Interaction of Foreland Structures with Waves

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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. Brushwood fences and summer dikes (submerged dikes) are applied in front of dikes as additional protection element.

Apart from their original function for land reclamation and protection of reclaimed land against summer storm tides both, brushwood fences and summer dikes, cause a reduction of energy of the incoming waves and therefore of wave run-up at the main dike. The wave reduction, i.e. the transmission coefficients, depending on water-level, incoming wave and design parameter of the protection elements was investigated in the wave tanks of the FRANZIUS-INSTITUT, Hannover, Germany.

Transmission coefficients are described in good agreement with empirical formulas for permeable and impermeable breakwaters depending on freeboard and wave steepness. Numerical modelling of the transmission process at summer dikes on the basis of energy decrease due to wave breaking according to Battjes and Janssen using phase averaged wave models showed good agreement with results from physical modelling.

BRUSHWOOD FENCES AND SUMMER DIKES AS WAVE REDUCING ELEMENTS

Forelands and salt marshes in front of the man made sea dikes contribute significantly to the protection and safety of the artificial coastline. Thus the forelands are an important element in the coastal protection system as a whole. To prevent the loss of sediments 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 using low brushwood fences in combination with a regular drainage system. Wooden stake and brushwood structures (fig. 1) create areas with lower waves and reduced currents resulting in enhanced sedimentation.

Summer dikes protect such reclaimed land against storm tides during summers and also the main dike in case of winter storm tides. Summer dikes are designed as overflow dikes with a crest height of approximately 2 m above mean high water, which corresponds to a ratio of freeboard R_C and wave height H_S, $R_C/H_S \approx -1$, during average winter storm tides, a crest width of 3 m and a seaward slope of 1:7 up to 1:12 and 1:5 up to 1:10 on the land side. Besides their function as protection against flooding during summer the overflow dike act as a submerged breakwater during winter storm tides reducing the height of incoming waves and therefore increases the safety for the hinterland by reducing wave run-up and overflow at the main dike.

The interaction of waves with such additional coastal protection elements have been studied using one dimensional physical modelling at prototype-scale in the wave tanks of the FRANZIUS-INSTITUT at the University of Hannover. To analyse the effects of brushwood fences under varying water levels different brushwood fences with variing porosities and heights were installed in the small wave flume (110 m length, 2.20 m width and 2 m depth). Wave transmission coefficients of these fences were obtained with orthogonal, regular and irregular waves. The effect of standard-type submerged dikes on irregular waves was investigated for different water-levels and wave parameters, i.e. significant wave height and mean wave period, in the Large Wave Tank (324 m length, 5 m width and 7 m depth).

In addition to physical modelling, numerical simulations of wave transmission at summer dikes have been performed using the models HISWA (Holthuijsen et al., 1985), SWAN (Ris, 1997) and MIKE 21 EMS (Madsen und Larsen, 1987).

ANALYTICAL BACKGROUND

The interaction of waves with brushwood fences and summer dikes can be distinguished into transmission, reflection, dissipation and breaking of the incoming waves. This is described by the transmission coefficient c_T, reflection coefficient c_R and loss coefficient c_V,

$$c_T = \frac{H_T}{H} \qquad c_R = \frac{H_R}{H} \qquad c_V^2 = 1 - c_T^2 - c_R^2 \tag{1}$$

where H is the height of the incident waves, H_T the transmitted wave height and H_R the reflected wave height. The coefficients c_T, c_R and c_V are calculated using the significant wave height $H = H_s$ when performing experiments with irregular waves.

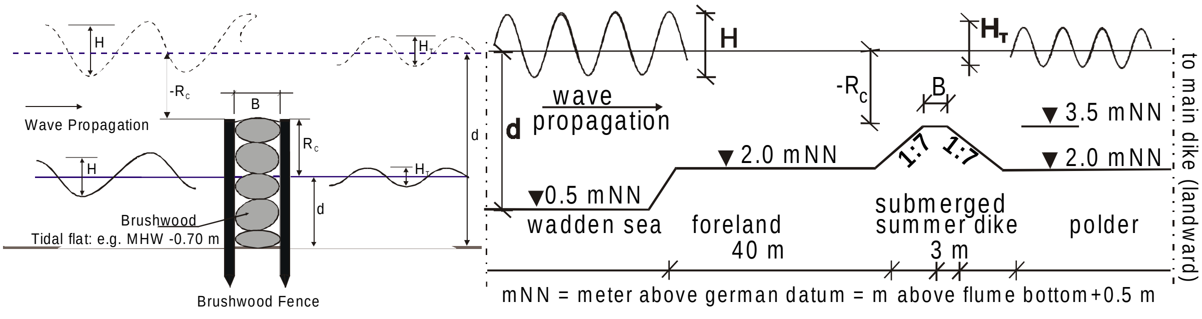

Fig. 1: Wave transmission at brushwood fence and submerged summer dike

Wave damping at brushwood fences and summer dikes, described by their transmission coefficients, can be described in analogy to the transmission at permeable and impermeable breakwaters as a function of relative freeboard R_C/H_S, relative crest width B/H_S and the Iribarren-parameter $\xi = \tan(\alpha)/(H_S/L)^{0.5}$ (d'Angremond et al., 1996):

$$c_T = -\beta_1 \cdot \frac{R_C}{H_S} + w \qquad \text{with} \qquad w = +\beta_2 \cdot \left(\frac{B}{H_S}\right)^{-\beta_3} \cdot \left(1 - e^{-\beta_4 \cdot \xi}\right) \tag{2}$$

The parameters β_i are for breakwaters given by d'Angremond et al. (1996) with $\beta_1 = 0.4$, $\beta_2 = 0.64$, $\beta_3 = 0.31$, $\beta_4 = 0.5$ (for permeable breakwaters) and $\beta_1 = 0.4$, $\beta_2 = 0.64$, $\beta_3 = 0.31$, $\beta_4 = 0.5$ (for impermeable breakwaters) and are calculated for the coastal elements, as described here, by least-squares-fit.

Besides the change of wave height at coastal structures a change of the mean wave T_m period might occur for irregular waves due to non-linear wave-wave interactions. This change in mean wave period r_T is described by the ratio of mean period of the transmitted waves $T_{m,T}$ to the incident waves T_m (Mai et al., 1998):

$$r_T = \frac{T_{m,T}}{T_m} \tag{3}$$

EXPERIMENTAL SET-UP AND PROCEDURES

Figure 2 shows the experimental set-up of a brushwood fence which was installed in the small wave flume of the FRANZIUS-INSTITUT at prototype-scale. The fence was built with original materials that have been applied over centuries, i.e. timber poles with bundled brushwood in between of varying height (fig. 1). Water level variations in front of and behind the brushwood fence were recorded with wave gauges (fig. 2).

The model of a summer dike in the Large Wave Tank of FRANZIUS-INSTITUT (fig. 2) was built on a "foreland" and consists of a sand core protected from erosion by a concrete filled geo-textile mattress simulating a clay cover with grass as applied in nature (Fig. 1, right). Waves were measured for varying water-levels and incident wave parameters. To identify the influence of the summer dike from the effect of the foreland the experiments were carried out on a foreland with and without summer dike.

Fig. 2: Prototype-scaled model of brushwood fence (left) and summer dike (right)

WAVE TRANSMISSION

Transmission coefficients were calculated for significant wave heights and mean wave periods according to equation (1) and (3).

Figure 3 shows the transmission coefficient c_T measured at a brushwood fence (left) and at a summer dike (right) as a function of relative freeboard (R_c/H_s).

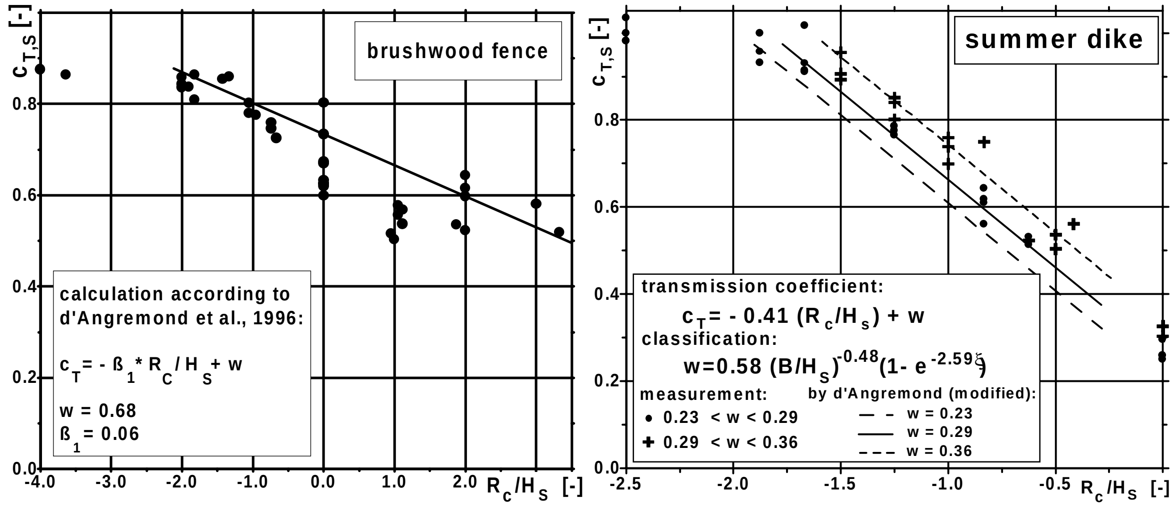

Fig. 3: Transmission c_T of waves at brushwood fences (left) and summer dikes (right) as function of relative freeboard

The transmission at brushwood fences increases linearly R_C/H_s from 1.0 up to approximately - 1.5. Below and above ($1.0 \le R_c/H_s \le 2.0$ and $- 2.0 \le R_c/H_s \le - 1.5$) the coefficient remains nearly constant. The wave damping of a brushwood fence decreases for water levels above its crest height. The transmission coefficients obtained from physical tests are slightly higher than those obtained from field measurements. This can be attributed to fine sediments and algae which settle within the natural brushwood fences and reduce their permeability over long term (von Lieberman et al., 1997).

No wave damping from summer dikes are obtained for a relative crest height $R_C/H_S < -1.75$. Transmission coefficients decrease linearly with decreasing water depth, i.e. increasing relative crest height. The slope of decay $|\beta_1| = 0.41$ is in good agreement with results obtained for impermeable breakwaters, e.g. d'Angremond et al., 1996. The measured transmission coefficients are classified using the parameter w increasing with decreasing relative crest width B/H_S and increasing Iribarren parameter ξ.

Using equation (2) to calculate the transmission coefficient a modified parameter set β_i was obtained by least-squares-fit:

- brushwood fences: $\beta_1 = 0.06$ $w = 0.68$ $r^2 = 0.77$ (4)
- summer dike: $\beta_1 = 0.41$ $\beta_2 = 0.58$ $\beta_3 = 2.59$ $\beta_4 = 0.52$ $r^2 = 0.98$ (5)

Transmission at brushwood fences is mainly affected by the relative freeboard, which includes the water depth, and depends only slightly on the wave period (eq. (4), von Lieberman et al., 1998) whereas the transmission coefficient at summer dikes is strongly dependent on wave period (eq. (5), Mai et al., 1998). The fit of the formula of d'Angremond et al. (1996, eq. (2)) to the experimental data obtained for brushwood fences is not as good as for summer dikes as indicated by the much lower explained variance r^2.

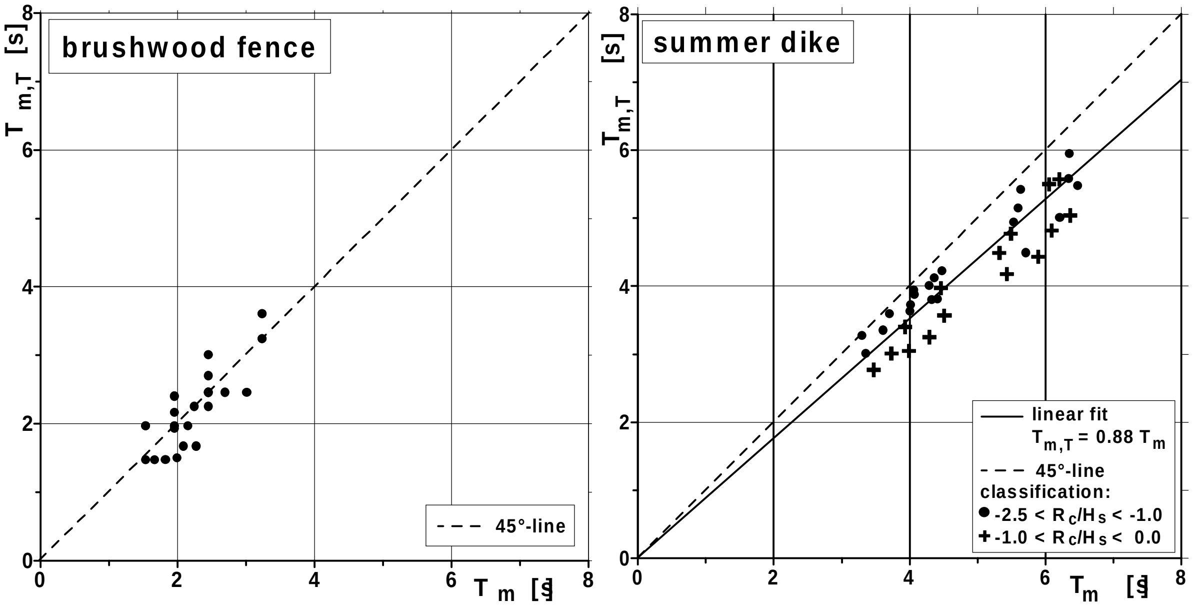

Fig. 4: Mean wave period $T_{m,T}$ after transmission at brushwood fences (left) and summer dikes (right) as a function of incoming wave period T_m

The transmitted mean wave period $T_{m,T}$ is shown as a function of incoming wave period, figure 4. While the mean wave period remains nearly constant, i.e. $r_T = 1$, in case of wave transmission at brushwood fences (fig. 4, left) it decreases approximately 12%, i.e. $r_T = 0.88$, in case of transmission at summer dikes (fig. 4, right).

COMPARISON OF RESULTS FROM PHYSICAL AND NUMERICAL MODELLING

The experiments on summer dikes have been used to calibrate the phase averaged wave models HIndcast Shallow WAves HISWA (Holthuijsen et al., 1985), Shallow Waves Near Shore SWAN (Ris, 1997) and MIKE 21 Elliptic Mild Slope (Madsen und Larsen, 1987). Figure 5 shows a comparison of physical and numerical modelling of the wave transmission at summer dikes.

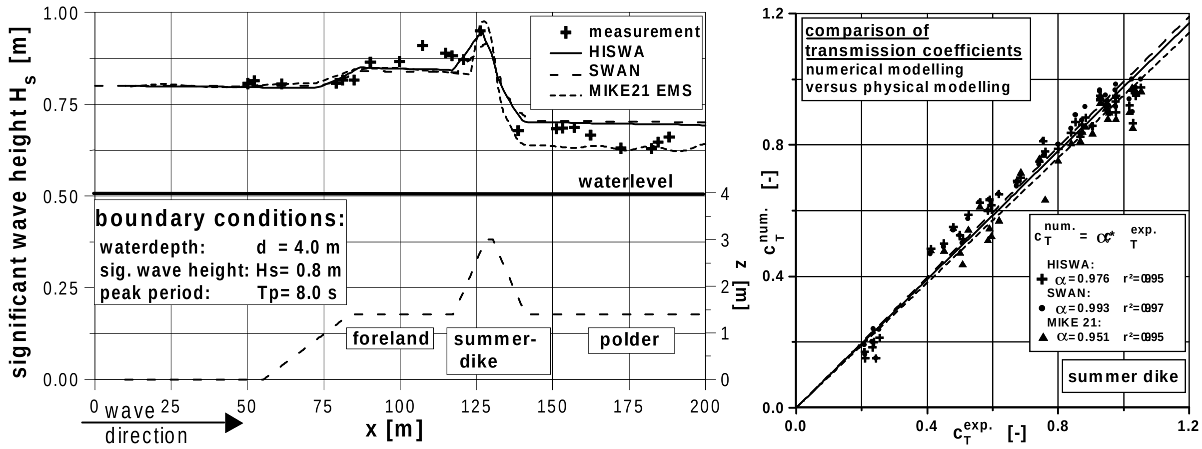

Fig. 5: Comparison of physical and numerical modelling

The left part of figure 5 presents the change in significant wave height H_S along the foreland with a summer dike for a water level of 4 m and incoming waves with a significant wave height $H_S = 0.8$ m and peak period $T_P = 8.0$ s. All models reproduce shoaling on the foreland and energy dissipation at the summer dike due to wave breaking quite well. Also the peak in wave height right in front of the summer dike occurs in all simulations. The calculated transmission coefficients using experimental and numerical data are in good agreement as shown, figure 5 (right). Best fit of transmission coefficients calculated on the basis of numerical simulations $c_T^{num.}$ with the calculated transmission coefficients using experimental data $c_T^{exp.}$ was achieved using the model SWAN. The variation of model parameters revealed wave breaking to be the most important process in tuning the numerical models. The mean dissipation rate D per area due to wave breaking is described in all models according to Battjes and Janssen (1978):

$$D = \frac{\alpha}{4}\, Q_b\, \bar{f}\, \rho\, g\, H_{max}^2 \quad ; \quad \frac{1 - Q_b}{\ln Q_b} = -\left(\frac{H_{rms}}{H_{max}}\right)^2 \quad ; \quad H_{max} = \frac{\gamma_1}{k} \tanh\left(\frac{\gamma_2}{\gamma_1} k \cdot d\right) \qquad (6)$$

with the fraction of breaking waves Q_b, the water density ρ, the wave number k, the water depth d, the root mean square H_{rms} and maximum wave height H_{max}. The empirical parameters α, γ_1, γ_2 were adjusted to give the best fit of numerical and experimental data:

- HISWA: $\alpha = 0.95$ $\gamma_1 = 0.85$ $\gamma_2 = 0.95$ (7)
- SWAN: $\alpha = 1.45$ $\gamma = 0.75$ (with $H_{max} = \gamma\, d$)
- MIKE 21 EMS: $\alpha = 1.00$ $\gamma_1 = 1.05$ $\gamma_2 = 0.85$

CONCLUSION

The interaction of foreland structures, i.e. brushwood fences and summer dikes, with waves can be described quite satisfactorily with a modified empirical formula for the calculation of the decrease in wave height published for impermeable and permeable breakwaters e.g. by d'Angremond et al., 1996. At the impermeable summer dike also the mean wave period decreases while it remains constant on transmission over the permeable brushwood fence. Due to the reduction of wave height and some extent of the wave period the wave load on the main dike is significantly reduced. Therefore brushwood fences and summer dikes are important elements to increase the safety of a coastal protection system non least because of their ecological compatibility.

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REFERENCES

Battjes, J.A., Janssen, J.P.F.M.: Energy Loss and Set-up due to Breaking of Random Waves, Proc. 16th ICCE, Hamburg, 1978

d’Angremond, K., van der Meer, J.W., De Jong, R.T.: Wave Transmission at Low-Crested Structures, Proc. 25th ICCE, Orlando, 1996

Holthuijsen, L.H., Booij, N.: A Numerical Model for Wave Boundary Conditions in Port Design, Int. Conf. Numerical and Hydraulic Modelling of Ports and Harbours, Birmingham, 1985

von Lieberman, N., Matheja, A., Zimmermann, C.: Foreland Stabilization under Waves in Shallow Tidal Waters, Proc. 2nd Indian National Conference on Harbour and Ocean Engineering, Thiruvanathapuram, India, 1997

von Lieberman, N., Matheja, A., Schwarze, H., Zimmermann, C.: Investigation on the Effects of Brushwood Fences via Simulation of the Hydrodynamical and Morphodynamical Interactions in Physical and Numerical Models, J of the Franzius-Institute for Hydraulics, Waterways and Coastal Engineering of the University of Hannover, no. 82, 1998 (original in german)

Madsen, P.A., Larsen, J.: An Efficient Finite-Difference Approach to the Mild-Slope Equation, Coastal Engineering, no. 11, 1987

Mai, S., Daemrich, K.-F., Zimmermann, C.: Wave Transmission at Summer Dikes, Wasser+Boden, no. 11, 1998 (original in german)

Ris, R.C.: Spectral Modelling of Wind Waves in Coastal Areas, Communications on Hydraulic and Geotechnical Engineering, report no. 97-4, 1997