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NUMERICAL SIMULATION OF WAVE PROPAGATION COMPARED TO PHYSICAL MODELING

by

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ABSTRACT

The design of sea dikes requires knowledge about the wave parameter right in front. Especially the wave propagation along the foreland with structures like brush wood fences and summer dikes, determines the wave characteristics at the toe of the dike. Shoaling, refraction, wave breaking and bottom friction are the predominant processes within this area.

Standard numerical models, like HISWA, SWAN and MIKE 21 EMS, are good tools for the simulation of these processes. Nevertheless large scale physical models are still needed to calibrate the parameter and validate the numerical models.

Experiments on wave transmission at summer dikes in the wave tank GROSSER WELLENKANAL of the FORSCHUNGSZENTRUM KÜSTE were used as a basis for validation and calibration of the numerical models which are mentioned above. The results on standard wave parameter and transmission coefficients, derived from using the different calibrated numerical models, were in good agreement with the experiment.

1. INTRODUCTION

Natural coastal protection elements in front of the man made sea dike like foreland and salt marsh and artificial protection elements like summer dikes (submerged dikes, overflow dikes) contribute significantly to the protection and safety of the German coastline (MAI ET AL., 1997). This can be attributed to the reduction of wave load on the sea dike caused by an increased energy dissipation due to wave breaking and bottom friction over foreland and summer dike.
The hydraulic effectiveness of a foreland with and without a summer dike was estimated by ERCHINGER (1974) using benchmarks of flotsam. Experiments on wave transmission over

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impermeable breakwaters in wave tanks (e.g. DAEMRICH, 1985) describe the effectiveness of submerged breakwaters with a slope of tan(α)≤1:4 but cannot be easily transferred because of the smaller slope of a summer dike (tan(α)=1:7 to 1:10)

Therefore experiments with a natural-scale model of foreland and summer dike were carried out in the large wave tank GROSSER WELLENKANAL of the FORSCHUNGSZENTRUM KÜSTE (MAI ET AL., 1998). The experimental results lead to a quantification of the hydraulic effectiveness depends on the water-level and the parameter of the incoming waves. Besides that the hydraulic effectiveness also depends on the foreland geometry, i.e. width and height of the foreland and the summer dike. The numerical models HINDCAST SHALLOW WAVES HISWA (BOOIJ ET AL., 1985), SHALLOW WAVES NEARSHORE SWAN (RIS, 1997) and MIKE 21 ELLIPTIC MILD SLOPE EMS (MADSEN AND LARSEN, 1987) may be used to answer this question on geometrical effects. This requires a calibration and validation of the numerical models on the basis of the wave tank experiments.

2. PHYSICAL MODEL

Two different experimental set-ups were installed in the wave tank GROSSER WELLENKANAL to study the effect of a foreland without summer dike and with summer dike (Fig. 1).

The foreland was build at natural scale using sand instead of clay in order to ease the building works. Its dimensions are characteristic of the coastal structure at Luetetsburg on the Lower Saxonian Coast of Germany. The width of the foreland was chosen to 150 m and its height to 1,5 m above the bottom of the flume, which equals 2 m above German Datum (mNN). The distance from the wave generator to the foreland was approximately 80 m.

In the second phase of the experiment a model of a summer dike was build on the foreland. It consisted of a sand core protected from erosion by a concrete filled geo-textile mattress simulating a clay cover with grass as applied in nature. Figure 2 shows the model of the summer dike during construction. The summer dike had a crest width of 3 m, a height of 1.5 m above the foreland and a base length of 24 m. The distance from the edge of the foreland to the summer dike was approximately 40 m (Fig. 1).

During both phases of the experiment the wave propagation in the wave tank was measured by 26 wave gauges (Fig. 1) and characterized using the significant wave height H_s and the mean wave period T_m. Figure 3 shows an example of the measured wave parameters along the foreland with and without summer dike for a water level of 3.5 m and incoming wave parameters of H_s = 1.2 m and T_m = 8.0 s. On propagation of the waves over the edge of the foreland the influence of shoaling becomes evident resulting in an increase of the significant wave height of approx. 7 %. Due to the reduced water depth on the foreland the dissipation caused by bottom friction leads to a decrease in the significant wave height. Wave breaking occurs at the summer dike. This is indicated by the sharp decrease of the wave height.

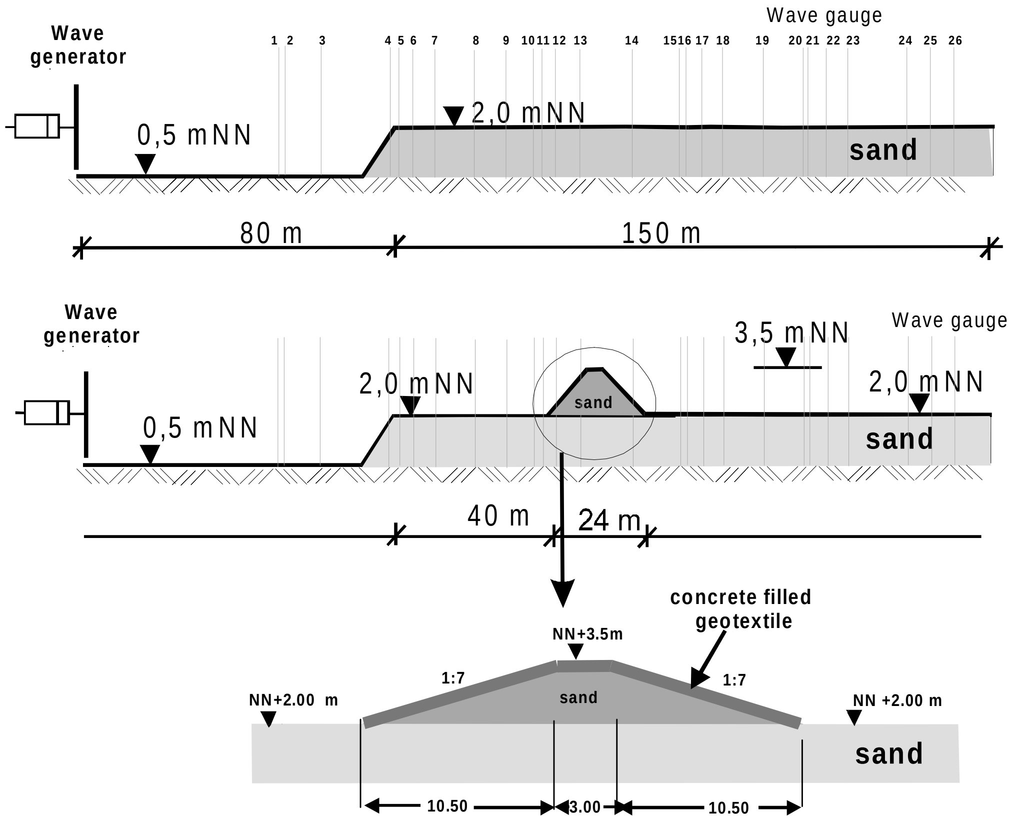

Figure 1: Cross-section of the experimental set-up in the wave tank (top: foreland without summer dike, bottom: foreland with summer dike)

Figure 2: Construction of the model of the summer dike in the GROSSER WELLENKANAL

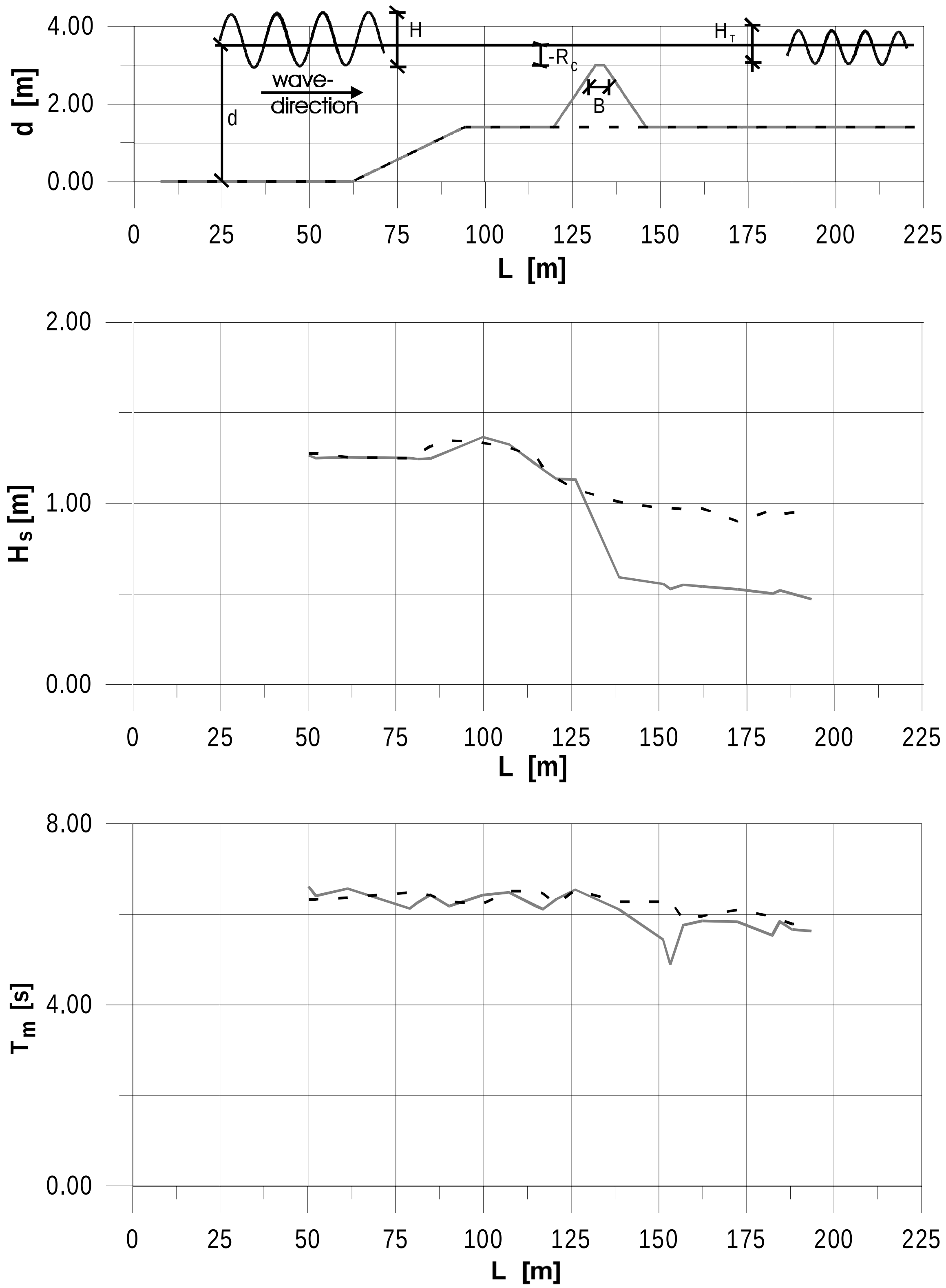

Figure 3: Experimental results on wave propagation along a foreland (top) with summer dike (solid line) and without summer dike (dashed line), characterized by significant wave height H_s (center) and mean wave period T_m (bottom) [Boundary conditions: water level 3.5 m, incoming wave characteristics: H_s = 1.2 m and T_p = 8.0 s]

The mean period of waves propagating along the foreland without a summer dike is nearly constant. The propagation over the summer dike leads to a reduction of the mean wave period of approx. 5 % for the boundary conditions presented in Figure 3. This reduction of the wave period is characteristic of a summer dike (MAI ET AL., 1999b).

A means to describe the hydraulic effectiveness is the transmission coefficient

$$c_T = \frac{H_T}{H}$$

with the significant wave height of the incoming waves H, measured by the wave gauges 1 to 3, and the significant waves height of the transmitted waves H_T, measured by the wave gauges 23 to 26 (Fig. 1, Fig.3(top)). An dependence analysis of the transmission coefficient on the boundary conditions, i.e. water-level d and incoming wave characteristics H_s and T_p, and the summer dike geometry, i.e. crest width B and freeboard R_c, can be found in MAI ET AL. (1998).

3. NUMERICAL MODELS

3.1 HISWA and SWAN

The wave model HISWA and the advanced model SWAN are based on the following action balance equation:

$$\frac{\partial}{\partial t}N + \frac{\partial}{\partial x}c_x N + \frac{\partial}{\partial y}c_y N + \frac{\partial}{\partial \sigma}c_\sigma N + \frac{\partial}{\partial \theta}c_\theta N = \frac{S_{ds,br} + S_{ds,br} + \ldots.}{\sigma}$$

where the geographical coordinates are x and y, the propagation direction is θ, the relative frequency is $\sigma = \omega - \vec{k} \cdot \bar{u}$, the wave number is $\vec{k}$, the depth-averaged underlying current is $\bar{u}$, the action density spectrum is $N = E/\sigma$, the propagation velocities are c_x, c_y, c_σ, c_θ of wave energy in geographical and spectral space. (RIS, 1997, HOLTHUIJSEN AND BOOIJ, 1987).

The influence of currents on wave propagation is not taken into consideration within our model tests, i.e. $|\bar{u}| = 0$. The processes of dissipation of wave energy due to water-depth induced breaking $S_{ds,br}$ or wave bottom interactions $S_{ds,b}$ are included. The time-dependence of the action balance equation is neglected in our model test of HISWA and SWAN although SWAN contains a non-stationary mode.

The dissipation of wave energy due to bottom friction is determined in all tested models using a quadratic bottom friction law. This includes k_0 and σ_0, as mean wave number and mean wave frequency and C_{bot} as the friction coefficient. The bottom friction coefficient is a constant model parameter in HISWA. Besides that the bottom friction formulations of COLLINS (1972) and of MADSEN ET AL. (1988) are included in SWAN.

The numerical formulation of wave breaking is described in HISWA and SWAN according to BATTJES AND JANSSEN (1978). This formulation includes the mean dissipation rate per area D_{br}, the fraction of breaking waves Q_b, the water density ρ, the maximum wave height H_{max}

and the adjustable coefficients α, γ_1, γ_2 . The total dissipation rate D is assigned to the dissipation rate for each spectral component (BOOIJ ET AL., 1985, RIS , 1997):

3.2 MIKE21 EMS

The wave model MIKE 21 EMS is based on the elliptic mild slope equation developed by MADSEN AND LARSEN, 1987. The formulation equation includes the processes of refraction, shoaling and diffraction. In order to include energy dissipation due to bed friction, wave breaking and energy loss inside porous structures in MIKE 21 EMS, the original elliptic mild slope equation is rewritten by introducing complex harmonic pseudo-fluxes P:

$$\frac{c_g}{c}\frac{\partial S}{\partial t}+\left(\frac{c_g}{c}\cdot i\cdot\omega+f_s\right)\cdot S+\frac{\partial P}{\partial x}=SS$$

$$\frac{c_g}{c}\frac{\partial P}{\partial t}+\left(\frac{c_g}{c}\cdot(i\cdot\omega+\omega\cdot f_p)+f_s+e_f+e_b\right)\cdot P+c_g^2\frac{\partial S}{\partial x}=0$$

where the phase velocity is $c=\omega\cdot k$, S is the wave amplitude, i is the imaginary unit, f_s and f_p are linear friction factors due to energy loss in an absorbing sponge layer or inside a porous structure and e_f and e_b are factors of energy dissipation due to bed friction and wave breaking (DHI, 1996).

In MIKE 21 EMS the friction model of DINGEMANS (1983) is used to calculate the dissipation rate per unit area D_b and includes f_e as an energy loss factor. The energy density E of the wave field is introduced in this formulation as

$$E=\frac{\rho\cdot g\cdot H_{rms}^2}{8}$$

The dissipation rate is used to calculate the factor of the total energy dissipation:

$$e_b\propto\frac{D_{br}}{E}$$

A detailed description of the mentioned processes and their mathematical formulation can be found in MAI ET AL., 1999a.

4. COMPARISION OF THE RESULTS

Figure 4 shows exemplary a comparison of physical and numerical modelling of wave transmission at summer dikes. For the given set of boundary conditions (water-level of 4 m, significant wave height of 1.0 m and peak-period of 6.5 s) MIKE 21 EMS reproduces shoaling, bottom friction and wave breaking at the summer dike best. All models give a correct reproduction of the transmission coefficient $c_T\approx 0{,}70$ to 0.75.

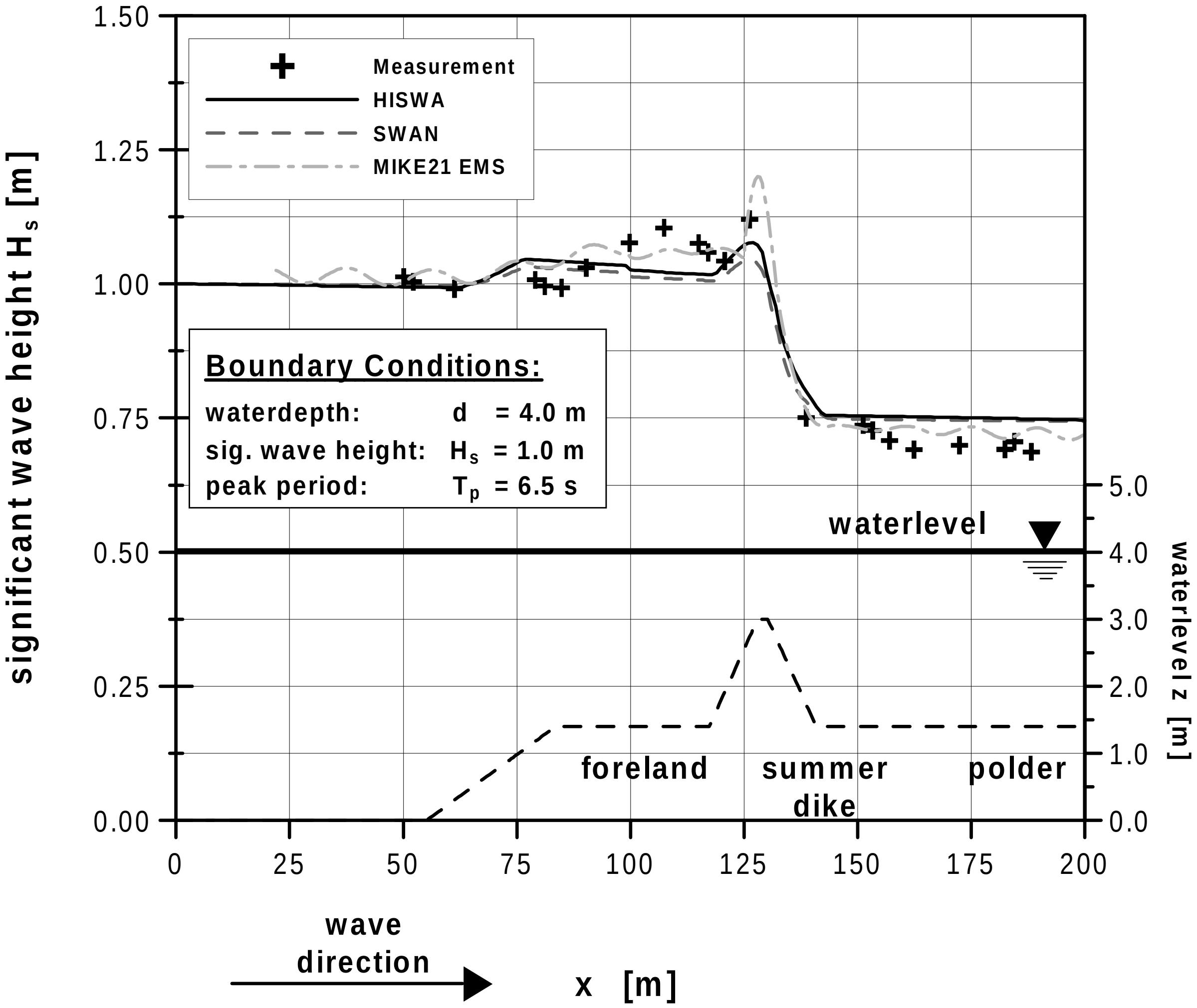

Figure 4: Comparison of the measured significant height of waves propagating in a wave tank with results of the models HISWA, SWAN, MIKE 21 EMS.

The transmission coefficient was used in order to calibrate the coefficients of bottom friction C_{fw} and K_N and of wave breaking α, γ_1 and γ_2. The calibration was carried out with the aim of minimizing the difference of experimentally and numerically determined transmission coefficients. Table 1 summarizes the calibrated set of model parameters and compares it with the standard set of parameters. Only few changes of the standard parameter were necessary to give an optimal agreement of the transmission coefficients calculated on the basis of experiments and numerical simulations.

Figure 5 shows the correlation of the transmission coefficients determined with the different numerical models and those calculated using the experiments.
Considering all experimental test cases SWAN reproduced the experimentally determined transmission coefficients best (Table 1).

NUMERICAL MODEL	HISWA			SWAN			MIKE 21 EMS		
DISSIPATION PROCESS	Para-meter	Stand-ard	Adjust-ed	Para-meter	Stand-ard	Adjust-ed	Para-meter	Stand-ard	Adjust-ed
Wave breaking	α γ_1 γ_2	1.00 0.80 1.00	0.95 0.85 0.95	α γ	1.50 0.73	1.45 0.75	α γ_1 γ_2	(1.00) 0.88 0.80	(1.00) 1.05 0.85
Bottom friction	C_{fw}	0.01	0.01	K_N	0.05	0.02	K_N	0.02	0.03
COMPARISON	**NUMERICAL MODEL VERSUS PHYSICAL MODEL**								
Slope of Regression	a	0.93	0.976	a	0.91	0.993	a	0.93	0.951
Regression Coefficient	r^2	0.95	0.995	r^2	0.93	0.997	r^2	0.97	0.995

Table 1: Standard and optimized set of model parameter

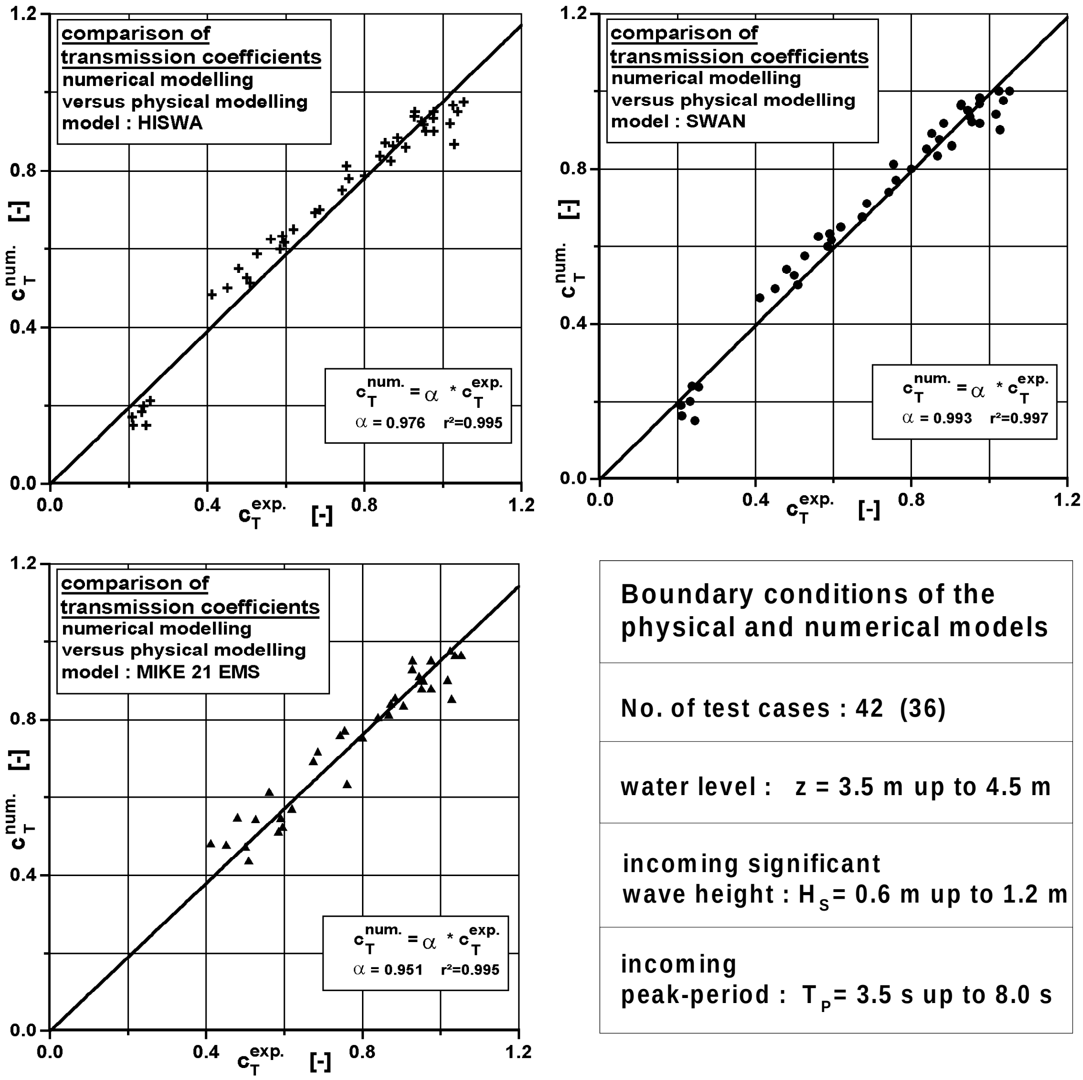

Figure 5 Comparison of the transmission coefficient calculated from the experiments in the wave flume $c_T^{exp.}$ with transm. coefficient calculated from numerical simulations $c_T^{num.}$ using the models HISWA, SWAN and MIKE 21 EMS (MAI ET AL., 1999a)

5. CONCLUSION

The wave models HISWA, SWAN and MIKE 21 EMS are applicable very well for forecasts of the transmission coefficient at forelands and summer dikes. Best results in comparison with experimental wave tank data were achieved with model parameters of friction and wave breaking only slightly changed from the recommend values in the manuals.

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