CHAPTER 105

Changing of wave climate due to breaking on a tidal inlet bar Hanz Dieter Niemever⁺

ABSTRACT

Changes of wave climate due to breaking on a tidal inlet bar are investigated by analysis of field measurements prosecuted offshore and onshore of the bar. Quantitative results for wave height reduction, period and length transformation and energy dissipation are presented as well as a study considering the dominating breaking criterion.

1. INTRODUCTION

The prevailing longshore drift along the East Frisian islands is eastward directionalized. The sand by passing the inlets leads to the configuration of the typical tidal delta: a number of shoals separated by channels leading from the updrift to the downdrift island like a chain. The landfall area of the sand on the downdrift island divides its beaches into an eroding and accretionary part. A very impressive example are the beaches of the island of Norderney (Fig. 1): Downdrift of the sand's landfall there are broad accretionary beaches while updrift the continuous erosion has forced man to build revetments and groynes, because the sand needed for supply is passing seaward. The only comforting thing is that the shoals act like a submerged breakwater on incident waves and attenuate especially the higher ones. In order to get quantitative information about this effect field measurements were carried out in the offshore area, on the island foreshore and in the tidal inlet of the island of Norderney (Fig. 2). The results gained up to now from these investigations are presented here.

⁺Department for Coastal Research, Norderney, F.R.o.GERMANY



Fig. 2: Map of the investigation area with measuring stations (I: offshore, II: island foreshore, III: tidal inlet)

2. BOUNDARY CONDITIONS OF THE FIELD MEASUREMENTS

The tidal inlet Norderneyer Seegat is ebbdominated with mixed energy with reference to the classification of HAYES (1979). The mean tidal range is about 2.4 m changing on the average up to 0.7 m due to spring and neap tide. Set-up occuring during storm tides has until now reached the measure of some 3 m. The water depth due to MHWL at the three measuring stations is 12.1 m (offshore), 4.8 m (island foreshore) and 3.2 m (tidal inlet). The measurements were carried out with ultrasonic wave gages, which unfortunately do not always guarantee undisturbed data registration, because this measuring principle is very sensitive due to air bubbles in the water. Further details considering the investigation area and especially its morphological boundary conditions have been published earlier (LUCK 1978; FITZGERALD, PENLAND + NUMMEDAL 1984).

3. WAVE HEIGHT REDUCTION

Comparing significant wave heights measured offshore and onshore of the tidal inlet bar makes their attenuation due to the crossing of the shoals evident, on the average there is a reduction of 42 % on the island foreshore and of 70 % in the inlet area in relation to offshore significant wave height (Fig. 3 + 4). But this general tendency is superimposed by a scattering of values due to variations of onshore parameters corresponding to offshore significant wave heights which nearly do not differ from each other.



The onshore wave heights also generally depend on the water level fluctuations in the investigation area: There is basically a tendency of bigger onshore significant wave heights for increasing water depths. But this relation is also characterized by a scattering of onshore wave heights occuring in coincidence with water depth, which have the some order of magnitude (Fig. 5+6). This process corresponds with the paradox of wave breaking on bars: For the same water depth an increase of offshore wave heights does not always effect an increase of those correspondently arriving onshore, but sometimes there is a decrease.





AND WATER DEPTH (ISLAND FDRESHDRE)

AND WATER DEPTH (TIDAL INLET)

This first interpretation of data leads to the conclusion that it is impossible to analyse the damping effect of a bar on wave height by taking into account only single related parameters. The interaction of the most important hydrodynamical and morphological boundary conditions governing this process, must be taken into consideration. As the shoals of a tidal inlet bar act on crossing waves like a submerged breakwater, the idea comes up to make use of the analytical formulation of boundary conditions, which was developped in previous research on this subject (ABDUHL KHADER + RAI 1980; JOHNSON, FUCHS + MORISON 1950). Additionally the investigations of DIEPHUIS (1957) on scale effects due the reproduction of wave breaking on bar in hydraulic models of small size were taken into account.

Transferring these results a statistical appromimation has been developped considering the following boundary conditions: Wave height/water depth relation in the offshore region and additionally as well relative length shortening due to shoaling, wave steepness and relative water depth in the offshore area as the relations of the bar crest height to offshore water depth and shoal width to offshore wave length.

$$\frac{H_{i}}{H_{a}} = a_{1} \left(\frac{H_{a}}{h_{a}}\right)^{b_{1}} + a_{2} \left(\frac{H_{a}}{L_{a}}\right)^{b_{2}} + a_{3} \left(\frac{H_{a}}{L_{a}}\right)^{b_{3}} + a_{4} \left(\frac{g \cdot T_{a}^{2}}{L_{a}}\right)^{b_{4}} + a_{5} \left(\frac{h_{a} - h_{R}}{h_{a}}\right)^{b_{5}} + a_{6} \left(\frac{H_{R}}{L_{a}}\right)^{b_{6}}$$

First the regression analysis is carried out particularly for each boundary condition in order to differentiate their importance for wave height transmission across the bar by means of correlation coefficients (Table 1).

		BOUNDARY CONDITION					
AREA	WAVE HEIGHT	H _a /h _a	H _a /L _a	h _a ∕L _a	$g \cdot T_a^2 \cdot L_a^{-1}$	(h _a -h _R)/h _a	^B _R ∕L _a
ISLAND	H _{max}	0,773	0,138	0,530	0,280	0,421	0,578
FORE-	Hs	0,859	0,475	0,399	0,663	0,303	0,447
SHORE	H	0,851	0,263	0,628	0,621	0,258	0,653
TIDAL	H max	0,717	0,256	0,340	0,010	0,252	0,367
INLET	Hs	0,764	0,347	0,464	0,192	0,146	0,481
	H	0,708	0,223	0,507	0,583	0,135	0,503

Table	1:	Partial	correlation	coefficients	for	single	boundary	condi-
		tions of	f wave height	c transmission	٦			

It is evident that offshore wave height/water depth ratio is the dominating boundary condition. All others are in comparison of less importance.

The results of this nonlinear multiple regression analysis are only demonstrated due to limited space for the significant wave heights: Measured and computed data show a rather good agreement (Fig. 7). In or-



der to check, if this method is also useful for other areas with similar boundary conditions, a second wave data set from the region of the tidal inlet of the West Frisian island of Schiermonnikoog (MAD DELFZIJL 1983) is additionally taken into consideration. The function gained from the regression analysis does also fit the composited data of both areas (Fig. 8).

Summarizing these results it becomes obvious that the formulation of boundary conditions for wave breaking on tidal inlet bars and their functional relationship as developped here are not only applicable to these processes in the investigation area itself but also in other regions with similar morphological boundary conditions.

4. PERIOD AND LENGTH TRANSFORMATION

The breaking of waves on the bar does not only create a damping of their heights but also a transformation of their periods and length. Data analysis for these parameters was carried out in the same manner as for wave heights. The partial correlation coefficients for significant wave period and length are summarized in table 2, separately for the island foreshore and the tidal inlet:

l .	ļ	80UNDARY CONDITION					
AREA	PARAMETER	H _a /h _a	H _a /L _a	h _a /L _a	g·T ² ·L ⁻¹	(h _a -h _R)/h _a	8 _R /L _a
ISLAND	T _{Hs}	0,708	0,365	0,707	0,683	0 , 275	0,336
SHORE	L _{Hs}	0,754	0,471	0,754	0,717	0,400	0,435
TIDAL	T _{Hs}	0 ,536	0,030	0,275	0 ,536	0,275	0 ,336
INLET	L _{Hs}	0 ,5 82	0,047	0,582	0,554	0,400	0,435

Table 2: Partial correlation coefficients for single boundary conditions

Obviously period and length transformation due to breaking on the tidal inlet bar does not depend primarily on a single boundary condition as wave height transmission by the offshore wave height/water depth ratio. It is also evident that wave breaking on the bar is different on its parts which separate the island foreshore and the tidal inlet itself

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from the offshore area. The transformation of periods and lengths do not depend to a similar extent on the same boundary conditions, which is apparently clear for offshore wave steepness.

A direct comparison of periods and lengths measured offshore and onshore of the bar (Fig. 9 + 10), shows that wave breaking on the bar leads to a decay of bigger offshore waves to shorter solitons (GALVIN 1972) or secondary waves (HULSBERGEN 1974).

Fig. 9b





Fig. 10a



Fig. 10b



In analogy to wave heights the nonlinear multiple regression analysis was not only carried out for the data measured in the investigation area itself but additionally in connection with those from the region of the West Frisian Island of Schiermonnikoog. Due to limited space only the results of the last are quoted here (Fig. 11 + 12). The data fitting to the treated function is of less accuracy than for wave heights, especially for those from the tidal inlet of the Norderney Seegat. This result agrees well with the order of magnitude of partial correlation coefficients (Table 2). Probably this lack of accuracy is partly created by disturbances in data sampling due to failures of the measuring devices as mentioned before.



ENERGY DISSIPATION

5.1 ENERGETICALLY REPRESENTATIVE WAVES

The energy of a wave is defined as follows:

$$E = \frac{1}{8} \cdot \rho \cdot g \cdot H^2 \cdot L$$

FÜHRBÖTER (1974) suggested determining the power of a wave in terms of electricity:

$$N = 1,225 \cdot \rho \cdot g \cdot H^2 \cdot \frac{L}{T} (kw)$$

In order to compute the power of an energetically representative wave for measured time series in the offshore area of the German North Sea coast DETTE and FÜHRBÖTER (1977) made the following substitution:

$$\frac{L}{T} = c = \sqrt{g \cdot h}$$

Additionally they introduced the significant wave height ${\rm H}_{\rm S}$ for the computation of wave power:

$$N = 1,225 \cdot \boldsymbol{\rho} \cdot g \cdot H_s^2 \cdot g \cdot h$$
 (kw)

But this solution includes two basic faults. Firstly the energetically representative wave height of a time series is in accordance with LONGUETT-HIGGINS (1953) $H_{\rm rms}$ and not $H_{\rm s}$. Secondly the use of the approximation for shallow water wave celerity is restricted to values of relative water depth of

$$h/L_{o}^{} \leq 0,05$$
 .

As well in the investigation area of DETTE and FÜHRBÖTER (1977) as at the measuring station in the offshore area of Norderney this assumption is not satisfied. Furthermore it seems to be convenient to consider the energy flux, represented by the ratio of wave group and phase velocity. Therefore the power of the energetically representative waves of all measured time series is computed in the following manner:

$$N = 1,225 \cdot n \cdot \boldsymbol{\rho} \cdot g \cdot H_{rms}^2 \cdot c$$
$$c = \frac{g}{2\pi} \cdot T_m \cdot tanh (k \cdot h)$$

A comparison of the results for data from the offshore area of Norderney with the computation method suggested by DETTE and FÜHRBÖTER (1977) shows, that their statement leads to an overestimation of wave power with hyperbolical character of about 400 % on the average (NIEMEYER 1983).

The determination of energy dissipation due to wave breaking is carried

out by comparing the power of the energetically representative waves of all time series measured correspondently offshore and onshore of the tidal inlet bar. In order to avoid an overestimation of longer waves the wave power is summarized per hour considering the possible number of waves which can occur during this unit of time due to their period.



The numerical results of these computations indicate the enormous sheltering effect of the bar for its onshore areas against wave action. There is a strong linear relationship between offshore wave energy and energy dissipation due to breaking on the bar (Fig. 13 + 19): On the average 92 % of wave energy in the offshore area dissipates on the bar's shoals seaward of the tidal inlet and 70 % on those separating the island foreshore from the open sea. These differences in dissipative efficiency of the two parts of the bar, which correspond with wave height damping, could be easily explained by the distinction of its morphological features: The shoals seaward of the bar are higher, have a larger aerial extension and are closer to each other than those surrounding the island foreshore (Fig. 1 + 15). It seems furthermore noteworthy that energy dissipation on both parts of the bar increases with the same tendency as offshore wave energy.

Though there is a strong linear relationship between offshore wave energy and its dissipation on the bar, it is not similarly succesful to





use it for the derivation of the residual wave energy in the onshore areas (Fig. 16 + 17). There is a remarkable scattering of values due to divergence from the functional average. The reason might be that the residual wave energy is much smaller than both the offshore wave energy and its rate of dissipation due to breaking. So probably the derivation leads to small differences of large numbers. But it is noteworthy that the functional average is well in accordance with the average rate of dissipation derivated above.

5.2 ENERGY SPECTRA

As well as for energetically representative waves of measured time

series, investigations of energy dissipation due to wave breaking have been carried out by comparison of spectra, which have been measured correspondently offshore and onshore of the bar. The intention was to get not only information about energy dissipation but also about energy shifting to other frequencies.

The spectra of two runs are used here for such an exemplary comparison. One is representative for high the other for very high offshore wave conditions (Table 3). Corresponding to the meteorological boundary conditions the energy of spectrum No. 51 is five times greater than that of No. 24 and the relation of peak energy density is even ten to one (Fig. 18 + 19, Table 3). Comparing the spectra onshore of the bar these differences have become remarkably smaller. This result also proves the already established fact that an increase of wave energy in the offshore area leads always to a higher dissipation due to breaking on the bar. The dissipation is not only characterized by a decrease of total energy



		RUN 24		Run 51			
PARAMETER	OFF SHORE	ISLAND FORESHORE	TIDAL INLET	OFF- SHORE	ISLAND FORESHORE	TIÐAL INLET	
E _{ges} (cm ²)	5 616	3 654	1 150	25 644	5 182	1 602	
E _{fmax} (cm ² s)	12 900	9 302	1 642	139 200	12 660	3 864	
f _{max} (Hz)	0,128	0,127	0,122	0,080	0,093	0,087	
T _p (s)	7,8	7,9	8,2	12,5	10,8	11,5	
H _s (m)	2,11	1,71	0,95	4,53	2,04	1,19	
T _{mO2} (s)	5,5	5,7	4,3	7,2	6,3	5,1	
ε	0,95	0,93	0,93	0,98	0,96	0,91	
Q _p	1,44	1,40	1,01	1,71	1,16	1,08	

Table 3: Comparison of Spectral Parameters

but also and to a larger extent of the energy peak concentration leading to multi-peak spectra in the onshore areas. The decay of peak concentration intensifies the more firstly the higher the spectral peak concentration in the offshore area and secondly the higher the dissipative efficiency of the shoals. So for both spectra the dissipation of energy is in comparison on the shoals offshore of the tidal inlet itself much larger than on those seaward of the island foreshore. Also the change of the spectral shape due to the decay of the single peak to a number of peaks of similar order of magnitude occur on the island foreshore only significantly for spectrum No. 51 with its very high energy peak concentration.

Analogous high energy dissipation due to the same boundary conditions - high shoals with large areal extension close to each other and high energy concentration in the offshore wave spectrum - effects an energy shifting to higher frequencies (Fig. 20). Considering this result and the correspondent change of spectral shape it is remarkable that there is even nearly no change in peak frequency from the single peak offshore spectrum to the corresponding ones in the onshore areas of the bar with a multi-peak shape. Therefore it seems necessary to reconsider the interpretation of multi-peak spectra by only one peak frequency.



6. HYDRODYNAMICAL CAUSES FOR WAVE BREAKING

In order to evaluate the hydrodynamical causes for wave breaking on the bar, the two breaking criteria for shallow water were correspondently taken into account. Firstly the limit of wave height/water depth ratio for North Sea conditions (FÜHRBÖTER 1974; SIEFERT 1974) and secondly the critical wave steepness (MICHE 1944) were computed for the measured offshore wave data. Additionally their transformation due to shoaling was considered. The investigations are based on a fictitious water depth on the bar corresponding to the highest areas of the shoals.

Even for this water depth, which is rather small with respect to site conditions a large number of significant wave heights calculated due to shoaling would not break on the bar (Fig. 21 + 22). On the contrary many more of these fictitious significant wave heights would break taking the critical steepness limit (MICHE 1944) into consideration (Fig. 23 + 24). This result leads to the conclusion that the dissipative efficiency of the bar does not only base on the restricted water depth on the highest part of its shoals but also and probably to a larger extent on shoaling water depth from the offshore area to the bar.



7. FINAL REMARKS AND ACKNOWLEDGEMENTS

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9. 9	SYME	301	_S
B _R		:	Representative shoal width
E		:	Wave energy
Е _F		:	Wave energy flux
E fm:	ax	:	Energy density peak
E	9.74 9.	:	Total spectral energy
f	0	:	Frequency
f	×	:	Peak frequency
g		:	Gravitational acceleration
h		:	Water depth
h		:	Offshore water depth
h _b		:	Water depth at breakpoint
h		:	Fictitious water depth above the bar
н		:	Wave height
Η		:	Offshore wave height
н		:	Breaker height
Η		:	Onshore wave height
л_Н		:	Significant wave height
H	s	:	Root-mean-square wave height
k	-	:	Wave number: $2\pi / L$
La		:	Offshore wave length
L		:	Onshore wave length
L		:	Deep water wave length
L _{Hs}		:	Significant wave length
MHW	L	:	Mean high tide water level
n		:	Ratio of wave group and phase velocity
Ν		:	Wave power
Q		:	Spectral peakednessparameter
Τ _a		:	Offahore wave period
THs		:	Significant wave period
T _i		:	Onshore wave period
Ţ		:	Spectral peakperiod
έ		:	Spectral width
ρ		:	Specific density of seawater
T _{mO:}	2	:	Mean spectral period