ANALYTICAL MODEL FOR WAVE TRANSMISSION AT ARTIFICIAL REEFS

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Artificial reefs are increasingly used as an active shore protection measure. Nevertheless, the physical processes occurring at these structures are still not well understood. Existing design formulae mostly take into account only a few of the governing parameters and do only account for the change in wave height over the reef. Based on a comprehensive literature review and subsequently conducted physical model tests an analytical model has been developed which proves to have a broader range of application than existing analytical models.

1. Introduction and Objective

In the existing design concepts for artificial reefs a global approach is adopted. The energy of the wave spectrum in front of the reef is compared to the spectrum behind the reef by means of the transmission coefficient $C_t = H_t / H_i$, H_t being the transmitted and H_i being the incoming wave height [m].

The fact that the shape of the spectrum is also deformed is only considered by using spectral wave parameters for the wave height. Nevertheless, the frequency of a wave (component) and thereby its period is a measure for the wave celerity, which is determinant for estimating the energy flux. Thus, the change of spectral shape can not be neglected for the design of coastal structures or for the assessment of sediment transport.

An other shortcoming of this empirical design formulae is the fact that they mostly rely on a limited number of data and do not account for all parameters relevant for the wave transformation at reefs. A fact becoming clear when looking at the influence of the reef length. From analytical models a kind of resonance can be identified, the transmission being maximal if the reef length B is a multiple of the wave length L . Nevertheless, this clear relationship is mostly not taken into account by empirical design formulae, because the wave length does not only depend on the wave period but also on the water depth, which is

one of the most important parameters affecting the wave transformation at reefs. On the other hand, analytical models do not account for energy losses and are only applicable in a very limited range because of the assumption of the underlying theory.

Most numerical models being able to account for most of these effects are quite demanding regarding the computational power required. Also there are other shortcomings, e.g. the most advanced models to date (VOF concept) are only capable to run regular wave tests due to the aforementioned computational requirements. In addition, in most of these numerical codes various parameters are used by which the model is adjusted. The physical meaning of these parameters is often not well-understood.

Therefore, the objective of this study is to develop an analytical model that describes the relations between the governing parameters and accounts for the process of energy losses based on the observed mechanisms.

2. Methodology

In former papers by the authors (BLECK and OUMERACI; 2001 and 2002) the effects at artificial reefs were subdivided in *global effects* (global energy loss and energy transfer within the wave spectrum) and *local effects* (wave breaking, vortex shedding and non-linear effects). Starting with an existing analytical model which is based on potential theory (IJIMA and SASAKI; 1971) the general form of the global effects will be accounted for. In a second step, the results of physical model tests which were conducted to get a better understanding of the physical processes at the reef will be incorporated to account for the different sources of energy losses.

The model tests within this study have been conducted at Leichtweiß-Institute at an idealized artificial reef (Fig.1). A rectangular box with different heights ($h = 0.4\text{m}$; 0.5m ; 0.6m) and widths ($B = 0.5\text{m}$; 1.0m) placed on the flume bottom has been used to represent the reef. In total six alternative geometries were investigated using regular waves and theoretical wave spectra. Water level elevations were recorded in front and behind the reef. In addition, a set-up to record the entire flow field has been applied. Instantaneous velocity fields based on PIV (Particle Image Velocimetry) principles (BLECK; 2003) were obtained. These recordings have also been used to get a better insight into the local processes at the reef. First results of the model tests have been reported based on the global approach (BLECK and OUMERACI; 2001) while further results have been focusing on the local effects (BLECK and OUMERACI; 2002).

Figure 1. Experimental Set-Up in the Wave Flume of LWI

3. Analytical Model

3.1. Basic Module

The core component of the applied analytical model is based on Laplace equation and on the same initial and linearized boundary conditions than used in linear wave theory. In each of the three regions around the reef with constant water depth a wave system can be found as a basic solution:

$$\Phi(x, y, z) = \left\{ \begin{aligned} & -\frac{i \cdot g}{\omega} \cdot a_1 \cdot \exp(i \cdot k_1 \cdot x) \cdot \frac{\cosh(k_1 \cdot [d + z])}{\cosh(k_1 \cdot d)} \cdot \exp[-i \cdot \omega \cdot t] \\ & + \sum_{j=2}^{\infty} \left(-\frac{i \cdot g}{\omega} \cdot a_j \cdot \exp(i \cdot k_j \cdot x) \cdot \frac{\cos(k_j \cdot [d + z])}{\cos(k_j \cdot d)} \cdot \exp[-i \cdot \omega \cdot t] \right) \end{aligned} \right\} \quad (1)$$

with: $\omega = (2\pi)/T$ - angular frequency [Hz], T - wave period [s],
 $k = (2\pi)/L$ - wave number [m^{-1}], L - wave length [m], d - water depth [m],
 t - time [s], x - spatial variable [m], a - complex amplitude [m],
 g - acceleration of gravity [m/s^2] and i - imaginary unit^a [-].

The wave number k is obtained from:

$$\omega^2 = g \cdot k \cdot \tanh(k \cdot d) \quad (2)$$

In addition to the common real solution ($k \in \mathbb{R}$) representing a progressive wave (first part of Eq. 1) an infinite number of imaginary solutions ($k \in \mathbb{I}$) of Eq. 2 exists which can be found as a solution of:

$$\omega^2 = -g \cdot |k_j| \cdot \tan(|k_j| \cdot d) \quad (3)$$

^a i - imaginary unit: $i^2 = -1$; $\sinh(ix) = i\sin(x)$; $\cosh(ix) = \cos(x)$

These solutions represent locally existing waves (second term of Eq. 1) and are needed to fulfill the matching conditions between the three regions of constant depth around the artificial reef as sketched in Fig. 2.

In region 1 the incident wave is present as an initial condition. Also a wave system as stated by Eq. 1 will be emitted by the two transitions at the front and end of the reef in both direction. Thereby in front of the reef the following velocity potential exists:

$$\Phi_I(x, y, z) = \left. \begin{aligned} & -\frac{i \cdot g}{\omega} \cdot a_{inc} \cdot \exp(i \cdot k_1 \cdot x) \cdot \frac{\cosh(k_1 \cdot [d + z])}{\cosh(k_1 \cdot d)} \cdot \exp[-i \cdot \omega \cdot t] \\ & -\frac{i \cdot g}{\omega} \cdot a_1 \cdot \exp(i \cdot k_1 \cdot x) \cdot \frac{\cosh(k_1 \cdot [d + z])}{\cosh(k_1 \cdot d)} \cdot \exp[-i \cdot \omega \cdot t] \\ & + \sum_{j=2}^{\infty} \left(-\frac{i \cdot g}{\omega} \cdot a_j \cdot \exp(i \cdot k_j \cdot x) \cdot \frac{\cos(k_j \cdot [d + z])}{\cos(k_j \cdot d)} \cdot \exp[-i \cdot \omega \cdot t] \right) \end{aligned} \right\} \quad (4)$$

On top of the reef (region 2) we will have two wave systems with opposite direction of propagation represented by:

$$\Phi_{II}(x, y, z) = \left. \begin{aligned} & -\frac{i \cdot g}{\omega} \cdot a_1 \cdot \exp(i \cdot k_1^* \cdot x) \cdot \frac{\cosh(k_1^* \cdot [d + z])}{\cosh(k_1^* \cdot d)} \cdot \exp[-i \cdot \omega \cdot t] \\ & + \sum_{j=2}^{\infty} \left(-\frac{i \cdot g}{\omega} \cdot a_j \cdot \exp(i \cdot k_j^* \cdot x) \cdot \frac{\cos(k_j^* \cdot [d + z])}{\cos(k_j^* \cdot d)} \cdot \exp[-i \cdot \omega \cdot t] \right) \\ & -\frac{i \cdot g}{\omega} \cdot a_1 \cdot \exp(i \cdot k_1^* \cdot x) \cdot \frac{\cosh(k_1^* \cdot [d + z])}{\cosh(k_1^* \cdot d)} \cdot \exp[-i \cdot \omega \cdot t] \\ & + \sum_{j=2}^{\infty} \left(-\frac{i \cdot g}{\omega} \cdot a_j \cdot \exp(i \cdot k_j^* \cdot x) \cdot \frac{\cos(k_j^* \cdot [d + z])}{\cos(k_j^* \cdot d)} \cdot \exp[-i \cdot \omega \cdot t] \right) \end{aligned} \right\} \quad (5).$$

The k_i^* in Eq.5 are calculated by setting the water depth d in the dispersion relationship (Eqs. 2 and 3) to d_r , the water depth on top of the reef. The k_i are calculated by using the water depth d_f in front of the reef (see Fig.2).

Behind the reef the transmitted wave system and its velocity potential is written as:

$$\Phi_I(x, y, z) = \left. \begin{aligned} & -\frac{i \cdot g}{\omega} \cdot a_1 \cdot \exp(i \cdot k_1 \cdot x) \cdot \frac{\cosh(k_1 \cdot [d + z])}{\cosh(k_1 \cdot d)} \cdot \exp[-i \cdot \omega \cdot t] \\ & + \sum_{j=2}^{\infty} \left(-\frac{i \cdot g}{\omega} \cdot a_j \cdot \exp(i \cdot k_j \cdot x) \cdot \frac{\cos(k_j \cdot [d + z])}{\cos(k_j \cdot d)} \cdot \exp[-i \cdot \omega \cdot t] \right) \end{aligned} \right\} \quad (6)$$

Figure 2. Principle Sketch for the Analytical Model

a_{inc} is the amplitude of the incident waves whereby the amplitudes a_i , b_i , c_i and d_i of the other waves have to be evaluated by applying the matching conditions.

These matching conditions result from the requirement of continuity in both velocity potential and velocity (first derivative of the velocity potential). Also the velocity perpendicular to the reef surface has to be zero (impermeable reef). At the front edge of the reef ($x = -B/2$) this is expressed by (see Fig.2):

$$\left(\frac{\partial \Phi}{\partial x} \right)_I = \begin{cases} \left(\frac{\partial \Phi}{\partial x} \right)_{II} & \text{for } -d_r \leq z \leq 0 \\ 0 & \text{for } -d_i \leq z \leq -d_r \end{cases} \quad (7)$$

and:

$$\Phi_I = \Phi_{II} \text{ for } -d_r \leq z \leq 0 \quad (8)$$

At the rear end ($x = B/2$) one gets:

$$\left(\frac{\partial \Phi}{\partial x} \right)_I = \begin{cases} \left(\frac{\partial \Phi}{\partial x} \right)_{II} & \text{for } -d_r \leq z \leq 0 \\ 0 & \text{for } -d_i \leq z \leq -d_r \end{cases} \quad (9)$$

and:

$$\Phi_I = \Phi_{II} \text{ for } -d_r \leq z \leq 0 \quad (10)$$

To get the amplitudes of the four progressive waves and the infinite number of local waves only four matching conditions exist. The solution is obtained by

applying the *Potential Matching Technique* (IJIMA and SASAKI; 1971) which is comparable to the Galerkin method. Plate 1 sums up the resulting system of equations.

$x = -B/2$:

$$\sum_{i=1}^{n_s} A_i^* \cdot \int_{-d_r}^0 \cosh[k_i \cdot (z + d_p)] \cdot \cosh[k_j \cdot (z + d_p)] \cdot dz + A_{inc}^* \cdot \int_{-d_r}^0 \cosh[k_1 \cdot (z + d_p)] \cdot \cosh[k_j \cdot (z + d_p)] \cdot dz = \sum_{i=1}^{n_s} B_i^* \cdot \int_{-d_r}^0 \cosh[k_i^* \cdot (z + d_p)] \cdot \cosh[k_j \cdot (z + d_p)] \cdot dz + \sum_{i=1}^{n_s} C_i^* \cdot \int_{-d_r}^0 \cosh[k_i^* \cdot (z + d_p)] \cdot \cosh[k_j \cdot (z + d_p)] \cdot dz \quad (P-1)$$

$$\sum_{i=1}^{n_s} A_i \cdot \int_{-d_r}^0 \cosh[k_i \cdot (z + d_p)] \cdot \cosh[k_j^* \cdot (z + d_p)] \cdot dz + A_{inc} \cdot \int_{-d_r}^0 \cosh[k_1 \cdot (z + d_p)] \cdot \cosh[k_j^* \cdot (z + d_p)] \cdot dz = \sum_{i=1}^{n_s} B_i \cdot \int_{-d_r}^0 \cosh[k_i \cdot (z + d_p)] \cdot \cosh[k_j^* \cdot (z + d_p)] \cdot dz + \sum_{i=1}^{n_s} C_i \cdot \int_{-d_r}^0 \cosh[k_i \cdot (z + d_p)] \cdot \cosh[k_j^* \cdot (z + d_p)] \cdot dz \quad (P-2)$$

$x = B/2$:

$$\sum_{i=1}^{n_s} B_i^* \cdot \int_{-d_r}^0 \cosh[k_i^* \cdot (z + d_p)] \cdot \cosh[k_j \cdot (z + d_p)] \cdot dz + \sum_{i=1}^{n_s} C_i^* \cdot \int_{-d_r}^0 \cosh[k_i^* \cdot (z + d_p)] \cdot \cosh[k_j \cdot (z + d_p)] \cdot dz = \sum_{i=1}^{n_s} D_i^* \cdot \int_{-d_r}^0 \cosh[k_i \cdot (z + d_p)] \cdot \cosh[k_j \cdot (z + d_p)] \cdot dz \quad (P-3)$$

an $x = B/2$

$$\sum_{i=1}^{n_s} B_i \cdot \int_{-d_r}^0 \cosh[k_i \cdot (z + d_p)] \cdot \cosh[k_j^* \cdot (z + d_p)] \cdot dz + \sum_{i=1}^{n_s} C_i \cdot \int_{-d_r}^0 \cosh[k_i \cdot (z + d_p)] \cdot \cosh[k_j^* \cdot (z + d_p)] \cdot dz = \sum_{i=1}^{n_s} D_i \cdot \int_{-d_r}^0 \cosh[k_i \cdot (z + d_p)] \cdot \cosh[k_j^* \cdot (z + d_p)] \cdot dz \quad (P-4)$$

with:

$$A_{inc}^* = \frac{k_1 \cdot g \cdot \exp[i k_1 (x + B/2) \cdot \exp(-i \omega t)]}{\omega \cdot \cosh(k_1 d_p)} \cdot a_{inc}^* ; \quad A_{inc} = \frac{-i \cdot g \cdot \exp[i k_1 (x + B/2) \cdot \exp(-i \omega t)]}{\omega \cdot \cosh(k_1 d_p)} \cdot a_{inc} ;$$

$$A_i^* = \frac{k_i \cdot g \cdot \exp[i k_i (x + B/2) \cdot \exp(-i \omega t)]}{\omega \cdot \cosh(k_i d_p)} \cdot a_i^* ; \quad A_i = \frac{-i \cdot g \cdot \exp[i k_i (x + B/2) \cdot \exp(-i \omega t)]}{\omega \cdot \cosh(k_i d_p)} \cdot a_i ;$$

$$B_i^* = \frac{k_i^* \cdot g \cdot \exp[i k_i^* (x + B/2) \cdot \exp(-i \omega t)]}{\omega \cdot \cosh(k_i^* d_p)} \cdot b_i^* ; \quad B_i = \frac{-i \cdot g \cdot \exp[i k_i^* (x + B/2) \cdot \exp(-i \omega t)]}{\omega \cdot \cosh(k_i^* d_p)} \cdot b_i ;$$

$$C_i^* = \frac{k_i^* \cdot g \cdot \exp[i k_i^* (x - B/2) \cdot \exp(-i \omega t)]}{\omega \cdot \cosh(k_i^* d_p)} \cdot c_i^* ; \quad C_i = \frac{-i \cdot g \cdot \exp[i k_i^* (x - B/2) \cdot \exp(-i \omega t)]}{\omega \cdot \cosh(k_i^* d_p)} \cdot c_i ;$$

$$D_i^* = \frac{k_i \cdot g \cdot \exp[i k_i (x - B/2) \cdot \exp(-i \omega t)]}{\omega \cdot \cosh(k_i d_p)} \cdot d_i^* ; \quad D_i = \frac{-i \cdot g \cdot \exp[i k_i (x - B/2) \cdot \exp(-i \omega t)]}{\omega \cdot \cosh(k_i d_p)} \cdot d_i ;$$

$j = 1; 2; 3; \dots; n_s$

Plate 1. Resulting Equation System

Unlike KOETHER (2002) who needed a number of more than 120 evanescent waves to reach convergence, in the present study convergence was reached using less than ten evanescent waves (BLECK; 2003).

3.2. Consideration of Energy Losses

In the improved version of the model the different sources of energy loss will be accounted for. Thereby breaking and non-breaking waves will be treated separately because of the different sources of energy loss. For non-breaking waves the general flow resistance of the reef, the bottom friction (especially on top of the reef) and the energy loss due to vortex shedding at the edges of the reef has to be considered. For the breaking waves additional sources of energy loss are considered which are initiated by the breaking process. The phenomenological description of this local effects at the reef can be found in BLECK and OUMERACI (2002) or more detailed in BLECK (2003). In this paper only the numerical implementation will be described.

The general friction and the bottom friction are considered by introducing a reduction coefficient following the approach of KEULEGAN (1950 a and b). After a certain length of travel x the wave height and thereby the potential is reduced by:

$$\delta_{fric}(\Delta x, d, T) = \frac{\Phi(\Delta x)}{\Phi_0} = \frac{H(\Delta x)}{H_0} = \exp[(\alpha_1 + \alpha_2) \cdot \Delta x] \quad (11)$$

with:

$\alpha_1 = -k^3 \cdot \nu \cdot T$ - coefficient for internal friction [m^{-1}],

$\alpha_2 = -\frac{4 \cdot \pi^{2/3} \cdot (\nu \cdot T)^{0.5}}{L^2 \cdot (\sinh(2 \cdot k \cdot d) + 2 \cdot k \cdot d)}$ - coefficient for bottom friction [m^{-1}],

ν - kinematic viscosity [m^2/s], T - wave period [s], d - local water depth [m], L - local wave length [m] and $k = 2\pi/L$ - wave number [m^{-1}].

Using this coefficient the parameters $B_i^{(*)}$ and $C_i^{(*)}$ are reduced:

$$B_{i,v}^{(*)} = \delta_{fric}(x + B/2, d_r, T_i) \cdot B_i^{(*)} \quad (12)$$

and:

$$C_{i,v}^{(*)} = \delta_{fric}(x + B/2, d_r, T_i) \cdot C_i^{(*)} \quad (13)$$

with: x - spatial coordinate of the transfer condition [m].

Also the height of the incoming, reflected and transmitted wave are reduced according to Eq.11 depending on the distance between the wave gage and the reef front.

The energy loss due to vortex shedding is considered by using a theoretical approach for a skimming wall by STIASSNIE (1984) which is adapted for the

different geometry using the differences in the exact solutions for both geometries by URSELL (1947):

$$\frac{E_{vortex}}{E_i} = 1.75 \cdot \frac{(k \cdot H_i)^{2/3}}{\left[k \cdot d_r \cdot \left(K_0^2(k \cdot d_r) + \pi^2 \cdot I_0^2(k \cdot d_r) \right) \right]^{4/3}} \quad (14)$$

with: I_0 - modified Bessel function of the first kind zero order;

K_0 - modified Bessel function of the second kind zero order.

The relative decrease of wave energy (and velocity potential) derives as:

$$\delta_{vortex} = \frac{E_x}{E_i} = \frac{H_x^2}{H_i^2} \left(\propto \frac{\Phi_x^2}{\Phi_i^2} \right) = \frac{E_i - E_{vortex}}{E_i} = 1 - \frac{E_{vortex}}{E_i} \quad (15)$$

As these energy losses occur on the seaward and landward side of the reef they are accounted for by increasing the coefficients $A_i^{(*)}$ and $D_i^{(*)}$

$$A_{i,v}^{(*)} = \frac{A_i^{(*)}}{\delta_{vortex}} \quad (16)$$

and:

$$D_{i,v}^{(*)} = \frac{D_i^{(*)}}{\delta_{vortex}} \quad (17)$$

resulting in smaller wave heights or amplitudes a_i and d_i respectively needed to fulfill the matching conditions.

The flow resistance of the reef is implemented by calculating the force imposed on the reef by the moving water (BOLLRICH; 1996):

$$F_{reef} = \int_{-d_f}^{-d_r} c_w \cdot \rho_w \cdot \frac{v_x(z)^2}{2} \cdot dz \quad (18)$$

with: v_x - horizontal orbital velocity [m/s] and $c_w = 2,0$.

The dissipated energy equals the work done by this force:

$$E_{Force} = \int_{t_0}^{t_0+T} F_{reef} \cdot \overline{v_x(z)} \cdot dt \quad (19)$$

The relative reduction of wave energy follows as:

$$\delta_{Force} = \frac{E_i - E_{Force}}{E_i} = 1 - \frac{E_{Force}}{E_i} \quad (20)$$

This reduction is accounted for at the front end of the reef where the incident wave hits the reef. It is considered by manipulating again the coefficient $A_i^{(*)}$ as done to implement the energy dissipation due to the vortex shedding:

$$A_{i,v-tot}^{(*)} = \frac{A_{,ri}^{(*)}}{\delta_{Force}} \quad (21)$$

For breaking waves ($d_r/H_i < 1,51$; BLECK; 2003) these sources of energy loss still remain. In addition, the energy loss due to the breaking process has to be considered. Due to the supercritical flow during breaking the waves generated at the landward edge of the reef no longer influence the seaward edge (and matching condition). The coefficients $C_i^{(*)}$ therefore will be set to zero. The energy loss in the breaker tongue will be considered by an additional damping coefficient δ_b for the $B_i^{(*)}$:

$$B_{i,v,b}^{(*)} = \delta_b (x + B/2, d_r) \cdot B_{,ri}^{(*)} \quad (21)$$

with: x - spatial coordinate of transfer condition [m].

The waves generally break at the seaward edge of the reef. The wave height evolution can be computed (MUTTRAY et al.; 2001):

$$\delta_b = \frac{H(x)}{H_{crit}(x)} = p + (1-p) \cdot \exp\left(-0.15 \cdot \frac{\Delta x}{d(x)}\right) \quad (22)$$

with: p – reduction factor in infinite distance from breaking point [-],

$d(x)$ - spatial function of water depth [m], $H_{crit}(x)$ - spatial function of critical wave height [m], Δx - travel distance after breaking [m].

The critical wave height in this study has been evaluated as $H_{crit} = 0,66 d_r$ and the relative decrease p follows as:

$$p = 0.8 - H / L \quad (22)$$

4. Selected Results

The model performance can be shown by comparing computational results with the data from the model tests. A good correlation can be observed (Fig.3). In this section the usefulness of the model will be demonstrated by a parameter study. Starting with a representative set of parameter the governing parameters

will be varied separately before the entire results will be utilized to show the influence of dimensionless parameters.

Figure 3. Comparison of Analytical Model Results and Experimental Data

4.1. Parameter Study Using Basic Variables

Starting with a representative set of parameters ($H_s = 0.10\text{m}$; $T_p = 3.0\text{s}$; $d_f = 0.70\text{m}$; $h = 0.50\text{m}$ and $B = 1.00\text{m}$) the influence of all of these parameters can be shown (Fig4).

The transmission coefficient C_t decreases with increasing wave height (Fig.4 a). Also for decreasing water depth (Fig.4 b) and increasing reef height (Fig.4 c) less wave transmission is obtained which is consistent with the underlying physics. Looking at the influence of the reef length (Fig.4 d) the very well known cyclic behavior can be observed. Also a tendency of increasing energy loss with growing reef length is obvious. Concerning the variation of the wave period (Fig.4 e) one gets a longer wave with growing wave period. Thereby the

reef length becomes shorter in relation to the wave. Fig.4 e can therefore be seen as a part of Fig.4 d representing the first part of the curves.

Figure 4. Influence of Governing Parameters on the Calculated Results

4.2. Parameter Study Using Dimensionless Variables

Taking all results from Fig.4 and plotting the transmission coefficient as a function of the relative water depths d_r/H_i and d_r/d_f , the wave steepness H_i/L_i and the relative reef length B/L_i (Fig.5) no clear correlation can be observed. Solely a lower limit for the transmission coefficient can be evaluated having the same form than the functions for this coefficient derived from the results of physical model tests (BLECK and OUMERACI; 2001).

For the other parameters also no clear relationship could be established and the increased scatter for the water depth can be explained by the large number of data sets displayed. In physical model tests only a limited range of parameter variation is investigated which leads to clear functional relationships. An analytical model has the advantage of taking into account all the relevant influencing parameters and the associated physical processes.

Figure 5. Influence of Dimensionless Parameters on Analytical Model Results

5. Conclusions

Based on a potential flow model and the results of hydraulic model tests with flow visualization an improved analytical model incorporating all sources of energy loss has been developed and experimentally validated. The model can be used as a practical tool for the design of artificial reefs. This tool has a broader range of application than existing empirical design formulae and does not have the shortcoming of numerical models which are commonly used for this purpose.

The model has been described in its basic version for regular waves of first order. The extension to wave spectra can easily be made (BLECK; 2003). The extension to waves of higher order also seems possible. Further hints concerning the application to varying geometries and 3D-situations are also given by BLECK (2003).

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