Diked Forelands and their Importance in Coastal Zone Management

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Abstract

Dike forelands are an important part of the coastal defence system. Compared to forelands without summer dikes diked forelands significantly reduce the wave load on the main dike during storm surge. The reduction of wave load is a consequence of the (due to the summer dike) reduced wave height and period of the approaching wave and of the reduced duration of wave attack. In case of extreme storm surges the total wave energy dissipating at the main dike lying behind a diked foreland is reduced to approximately 75 % compared to the wave energy behind a foreland without summer dike.

Introduction

The German Coast is densely populated. Therefore the most important aspect of a coastal zone management is the protection of the hinterland from flooding during storm surges. While in the past the focus was put on the main dike, today additional defense elements like forelands, summer dikes, and land reclamation fields are more and more taken into consideration [ERCHINGER, 1993, MAI ET AL., 1997, OUMERACI, 2002, ZIMMERMANN AND MAI, 1998]. However, the demands of coastal defence compete with the demands of other uses of the coastal area, like tourism and nature conservation. These often contradictory demands of the different uses have to be taken into account especially within environmental impact assessments carried out for example during the approval process for harbour extensions [e.g. BARTELS, 2001] or dredging works [e.g. FERK, 2001].

Nowadays a renaturation of diked forelands is discussed in order to compensate the negative impacts of construction works within the coastal zone. Examples of the renaturation of diked forelands at the German North Sea Coasts can be found at the Hauener Hooge west of Greetsiel and southwest of Berensch [FRÄMBS ET AL., 2000]. Further projects were respectively are discussed on the island Langeoog and near Belum [FERK, 2001] as well as at two sites near Luetetsburg and Spieka-Neufeld [BARTELS, 2001] being focussed in the following.

The renaturation of diked forelands to salt marshes requires a restoration of a permanent tidal in- and outflow of salt water. The restoration of the tidal influence in the diked foreland is achieved by drainage pipes, sluices or the total or partial removal of the dike enclosing the foreland [MAI AND VON LIEBERMAN, 2001]. The latter opening method is recommended by ecologists as the best way towards a renaturation. However it also implies the strongest effects in coastal defense management.

Characteristics of diked forelands

The typical structure of a coastal defense system with brush wood fences (land reclamation fields), foreland, summer dike, summer polder (diked foreland), and main dike is given in figure 1. A single land reclamation field covers an area of approx. 200 m x 150 m. The height of the surrounding brush wood fence is approx. mean tidal high water. The width of summer polders in front of the main dike varies from 200 m to 600 m at the East Frisian coast respectively 400 m to 1200 at the coast of the region Land Wursten, its length varies from 2100 m to 4800 m at the East Frisian coast respectively 2600 m to 6200 m at the coast of the region Land Wursten. The height of the diked foreland is approximately 0.5 m above mean tidal high water. The height of the summer dikes surrounding the polder equals 1.5 m to 2 m above mean tidal high water. The slopes of the summer dike equal 1:7 to 1:10. A cross-section of the summer dike is given in figure 2.

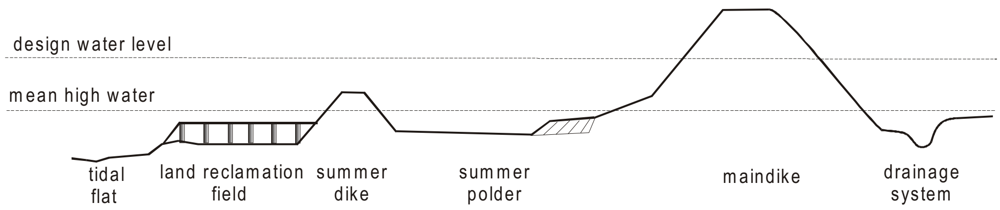

Figure 1: Structure of a Coastal Defence System with Diked Foreland

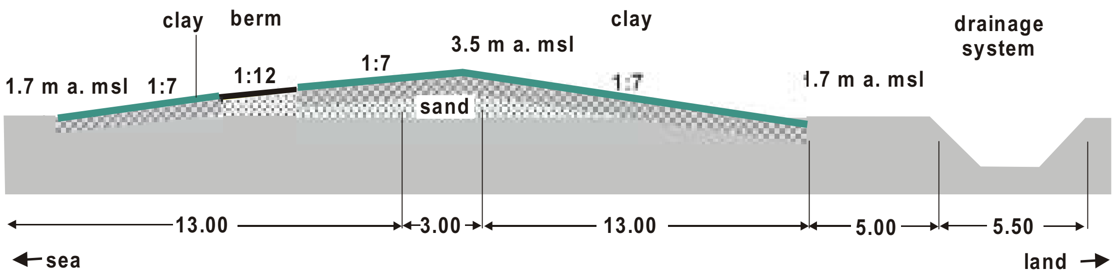

Figure 2: Cross-section of a Summer Dike

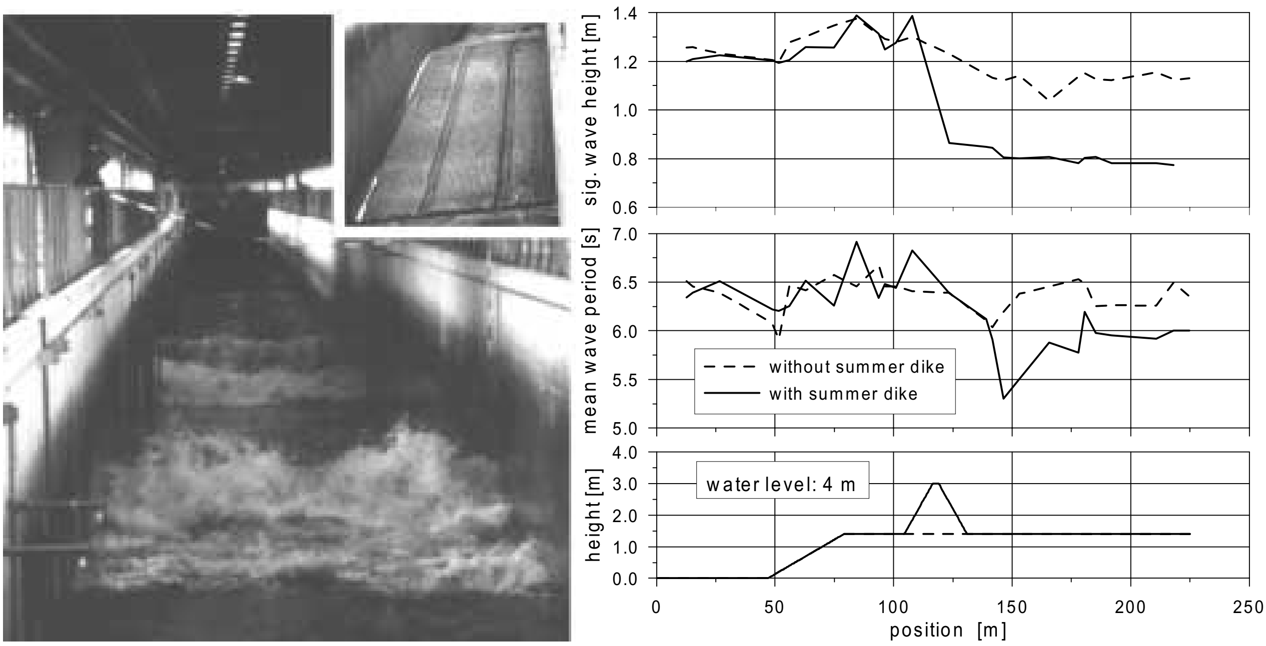

Figure 3: Change in Significant Wave Height and Mean Wave Period at a Foreland with Summer Dike – Experimental Results Obtained in the Large Wave Flume GWK

From the coastal engineering point of view diked forelands are advantageous compared to forelands without summer dike because summer dikes prevent the polder from being flooded during low to moderate storm surges and reduce the wave attack on the main dike during extreme storm surges. The frequency of flooding is reduced by a summer dike (with a crest height of 1 m above the foreland) from approximately 2 % to approximately 0.2 %.

The reduction of wave attack on the main dike by a summer dike relates on the one hand side to a reduced intensity and on the other hand side to a reduced duration. The reduced intensity of wave attack can be attributed to a reduction in significant wave height and in wave period (see figure 3).

This reduction is quantified using the transmission coefficient c_T resp. r_T for significant wave height resp. mean wave period [MAI ET AL., 1999a]

$$c_T = \frac{H_{s,trans}}{H_{s,in}} \qquad\qquad r_T = \frac{T_{m,trans}}{T_{m,in}}$$

with

$H_{s,trans}$, $H_{s,in}$ significant wave height at the main dike and at the drop of the foreland
$T_{m,trans}$, $T_{m,in}$ mean wave period at the main dike and at the drop of the foreland

The transmission coefficients c_T and r_T are functions of the freeboard relative to the significant wave height in front of the summer dike resp. of the freeboard relative to the deep water peak wave length in front of the summer dike as physical model tests reveal [D' ANGREMOND ET AL., 1996, DAEMRICH ET AL., 2001]. Figure 4 visualises these parameters.

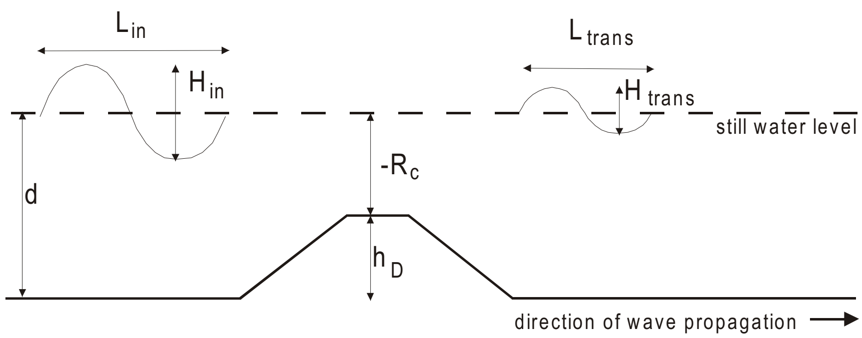

Figure 4: Parameters Describing Wave Transmission

The following empirical formulas are derived from physical model tests in the large wave flume GWK and in a side channel of the wave basin WBM of the University of Hannover Germany [MAI ET AL., 1999a, Daemrich et al., 2001]:

$$c_T = -\beta_1 \frac{R_C}{H_{s,in}} + \beta_2 \cdot \left(\frac{B}{H_{s,in}}\right)^{-\beta_3} \cdot \left(1 - e^{-\beta_4 \cdot \tan(\alpha) / \sqrt{H_{s,in} / (g/(2\cdot\pi)\cdot T_{p,in}^2)}}\right)$$

$$r_T = \tanh\left(-\beta_5 \cdot \frac{R_c}{g/(2\cdot\pi)\cdot T_{p,in}^2}\right)^{\beta_6}$$

with

B width of the crest of the summer dike

g	acceleration of gravity
$H_{s,in}$	significant wave height in front of the summer dike
R_c	freeboard of the crest of the summer dike ($R_c = h_d - h_{wl}$)
h_d	height of the summer dike
h_{wl}	water level
T_p	peak wave period
α	slope of the summer dike
$\beta_1, \beta_2, \beta_3, \beta_4, \beta_5$	parameter of the empirical formulas ($\beta_1 = 0.41$, $\beta_2 = 0.58$, $\beta_3 = 0.48$, $\beta_4 = 2.59$, $\beta_5 = 13.8$, $\beta_6 = 0.178$)

After calibration analogous results are also obtained using numerical simulation with the models MIKE 21 EMS and SWAN [MAI ET AL., 1999b]. Applications of the models SWAN and MIKE 21 EMS are given in the case studies presented in the following paragraphs.

Besides of the reduction of the intensity of the wave attack its duration during storm surges is also reduced by summer dikes as figure 5 indicates for typical conditions. In order to estimate the overall effect of forelands with and without summer dikes the total wave energy dissipating at the main dike during storm surge is a good measure [FÜHRBÖTER, 1979]. The total wave energy E_{tot} equals the transport of wave energy P(t) integrated over time t:

$$E_{tot} = \int P(t)\,dt$$

The transport of wave energy P(t) equals

$$P(t) = \tfrac{1}{8} \cdot \rho_w \cdot \left(H_{s,trans}(t)\right)^2 \cdot c(t) = \tfrac{1}{8} \cdot \rho_w \cdot \left(c_T(t) \cdot H_{s,in}(t)\right)^2 \cdot \sqrt{g \cdot (h_{wl} - h_f)}$$

with

c	group velocity of waves
c_T	transmission coefficient related to wave height
g	accelaration of gravity
h_f	height of the foreland
$H_{s,in}$	significant wave height at the drop of the foreland
$H_{s,trans}$	significant wave height in front of the main dike
h_{wl}	water level
ρ_w	density of water

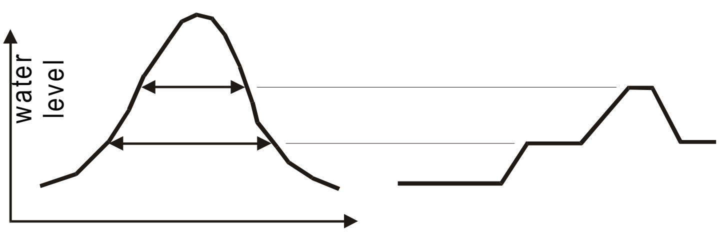

Figure 5: Schematic tide Curve During a Storm Surge

Case Study – diked forelands near Spieka-Neufeld south of Cuxhaven

Figure 6 gives an overview over the study area north of Spieka-Neufeld and south of Cuxhaven and a cross-section of the diked foreland. The statistics of tidal high water levels is given in figure 7 revealing that the frequency of flooding of the polder will increase from 0.002 (1.4 times a year) to 0.02 (15 times a year) in case of an opening of the summer dike. The wave conditions at the drop of the foreland were calculated using a two-dimensional wave model for the estuaries Jade and Weser set-up with SWAN [MAI AND VON LIEBERMAN, 2000] and are given in figure 8. Using these boundary conditions the wave transmission along the foreland with and without summer dike was calculated using a one-dimensional SWAN model.

Figure 9 exemplifies the wave propagation along the foreland with and without summer dike for various conditions of water levels. The wave parameter in front of the main dike behind the foreland with or without a summer dike are summarized in figure 10. Combining the results of figure 8 and 10 leads to the transmission coefficients presented in figure 11. In case of the design water level of h_{wl} = 5.95 m above mean sea level north of Spieka-Neufeld the transmission coefficients equal c_T = 0.66 and r_T = 0.79.

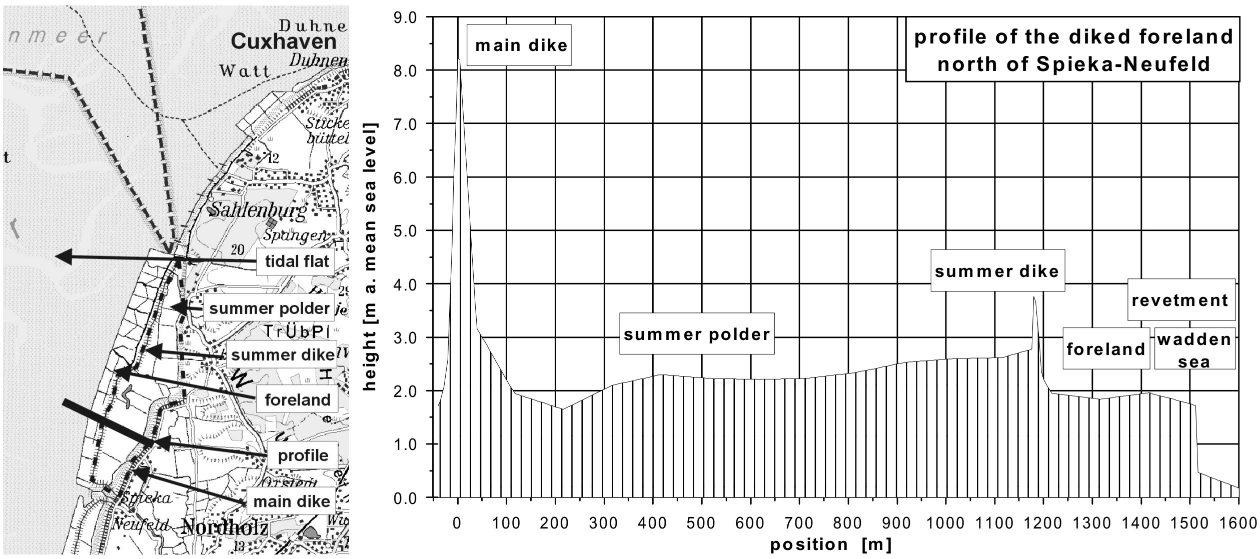

Figure 6: Overview over the Study Area North of Spieka-Neufeld and Cross-Section of the Diked Foreland

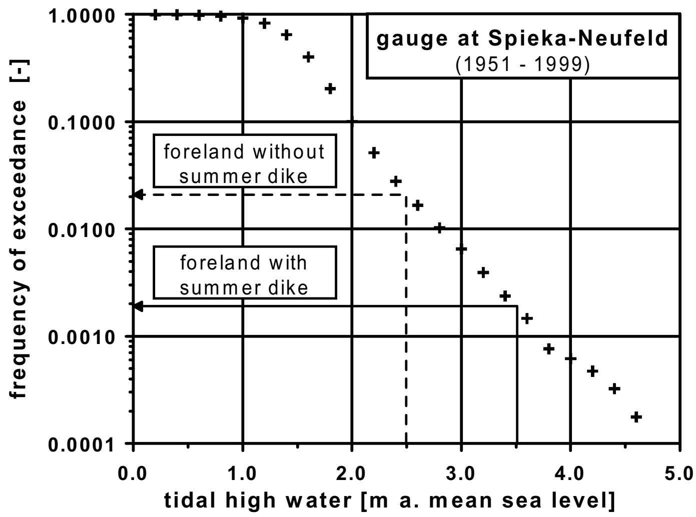

Figure 7: Statistics of Tidal High Water at Spieka-Neufeld [MAI AND ZIMMERMANN, 2000]

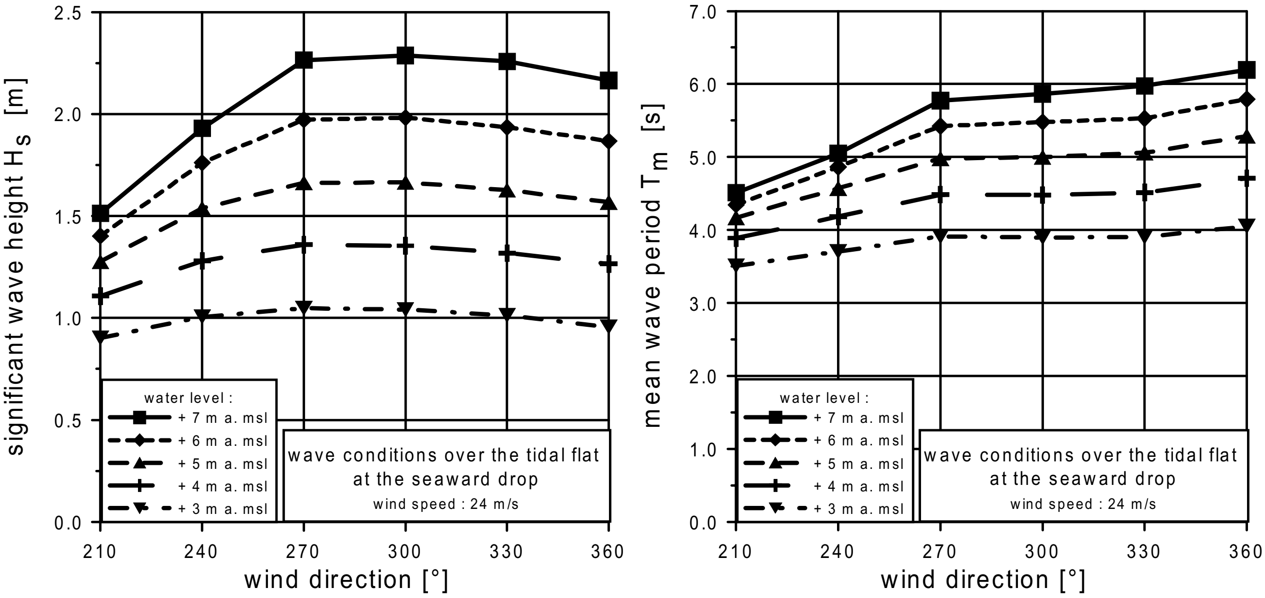

Figure 8: Wave Conditions at the Drop of the Foreland

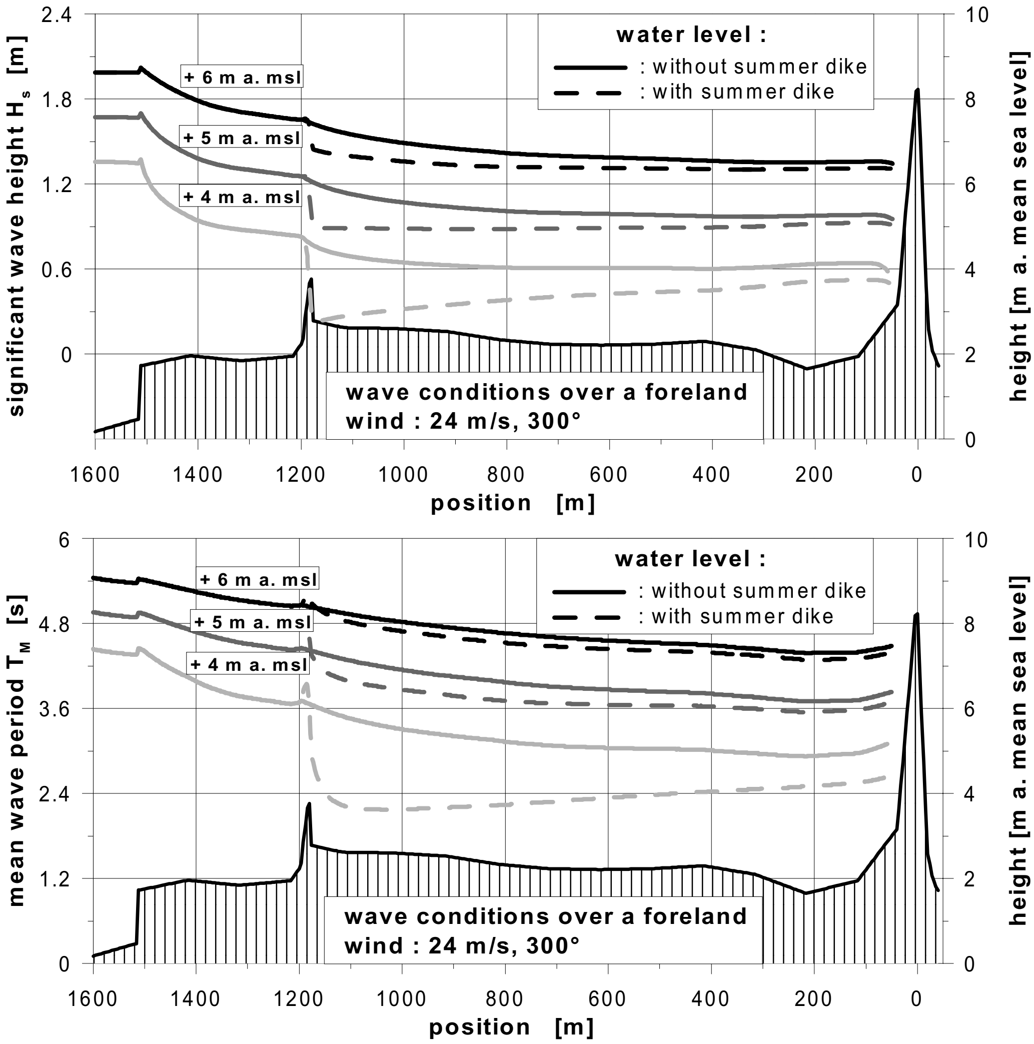

Figure 9: Wave Propagation along the Foreland with and without Summer Dike for Various Water Levels

For the maximum historically recorded tidal high water level of h_{wl} = 5.15 m above mean sea level (3rd of January 1976) the transmission coefficients equal c_T = 0.55 and r_T = 0.70. The tidal curve of the 3rd of January 1976 at Spieka-Neufeld is given in figure 12. For this storm surge with north-westerly winds and wind speeds of 24 m/s table 1 compares the energy dissipating at the main dike behind a foreland with and without a summer dike. The wave energy attacking the main dike will increase by approximately 50 % in case of a complete removal of the summer dike. This increase in wave energy should be taken into account designing the outer slope of the main dike according to KRAMER [1977].

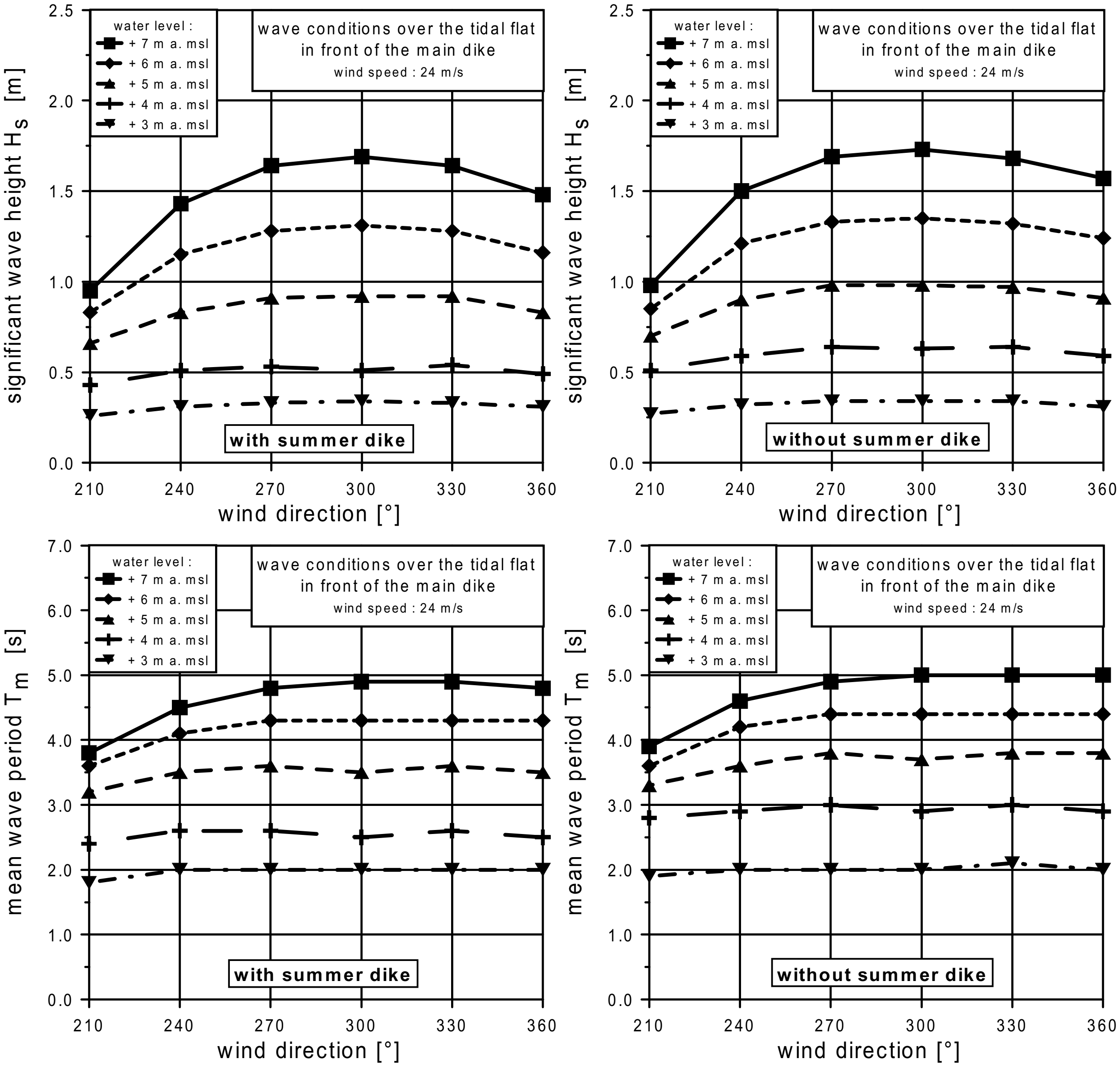

Figure 10: Wave Conditions at the Main Dike behind a Foreland with (left) and without (right) a Summer Dike

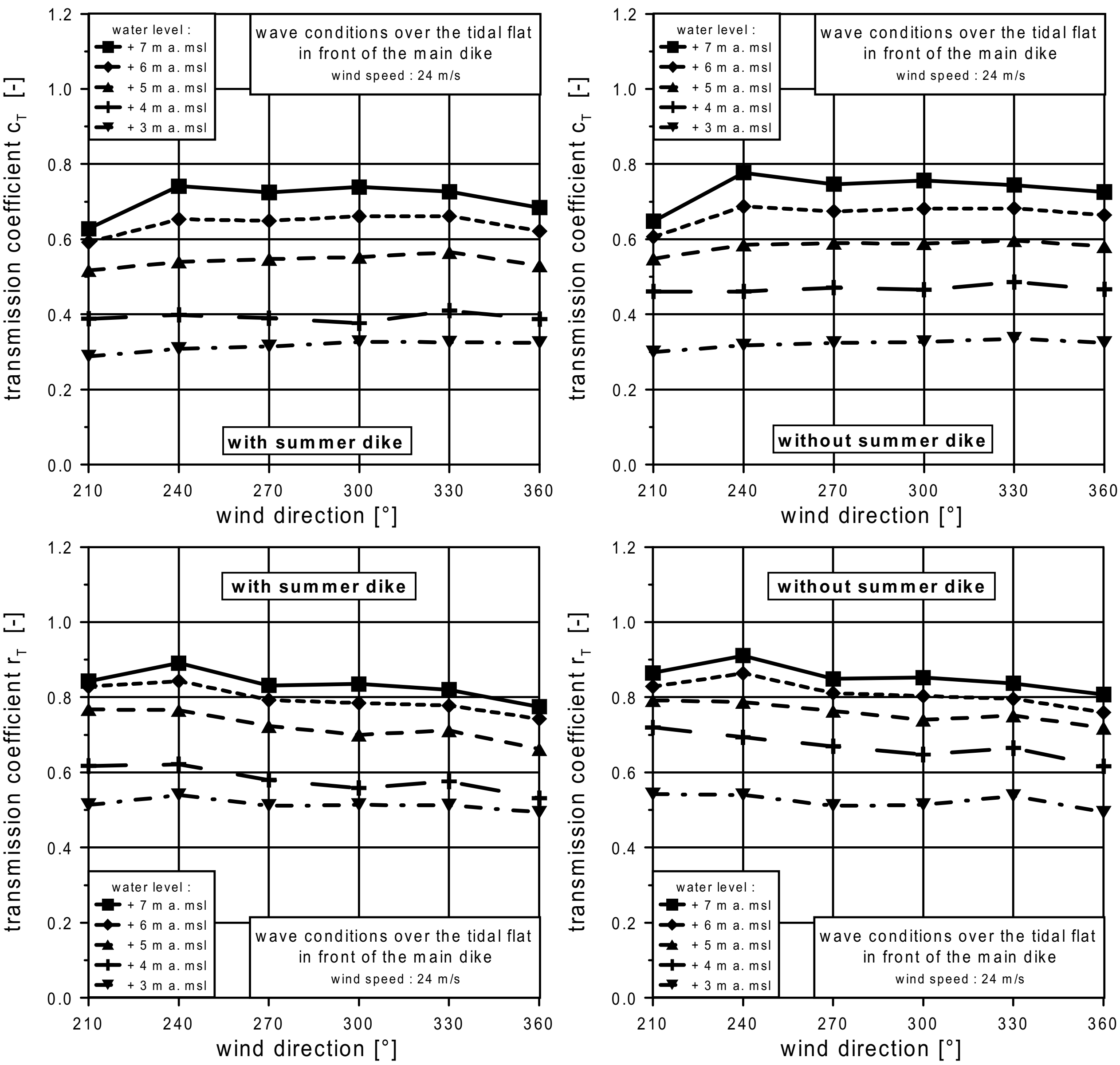

Figure 11: Transmission Coefficients of a Foreland with and without a Summer Dike

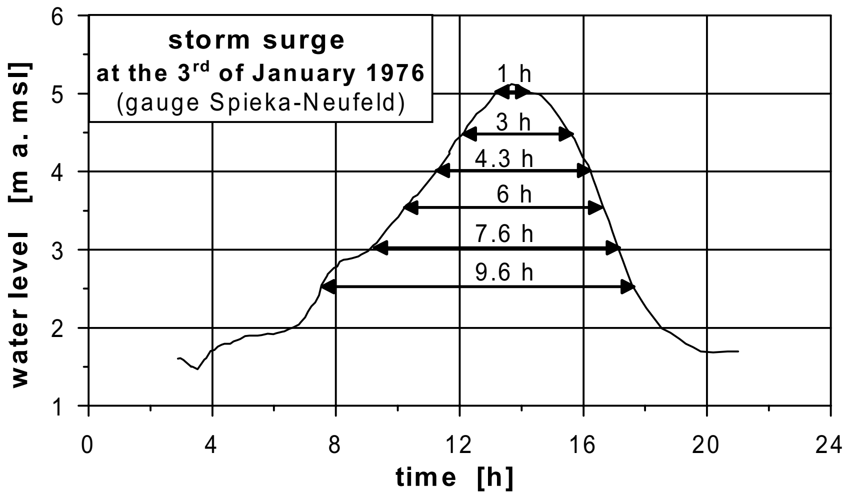

Figure 12: Tidal Curve of the Storm Surge, 3rd of January 1976

		with summer dike			without summer dike		
water level	duration	H_s	T_m	P	H_s	T_m	P
m a. msl	h	m	s	W / m	m	s	W / m
3	1,6	-	-	-	0,34	2	125,0
3,5	1,7	0,425	2,25	239,8	0,485	2,45	400,3
4	1,3	0,51	2,5	360,5	0,63	2,9	675,5
4,5	2	0,715	3	1044,3	0,805	3,3	1374,3
5	1	0,92	3,5	1728,0	0,98	3,7	2073,0
		E_{tot} = 4692,7 Wh / m			E_{tot} = 6580,1 Wh / m		

Table 1: Energy of Waves attacking the Main Dike behind a Foreland with and without a Summer Dike

Case Study – diked forelands near Luetetsburg east of Norddeich

Besides of a complete removal as presented in the case study for the diked foreland near Spieka-Neufeld a partial removal of the summer dike is possible as presented in the following for a diked foreland near Luetetsburg east of Norddeich. Figure 13 gives an overview over the study area west of Norddeich. For different opening strategies the wave propagation over the foreland was modelled using MIKE 21 EMS. A selection of results is given in figure 15. It is shown that in case of partial removal of the summer dike (opening width = 320 m) the wave parameter at the main dike will increase behind the openings. The increase is comparable to a complete removal of the summer dike, i.e. the influence of diffraction is only very low. Additional dike segments behind the openings will re-establish the complete effect of wave damping as shown in figure 14.

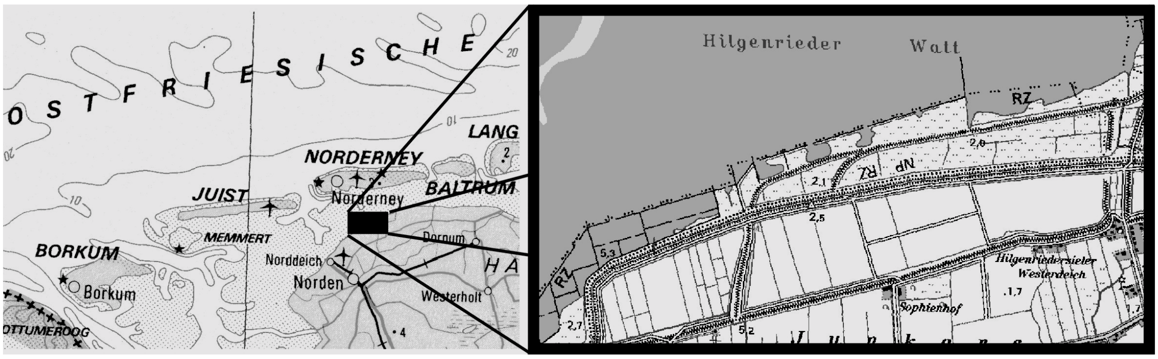

Figure 13: Overview over the Study Area West of Norddeich and Cross-Section of the Diked Foreland

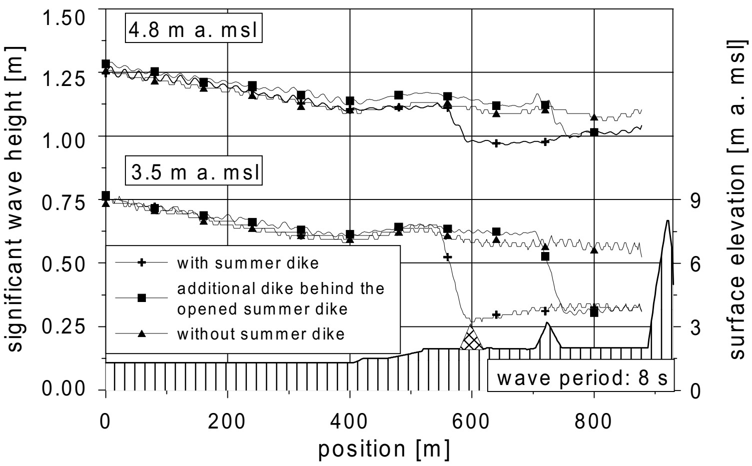

Figure 14: Wave Height in the Polder near Luetetsburg Assuming Different Opening Strategies of the Summer Dike [MAI AND V. LIEBERMAN, 2001]

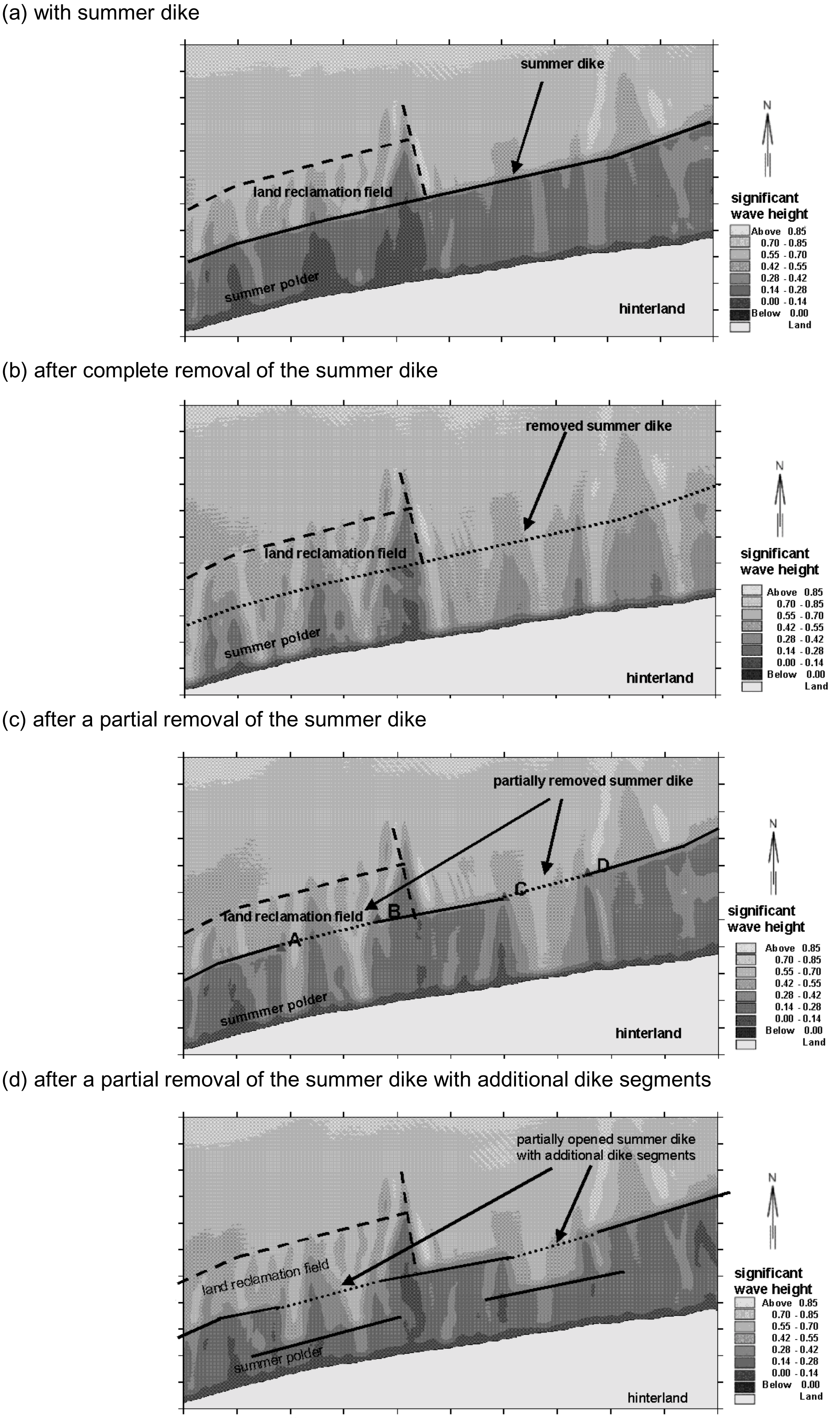

Figure 15: Wave Propagation in the Polder near Luetetsburg Assuming Different Opening Strategies of the Summer Dike [MAI AND V. LIEBERMAN, 2001]

Conclusions

From the coastal engineering point of view diked forelands in front of the main dike are favourable compared to forelands without summer dikes because the frequency of sea water attacking the dike and the wave attack will increase. The increase in wave attack results from an increase in duration and intensity. In case of only partial openings in the summer dike the increase of wave attack is restricted to the sections of the main dike behind the openings. The installation of additional dike segments behind the openings re-establishes the complete effect of summer dikes on waves.

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