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Improved representation of breaking wave energy dissipation in parametric wave transformation models

J.M. Alsina [1], T.E. Baldock *

Department of Civil Engineering, University of Queensland, Brisbane, Qld 4072, Australia

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Abstract

An improved formulation to describe breaking wave energy dissipation is presented and incorporated into a previous parametric cross-shore wave transformation model [Baldock, T.E., Holmes, P., Bunker, S., Van Weert, P., 1998. Cross-shore hydrodynamics within an unsaturated surf zone. Coastal Engineering 34, 173–196]. The new formulation accounts for a term in the bore dissipation equation neglected in some previous modelling, but which is shown to be important in the inner surf zone. The only free model parameter remains the choice of γ, the ratio of wave height to water depth at initial breaking, and a well-established standard parameter is used for all model runs. The proposed model is compared to three sets of experimental data and a previous version of the model which was extensively calibrated against field and laboratory data. The model is also compared to the widely used model presented by Thornton and Guza (1983) [Thornton, E.B., Guza, R.T., 1983. Transformation of wave height distribution. Journal of Geophysical Research 88 (No.C10), 5925–5938].

The new formulation leads to an important improvement in predicting wave height condition close to the shoreline in non-saturated surf zone conditions. The approach overcomes a problem in the original model, where amplification by shoaling could exceed energy dissipation by breaking in very shallow water, i.e. approaching the swash zone. In dissipative conditions an improvement is also noticeable. Of the four models considered, the new model gives the smallest error between predicted and measured wave heights for all three data sets presented.

Keywords: Wave transformation; Wave breaking; Unsaturated surf zone hydrodynamics; Swash zone boundary conditions; Energy dissipation; Parametric modelling

1. Introduction

Parametric wave propagation models are commonly used to predict wave properties in a broad range of coastal area problems. Their success is based on their simplicity and relatively high accuracy, which ranges between 10–20% after parameter fitting (Ruessink et al., 2003; van Rijn et al., 2003). This accuracy is sufficient for many coastal engineering applications. However, wave propagation models are also very often the first step to compute other hydro-morphodynamic variables, including wave set-up, wave-induced currents, swash zone boundary conditions (Guard and Baldock, 2007) and sediment transport, and errors in the wave transformation model may propagate in the computation scheme (de Vriend et al., 1993). Therefore, error reduction in computing wave propagation is an important issue.

Following the pioneering model of Battjes and Janssen (1978), hereafter BJ78, Thornton and Guza (1983) proposed a more advanced model by multiplying the energy dissipation for a breaking wave by the probability of that wave occurring and integrated over an empirical breaking wave probability density function derived from field data. Baldock et al. (1998) (hereafter B98) followed a similar approach and developed a model for wave transformation in non-saturated (i.e. not depth-limited) surf zone conditions, where a significant proportion of the incident wave energy remains at the shoreline in the form of short wave bores. They proposed a parametric model based on a full Rayleigh wave height distribution for breaking waves, which improved prediction of wave height close to the shoreline. For this purpose, Ruessink et al. (2003), hereafter R03, calibrated the B98 model against numerous laboratory and field data. R03 found that the model could be improved further, replacing the usual wave height to water depth ratio at the point

* Corresponding author. Tel.: +61 07 336 54170; fax: +61 07 336 54599.
E-mail addresses: josealsina@uq.edu.au (J.M. Alsina), t.baldock@uq.edu.au (T.E. Baldock).
[1] Tel.: +61 07 336 54170; fax: +61 07 336 54599.

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of initial breaking, γ, with an empirical free model parameter (here denoted by γ_{free}) obtained and optimised by inverse modelling. R03 found that the γ_{free} decreased in shallow water, which in the model represents greater energy dissipation for the same wave height and fraction of broken waves.

The aim of this study is to remove this additional empiricism from the model; firstly, to better describe the physics, and secondly, so that the model may be applied for conditions outside of those for which γ_{free} was determined by R03. The B98 model has been reformulated based on the theoretical developments first proposed by BJ78 using the turbulent bore dissipation model proposed by Le Méhauthé (1962). The suggested modification provides a better wave height prediction in the inner surf zone for a range of laboratory experiments data. Quantitative error analysis also indicates that the new model provides a better overall prediction of the data than the R03 calibration.

2. Parametric surf zone modelling

The wave transformation is modelled using the energy flux equation,

$$\frac{\partial E_{fx}}{\partial x} = -D \tag{1}$$

where E_{fx} is the energy flux and is assumed to be equal to EC_g, E is the wave energy and C_g is the group velocity given by:

$$E = \frac{1}{8}\rho g H\mathrm{rms}^2 \tag{2}$$

$$C_g = C\frac{1}{2}\left(1 + \frac{2kh}{\sinh 2kh}\right)\cos\theta \tag{3}$$

where C is the wave phase velocity, ρ is the water density and g is gravitational acceleration, k the wave number, h the water depth and θ is the incident wave angle. D represents a time averaged wave energy dissipation term which takes into account energy losses due to wave breaking and friction. Wave friction in the surf zone is reported as a relatively minor dissipation term compared to breaking dissipation and is consequently neglected here. Wave reflection is also neglected, since reflection analyses over sloping bathymetry (Baldock and Simmonds, 1999) indicates that the reflected short wave energy is likely to be less than about 5% of the incident short wave energy for typical Iribarren numbers.

For a single breaking wave the energy dissipation is estimated from the bore dissipation (Le Méhauthé, 1962; Battjes and Janssen, 1978) given by:

$$D = \frac{1}{4}\rho g f_p B\frac{H^3}{h} \tag{4}$$

where f_p is the peak frequency and B is a fitting parameter taken equal to 1. In an irregular wave field, the overall dissipation term can be computed multiplying (Eq. (4)) by the number of waves breaking over the total number of waves in the wave field.

BJ78 used Eq. (4) assuming that the relationship H / h is close to 1 in the surf zone. Furthermore, they obtained an implicit equation for the fraction of waves breaking, Q_b, assuming a clipped Rayleigh probability distribution function (pdf) truncated at the maximum wave height H_b. Therefore in the surf zone when $H_{rms} \rightarrow H_b$; $Q_b = 1$ (i.e. saturated surf conditions).

Thornton and Guza (1983), hereafter TG83, proposed an empirical pdf for the breaking waves with a weighted Rayleigh distribution based on field data from Torrey Pines beach. They obtained the total energy dissipation in the wave field by integrating (Eq. (4)) over the proposed pdf. B98 followed the TG83 approach, but replaced the truncated Rayleigh pdf in BJ78 and the empirical pdf in TG83 with a full Rayleigh distribution and abandoned the depth limiting constraint in the inner surf zone. This approach is supported by several laboratory and field observations (e.g. Thornton and Guza, 1983). The Rayleigh wave height pdf is:

$$p\left(\frac{H}{H_{rms}}\right) = 2\frac{H}{H_{rms}}\exp\left[-\left(\frac{H}{H_{rms}}\right)^2\right]. \tag{5}$$

Therefore, given a breaking wave height H_b, the fraction of broken waves is found by integration of the Rayleigh distribution over all waves for which $H / H_{rms} \geq H_b / H_{rms}$. Following BJ78, B98 used Eq. (4) assuming that the relationship H / h is close to 1 in the surf zone, which gives a simple explicit equation for the total energy dissipation in B98 and an analytical expression for the fraction of broken waves, Q_b, see B98 for details.

$$Q_b = \exp\left[-\left(\frac{H_b}{H_{rms}}\right)^2\right]. \tag{6}$$

The maximum wave height prior to breaking is obtained by

$$H_b = \frac{0.88}{k}\tanh\left(\gamma\frac{kh}{0.88}\right) \tag{7}$$

where γ is the only free parameter in the model. Several expressions exist to compute γ, with perhaps the most widely used that due to Battjes and Stive (1985):

$$\gamma = 0.5 + 0.4\tanh(33S_0) \tag{8}$$

where S_0 is the deep water wave steepness (H_0 / L_0).

Using the B98 model, R03 found that it was necessary to decrease γ_{free} in shallow water to obtain optimum fit to a large range of measured data, and this is equivalent to increasing the dissipation rate in the model. Recently, Apotsos et al. (2007) compared a number of wave models to an extensive surf zone wave height data set and found that B98 provided the most accurate predictions of the unfitted wave models (i.e. when model parameters were not optimised for each model run).

While good overall wave height predictions have been obtained using the original B98 model, some significant errors have been identified when simulating wave heights after wave breaking over a bar (Ruessink et al., 2001) and in areas close to the inner surf zone on steep beaches (Baldock et al., 1998). BJ78 found that their model underestimated the dissipation in the inner surf zone and applied depth-limited conditions, i.e. forcing $H_{\mathrm{rms}} = \gamma d$. T. T. Janssen (pers. comm.) noted a similar problem in B98, where for certain conditions the energy dissipation was insufficient compared to the influence of shoaling, and this prompted the present re-evaluation of the dissipation function in the model.

3. New dissipation term formulation

The overall approach follows the B98 model but the original formulation for the energy dissipation is retained, Eq. (4), i.e. assuming that H / h is not equal to 1. Indeed, field and laboratory data show that this is often not the case close to the shoreline (e.g. Raubenheimer et al., 1996). TG83 also retained H^3 / h in Eq. (4), but integrated over their empirical breaking wave pdf obtained from Torrey Pines beach, which was gently sloping and had no longshore bar.

Therefore, following TG83 and B98, the total energy dissipation rate can be obtained by integrating the product of Eqs. (4) and (5):

$$D = A\int_{H*}^{\infty}\frac{H^3}{h}p\left(\frac{H}{H_{\mathrm{rms}}}\right)d\left(\frac{H}{H_{\mathrm{rms}}}\right) \tag{9}$$

where A is given by:

$$A = \frac{1}{4}\rho g f_{\mathrm{p}} B. \tag{10}$$

Analytical integration of Eq. (9) gives:

$$D = A\frac{H_{\mathrm{rms}}^3}{h}\left[\left(\left(\frac{H_{\mathrm{b}}}{H_{\mathrm{rms}}}\right)^3+\frac{3}{2}\frac{H_{\mathrm{b}}}{H_{\mathrm{rms}}}\right)\cdot\exp\left(-\left(\frac{H_{\mathrm{b}}}{H_{\mathrm{rms}}}\right)^2\right) + \frac{3}{4}\sqrt{\pi}\left(1-\mathrm{erf}\left(\frac{H_{\mathrm{b}}}{H_{\mathrm{rms}}}\right)\right)\right] \tag{11}$$

where erf represents the error function (also called the Gauss error function). Independently of this study, Janssen and Battjes (in press) have also obtained Eq. (11) following the B98 approach. Many expressions are available to evaluate the error function, together with several numerical routines (e.g. Cody, 1993) and it is a standard function in many software programs. Eq. (1) is then integrated numerically using the breaking dissipation rate given in Eq. (11). Eqs. (7) and (8) are used to estimate the maximum wave height prior to wave breaking.

Wave height propagation is computed up to the most seaward run-down position, locations further landward are considered to be the swash zone, where the model physics are invalid. The maximum run-down is estimated using the Hunt (1959) formulation:

$$R_{\mathrm{u}} = K\beta\sqrt{H_0 L_0} \tag{12}$$

where R_{u} is the run-up vertical elevation above the offshore mean water level (MWL), K is a calibration constant specified between 0.7–0.8 (e.g. Stockdon et al., 2006) and β is the beach slope. Using the random wave data presented below, the run-down elevation below the MWL is estimated as 0.15 R_{u}.

4. Results

Wave transformation simulations using the present dissipation formulation and the original B98 model are presented in Fig. 1. Simulations are performed for two different beach slopes; 1:10 and 1:50. Wave height, bathymetry and the H_{rms} / h relationship are presented. It is apparent that the previously simplified term H^3 / h becomes important in shallow water, and that including this term gives significantly greater energy dissipation on steep beaches, where waves approach close to the shore before dissipating most of their energy.

To validate the model more fully and to quantify model errors, the new model, and the B98 and R03 models are compared to a set of different data from high and low energy conditions from a large wave flume facility obtained during the LIP-11 experiments (Sánchez-Arcilla et al., 1994), barred beach laboratory experiments (Baldock et al., 2004) and non-saturated plane beach conditions (B98). Following comments in the review process, comparisons are also made to the TG83 model. The TG83 model is based on Eqs. (21) and (26) in the original paper, with the free parameters γ and B set equal to 0.42 and 0.8 respectively. $B = 0.8$ provides the best fit to the data presented here. The experimental conditions are given in Table 1. In all experiments, the measured set up has been included in the input water depths to minimize errors due to using a computed mean water level, and to be consistent with R03. Mean water level prediction is beyond the scope of the present study.

The cross-shore distribution of wave height and fraction of broken waves for non-saturated conditions (case J2) are shown in Fig. 2. It is clear that B98 and R03 do not provide enough dissipation in the very inner surf zone while at the same time over-estimating the fraction of broken waves. These errors are significant when accurate wave height prediction is required in

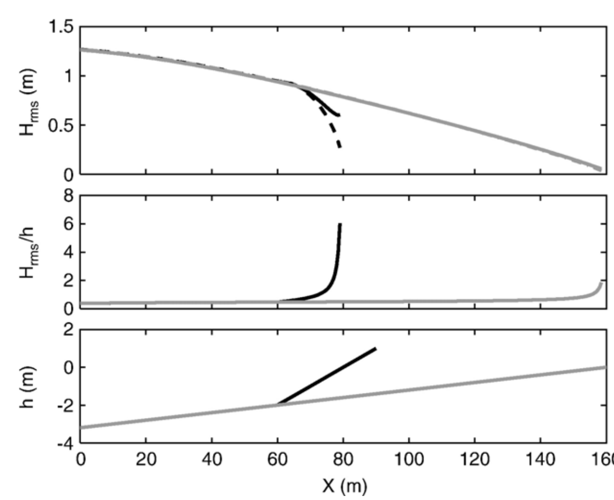

Fig. 1. Modelled cross-shore distribution of wave height (top) and H_{rms}/h (middle) for 1:10 (black lines), and 1:50 (grey lines) beach slopes. Dashed line — present model; Solid line — B98 model.

Table 1
Experimental data sets

Data set	Case	H_{rms0} (cm)	T_p (s)	H_{rms0}/L_0	Surf similarity, ζ
LIP 11	Test1a	90	5.0	0.032	0.15
	Test1b	140	5.0	0.047	0.14
	Test1c	60	8.0	0.012	0.31
Baldock et al. (1998)	J2	7.4	1.5	0.036	0.61
	J3	4.6	1.0	0.035	0.57
Baldock et al. (2004)	J6033A	10	1.67	0.038	0.61
	J6033B	7.5	1.67	0.031	0.71
	J6033C	5	1.67	0.021	0.87

the inner surf zone. The new formulation gives a better representation of both height and Q_b distribution at these locations.

Wave height predictions and bathymetry corresponding to the LIP-11 data set are shown in Fig. 3. While all the models underestimate the wave height, for these data B98 performs better than R03 and the present model again shows the best comparisons, although the improvement is relatively minor. Model-data comparisons for the barred beach data are presented in Fig. 4. B98, R03 and the present model tend to over-predict the wave height on the offshore face of the bar. This may be a result of the influence of breakpoint generated surf beat (Baldock et al., 2000) offshore of the bar in the experimental data, and which is neglected in the models. This is consistent with Baldock and O'Hare (2004), who show that the presence of free long waves tends to reduce the short wave energy in the surf zone. TG83, on the other hand, gives a good prediction close to the breaking point but does not perform well when modelling wave re-formation in the bar trough, under predicting the wave height. Overall all the models give a good fit to data. The present model and R03 perform almost equally, and it should be noted that the calibration of R03 focused particularly on barred beach data.

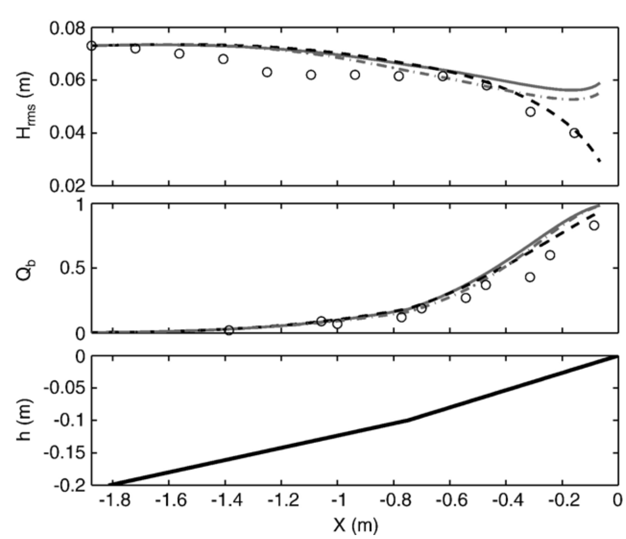

Fig. 2. Measured and modelled cross-shore distribution of wave height (top) and fraction of broken waves (middle), plus bathymetry (bottom) for case J2. Circles — measured data; solid grey line — B98 model; dash-dotted grey line — R03 model; dashed black line — present model.

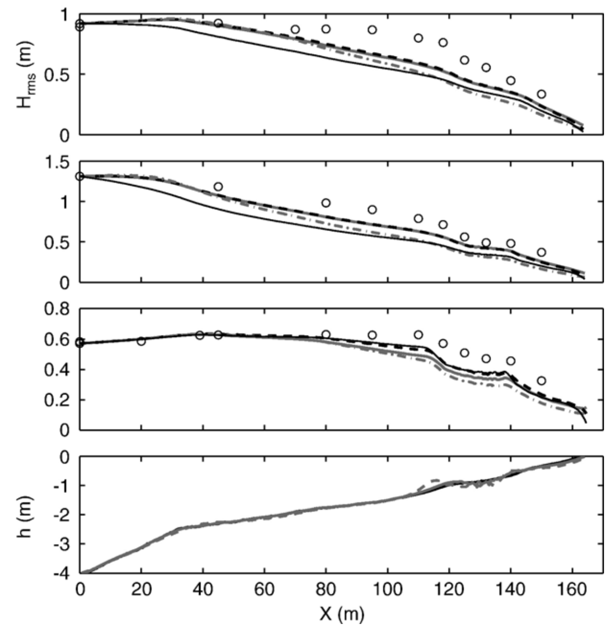

Fig. 3. Cross-shore distribution of measured and predicted wave height for LIP-11 experiments, top: test 1a, 2nd panel: test 1b, third panel test 1c. Bathymetry (bottom panel), black solid line — test 1a; grey solid line — test 1b; dashed grey line — test 1c. Circles — measured data; solid grey line — B98 model; dash-dotted grey line — R03 model; black solid line — TG83 model; dashed black line — present model.

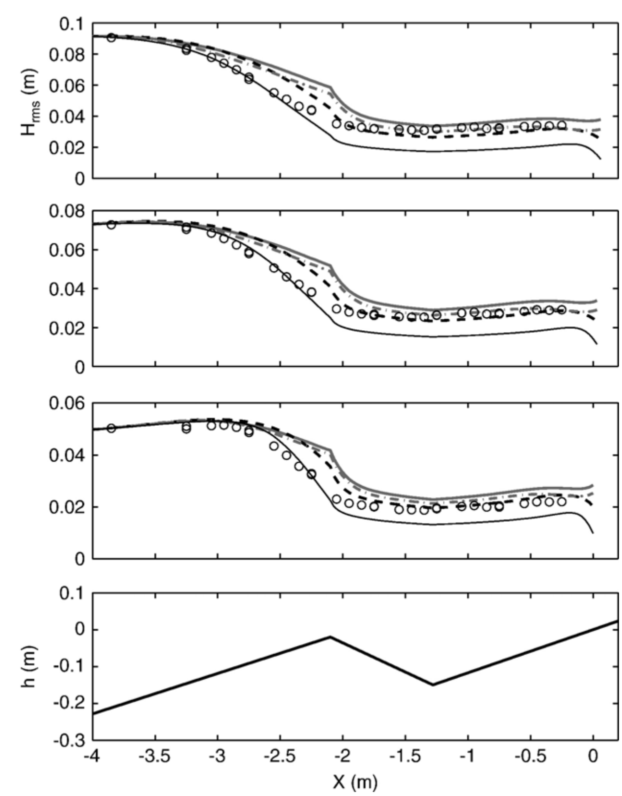

Fig. 4. Cross-shore distribution of measured and predicted wave height for barred beach experiments. Top panel — test J6033a; 2nd panel — test J6033b; 3rd panel — test J6033c; bottom panel — bathymetry. Circles — measured data; solid grey line — B98 model; dash-dotted grey line — R03 model; black solid line — TG83 model; dashed black line — present model.

Table 2
Computed root mean square relative errors for the model runs in Table 1

	TG83	B98	R03	Present model
Lip 11D				
Test1a	19.9	13.5	18.5	12.7
Test1b	16	8.8	15.3	8.8
Test1c	9.3	13.2	16.5	10
Baldock et al. (2004)				
J6033A	8.3	7.6	4.7	5.4
J6033B	8.8	9.0	5.7	5.4
J6033C	7.7	10.6	8.1	6.3
Baldock et al. (2004)				
J2	8.2	8.6	6.7	6.2
J3	8.3	5.6	5.6	6.0
Overall mean	12.3	9.6	10.1	7.6

Finally, Table 2 provides a quantitative assessment of the relative performance of the models. For each model run, root mean square error is calculated using H_{rms} made dimensionless with initial wave height (H_{rms0}); therefore the error is expressed as the percentage error in estimating the wave height with respect to the initial height. The error (ε) is expressed as:

$$\varepsilon = \frac{1}{N}\frac{\sum\sqrt{\left(H_{\mathrm{comp}} - H_{\mathrm{meas}}\right)^2}}{H_0} \tag{13}$$

in which N is the total number of data points, H_0 is the initial wave height and H_{comp} and H_{meas} are the computed and measured wave heights, respectively. The new model performs better than B98 and TG83 in all cases except one, and considerably better overall. The new model performs significantly better than R03 for the LIP-11 data, and results in the smallest error over all the data sets. Therefore, for these data overall, retaining the H^3 / h term in the bore dissipation model provides an improved wave transformation model applicable in very shallow water without the need for the empirical and variable parameter γ_{free}.

5. Conclusions

Breaking wave dissipation in parametric random wave transformation models has been revisited. For some cases, particularly on steep beaches in non-saturated surf zone conditions, the widely used breaking dissipation model adopted by Battjes and Janssen (1978), Baldock et al. (1998) and Ruessink et al. (2003) may underestimate the energy dissipation, and wave heights are over-predicted as a result of continued wave shoaling. A new model is proposed, within which the influence of the wave height over water depth ratio is retained in the energy dissipation formulation for a single bore. This is integrated using a Rayleigh probability density function to provide a new formulation for the total breaking wave energy dissipation rate in a non-saturated random wave field. The model is compared to a range of laboratory data, the original model of Baldock et al. (1998) and the models of Thornton and Guza (1983) and Ruessink et al. (2003). The latter was extensively calibrated using a large field and laboratory data set. Overall, the new model provides an improvement over all three previous models without the need for further empirical parameters.

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