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Effectiveness of Forelands Reducing the Wave Load on Dikes

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Abstract

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 farming 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 on the forelands (e.g. height, width, slope). The effectiveness was so far investigated using especially field data (e.g. Führböter, 1979). 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 (Lieberman et al., 1997 / Mai and von Lieberman, 1999) as well as numerical simulations (Mai et al., 1999) was carried out at the Franzius-Institut of the University of Hannover, Germany, in order to derive an optimal foreland design.

1 Introduction

In front of the dike – the main protection element at the German North Sea coast – various other protection elements are located (Mai et al., 1997). One of these elements is the foreland (Fig. 1). Other coastal protection elements in the vicinity of the main dike are e.g. brushwood fences and summer dikes (Mai and von Lieberman, 1999).

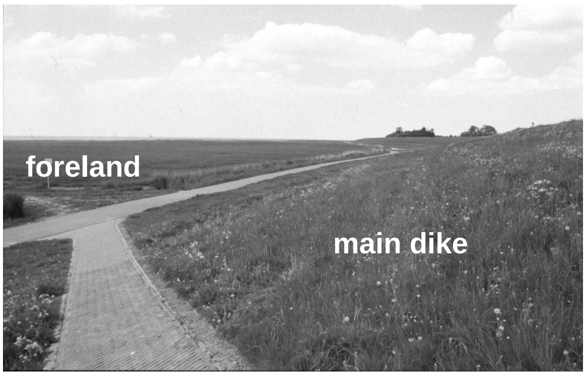


Fig. 1: Natural Forelands under Mean Tidal Conditions (left) and during Storm Tides (right)

Forelands reduce the energy of the incoming waves and therefore cause a decrease of the wave run-up at the main dike. The amount of a reduction in wave height depends on the foreland geometry (e.g. height, width, and slope of the foreland) as shown in figure 2.

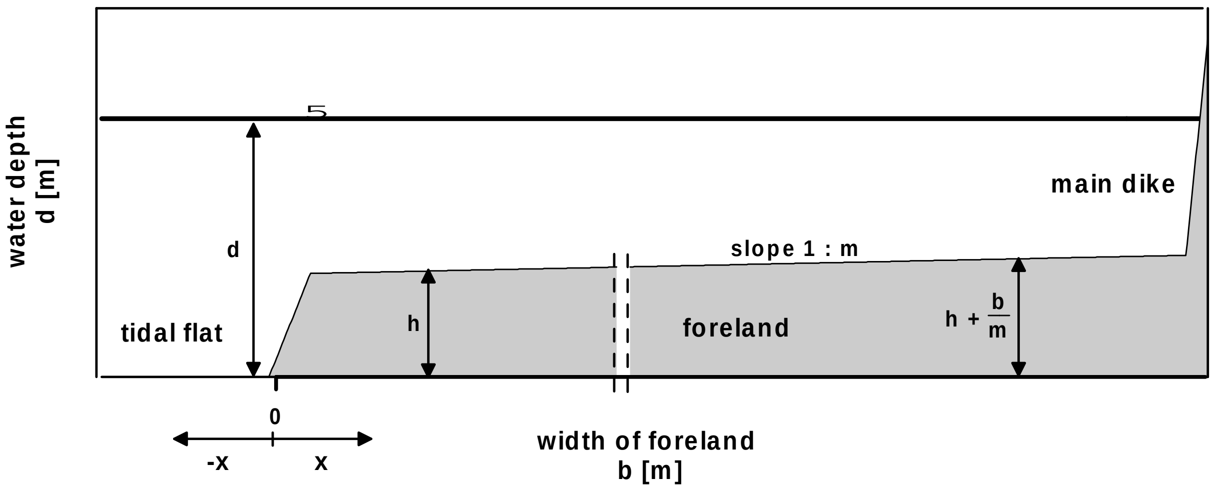


Fig. 2: Foreland Geometry

Beside the width, height, and the slope of the foreland the geometry of the seaward drop influences the wave propagation towards the dike. Figure 3 shows examples of typical seaward drops on the German North Sea coast.

Fig. 3: Seaward Drops of Natural Forelands; Sloped (left) and Vertical (right)

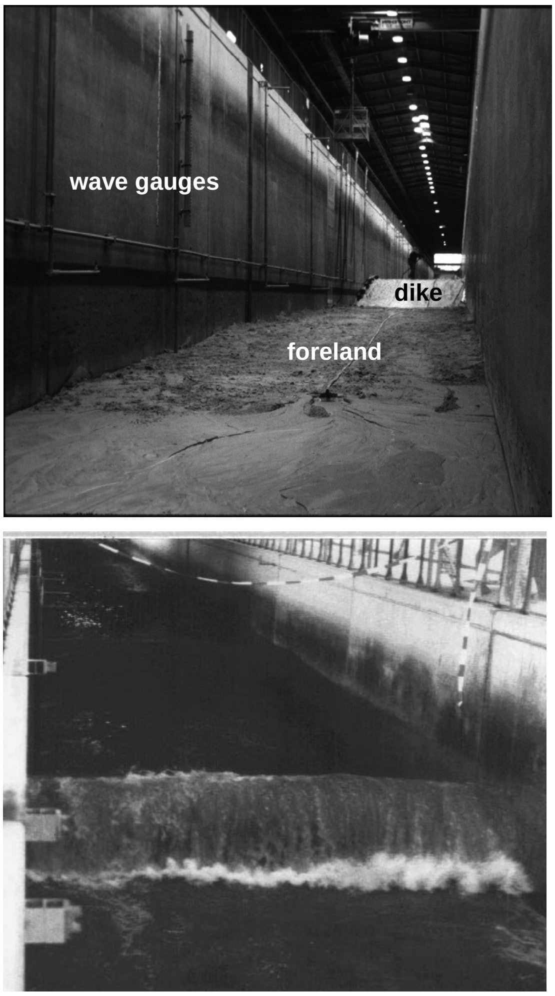
The influence of the foreland width was investigated e.g. by Hensen (1954) using a 1:20 scaled physical model. He recommended a minimum width of the foreland of 150 m to 200 m. So did Lüders et al. (1957). Field investigations were carried out by Kramer (1967) and Erchinger (1974). Kramers (1967) results revealed a dependence of the width of the foreland necessary for an optimal coastal protection on the height of the foreland. For a height of the foreland of 1.65 m above German datum (mNN) – approximately 1.65 m above MSL – and a high water-level of 4.75 mNN the optimal width of the foreland of 150 m to 200 m was confirmed. In case of lower forelands the optimal width of the foreland increases to 300 m.

Niemeyer (1977) analysed the hydraulic effectiveness of forelands on the basis of field measurements using the transmission coefficient, i.e. the relation of wave heights influenced by the foreland and the height of the incoming waves. He stated that the transmission coefficient decreases significantly with an increase of the width of the foreland up to 900 m.

The investigations of the above mentioned authors were e.g. considered in the general plan for reinforcement of dikes, reduction of the length of dikes, and coastal protection in Schleswig-Holstein, Germany (Der Minister für Ernährung, Landwirtschaft und Forsten des Landes Schleswig-Holstein, 1986). In order to revise the recommendation on the required foreland geometry in this general plan the investigations presented here were carried out using numerical and prototype scaled physical models.

2 Set-Up of the Physical Model

A prototype scaled model of a foreland was built using sand in the Large Wave Tank (GWK) of the Forschungszentrum Küste FZK, Hannover (Fig. 4). 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. 4). 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 5.



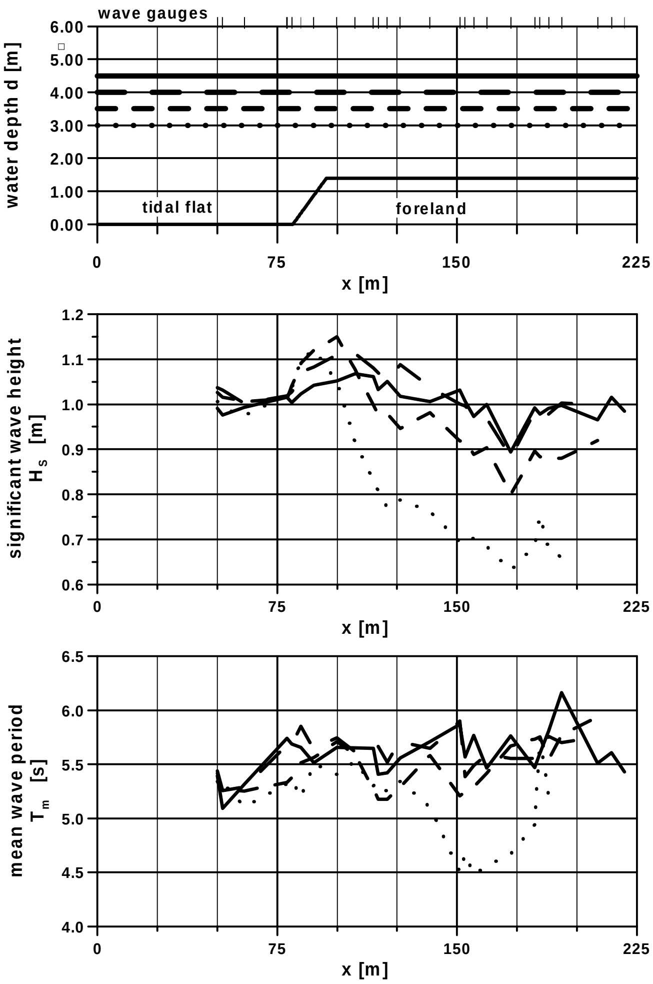


Fig. 4: Experimental Set-up in the GWK

Fig. 5: Results of the Wave Propagation

The example given in figure 5 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.

3 Set-up of the Numerical Model

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 6, 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. 6a to 6c)) and two different types of the seaward drop of the foreland (sloped (Fig. 6a), vertical (Fig. 6c)) were investigated. Beside that the influence of a sloped foreland (1:1.200 (Fig. 6e), 1:400 (Fig. 6f)) was examined.

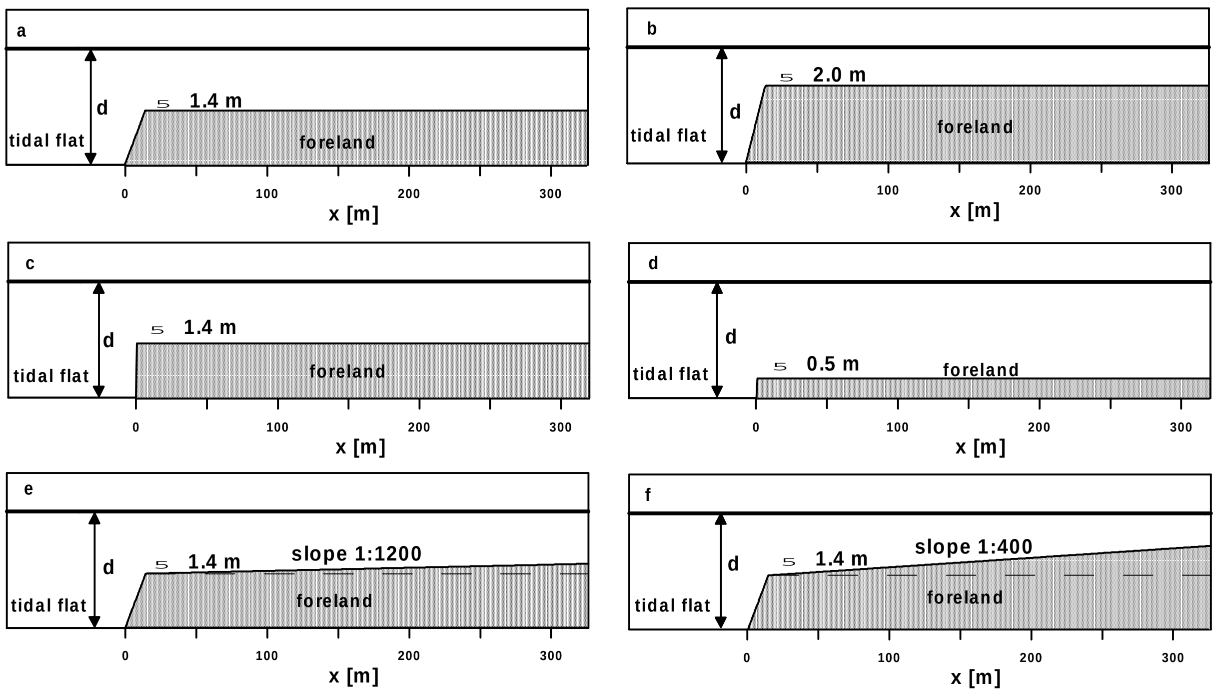


Fig. 6: Foreland Geometries Analysed in the Numerical Model

The foreland geometry of figure 6a 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 breaking and triad-wave interactions.

The model SWAN describes the breaking processes using the formula of Battjes and Janssen (1978). Figure 7 shows the results of the calibration of the model parameters describing breaking for a single set of boundary conditions. The best fit comparing experimental results and numerical results on the significant wave height was achieved using the following model coefficients for the

rate of dissipation: $\alpha = 1.45$ breaker parameter: $\gamma = 0.78$

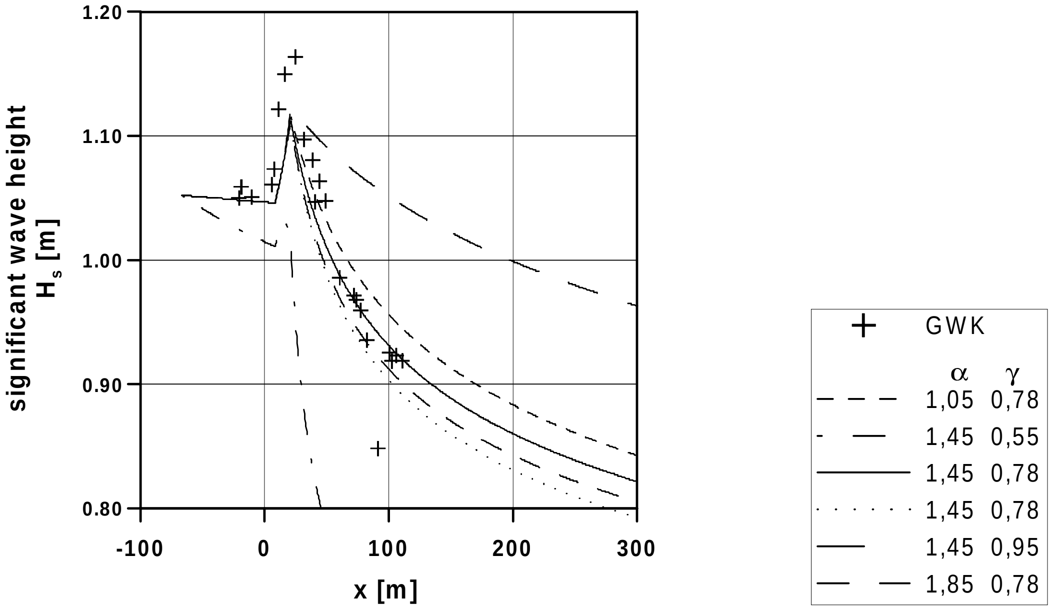


Fig. 7: Calibration of the Model Parameters Describing Breaking

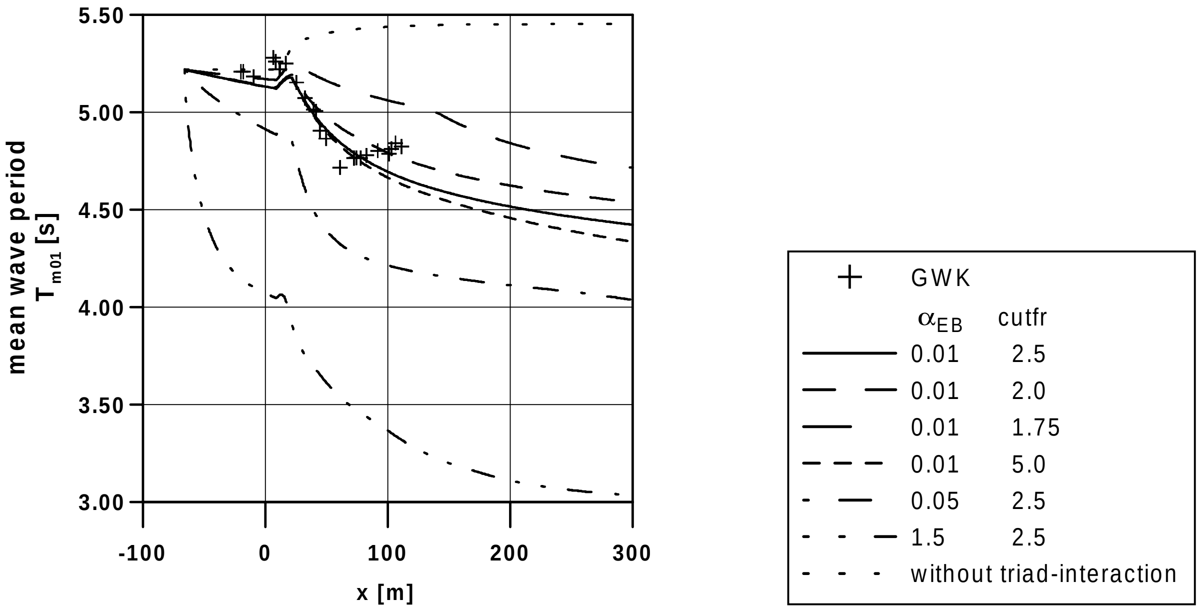


Fig. 8: Calibration of the Model Parameters Describing Triad-Interaction

The triad-wave interactions are especially important for a correct description of the mean wave period by the numerical model. The model SWAN describes the triad-wave interactions using the formula of Eldeberky and Battjes (1995). Figure 8 shows the results of the calibration of the model parameters describing triad-wave interactions for a single set of boundary conditions. The best fit comparing experimental results and numerical results on the mean wave period was achieved using the following model coefficients for the

magnitude of interaction: $\alpha_{EB} = 0.01$ cut-off frequency: cutfr = 2.5

The experiments carried out in the wave tank show that triad-interaction has to be considered because otherwise the decrease of the mean wave period cannot be modeled.

Using this calibration figure 9 compares the wave parameter – significant wave height and mean wave period – derived from the experiment and the numerical simulation at all positions of the wave gauges. For this single set of boundary conditions (d = 3.5 m / $H_{s,\,in}$ = 1.0 m / $T_{p,\,in}$ = 8.0 s) the deviation is less than 5%.

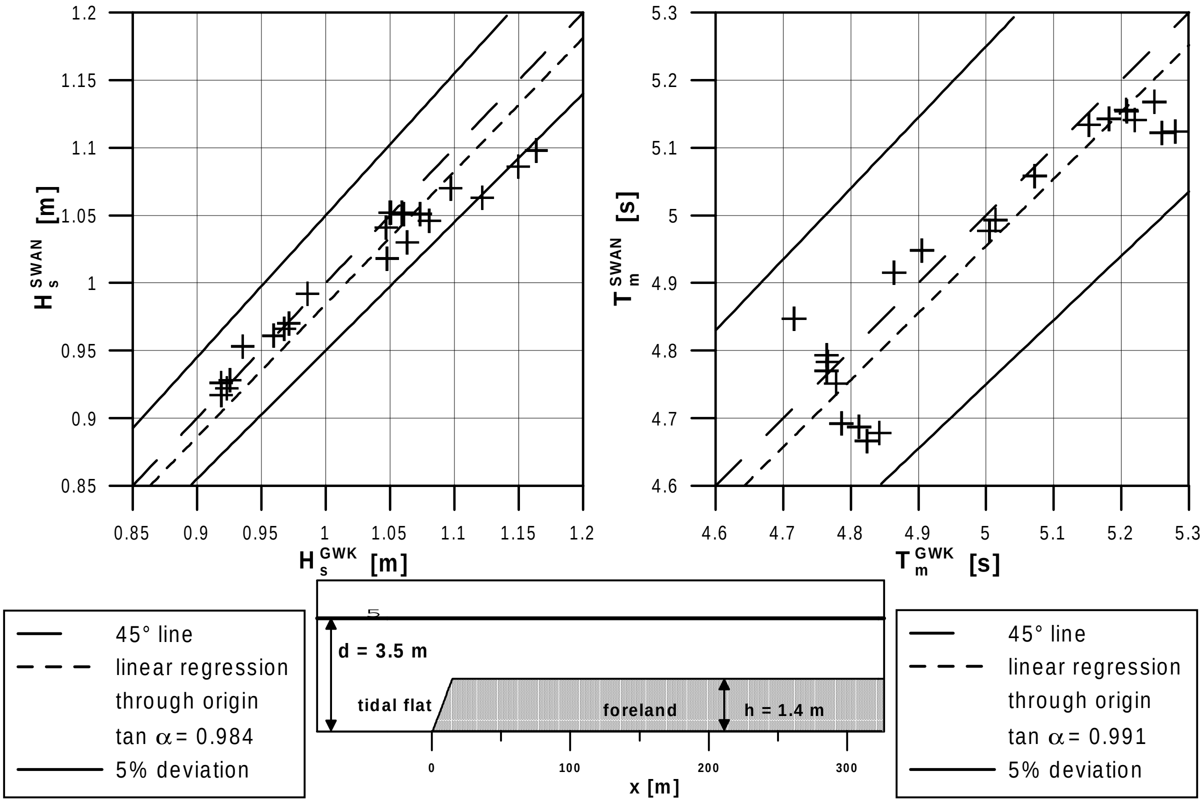


Fig. 9: Numerical Results Compared to Physical Model Tests at Different Positions of Wave Gauges (1 to 22) for a Single Set of Boundary Conditions (d = 3.5 m / $H_{s,\,in}$ = 1.0 m / $T_{p,\,in}$ = 8.0 s)

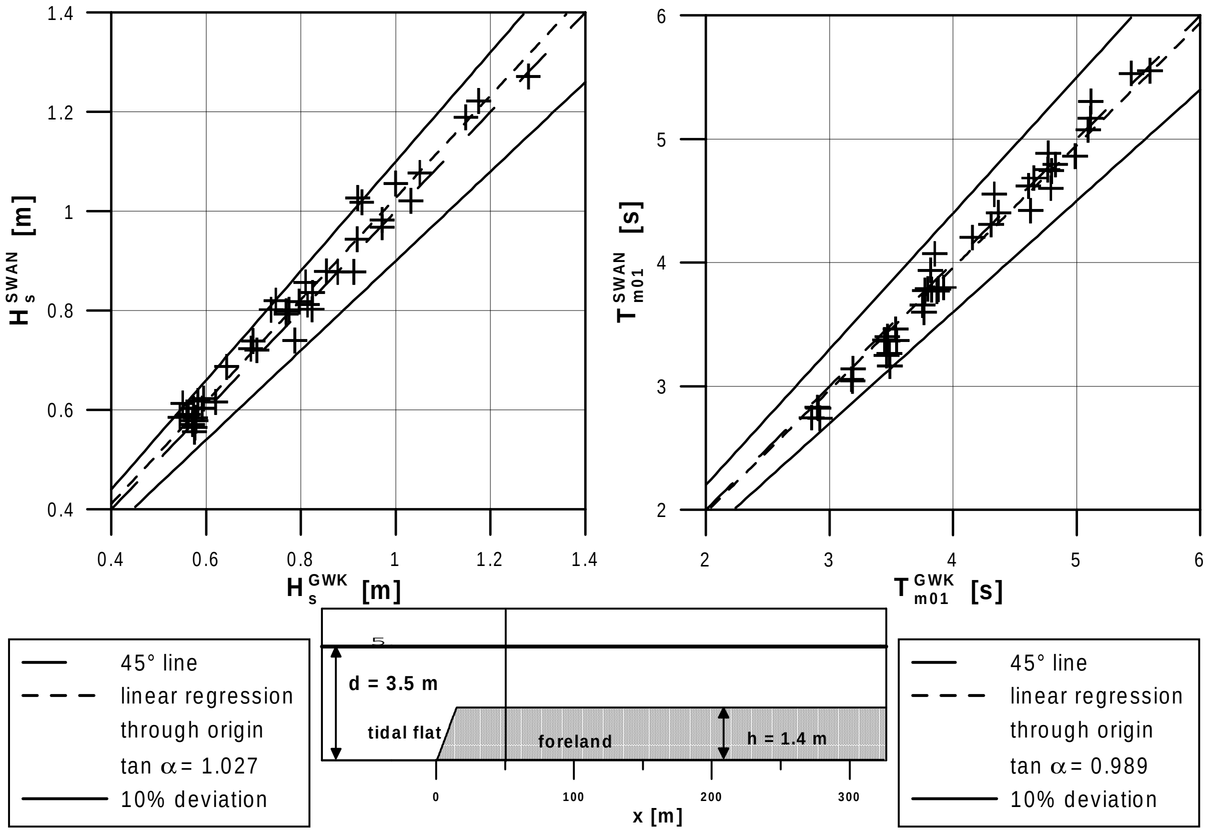


Fig. 10: Numerical Results Compared to Physical Model Tests 75 m behind Seaward Drop of the Foreland for all Sets of Boundary Conditions (46 Cases)

In Figure 10 the wave parameter of experiment and numerical simulation at a single position of the wave gauge 75 m behind the seaward drop of the foreland were compared. For all sets of boundary conditions the deviation is less than 10%.

Other parameters of the numerical model influencing the processes wave direction and bottom friction were adjusted in the same way using flume data. The influence of wave generation due to wind was investigated using field data (Mai et al., 1999).

4 Influence of Foreland Geometry

The influence of water depth on the wave propagation along the foreland was investigated for the geometry shown in figure 6a. An example of the results is given in figure 11. It can be shown that the wave height decreases while the foreland width increases. The higher the wave height and the lower the water depth the more effective is the wave damping.

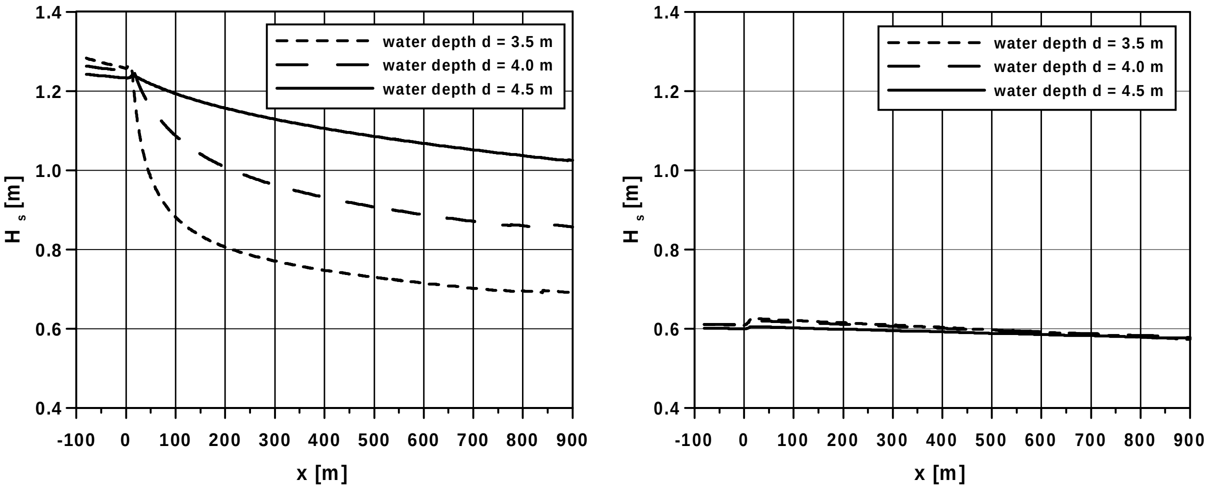


Fig. 11: Relation between Significant Wave Height and Width of the Foreland ($T_{p,\,in}$ = 5.0 s / $H_{s,\,in}$ = 1.25 m (left) resp. $H_{s,\,in}$ = 0.60 m (right))

Figure 11 indicates that the foreland does not influence the incoming waves with a wave height of 0.60 m for water depths in front of the foreland of 3.5 m to 4.5 m which were investigated. Wave heights of 1.20 m are reduced to approximately 0.70 m for a water depth of 3.5 m and to approxiamtely 1.05 m for a water depth of 4.5 m at a distance of 800 m behind the seaward drop. The initial reduction of wave height due to breaking is limited to the first 400 m of the foreland behind the seaward drop.

Effects comparable to the influence of the water depth on the hydraulic efficiency of the foreland occur for different heights of the foreland.

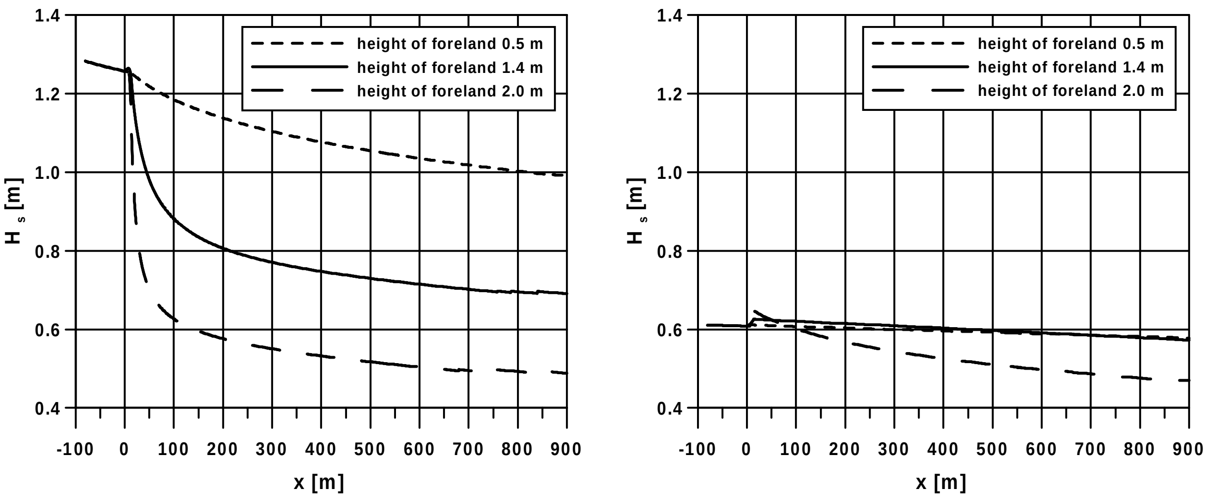


Fig. 12: Relation between Significant Wave Height and Height of the Foreland for a Water Depth of 3.5 m ($T_{p,\,in}$ = 5.0 s / $H_{s,\,in}$ = 1.25 m (left) resp. $H_{s,\,in}$ = 0.60 m (right))

An example of the influence of the height of the foreland on the wave propagation along the foreland is given in figure 12. The investigations were carried out for three different geometries (Fig. 6a to Fig. 6c). It is obvious that wave heights of 0.60 m are only reduced significantly by a foreland of 2.00 m height above the tidal flat and a water depth of 3.5 m in front of the foreland. In case of wave heights of 1.20 m a reduction to approximately 0.50 m for a height of the foreland of 2.00 m above the tidal flat and to approximately 1.00 m for a water depth of 3.50 m at a distance of 800 m behind the seaward drop can be identified.

The hydraulic effectiveness of a foreland can be described with a transmission coefficient as the relation between the wave height at a certain position on the foreland and the incoming significant wave height. Both effects – the influence of the height of the foreland and the influence of the water depth – on the transmission coefficient c_T are analysed using the relation of water depth over the foreland $d_{foreland}$ and the incoming significant wave height $H_{S,\,in}$ as a dimensionless parameter (Fig. 13 and Fig. 14).

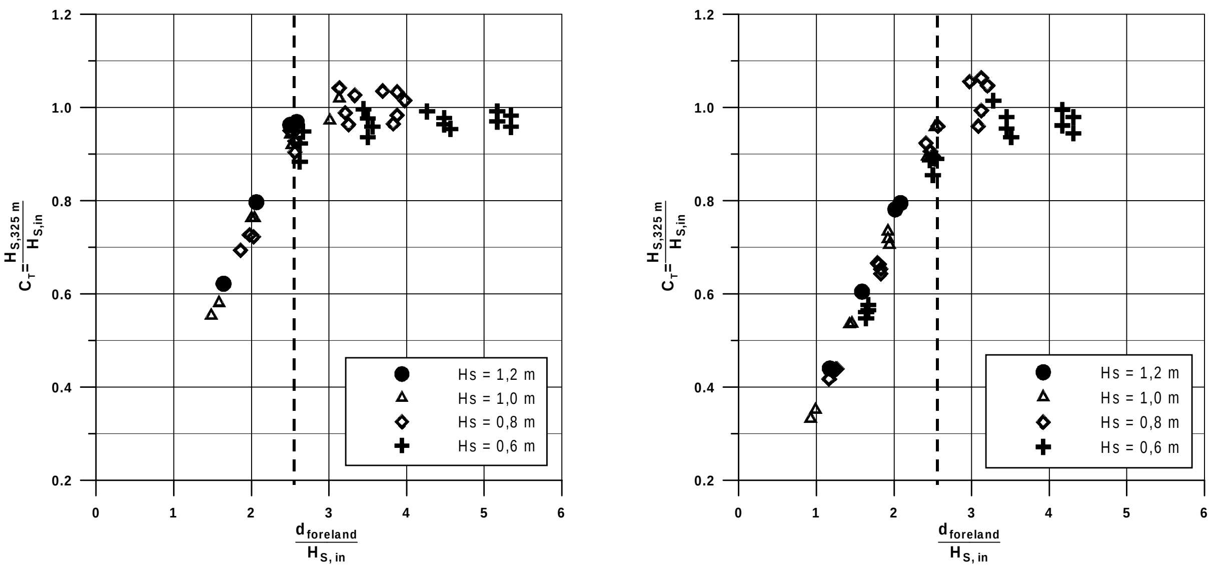


Fig. 13: Transmission Coefficients of a Foreland with a Height of 1.4 m (left) respectively of 2.0 m (right) 325 m Behind the Seaward Drop

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 the transmission coefficient is lower than 0.9 up to $d_{foreland}/H_{S,\,in} \leq 2.6$ (Fig. 13). At a position of 175 m respectively 725 m behind the seaward drop a comparable behaviour of the transmission coefficient is visible (Fig. 14).

Nevertheless, the comparison of the results on the transmission coefficient at different positions shows that a transmission coefficient of less than 0.9 corresponds to a ratio of $d_{foreland}/H_{S,\,in} \leq 2.2$ for a distance of 175 m behind the seaword drop respectively to a ratio of $d_{foreland}/H_{S,\,in} \leq 2.6$ for a distance of 325 m and 725 m. Therefore this results can be used in order to define an optimal width of a foreland of at least 325 m.

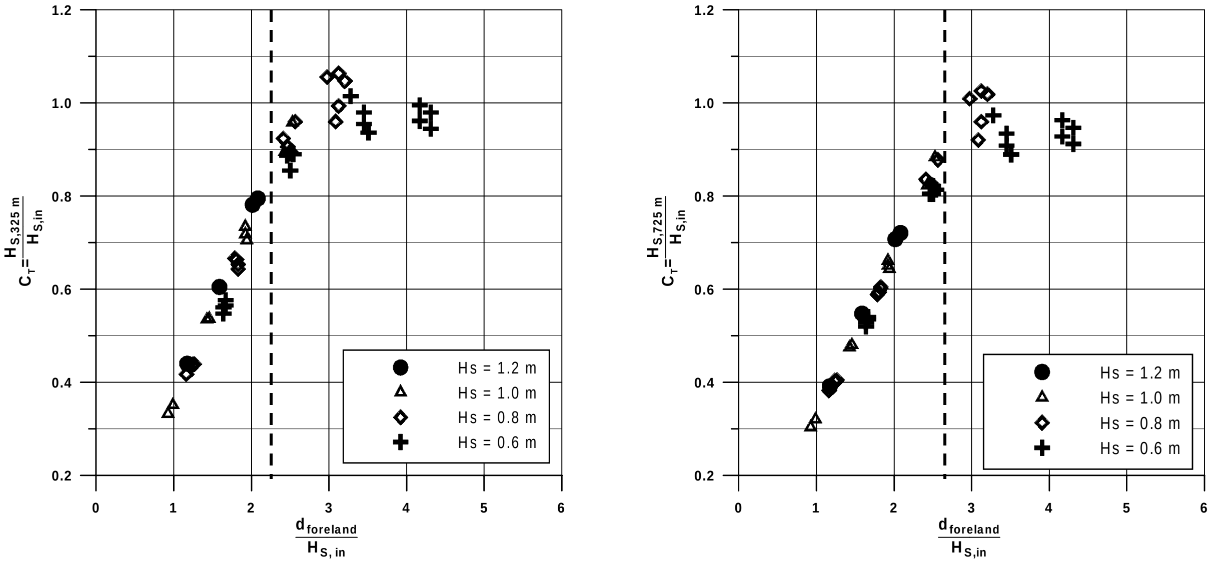


Fig. 14: Transmission Coefficients of a Foreland with a Height of 1.4 m (left) respectively of 2.0 m (right) 725 m Behind the Seaward Drop

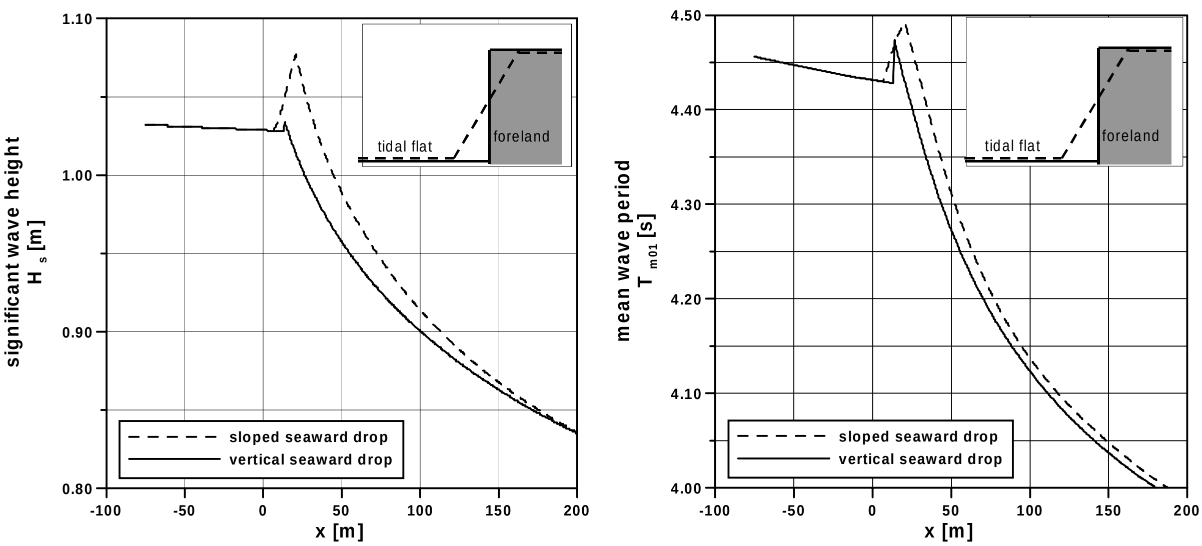


Fig. 15: Significant Wave Height (left) respectively Mean Wave Period (right) along the Foreland for Different Seaward Drops (d = 3.50 m / $T_{p,\,in}$ = 6.5 s / $H_{s,\,in}$ = 1.00 m)

The influence of the geometry of the seaward drop is shown in figure 15. The geometries used in the numerical simulations – a sloped and a vertical drop – relate to the figures 6a and 6c. Differences in wave height and wave period only occur close to the seaward drop. At a distance of approximately 200 m behind the seaward drop nearly no differences can be found. A detailed study on the effects of different geometries of seaward drops taking also into account reflection and using field data is in preparation.

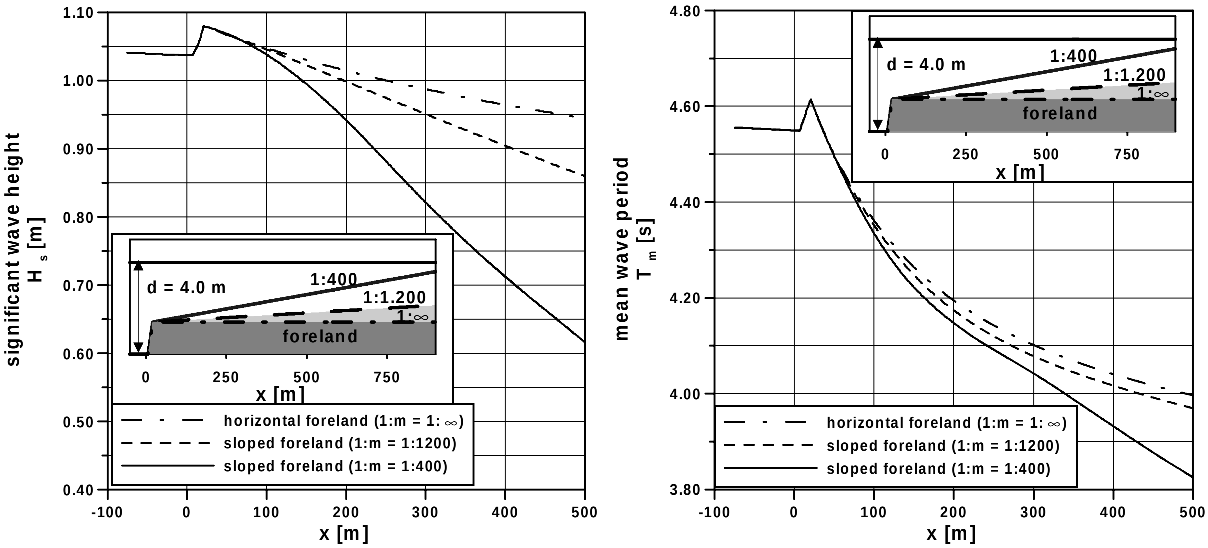


Fig. 16: Significant Wave Height (left) Respectively Mean Wave Period (right) along the Foreland for Different Slopes (d = 4.00 m / $T_{p, in}$ = 6.5 s / $H_{s, in}$ = 1.00 m)

The slope of the foreland influences wave height and wave period due to the decrease in water depth as shown in figure 16. The investigations on sloped forelands were carried out for three different slopes (Fig. 6a, Fig. 6e and Fig. 6f). The transmission coefficients of sloped forelands can be estimated using figures 13 and 14 calculating the ratio $d_{foreland}/H_{S, in}$ with the local water depth at the position of interest. The influence of a negative sloped foreland, as it often occurs in nature, is investigated presently.

5 Conclusion

The interaction of forelands with different geometries with waves can be described quite satisfactorily with the numerical model SWAN. Based on the numerical simulations a necessary width of the foreland of at least 325 m can be derived. The hydraulic effectiveness of forelands were described using transmission coefficients which depend on the relation of water depth over the foreland $d_{foreland}$ and the incoming significant wave height $H_{S, in}$.

6 Acknowledgement

We thank the staff of the wave tank GWK of the UNIVERSITY OF HANNOVER who helped to design the experimental set-up and to carry out the experiments.

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