RANDOM WAVE BREAKING MODELS - HISTORY AND DISCUSSION

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An overview is presented of thirty years of development of parametric models for energy dissipation due to depth-induced breaking of random waves, starting with Battjes and Janssen at the 16th ICCE in Hamburg, 1978. Particular emphasis is given to the models' behaviour on a slope near the waterline. Results are presented of an evaluation and intercomparison of overall model performance from deep to shallow water. Most models have approximately equal predictive skill, regardless of the various modifications aimed at improvement. Better parameterization of γ, the primary tunable model coefficient, which controls the probability of breaking and the energy level in shallow-water saturation, appears to offer room for improvement within the considered class of parametric models.

INTRODUCTION

Coastal wave evolution is affected by many linear and nonlinear physical processes. In the very nearshore zone, wave breaking has by far the largest impact on wave evolution, and plays a pivotal role in the dynamics of many other coastal processes such as sediment transport and coastal circulation. The complexity of breaker dynamics hampers a first-principle modeling approach in large-scale coastal wave and circulation models. Instead, parametric models have been developed, which do not resolve the micro scales but instead model the macro-scale effects of the wave breaking process in terms of the averaged loss of energy of the ordered wave motion.

To be more precise, the parametric models to be considered here allow the calculation of the phase-averaged rate of energy dissipation due to depth-induced breaking in a random wave train as a function of the local depth and local wave characteristics. Using this in an energy balance, possibly in combination with other sinks or sources, allows the calculation of the evolution of a wave field as it propagates shoreward in regions of variable depth.

The first model of this category was presented by Battjes and (Hans) Janssen (1978) (BJ78 hereafter). In the following, we present a brief resume of the BJ78 model and of the key modified versions of it that have been introduced later, viz. Thornton and Guza 1983 (which in turn has been modified by Whitford 1988), Baldock *et al.* 1998, and (Tim) Janssen 2006 (see also Janssen and Battjes 2007 and Alsina and Baldock 2007).

Validation studies of these models by the original authors, or independently thereof by others, have shown that their overall prediction capabilities are quite similar, provided appropriate parameter values are used (see Apotsos *et al.* 2008 for a recent evaluation and intercomparison).

An exception to the previous statement must be made for the behaviour very

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near the waterline on a sloping bed (beach), where the depth gradually approaches zero. As will be shown below, all models but the most recent one become internally inconsistent there, which from a fundamental point of view detracts from their value. For that reason, the present contribution concentrates on this aspect. It is however admitted that this is mainly of academic interest for a number of reasons: (1) in many applications, zero or near-zero depth does not occur; (2) if it occurs, other sinks such as bed friction easily prevent the inconsistency from arising; (3) the inconsistency, if it occurs, is usually confined to a narrow strip along the water's edge; (4) despite the model inconsistencies, the outcomes may still be realistic enough to be useful in practice (thanks to some *ad hoc* adaptations, see below), and (5), more fundamentally, very near the waterline the wave motion transforms into swash, for which a phase-averaged, linear description of waves in an average depth loses its validity.

Following a resume of the various models, with special emphasis on their behaviour near the waterline, an impression is given of their performance, for which we use results of Apotsos *et al.*, 2008. First, the energy balance is stated because it is used for the simulations with all the dissipation models.

ENERGY BALANCE

For one-dimensional propagation in the x-direction, in absence of sources and sinks other than breaking, and assuming a steady state on the time scale of several (periodic) waves or (random) wave groups, the energy balance can be written as

$$\frac{\mathrm{d}F}{\mathrm{d}x} + D = 0 \qquad (1)$$

in which F is the average wave energy flux per unit span and D the average rate of energy dissipation per unit area due to breaking. In the linear approximation, the flux can be expressed as

$$F = Ec_{\mathrm{g}} = \frac{1}{8}\rho g H_{\mathrm{rms}}{}^{2} c_{\mathrm{g}} \qquad (2)$$

in which E is the average wave energy per unit area, H_{rms} the root-mean-square wave height, and c_{g} the group velocity, which for given depth and wave frequency is determined by the linear dispersion relation.

The energy balance can be integrated simultaneously with the wave-averaged momentum balance so as to include wave-induced effects on the mean water level and flow field.

RESUME OF DISSIPATION MODELS

Battjes and Janssen (1978)

Model formulation. Following Le Méhauté (1962), BJ78 estimate the energy dissipation rate per unit span $(D_{\mathrm{b}}{}^{*})$ in a single (solitary) wave of height H_{b}, breaking in shallow water of mean depth h, after the well-known rate of dissipation in a bore or hydraulic jump, with the result

$$D_b^* \approx \frac{1}{4}\rho g H_b^3 \sqrt{\frac{g}{h}} \qquad (3)$$

In a sequence of periodic waves with frequency f and wavelength in shallow water given by

$$\lambda \approx f^{-1}\sqrt{gh} \qquad (4)$$

the mean dissipation rate per unit area due to breaking (D_b) becomes

$$D_b = \frac{D_b^*}{\lambda} \approx \frac{1}{4} f \rho g \frac{H_b^3}{h} \qquad (5)$$

The mean dissipation rate in breaking waves in a random wave sequence is obtained by averaging (5) over all waves that are breaking, denoted by <...>. Assuming that frequency and height are uncorrelated, this gives:

$$< D_b > \approx \frac{1}{4} \bar{f} \rho g \frac{< H_b^3 >}{h} \qquad (6)$$

in which $\bar{f}$ is the spectral mean frequency. Note that this is a conditional expression, applying only to the waves that are breaking. To find the rate averaged over all waves (D), the expression in the right-hand side should be multiplied with the probability (Q_b) that a wave drawn at random is breaking, in other words: with the fraction of breaking waves.

For lack of more exact information, BJ78 tentatively assumed that the heights of the breaking waves are narrowly distributed, all being of the same order of magnitude as the nominal height for incipient breaking of periodic waves of the same frequency and in the same depth, denoted by H_m, for which they used a Miche-type expression, which in shallow water reduces to

$$H_m = \gamma h \qquad (7)$$

This allows the approximations

$$< H_b^3 > / h \approx H_m^3 / h \approx H_m^2 \qquad (8)$$

Furthermore, the assumption of H_b being narrowly distributed around H_m allows the fraction of breaking waves (Q_b) to be estimated as the probability that the heights of all the waves, if these would be nonbreaking, would exceed the value H_m. Q_b can then be expressed in terms of the ratio of the (unknown) local rms wave height (H_{rms}) to H_m, representing a measure of saturation:

$$\frac{1-Q_b}{\ln Q_b^{-1}} = \left(\frac{H_{rms}}{H_m}\right)^2 \qquad (9)$$

According to this transcendental equation, Q_b varies in the physically relevant range from 0 to 1 as H_{rms}/H_m increases from 0 (deep water) to 1 (shallow-water saturation). [For later use we note that Eq. 9 admits solutions $Q_b > 1$ for $H_{rms}/H_m > 1$.]

Collecting these result gives the following final expression for the overall mean dissipation rate per unit area due to breaking, D:

$$D = Q_b < D_b > = \frac{\alpha}{4} Q_b \bar{f} \rho g H_m^2 \qquad (10)$$

in which α is a proportionality coefficient, which presumably is of order 1.

Eq. 10, together with Eq. 9, is the key result of the BJ78 model. Integrating the energy balance equation (Eq. 1) with this formulation for the dissipation rate D, the unknowns Q_b and H_{rms} are solved simultaneously. Q_b and therewith the dissipation responds to changes in depth through variations of H_m.

BJ78 show comparisons of this model, tentatively assuming $\alpha = 1$ and $\gamma = 0.8$ (no tuning), with wave height variations measured in a laboratory flume over a plane slope as well as over an idealized bar-trough profile, finding virtually no bias and relative errors on the order of 10%, which is not bad considering the complexity of the phenomenon and the simplicity of the model. A noteworthy feature is the very good model representation of the wave response over the bar-trough profile, showing concentration of dissipation over the bar and gradual cessation of dissipation in increasing depth shoreward of the bar. Similar satisfactory results with BJ78 have been reported elsewhere.

The parameters α and γ control the level of the dissipation in a breaker and the probability of breaking, respectively. Variations in their values can largely compensate each other so as to give approximately the same mean energy dissipation rate. From this point of view, the model has in essence only one free parameter. This was pointed out and utilized by Battjes and Stive (1985) in a calibration of BJ78 against an extensive set of lab and field data. Keeping $\alpha = 1$, they proposed an explicit parameterization of γ in terms of the deep-water steepness s_o, based on the rms wave height and the wave length corresponding to the peak frequency:

$$\gamma = 0.5 + 0.4 \tanh(33 s_o) \qquad (11)$$

The steepness ranged from 0.01 to 0.04, corresponding to a weak variation of γ between 0.6 and 0.8, approximately. This parameterization is based on best-fit results for the wave height variation only. At the time no data were available for the fraction of breaking waves. Tuning the model to both Q_b and H_{rms} may require independent variation of both α and γ.

Using a more extensive data set, Nairn (1990) modified this parameterization to

$$\gamma = 0.39 + 0.56 \tanh(33 s_o) \qquad (12)$$

Behaviour near the waterline. When integrating the energy balance (Eq. 1) in a region of diminishing depth, using the BJ78 dissipation, a point is reached in shallow water where $H_{rms} = H_m$ (saturation) and $Q_b = 1$. Continuing the integration shoreward from this point while adhering to Eq. 9 reasults in $H_{rms} > H_m$, i.e. oversaturation, which is acceptable, but also values of Q_b larger than 1, which is physically not realistic. In order to avoid this, BJ78 used *ad hoc* the local saturation values $H_{rms} = H_m$ from that point onward, which in essence amounts to a wave height decay in proportion to the depth. At the point of transition, a kink occurs in the cross-shore wave height profile. However, on gentle slopes this kink is weak and it occurs rather close to the waterline, so that in most of the domain the solution is smooth.

Although physically unrealistic, continuing shoreward integration of the energy balance equation while adhering to Eqs. 9 and 10 is algebraically possible. It yields a smooth solution everywhere, with oversaturation and $Q_b > 1$ shoreward of the point where Q_b first reaches the value 1. An example is given in Figure 1, showing the resulting cross-shore variation of H_{rms} on two plane slopes of 1: 20 (left panel) and 1:100 (right panel), respectively, for a mean frequency of 0.1 Hz and a deep-water rms wave height ($H_{rms,o}$) of 1 m. Here and in the following, the energy balance has been integrated using a 4^{th}-order Runge - Kutta scheme. The results of the *ad hoc* BJ78 saturation values in the final stretch ($H_{rms} = H_m$) are shown as well (dotted). For clarity, only the innermost cross-shore interval is presented, for depths $h < h_o = 10$ m. It can be seen that the solution for continued

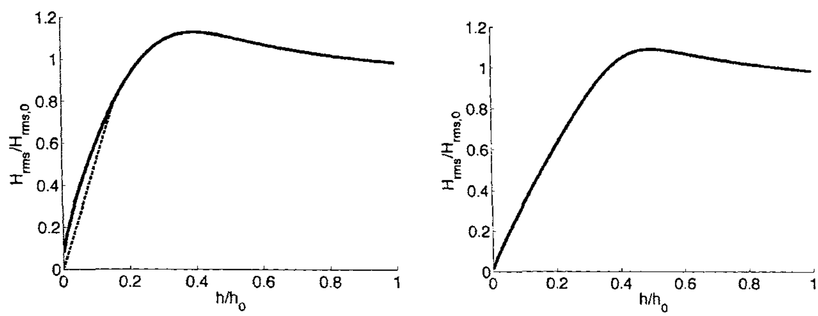

Figure 1. Normalized calculated H_{rms} vs. normalized depth. Drawn line: BJ78 with continued shoreward integration; dashed line: BJ78 set to saturation values shoreward of the point where this is reached first. Left panel: slope 1:20; right panel: slope 1:100.

shoreward integration is indeed smooth everywhere and converging to zero wave height at the waterline. The differences with the *ad hoc* saturation approximation are relatively minor, in fact not even visible on the milder slope of 1:100.

Thornton and Guza (1983)

Model formulation. For lack of observations, BJ78 tentatively assumed that the heights of waves breaking due to limited depth would be of the order of the nominal height for onset of breaking, H_m. This was approximated algebraically as a cut-off of the wave height distribution at $H = H_m$. Thornton and Guza (1983) (TG83 hereafter) observed in the field that despite the restricted depths the wave heights were approximately Rayleigh distributed, even in the surf zone, instead of showing an upper limit. Accordingly, they introduced a modification to BJ78 consisting of the use of a (non-clipped) Rayleigh probability density function (pdf) for all wave heights, with a weighting function $W(H)$ describing the fraction of the wave heights H associated with breaking waves and thus with dissipation. Consistent with the assumed unlimited range of H, the approximations (8) were not used. In this approach, the overall average dissipation rate D due to breaking becomes

$$D = \int_0^\infty D_b(H)W(H)p(H)dH \qquad (13)$$

in which $p(H)$ represents the Rayleigh pdf, and where D_b is given by the right hand side of Eq. 5, with H_b replaced by BH, in which B is a tuning coefficient, nominally related to the proportion of the foam region on the face of a breaker.

TG83 use two assumed forms for the weighting function $W(H)$, both increasing with the rms wave height-over-depth ratio. For brevity, both are here represented by a single expression:

$$W_{1,2}(H) = [1 - \exp(-(\frac{H}{\gamma h})^2)]^m (\frac{H_{rms}}{\gamma h})^n \qquad (14)$$

For W_1, $m = 0$, making W_1 independent of the wave height H, and $n = 4$. For W_2, $m = 1$, inducing wave height dependence, with the expression between brackets making a smooth transition from 0 to 1 as H increases from being much smaller than γh to much larger than γh, and $n = 2$. (TG83 do not assign *a priori* values to n, but in their elaborations the values given above are used.) W_2 is more realistic than W_1 because the probability of breaking according to W_2 increases with increasing wave height, and in fact compares (more) favorably with field data.

Substituting Eq. 14 in Eq. 13 and evaluating the integrals for both weighting functions separately gives the following results for the corresponding dissipation rates:

$$D_{1,2} = \frac{3\sqrt{\pi}B^3}{16} \frac{\bar{f}\rho g H_{rms}^{\ 3}}{h} [1 - (1 + (\frac{H_{rms}}{\gamma h})^2)^{-5/2}]^m (\frac{H_{rms}}{\gamma h})^n \qquad (15)$$

with $m = 0$, $n = 4$ for D_1 and $m = 1$, $n = 2$ for D_2.

The TG83 model contains in principle two adjustable coefficients (as does BJ78), B and γ. TG83 admit that these could have been combined into one coefficient but they prefer to keep them separate. They set γ at 0.42, based on analyses of field data by Thornton and Guza (1982) (Thornton, personal communication 2008). B is said to be the only free parameter in the model. Its optimal value for (apparently) the same set of field data is found to be about 1.5.

It is not clear from *a priori* reasoning, nor from the evidence presented, why variation should be allowed in B only and none in γ. Be this as it may, the model results were found in good agreement with observations, but it must be kept in mind that the model coefficients were based on the same data, which moreover were taken at one site.

For later reference, we mention Whitford (1988) (Wh88 hereafter), who – according to the quotation by Apotsos *et al.* (2008) - proposed a modification of the weighting function W_2 of TG83 consisting of the replacement of the factor $(H_{\mathrm{rms}}/\gamma h)^2$ in (14) by $[1+\tanh(8(H_{\mathrm{rms}}/\gamma h)-1)]$.

Behaviour near the waterline. Substituting D_1 into Eq. 1 and integrating in a region of decreasing depth, a point is reached in shallow water where H_{rms} starts to exceed H_{m} (oversaturation). Because of (14), this implies $W_1 > 0$ and $Q_{\mathrm{b}} > 1$, a behaviour not pointed out by TG83 (it has been noted before by Lippmann *et al.*, 1996). This unrealistic result can occur because TG83 multiply the entire wave height pdf with a factor which is intended not to exceed 1, but which in fact is allowed to do so.

As the waterline is approached, the wave height goes to zero according to $H_{\mathrm{rms}} \sim h^{9/10} \rightarrow 0$ as $h \rightarrow 0$. Similar results are obtained for W_2.

Although the results for the wave height variation may be reasonable even near the waterline, in that region the model is in fact used beyond its domain of validity because it is obviously impossible that more than 100% of the waves are breaking.

Baldock et al. (1998)

Model formulation. Baldock *et al.* (1998) (Ba98 hereafter) presented a variant aimed at improving the BJ78 model on steep slopes near the waterline. Like TG83, they use a full (non-clipped) Rayleigh distribution for all wave heights. In contrast to allowing both nonbreaking waves and breaking waves for each wave height class, they assume all waves with height $H < H_{\mathrm{m}}$ to be nonbreaking, and those with $H > H_{\mathrm{m}}$ to be breaking. This implies that Q_{b} equals the probability that the wave height will exceed H_{m}; with this definition, Q_{b} cannot exceed 1.

In their further elaboration, Ba98 use the approximation $H_{\mathrm{b}}^3/h \approx H_{\mathrm{b}}^2$ in (5). On these assumptions, the dissipation rate D is evaluated from

$$D = \frac{B}{4} f_{\mathrm{p}} \rho g \int_{H_{\mathrm{m}}}^{\infty} H^2 p(H) dH \qquad (16)$$

which yields

$$D = \frac{B}{4} f_{\mathrm{p}} \rho g \exp[-(\frac{H_{\mathrm{m}}}{H_{\mathrm{rms}}})^2](H_{\mathrm{m}}^2 + H_{\mathrm{rms}}^2) \qquad (17)$$

in which B is an adjustable parameter of order one and f_p is the peak frequency. In their simulations, Ba98 use $B = 1$ and the parameterization of γ presented by Nairn (1990), given in Eq. 12.

With these parameter values, the model predictions are found to be in good agreement with observations on a 1:10 slope. In the region near the waterline, the performance is better than that of BJ78 (with the *ad hoc* saturation recipe near the waterline). On gentler slopes, not tested by Ba98, the differences are smaller.

Using the Ba98 model, Ruessink *et al.* (2003) applied inverse modelling to a set of data on the barred beach at Duck, North Carolina, to obtain point values of γ in a cross-shore transect (commonly, γ is held constant across-shore). They noted a dependence on local depth, which they parameterized as

$$\gamma = 0.76\,kh + 0.29 \tag{18}$$

in which k is the local wave number "of the representative period." The range of kh was from about 0.3 to 0.7, and that of γ from about 0.5 to 0.8. Verification of this result against independent data on barred beaches showed a significant improvement in predictive skill as compared to BJ78 combined with the γ-parameterization (11) by Battjes and Stive (1985).

Despite this apparent improvement, the model Ba98 suffers from a conceptual shortcoming, as first pointed out by Janssen (2006): the approximation $H_b^{\,3} / h \approx H_b^{\,2}$ is inconsistent with the assumed unlimited range of possible breaking wave heights, implied by the use of a Rayleigh distribution without cut-off. Note that the approximation (8) by BJ78 is consistent with their assumption that all breaking-wave heights are comparable to H_m.

Behaviour near the waterline. A result of the inconsistency noted above, also first pointed out by Janssen (2006), is that the dissipation in waves shoaling in very shallow water cannot cope with the wave enhancement due to shoaling (Green's law), causing the wave heights to diverge in a very narrow zone near the waterline. This effect is neither noted by Ba98 nor visible in their plots.

Janssen (2006)

Model formulation. Janssen (2006) developed an improved model, based on Ba98, by removing the inconsistency in that model noted above, i.e. by replacing H^2 in Eq. 16 by H^3/h. He used the same wave height distribution as Ba98. The dissipation rate then becomes

$$D = \frac{B}{4}\frac{\bar{f}\rho g}{h}\int_{H_m}^{\infty} H^3 p(H)\,dH$$

$$= \frac{3\sqrt{\pi}B}{16}\frac{\overline{f}\rho g H_{rms}^{3}}{h}[1+\frac{4}{3\sqrt{\pi}}(R^3+\frac{3}{2}R)\exp(-R^2)-\mathrm{erf}(R)] \qquad (19)$$

in which $R = H_m/H_{rms}$ and erf(..) is the error function.

A literature source for this model which is more widely available than the Janssen 2006 doctoral thesis is Janssen and Battjes (2007), for which reason we will use this as the reference for this model (JB07 hereafter).

Exactly the same model has been presented independently by Alsina and Baldock (2007), after having been notified by Janssen that the Ba98 model diverges as the waterline is approached.

Behaviour near the waterline. The JB07 model is well-behaved near the waterline, i.e. $Q_b \rightarrow 1$ and $H_{rms} \sim h^{1/2} \rightarrow 0$ as $h \rightarrow 0$. It appears that using a dissipation proportional to the third power of the wave height instead of the second (retaining H_b^3/h instead of reducing it to H_b^2) is sufficient to remove the nearshore singularity. This yields a physically realistic solution that is internally consistent and uniformly valid from deep water to the waterline, as illustrated in Figure 2, showing results of the two models Ba98 and JB07 for the same conditions as in Figure 1, again in the innermost region only. For the 1:20 slope, the divergence near the waterline in Ba 98 is clearly visible. On the 1:100 slope the divergence occurs even closer to the waterline. The resolution is not enough to show it.

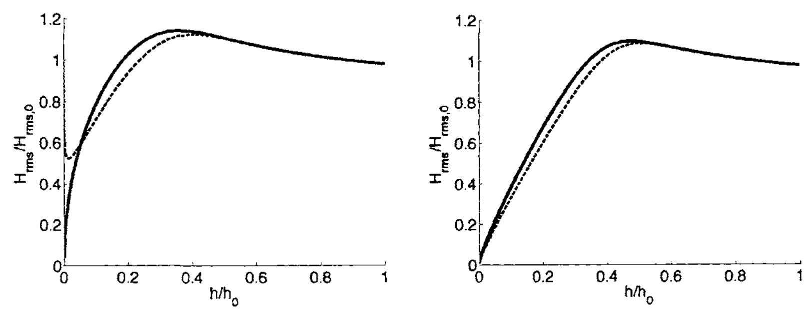

Figure 2. Normalized calculated H_{rms} vs. normalized depth; drawn line: JB07; dashed line: Ba98. Left panel: slope 1:20. Right panel: slope 1:100.

EVALUATION AND INTERCOMPARISON OF MODEL PERFORMANCE

Apotsos *et al.* (2008) present an extensive evaluation and intercomparison of parametric wave energy dissipation models for various combinations of basic model and parameter values. In addition to those described above, they considered the model by Lippmann *et al.* (1996) (Li96 hereafter), who exploit the roller concept to estimate the energy dissipation in breaking waves. Interestingly, their result is almost identical to the classical bore-based expression of Eq. 5. The TG83 distribution of breaking-wave heights is used, with the original weighting function

W_2 and its modification proposed by Whitford (1988). However, in their model comparisons Apotsos *et al.* use only the latter variant of Li96.

Below we present some results of Apotsos *et al.* to give an impression of the relative performance of the various models.

Apotsos *et al.* held α and B constant at 1, and used three modes of evaluation of the models with respect to the parameter γ: (1) a so-called default mode, using the constants or parameterizations as originally proposed or used by the respective authors, (2) a best-fit mode, in which for each model the best-fit γ was estimated for each combination of wave field and site ("run" hereafter) separately, and (3) a newly derived parameterization of γ in terms of the deep-water wave height, having the same form for all models and model-specific coefficients, the same for all runs. In this parameterization, γ is expressed in terms of the deep-water wave height H_o as

$$\gamma = a + b\tanh(cH_o) \tag{20}$$

For each model considered by Apotsos *et al.*, they present one set of numerical values of the calibration coefficients a, b and c. Note that this parameterization is not dimensionally homogeneous, which detracts from its value and limits its range of applicability.

Data were used from various field measurement campaigns on barred and unbarred beaches at three different field sites, two at the Dutch North Sea coast (Egmont and Terschelling), one at the US East coast (Duck) and one at the US West coast (La Jolla). For each combination of model and "run", errors in calculated local H_{rms} were expressed as a percentage of the local observed value, and the rms value of these errors was determined by weighted averaging over the sensors in the cross-shore profile. For each model and each site, the ensemble of runs yields an ensemble of rms errors, of which the 50% quantiles (median) were determined and presented, for each of the three modes defined above. (For the default mode, the 5% and the 95 % quantiles are given as well.)

Table 1 presents a condensed version of these results, viz. for each model the median rms % error averaged over all the sites, for each of the three modes of comparison. The models are placed in chronological order. The second row shows which value or parameterization of γ was used in the default mode (where applicable): BS stands for the one by Battjes and Stive (Eq. 11), Na for the one by

Table 1. Site-averaged median rms % errors in H_{rms}, from Apotsos *et al.* (2008). Mode 1: default; mode 2: best fit; mode 3: $\gamma - H_o$ parameterization

Model	BJ78		TG83	Wh88	Li96	Ba98		JB07
γ	BS	Na	0.42	0.34	0.32	Na	Ru	(Na)
Mode 1	14.3	12.3	15.0	15.3	14.5	13.2	14.7	(16.7)
Mode 2	7.0		7.2	9.5	8.3	7.0		6.8
Mode 3	12.0		11.3	15.5	15.0	12.5		12.0

Nairn (Eq. 12), and Ru for the one by Ruessink *et al.* (Eq. 18). The reference to Nairn for JB07 and the corresponding error are placed in parentheses because JB07 do not in fact propose a default parameterization, although they did use Nairn (Eq. 12) in their example calculations, following Ba98.

Needless to say, the lowest errors occur for the best-fit mode (2), which is expected because it results from fitting rather than prediction. The significant difference in performance compared with the predictive modes (1) and (3) indicates that there is room for improvement of these models in a better γ-parameterization.

A second point to note in Table 1 is the mutually comparable performance of all model variants except Wh88 and Li96. A comparable model performance is also present in the underlying data per site: none of the models performs best at all sites or for all records (Apotsos *et al.*, 2008).

DISCUSSION

A striking feature in the above resume and evaluation is the robustness of the basic model, both with respect to the range of conditions for which it performs rather well (lab & field, non-barred beaches & beaches with one or multiple bars), and with respect to its insensitivity to the various modifications that have been proposed, which in the main have not changed the predictive capability significantly through the years.

The relatively good performance of the basic model and its modifications, despite its conceptual simplicity when projected against the complexity of the physical processes, implies that the essence of the macroscopic effects of these processes has been successfully captured.

The model insensitivity to modifications can be understood from the common use of two principal model components: on the one hand, all models considered here estimate the energy dissipation in breaking waves in like manner from the analogy with a bore or hydraulic jump (it can be argued that this also holds in essence for the roller-based model by Lippmann *et al.* (1996), which in fact is a model for the internal dynamics of a bore), and on the other hand they all estimate the probability of breaking on the basis of a Rayleigh distribution for the random wave heights.

At first sight, the details of the height distributions for breaking waves differ significantly between the models, but in one way or another they all use a weighted average of the upper tail of a Rayleigh pdf. This leads to nearly similar functional dependencies (exponents), although with different numerical factors. That is also why each model has its own optimal γ-values, which for the same conditions may be quite different between various models. It is therefore futile to attempt to arrive at optimal γ-values that would be common to all these models. Likewise, it is meaningless to compare values of the model - γ's to observed wave height-over-depth ratios, or to use the latter to estimate *a priori* values of a model γ.

For a look to the future, one can wonder, both from a scientific and a practical point of view, whether significant improvements in predictive capability of these or other types of models can be expected for the processes considered.

The significant difference in model performance between best-fit and predictive modes (Table 1), in combination with the insensitivity of the present class of models to modifications, suggests that improvements within this class of models must primarily be sought in improved parameterizations of the model coefficients. In this respect it is noted that allowing variation both in γ and in α or B will give more degrees of freedom, which in principle can result in better fits, albeit at the expense of more intricate parameter estimation procedures and less robustness in the end.

Another option, in part already available, is the use of more detailed, phase-resolving models, such as Boussinesq models or even VOF and similar models. However, for routine applications to large areas the latter are prohibitively demanding in computer memory and CPU time. Boussinesq models offer a more attractive balance between effort and result in applications for which parametric models are deemed inadequate.

CONCLUSIONS

Based on the overview and evaluation of the class of parametric models for energy dissipation due to depth-induced breaking of random waves presented above, the following conclusions are drawn.

From an algebraic point of view, the *ad hoc* assumption by Battjes and Janssen (1978) of saturation in the region near the waterline can be replaced by continued shoreward integration. This yields a smooth solution everywhere, although at the expense of physically unrealistic values of the fraction of breaking waves (exceeding 100%).

A similar physically unrealistic result occurs in the continued shoreward integration of the model by Thornton and Guza (1983).

The model by Baldock *et al.* (1998) is internally inconsistent, and its solution for the wave height diverges as the waterline is approached.

For waves on beaches, the new dissipation model by Janssen (2006) (see Janssen and Battjes, 2007) is the only model in the class of models considered here that is internally consistent from deep water to the waterline.

Most models within the class considered perform about equally well. They are rather insensitive to modifications, even though the latter appear to be improvements of the representation of the underlying physical processes.

There may be room for improvement of the models considered here in improved parameterizations of the breaker proportionality coefficient γ, possibly in combination with parameterized variations of the coefficient of proportionality in the expression for the dissipation rate, α or B.

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