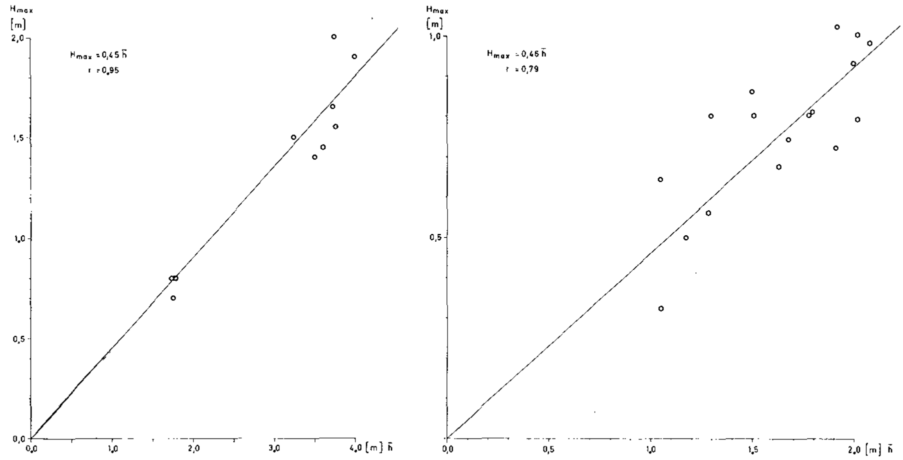

Fig. 16: Relation of Maximum Wave Height and Water Depth at the two Stations (8 + 12) on the Mainland Coast

5. Investigations on wave run-up

These investigations on wave climate are combined with those on wave run-up on sea dykes. Therefore four wave run-up gauges were meanwhile placed on sea dykes. But undisturbed wave run-up measurements can only be carried out at the occurence of very high storm tide water levels. As such an event has not yet happened since the start of the measurements with the run-up gauges, there are not until now any measurements leading to new results.

But the influence of wave parameters on wave run-up has already been analysed by the investigations of HUNT (1959) on monochromatic waves as well as by those of VAN OORSCHOT and D'ANGREMOND (1968) on wave spectra.

Their commonly accepted results show that the height of wave run-up in respect of the occuring spectrum is dependent on the wave period and the square root of wave height. Accordingly wave run-up is here described as wave run-up potential only considering wave parameters and neglecting all other influences (NIEMEYER 1977b).

The data of 17 wave records of field measurements which include about 1800 waves are used for computing wave run-up potential with respect to the higher and longer waves of the spectrum. Important for the highest five per cent of wave run-up potential are the highest and longest ten per cent of waves. But the maximum wave run-up potential for every record is caused by its highest and longest waves. In figure 17 computations of wave run-up potential for all 17 records are shown for comparison (FIG.17):

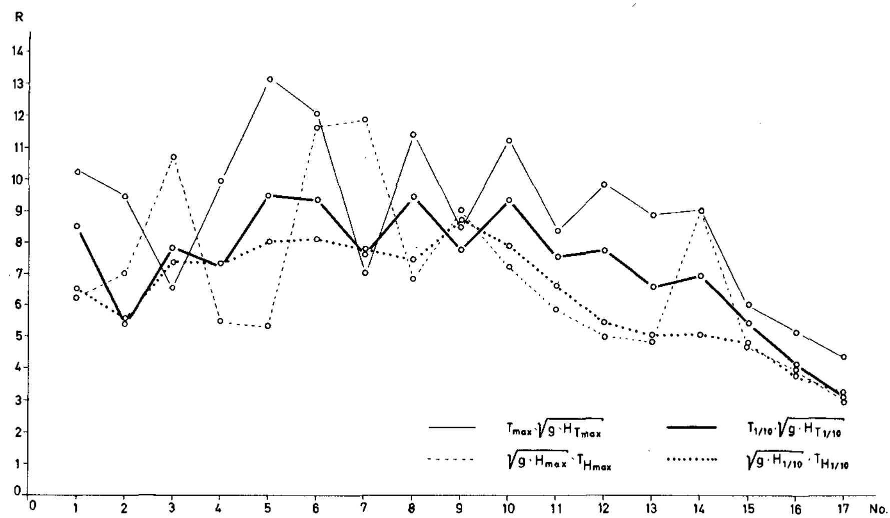

Fig. 17: Comparison of Several Computed Wave Run-Up Potentials by Using Wave Data of Field Measurements

1. wave run-up potential R_{Tmax} of the longest wave with period T_{max} and height H_{Tmax}
2. wave run-up potential R_{Hmax} of the highest wave with height H_{max} and period T_{Hmax}
3. wave run-up potential $R_{T1/10}$ of a wave with the mean period $T_{1/10}$ and the mean height $H_{T1/10}$ of the longest ten per cent of waves
4. wave run-up potential $R_{H1/10}$ of a wave with the mean height $H_{1/10}$ and the mean period $T_{H1/10}$ of the highest ten per cent of waves

Mostly the highest computed wave run-up potential is caused by the longest wave of the considered records. Comparing all computed wave run-up potentials the following relations are gained:

$$R_{T1/10} = 0,82\ R_{Tmax} \tag{5}$$

$$R_{Hmax} = 0,78\ R_{Tmax} \tag{6}$$

$$R_{H1/10} = 0,72\ R_{Tmax} \tag{7}$$

$$R_{H1/10} = 0,92\ R_{Hmax} \tag{8}$$

6. Summary

The Research Station for Island and Coast Protection Norderney has been operating the wave measurement program East Frisian Island and Coast for two years. The first results of this study can be summarized in the following manner:

1. There is a high correlation between the wind speed prevailing the last three hours and the heights of local waves subsequently occuring.
2. Wave energy dissipation on the bar enclosing the tidal inlet and the northwestern shore of the island situated westward of the inlet can be described in a quantitative manner in respect of the different morphological features of the bar.
3. The intensive wave energy dissipation on the bar prevents the breaking of waves spreading out over the tidal flats due to limited water depth, which indicates in spite of that a wave height damping in a certain order of magnitude.
4. The continuous wave damping on the tidal flats leads to such a decreasement of heights that there cannot occur any wave breaking due to restricted water depth during the duration of high storm tide water levels.
5. It seemed to be that not the highest, but mainly the longer waves induce the heighest wave run-up on sea dykes.

7. Acknowledgements

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9. List of symbols

g	gravitational acceleration
h	water depth
h_b	depth of water at breaking wave
H_b	wave height at breaking
$H_{1/3}$	significant wave height
$H_{1/10}$	average height of highest ten per cent of waves for given rime period
H_{max}	maximum wave height for specified period of time
$H_{T1/10}$	average height of longest ten per cent of waves for given time period
H_{Tmax}	height of the longest wave for specified period of time

H_I, H_{II}, ... H_{XII}	wave height measured at stations 1, 2, ... 12
$R_{H1/10}$	wave run-up potential of a wave with average height and period of highest ten per cent of waves for given period of time
R_{Hmax}	wave run-up potential of the highest wave for specified period of time
$R_{T1/10}$	wave run-up potential of a wave with average height and period of the longest ten per cent of waves for given period of time
R_{Tmax}	wave run-up potential of the longest wave for specified period of time
$T_{1/10}$	average period of longest ten per cent of waves for given period of time
T_{max}	maximum wave period for specified period of time
$\bar{U}$	wind speed
$\bar{U}_{(\overline{3h})}$	mean wind speed prevailing the last three hours before starting wave measurements
$\bar{U}_{(\overline{6h})}$	mean wind speed prevailing the last six hours before starting wave measurements
W_{PN}	height of tide water level
$\Delta H_I/H_{III}$	difference of wave heights measured at station 1 and 3
r	correlation coefficient