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Wave Transmission over Natural and Artificial Forelands

Dr.-Ing. Nicole von Lieberman, Dipl.-Phys. Dipl.-Ing. Stephan Mai
Franzius-Institut for Hydraulic, Waterways and Coastal Engineering
University of Hannover, Germany
Nienburger Strasse 4
30167 Hannover

ABSTRACT

The coastal protection system at the German North Sea coast consists of several protection elements, like natural and artificial forelands. The hydraulic effectiveness of these forelands depends on the characteristics of the incoming wave field, i.e. wave height and wave period, and the geometry of the forelands. Within this paper the hydraulic effectiveness of forelands was investigated using physical model tests in the large wave tank of the University of Hannover, results of a monitoring program carried out at the coast of Dithmarschen in Schleswick-Holstein, Germany, as well as numerical simulations with the model Shallow Waves Nearshore (SWAN). The results of the wave load and wave propagation on forelands reveal that the wave height, but also the wave period, is significantly reduced over the foreland. Besides that the spectral shape changes significantly.

KEY WORDS: Forelands, wave propagation, wave transmission, on site measurement, physical modelling, numerical modelling.

INTRODUCTION

Forelands (fig. 1, left) in front of the sea dikes are important for the protection and safety of the coastlines since they reduce significantly the energy of incoming wave fields. To prevent the loss of natural created forelands and even support natural sedimentation, artificial reclamation methods are applied. At the German North Sea Coast sedimentation was achieved for centuries by systematic reclamation works with the installation of large-scale sedimentation fields enclosed by brushwood fences in combination with drainage systems. The wooden stakes and the brushwood filling (fig. 1, right) create areas with lower waves and reduced currents resulting in enhanced sedimentation (Schulz and Zimmermann, 1994).

Fig. 1: Characteristic Natural Foreland and Cross-section of a Brushwood Fence in Northern Germany

The reduction of wave height over forelands has so far been analysed by on site measurements and by physical (Hensen, 1954) and numerical modelling (Mai et al., 1999). Furthermore indirect techniques like measurements of the debris line are used to study the effect of forelands on wave height and wave run-up (Niemeyer, 1977). Beside the reduction of wave heights over foreland also reduced wave periods can be found. For this reason the wave load on the dike, especially the run-up, is also significantly reduced. In order to analyse the hydraulic effectiveness of forelands as a whole physical model tests in the large wave tank of the University of Hannover and results of a monitoring program at the coast of Schleswick-Holstein in Northern Germany as well as numerical simulations with the model SWAN (Shallow Waves Nearshore, Ris, 1997) were analysed.

EXPERIMENTAL SET-UP OF THE PHYSICAL MODEL

Figure 2 shows the experimental set-up of a foreland which was installed in the Large Wave Tank (GWK) of the "Forschungszentrum Küste" in Hannover. The prototype scaled model of the non-sloped foreland was built using sand. The height of the foreland was approximately 1.40 m above the bottom of the tank representing the tidal flat. The foreland was non-sloped. The distance between the wave generator and the drop of the foreland was approximately 75 m. At 26 positions within the tank water level elevations were measured by electric level gauges in order to calculate wave characteristics to identify the influence of the foreland (Mai and von Lieberman, 1999).

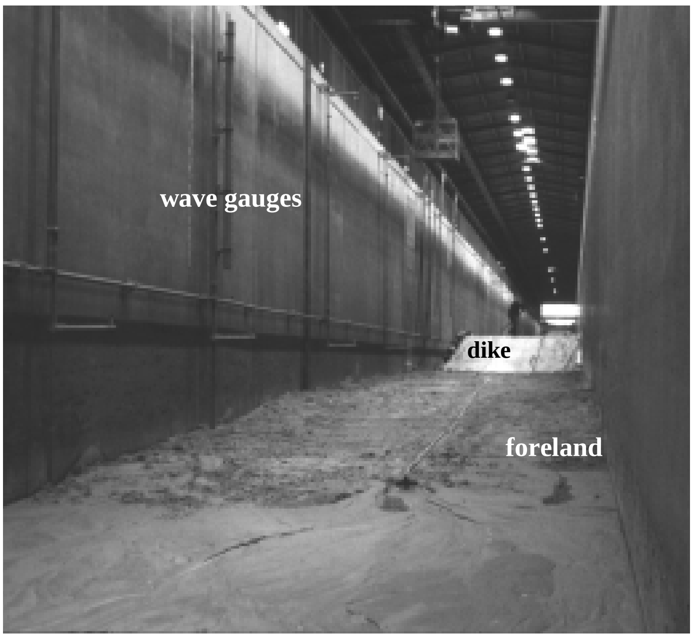

Fig. 2: Experimental Set-up in the GWK

EXPERIMENTAL SET-UP OF THE ON SITE MEASUREMENTS

The results of on site measurements described in the following, were obtained along the foreland "Heringsand" at the coast of Dithmarschen in Schleswick-Holstein, Northern Germany. Wave characteristics were measured by pressure gauges at three different positions along the foreland in December 1991.

INFLUENCE OF FORELANDS ON CHARACTERISTIC WAVE PARAMETERS

An example of the significant wave height and the mean wave period measured for different water levels, a significant wave height of 1 m, and a mean wave period of 5.4 s of the incoming wave field in the GWK is shown in figure 3. The example reveals a large reduction in wave height directly at the seaward drop of the foreland, which is caused by wave breaking and depends on the water level above the foreland. For a water depth of 1.60 m above the foreland the incoming wave height of 1 m is reduced to 0.70 m within 100 m behind the seaward drop of the foreland while for a water depth of 3.10 m the wave height remains nearly constant (von Lieberman and Mai, 2000a).

Figure 4 gives an example of the wave field along the foreland at the coast of Dithmarschen for a water level of 3.8 m above German datum, a wind direction of 300° and a wind velocity of 20 m/s. At the seaward drop of the foreland the significant wave height is approximately 0.70 m and the mean wave period is approximately 4 s. Using these wave data the wave characteristics along the foreland of Heringsand were calculated with a one-dimensional SWAN model. Like the results of the physical model, figure 4 shows the wave propagation along the foreland. It can be seen that the significant wave height decreases to approximately 0.50 m at the toe of the dike, while the mean wave period decreases to 3.4 s at the toe of the dike (Mai and von Lieberman, 2001).

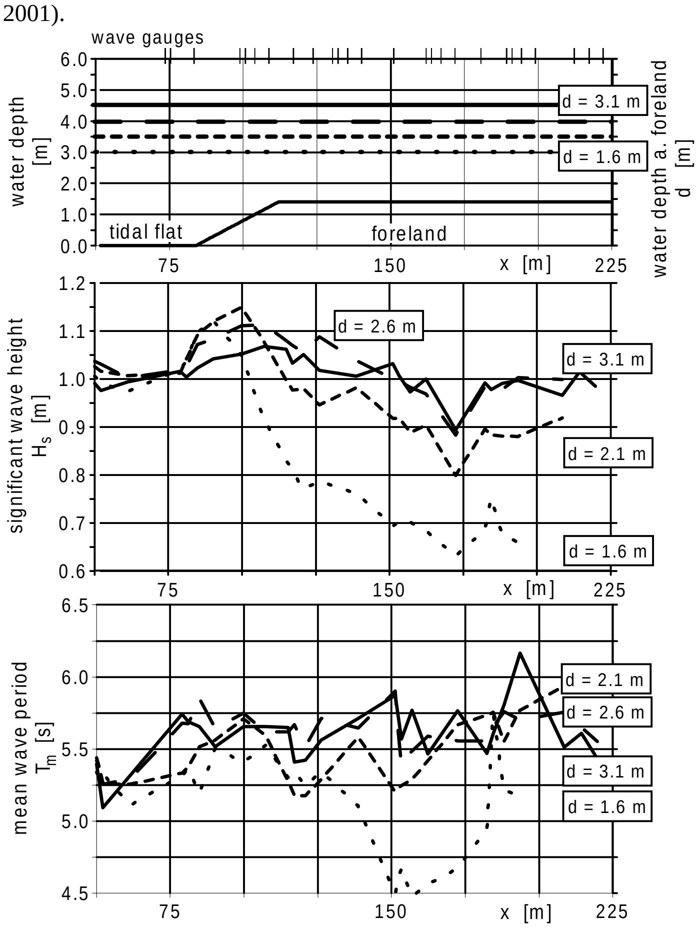

Fig. 3: Results of the Physical Model Tests
(Mai and von Lieberman, 1999)

The hydraulic effectiveness of forelands in respect to wave damping can be described with a transmission coefficient, i.e. the relation between transmitted wave height and incoming wave height: $c_T = H_{s,\,x} / H_{s,\,in}$. The transmission coefficient of forelands in respect to the wave period can be described analogous with $r_T = T_{m,\,x} / T_{m,\,in}$. The influence of the foreland height and the foreland width was investigated introducing the dimensionless parameter $d_{foreland}/H_{s,\,in}$ with $d_{foreland}$ being the water depth over the foreland and $H_{s,\,in}$ the incoming significant wave height (Mai and von Lieberman, 1999). Figure 5 gives an example for the relation between the transmission coefficient and the dimensionless parameter derived from the physical model within the Large Wave Tank.

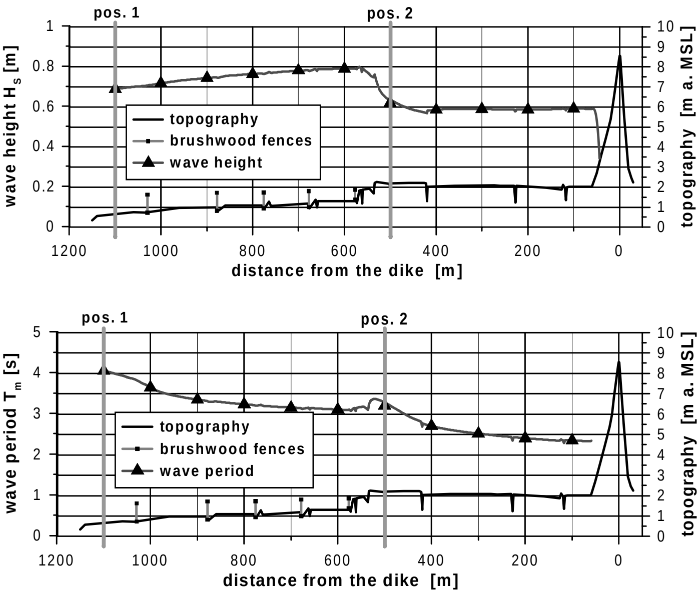

Fig. 4: Wave Parameter over a Foreland at the Coast of Dithmarschen – Significant Wave Height (top) and Mean Wave Period (bottom) for a Water Level of 3.8 m a. MSL and a Wind of 20 m/s and 300° (Mai and von Lieberman, 2001)

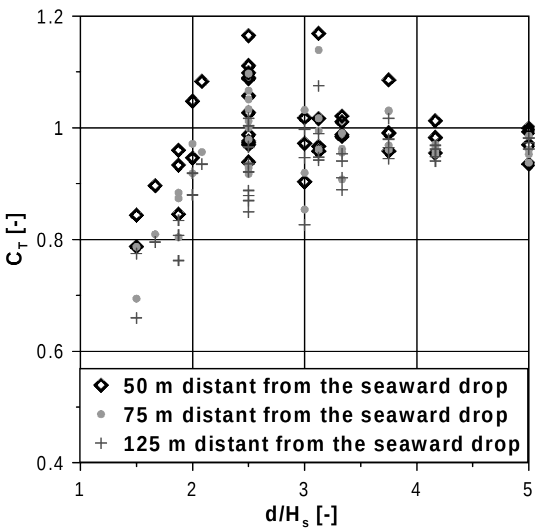

Fig. 5: Transmission Coefficient c_T as a Function of Relative Water Depth over the Foreland within the Large Wave Tank at different Distances from the Seaward Drop (Mai und von Lieberman, 2001)

In order to receive additional information on the wave damping effects of forelands of different width numerical simulations were carried out on the basis of the physical model tests. The simulations were performed using the phase-averaged model SWAN. Figure 6 (left) shows the transmission coefficients of a 1.4 m high foreland at a distance of 325 m behind the seaward drop. The transmission coefficient decreases with increasing foreland width, e.g. a transmission coefficient c_T of 90% is related to the dimensionless parameter $d_{foreland}/H_{s,\,in}$ of 2.6. Further investigation by von Lieberman and Mai (2000a) revealed that a foreland width of more than 325 m does not lead to any further reduction of the transmission coefficient. The transmission coefficient r_T of a 1.4 m high foreland 325 m behind the seaward drop in respect to the wave period is given in figure 6 (right). The transmission coefficient increases almost linearly with the increasing ratio $d_{foreland}/H_{s,\,in}$ up to $d_{foreland}/H_{s,\,in} = 2.6$.

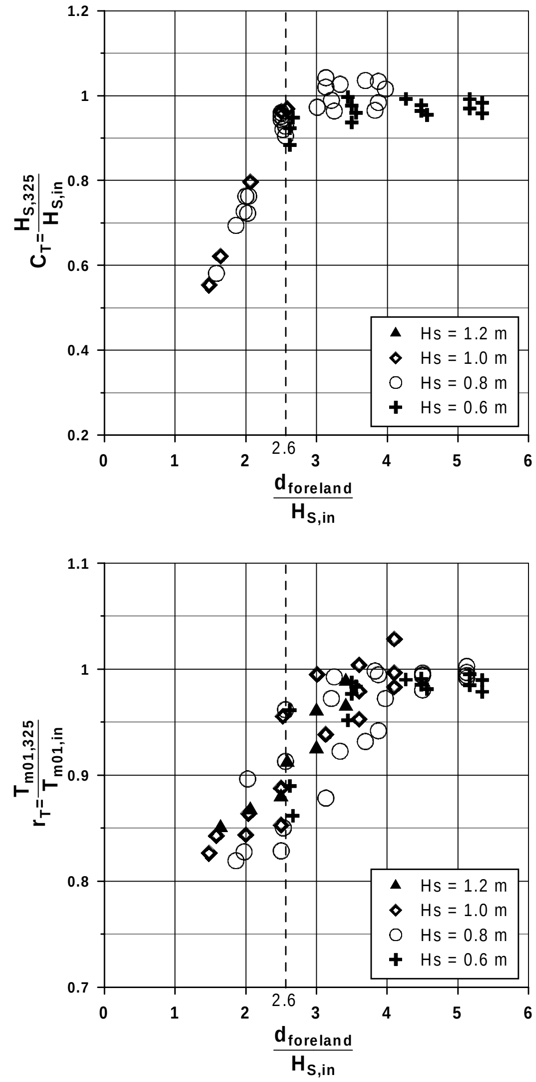

Fig. 6: Effects of a 1.4 m high Foreland on Wave Height (left) and Effects on Wave Period (right)
325 m behind Seaward Drop carried out with the Model SWAN (von Lieberman and Mai, 2000b)

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INFLUENCE OF FORELANDS ON WAVE SPECTRA

The reduction of the wave period along the foreland shown in Figure 6 (right) corresponds to a shift of power spectral density in the wave spectrum to higher frequencies as shown in figure 7. The energy transfer is traced back to triad interactions as numerical simulations with SWAN revealed (von Lieberman und Mai, 2000b). This is also the cause for the transformation of the incoming single peak TMA-spectrum to a double peak spectrum. The formation of a second peak in the spectrum (at the doubled peak frequency) is found in the results of the physical model as well as in the results of the numerical model. However, the magnitude of the second peak strongly depends on the peak period of the incoming wave field. The amplitude of the second peak is the higher the higher the peak period of the incoming waves. While e.g. for a peak period of the incoming wave field of 8 s a well developed second peak is found (fig. 7) almost no second peak occurs for a peak period of 5 s (fig. 8).
Besides the influence of the peak period of the incoming wave field an effect of the water depth on the development of the second spectral peak can be found as indicated by the analysis of wave spectra along the foreland of Heringsand (fig. 4). Although the wave period is similar to the one in figure 8 a second peak develops because of the reduced water depth of 1.8 m above the foreland compared to 2.6 m.

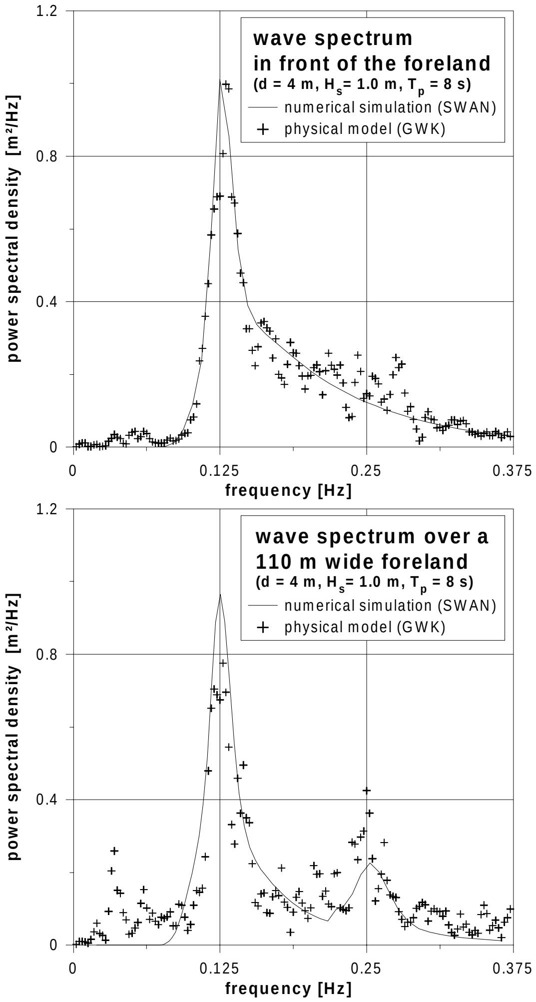

Fig. 7: Wave Spectrum in front of the Foreland (left) and over a 110 m width Foreland (right) for a water depth of 4 m, a Significant Wave Height of 1 m and a Peak Period of 8 s (Results of Physical and Numerical Modelling)

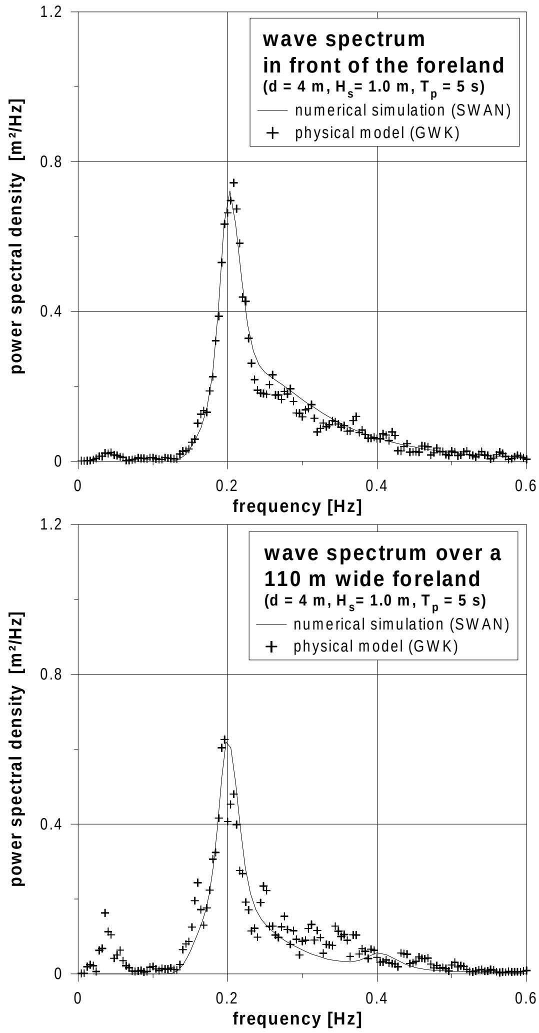

Fig. 8: Wave Spectrum in front of the Foreland (left) and over a 110 m width Foreland (right) for a Water Depth of 4 m, a Significant Wave Height of 1 m and a Peak Period of 5 s (Results of Physical and Numerical Modelling)

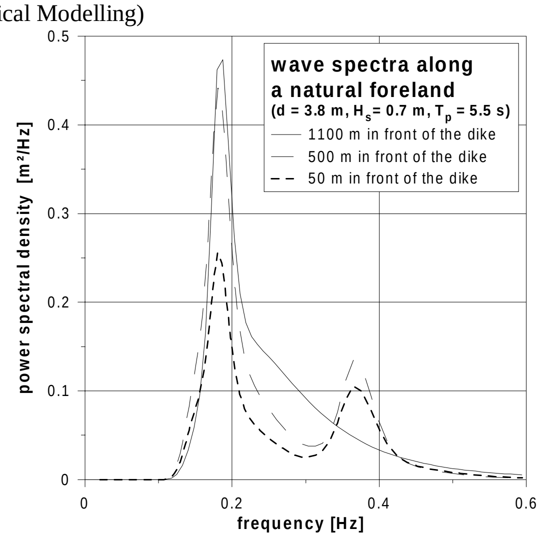

Fig. 9: Wave Spectra along a Natural Foreland for a Water Depth of 3.8 m, a Significant Wave Height of 0.7 m and a Peak Period of 5.5 s at different Positions in front of the Dike (Results of Numerical Modelling)

CONCLUSION

Wave propagation along forelands depends on wave breaking, bottom friction and non-linear wave-wave interactions. While the wave breaking and the bottom friction reduce the wave energy respectively the wave height along forelands, non-linear interactions alter the shape of the wave spectrum. Depending on the water depth and wave period a double peak spectrum develops resulting in a lower mean wave period. Both, the reduction of wave height and of the wave period lead to reduced loads on coastal structures, e.g. dikes.

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