Analysis of an Optimal Foreland Design

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Abstract

Forelands are important coastal protection elements at the German North Sea Coast. Reducing the energy of the incoming waves they cause a decrease in wave run-up at the main dike. In order to derive an optimal design of the foreland different geometries of forelands were analysed using physical model tests in the Large Wave Flume of the University of Hannover and numerical simulations with SWAN. The width of the foreland should be at least 325 m.

Introduction

The protection system of the German North Sea coast comprises a series of elements with the dike supplying the main protection. Forelands – traditionally used for agricultural purposes – are applied in front of dikes as additional protection element. Reducing the energy of the incoming waves forelands cause a decrease of the wave run-up at the main dike. The hydraulic effectiveness of a foreland depends on the characteristics of the incoming wave field, i.e. wave height and wave period, and the geometry of the forelands (e.g. height, width). The hydraulic effectiveness of forelands was so far investigated using especially field data. First analyses on the influence of the geometry were carried out by Niemeyer and Kaiser (1998) using a numerical wave model.

Taking the above mentioned results into account a combined programme using physical model tests (von Lieberman et al., 1997 / Mai et al., 1999a) as well as numerical simulations (Mai et al., 1999b) was carried out at the Franzius-Institut of the University of Hannover, Germany, in order to derive an optimal foreland design

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to be included in the master plan for coastal protection in Schleswick-Holstein, Germany.

Physical Modelling

A prototype scaled model of a foreland was built using sand in the Large Wave Tank (GWK) of the Forschungszentrum Küste, Hannover (Fig. 1). The height of the foreland was approximately 1.40 m above the bottom of the tank representing the tidal flat. 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 in order to calculate wave characteristics to identify the influence of the foreland (Fig. 1). An example of the significant wave height and the mean wave period measured for different water-levels and a significant wave height of 1 m and a mean wave period of 5.4 s of the incoming wave field is shown in figure 2.

The example given in figure 2 reveals a large reduction in wave height directly at the seaward drop of the foreland caused by wave breaking. The amount of reduction 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.

Using these measurements the transmission coefficient of the wave heights c_T and wave periods r_T were determined for different boundary conditions, i.e. water level, incoming wave characteristics.

$$c_T = H_{s,\,x} / H_{s,\,in} \tag{1}$$

$$r_T = T_{m,\,x} / T_{m,\,in} \tag{2}$$

$H_{s,\,in}$ and $T_{m,\,in}$ represent the incoming wave parameters, and $H_{s,\,x}$ and $T_{m,\,x}$ the parameters at a certain position along the foreland.

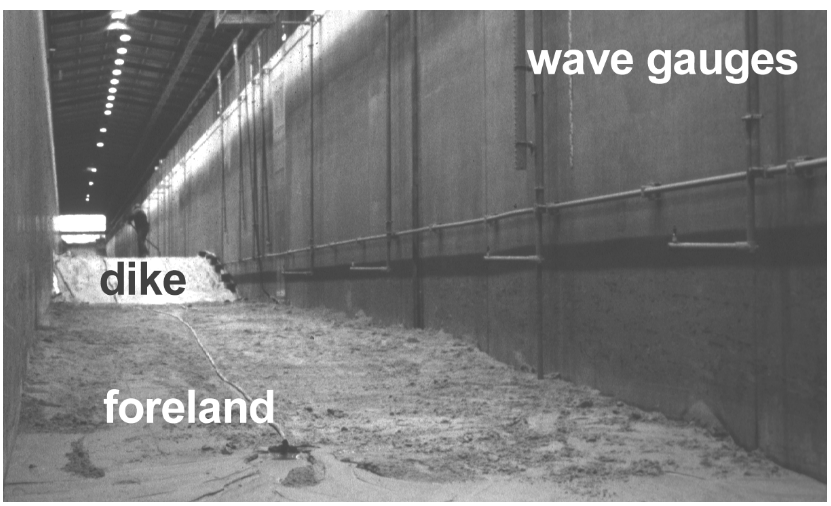

Figure 1. Experimental Set-up in the GWK

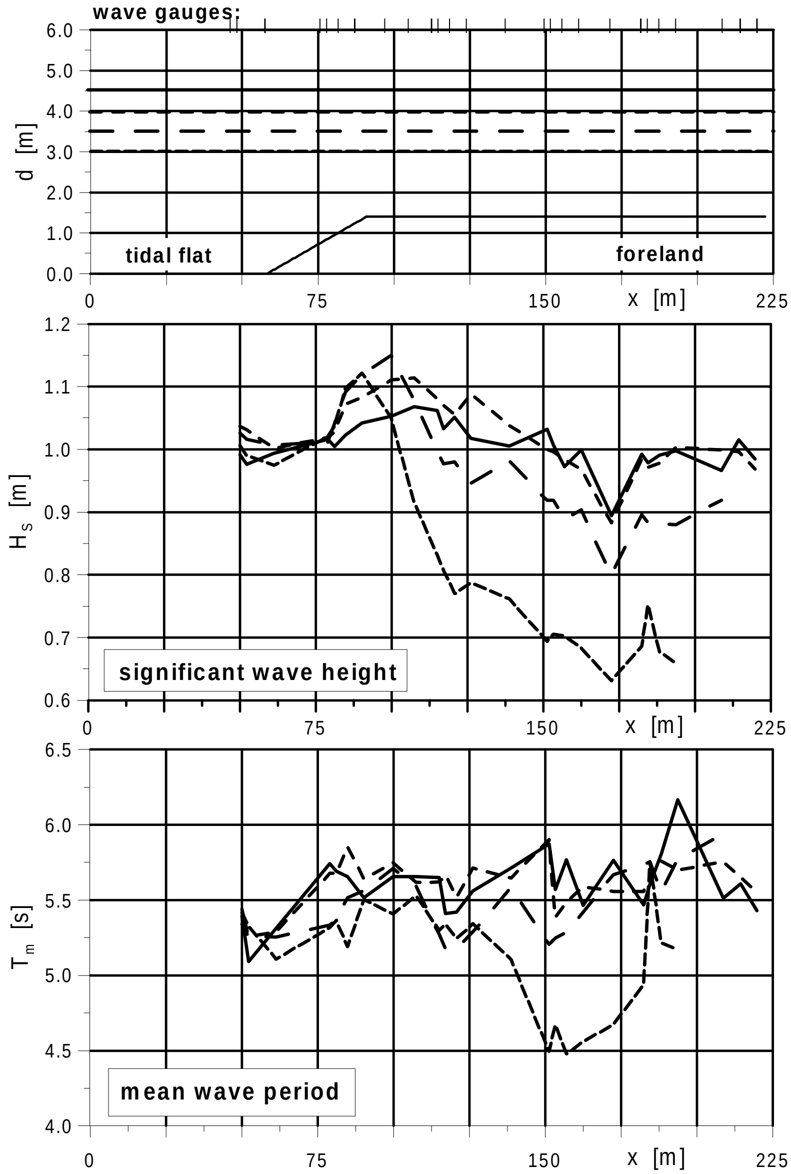

Figure 2. Wave Propagation along the Model Foreland
(von Lieberman and Mai, 2000)

Numerical Modelling

On the basis of the physical model tests carried for a single foreland geometry a numerical model was set up in order to analyse the influence of the different parameters describing the foreland geometry, e.g. height, width, slope, and seaward drop. The numerical simulations were carried out using the phase-averaged model SWAN (**S**hallow **Wa**ves **N**ear Shore, Ris, 1997). The calculations were performed for different foreland geometries, as shown in figure 3, in order to analyse the influence of geometry on the hydraulic effectiveness of the foreland. Therefore three different heights of the foreland (0.50 mNN, 1.40 mNN, 2.00 mNN (Fig. 3a to 3c)) and two different types of the seaward drop of the foreland (sloped (Fig. 3a), vertical (Fig. 3c)) were investigated. Beside that the influence of a sloped foreland (1:1.200 (Fig. 3e), 1:400 (Fig. 3f) and –1:1200 (Fig 3g)) was examined.

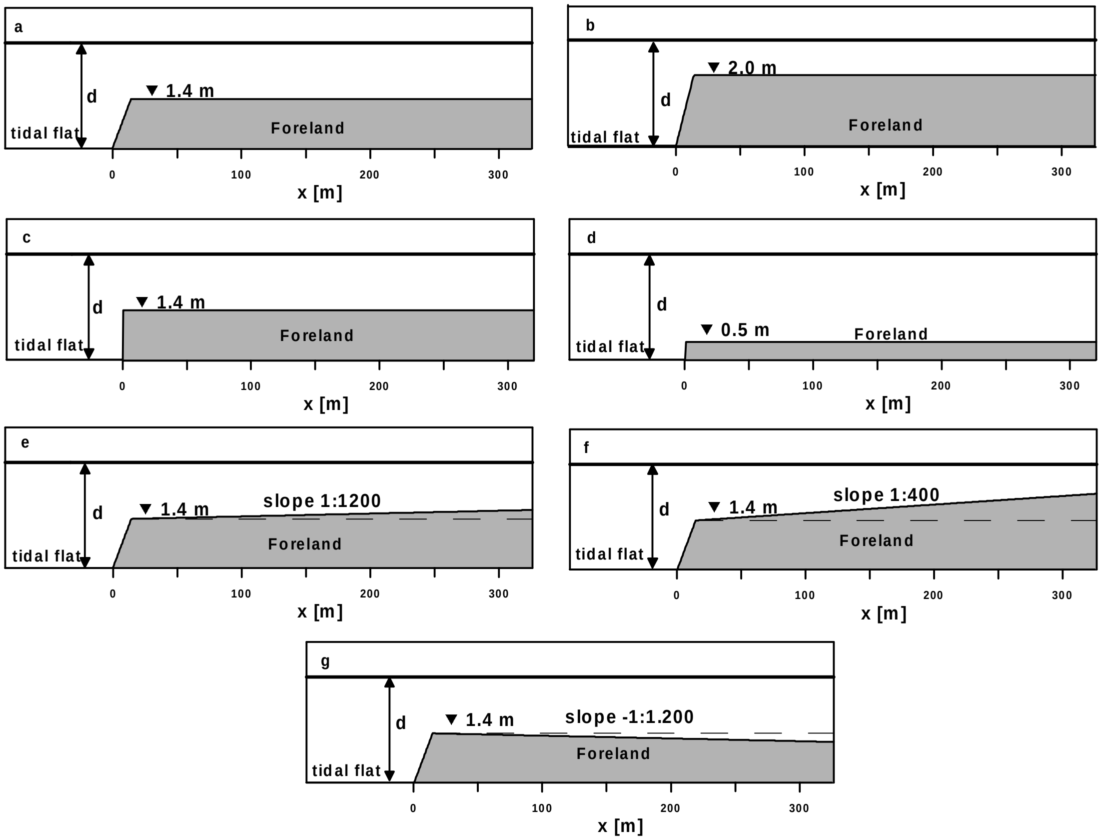

Figure 3. Foreland Geometries Analysed in the Numerical Model (von Lieberman and Mai, 1999)

The foreland geometry of figure 3a corresponds to the geometry of the foreland built in the wave tank. Therefore this profile was used for the calibration of the numerical model. The most important processes to be calibrated were wave breaking and triad-wave interactions.

Figure 4 gives an example of the calibration of the process of non-linear wave wave interaction. The best fit between numerical and physical model was achieved using the formulation of Eldeberky and Battjes (1995) with $\alpha_{EB} = 0.01$ (magnitude of interaction) and a cut-off frequency of 2.5 s^{-1}. Besides that the processes bottom friction and wave breaking were calibrated (von Lieberman and Mai, 2000). The final calibration results in a good estimate of the wave height and period measured in the flume by the numerical simulations. Figure 5 gives an example of the quality of the numerical simulations, here at a position 25 m behind the seaward drop, taking into account all sets of boundary conditions.

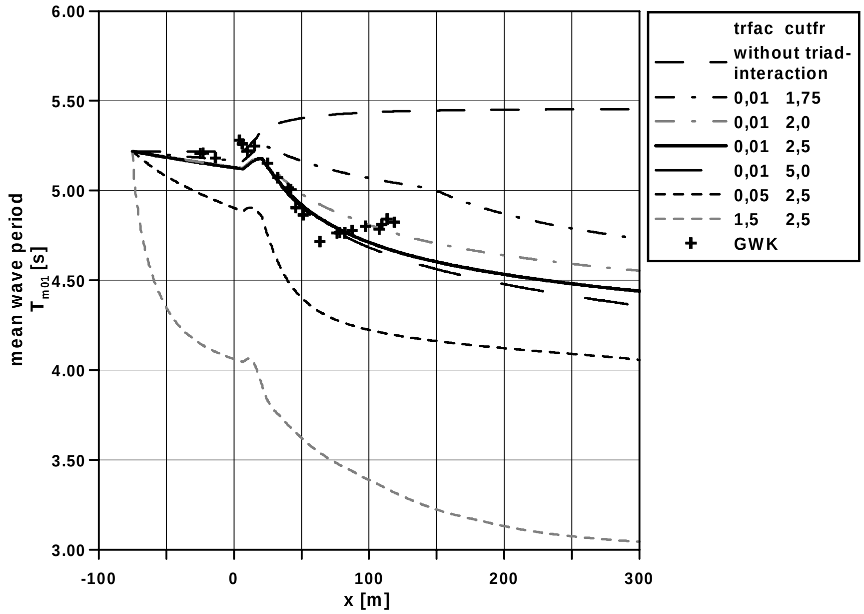

Figure 4. Calibration of the Model Parameters Describing Triad Interaction (von Lieberman and Mai, 2000)

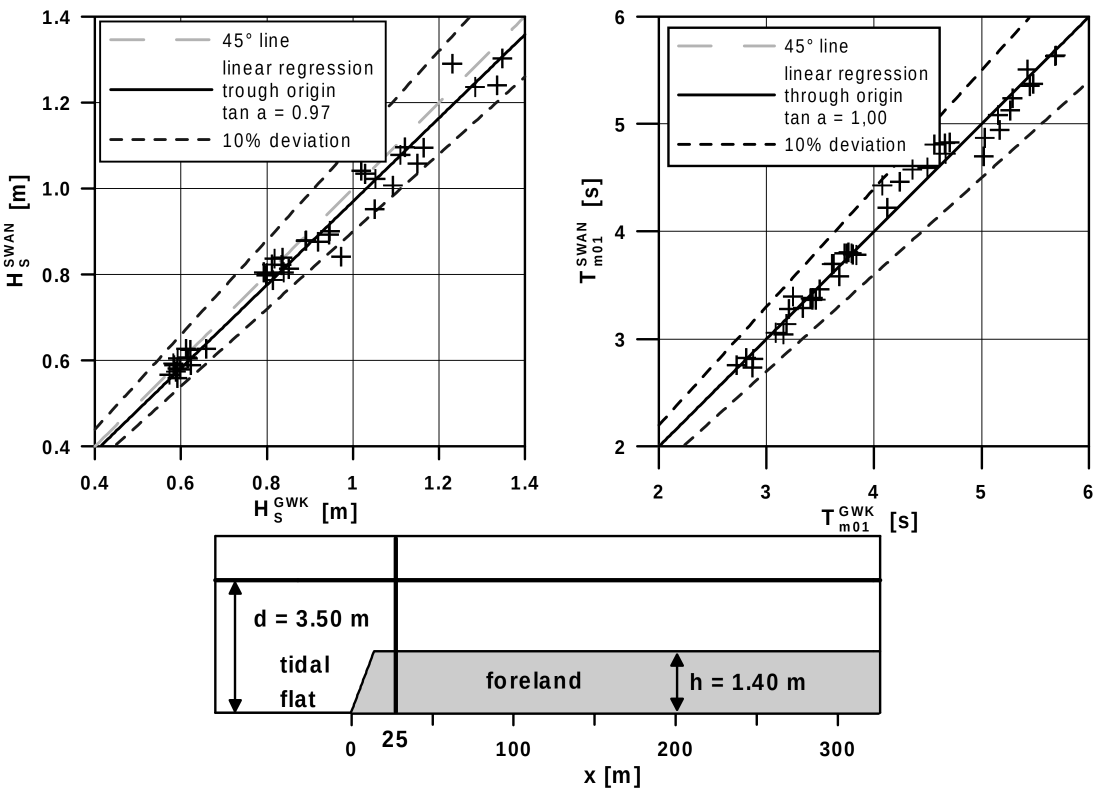

Figure 5. Comparison of the Wave Parameter Calculated by the Calibrated Numerical Model and Measured in the Physical Model
(von Lieberman and Mai, 2000)

Results

Using the calibration an analysis of the wave propagation along different types of forelands as presented in figure 3 was carried out. Within this analysis special focus was put on the wave height at three different distances from the seaward drop – 175 m, 325 m, and 725 m (see fig. 6). An example of the decrease in wave height along the foreland for an incoming wave height of 1.30 m and different heights of the foreland is shown in figure 6.

The influence of the foreland geometry was investigated according to the equations 1 and 2 and with the dimensionless parameter $d_{foreland}/H_{s,\,in}$. Here $d_{foreland}$ describes the water depth over the foreland and $H_{s,\,in}$ the incoming significant wave height. The example of the numerical simulations (fig. 6) shows that the transmission coefficients decrease with an increase in the height of the foreland (cf. fig. 2). A detailed analysis of the dependence of the transmission coefficient on the water depth and the incoming wave field for different sets of typical boundary conditions is shown in the following analysis of the geometrie (width and height of the foreland, seaward drop, slope).

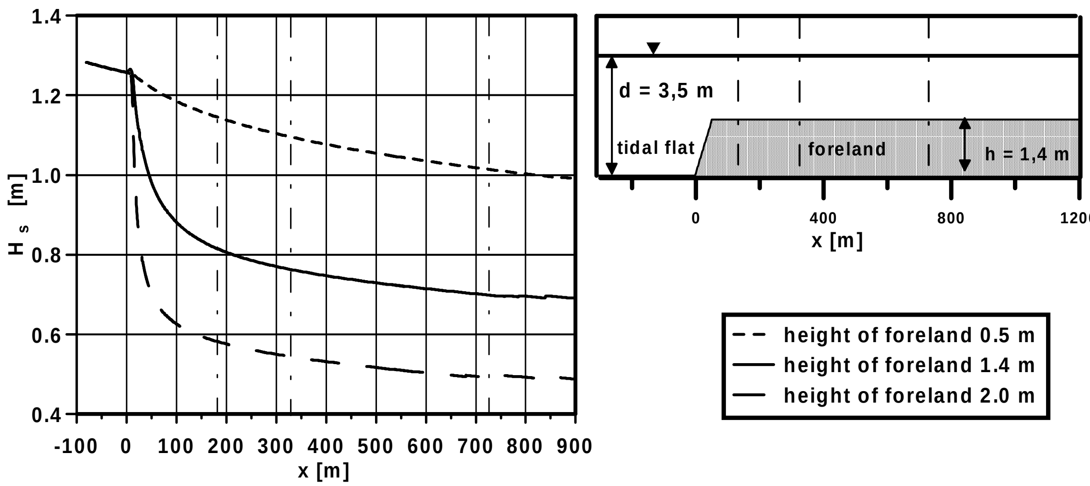

Figure 6. Decrease of Wave Height along the Foreland for Different Heights of the Incoming Wave Field

Width of the Foreland. Figure 7 shows the transmission coefficients of a 1.4 m high foreland at a distance of 175 m, 325 m, and 725 m behind the seaward drop. It is obvious that the transmission coefficients decrease with an increasing width of the foreland. The transmission coefficient c_T of 90% is related to the dimensionless parameter $d_{foreland}/H_{s,\,in}$ of 2.1 175 m behind the seaward drop and of 2.6 325 m behind the seaward drop. A foreland width of more than 325 m does not lead to any further reduction of the transmission coefficient.

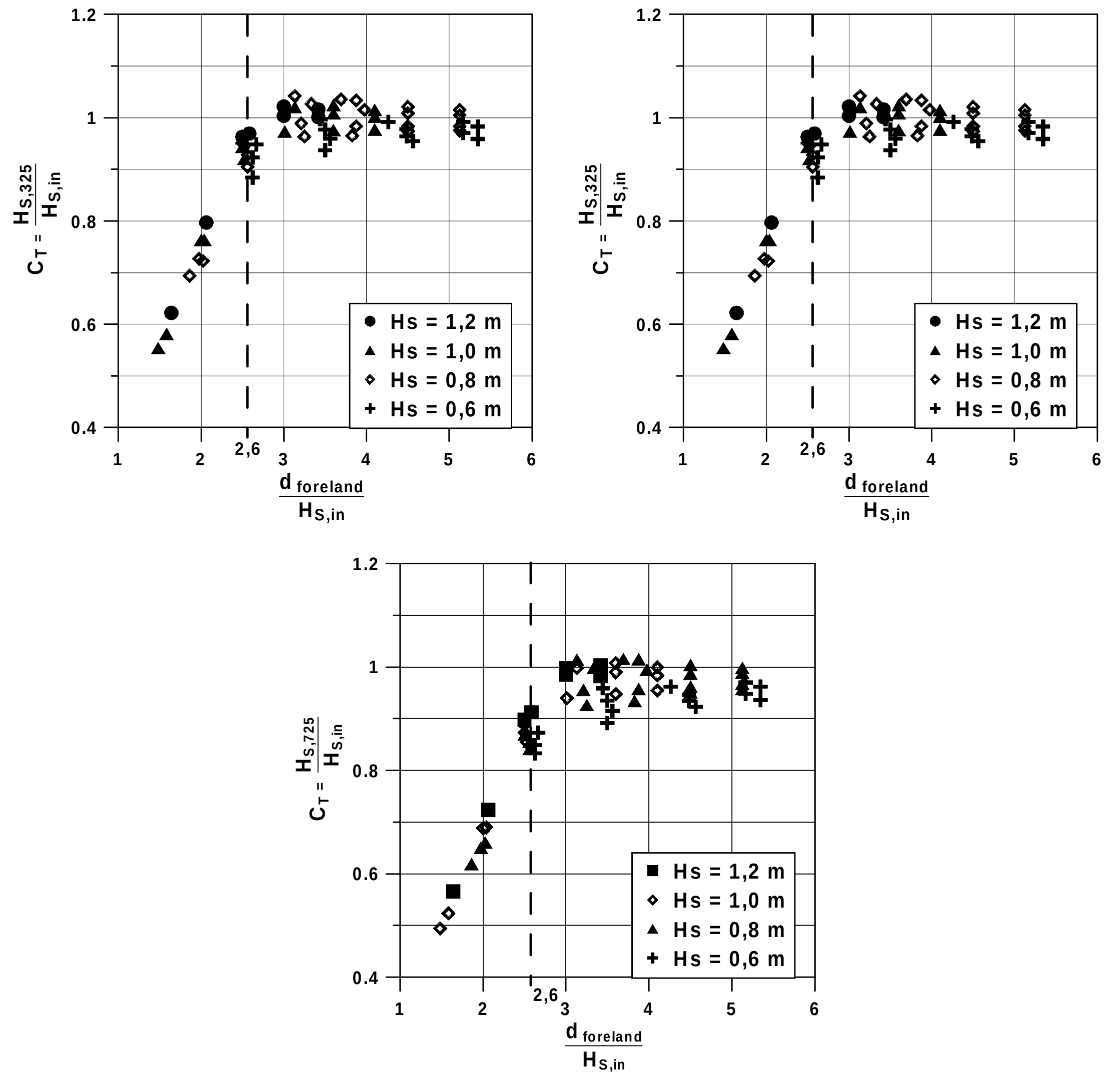

Figure 7. Transmission Coefficients of a 1.4 m high Foreland 175 m, 325 m respectively 725 m behind the Seaward Drop (von Lieberman and Mai, 2000)

Height of the Foreland. At a position of 325 m behind the seaward drop the transmission coefficient increases almost linearly with the dimensionless parameter $d_{foreland}/H_{S,\,in}$. For both heights of a foreland investigated (1.40 m and 2.00 m) the transmission coefficient is lower than 90% up to the ratio $d_{foreland}/H_{S,\,in} \leq 2.6$ (Fig. 8).

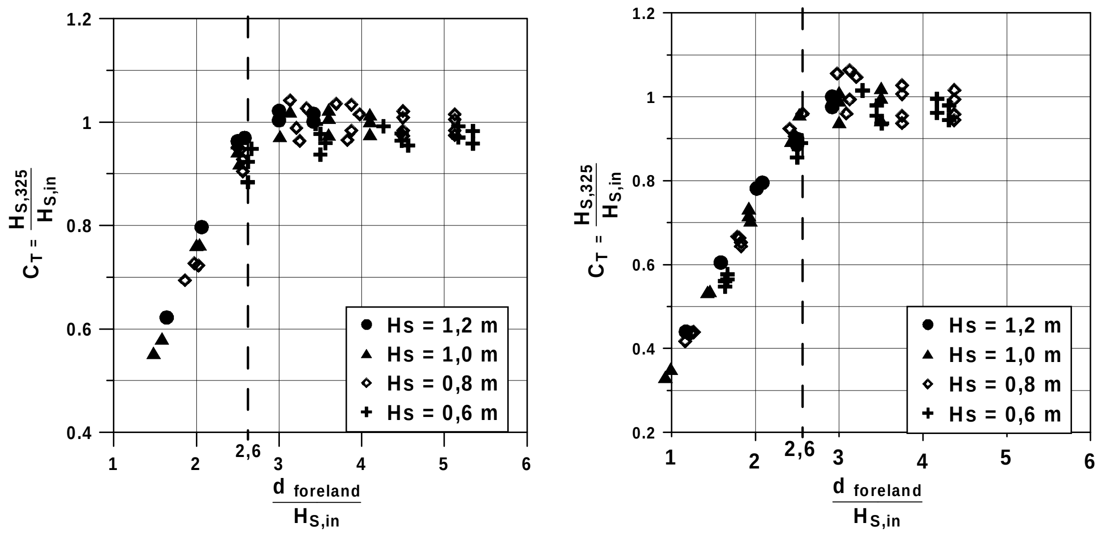

Figure 8. Transmission Coefficients of Forelands of
1.40 m and 2.00 m Height 325 m behind the Seaward Drop
– Effects on Wave Heights
(von Lieberman and Mai, 2000)

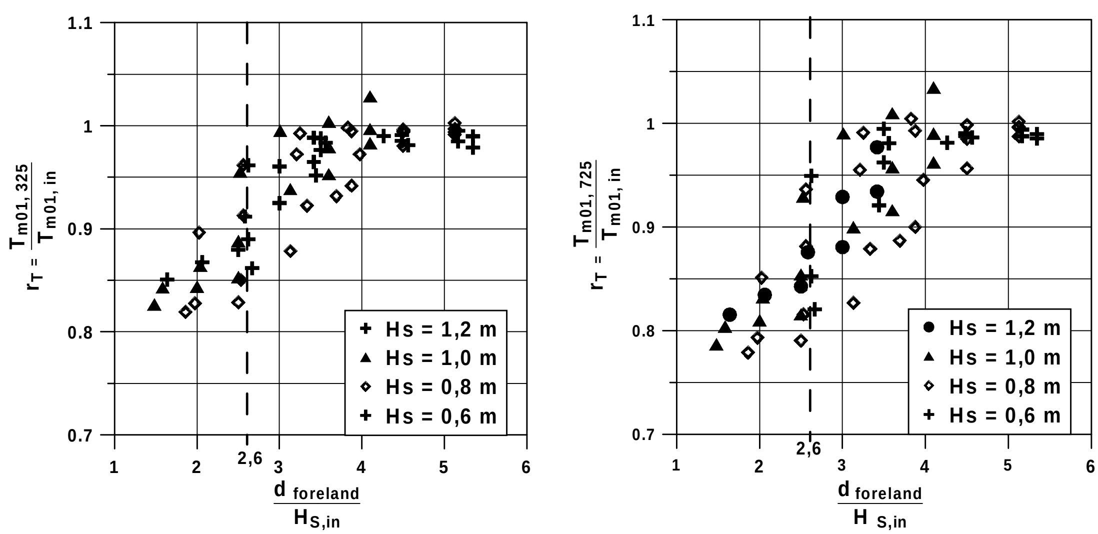

Figure 9. Transmission Coefficients of Forelands 325 m
respectively 725 m behind the Seaward Drop
– Effects on Wave Periods
(von Lieberman and Mai, 2000)

Figure 9 shows the transmission coefficient of a 1.4 m high foreland 325 m respectively 725 m behind the seaward drop in respect to the wave period. It is obvious that also the wave period decreases in case of wave propagation over forelands. The transmission coefficient also depends on the dimensionless parameter $d_{foreland}/H_{s,\,in}$. It increases almost linearly with increasing ratio $d_{foreland}/H_{s,\,in}$ up to 3.

Slope of the Foreland. The slope of the foreland influences wave height and wave period as shown in figure 10. The investigations on sloped forelands were carried out for four different slopes (fig. 3a, fig. 3e, fig. 3f, fig. 3g). The decrease in wave height and in wave period is the higher the larger the slope. For negative sloped forelands the significant wave height is nearly not reduced, however there is a significant reduction in wave period.

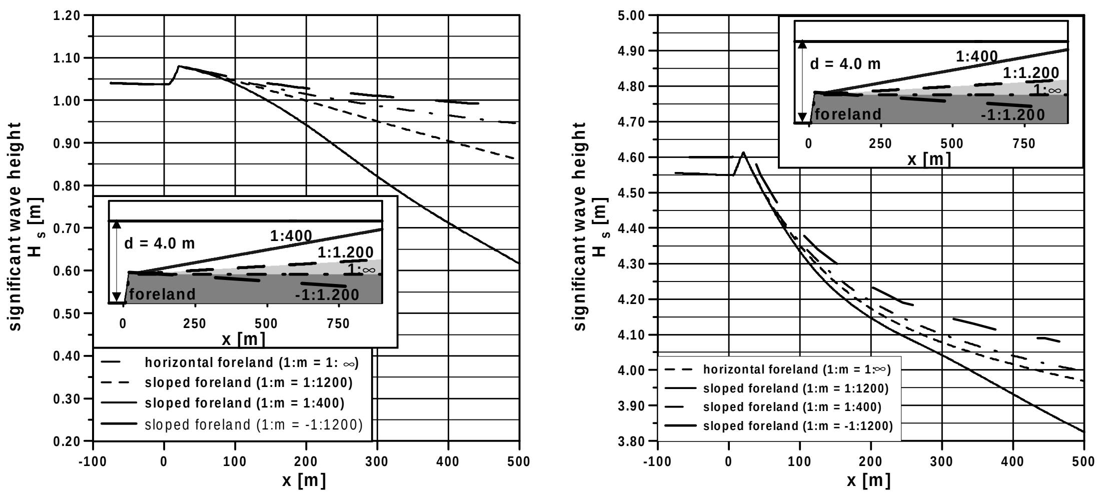

Figure 10. Significant Wave Height (left) respectively
Mean Wave Period (right) along a Foreland with Different Slopes

Seaward Drop of the Foreland. The influence of the geometry of the seaward drop was investigated using two different geometries – a sloped and a vertical drop (fig. 3a and fig. 3c). Differences in wave height and wave period only occur close to the seaward drop. A detailed study on the effects of different geometries of seaward drops taking also into account reflection and using field data is in preparation.

Conclusions

The numerical and physical investigations reveal that a foreland of 325 m width is sufficient to provide optimal wave damping in front of the main dike. The transmission coefficients for significant wave height and mean wave period are almost only dependent on the dimensionless parameter $d_{foreland}/H_{s,\,in}$. The shape of the seaward drop of the foreland does not influence the transmission coefficient.

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