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Comparison of dissipation models for irregular breaking waves

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Abstract

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The irregular wave height transformation has been a subject of study for decades because of its importance in studying beach deformations and the design of coastal structures. The energy dissipation is an essential requirement in the computation of wave height transformation. During the past few decades, many dissipation models have been developed, for regular wave see Rattanapitikon and Leangruxa (2001). This study is undertaken to examine the accuracy of 7 existing dissipation models for irregular breaking waves, i.e., the models of Battjes and Janssen (1978), Thornton and Guza (1983) (2 models), Battjes and Stive (1984), Southgate and Nairn (1993), Baldock *et al*. (1998), and Rattanapitikon and Shibayama (1998). The coefficients of the models are re-calibrated and the overall accuracy of the models is compared. A large number and wide range of wave and bottom topography conditions (total 385 cases from 9 sources of published laboratory data) are used to re-calibrate and compare the accuracy of the 7 models. It appears that the model of Rattanapitikon and Shibayama (1998) gives the best prediction for general cases.

Key words : energy dissipation, dissipation model, irregular wave model

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Snell's law is employed to describe wave refraction.

$$\frac{\sin\theta}{c} = \text{constant}, \quad (2)$$

where c is the phase velocity.

From linear wave theory, the wave energy density (E) is equal to $\rho g H_{rms}^2/8$. Therefore, Eq. (1) can be written in the term of wave height as

$$\frac{\rho g}{8}\frac{\partial(H_{rms}^2 c_g \cos\theta)}{\partial x} = -D_B, \quad (3)$$

where ρ is the water density, g is the acceleration due to gravity, and H_{rms} is the root mean square wave height.

The wave height transformation can be computed from Eq. (3) by substituting the formula of energy dissipation rate, D_B, and numerical integration along distance x from offshore to shoreline. However, a formulation for the energy dissipation rate, D_B, is required to solve Eq. (3).

During the past few decades, various dissipation models have been proposed. Due to the complication of the wave breaking mechanism, most of the dissipation models have to be based on an empirical or semi-empirical formula calibrated from the experimental data. In order to make the models reliable, it is necessary to calibrate or verify the models against a wide range and large amount of experimental data.

Some of the existing models were developed with the limited experimental conditions. Therefore, the coefficient in each model may not be the optimal values for a wide range of experimental conditions. Moreover, no direct literature has been made to describe clearly the applicability and accuracy of each model. Therefore, the present study aims at re-calibrating and comparing seven existing models using a wide range of experimental data. The selected models are the models of Battjes and Janssen (1978), Thornton and Guza (1983) (2 models), Battjes and Stive (1984), Southgate and Nairn (1993), Baldock *et al.* (1998), and Rattanapitikon and Shibayama (1998). These selected models require short computation time to compute the beach deformation.

Dissipation Models

Widely used concept in the parametric approach is the model proposed by Battjes and Janssen (1978). Their energy dissipation rate, D_B, is described by combining the energy dissipation of a single broken wave with a parametric describing the fraction of breaking waves (probability of occurrence of breaking waves). Several researchers have proposed slightly different forms of the energy dissipation. A brief review of the selected 7 models are described as follows:

a) Battjes and Janssen (1978), hereafter referred to as BJ78, proposed to compute D_B by multiplying the fraction of irregular breaking waves (Q_b) by the energy dissipation of a single broken wave. The energy dissipation of a broken wave is described by the bore analogy and assuming that all broken waves have a height equal to breaking wave height (H_b) as

$$D_B = K_1 Q_b \frac{\rho g H_b^2}{4T_p}, \quad (4)$$

where T_p is the peak period of the wave spectrum, and K_1 is the coefficient introduced to account for the difference between breaking wave and hydraulic jump. The published value of K_1 is 1.0.

The fraction of breaking waves, Q_b, was derived based on the assumption that the probability density function (*pdf*) of wave height could be modeled with Rayleigh distribution truncated at the breaking wave height (H_b) and all broken waves have a height equal to the breaking wave height. The result is

$$\frac{1-Q_b}{-\ln Q_b} = \left(\frac{H_{rms}}{H_b}\right)^2. \quad (5)$$

The breaking wave height is determined from the formula of Miche (1944) including an adjustable coefficient γ_B.

$$H_b = 0.14L\tanh\left(\gamma_B\frac{2\pi h}{L}\right), \quad (6)$$

where L is the wavelength related to T_p, and h is the water depth. After calibration, the adjustable coefficient γ_B was found to be equal to 0.91.

Since Eq. (5) is an implicit equation, an iteration process is necessary to compute the fraction of breaking waves, Q_b. It will be more convenient if we can compute Q_b from the explicit form of Eq. (5). Rattanapitikon and Shibayama (1998) proposed that the explicit form of Q_b based on multiple regression analysis (with correlation coefficient R^2 = 0.999) is

$$Q_b = \begin{cases} 0 & for\ \dfrac{H_{rms}}{H_b} \le 0.43\ , \\ -0.738\left(\dfrac{H_{rms}}{H_b}\right) - 0.280\left(\dfrac{H_{rms}}{H_b}\right)^2 + 1.785\left(\dfrac{H_{rms}}{H_b}\right)^3 + 0.235 & for\ \dfrac{H_{rms}}{H_b} > 0.43\ . \end{cases} \tag{7}$$

Eqs. (5) and (7) give almost identical results (R^2 = 0.999), Eq. (7) is, therefore, used in this study.

b) Thornton and Guza (1983), hereafter referred to as TG83, proposed to compute D_B by integrating from 0 to ∞ of the product of the dissipation for a single broken wave and the *pdf* of the breaking wave height. The energy dissipation of a single broken wave is described by the bore model which is slightly different from the bore model of BJ78 (for more detail please see Rattanapitikon and Leangruxa, 2001). The *pdf* of breaking wave height is expressed as a weighting of the Rayleigh distribution. By introducing two forms of the weighting,two models of D_B were proposed.

Model 1 (hereafter referred to as TG83-1):

$$D_B = K_2 \frac{3\sqrt{\pi}}{4}\left(\frac{H_{rms}}{0.42h}\right)^4 \frac{\rho g H_{rms}^3}{4T_p h}\ , \tag{8}$$

where K_2 is the coefficient introduced to account for the difference between breaking wave and hydraulic jump. The published value of K_2 is 0.51.

Model 2 (hereafter referred to as TG83-2):

$$D_B = K_3 \frac{3\sqrt{\pi}}{4}\left(\frac{H_{rms}}{0.42h}\right)^2 \left\{1 - \frac{1}{\left[1+(H_{rms}/0.42\mathrm{h})^2\right]^{2.5}}\right\} \frac{\rho g H_{rms}^3}{4T_p h}\ , \tag{9}$$

where K_3 is the coefficient introduced to account for the difference between breaking wave and hydraulic jump. The published value of K_3 is 0.51.

c) Battjes and Stive (1984), hereafter referred to as BS84, used the same energy dissipation model as that of BJ78.

$$D_B = K_4 Q_b \frac{\rho g H_b^2}{4T_p}\ , \tag{10}$$

where K_4 is the coefficient. The published value of K_4 is 1.0, and Q_b is computed from Eq. (7).

They modified the model of BJ78 by re-calibrating the coefficient γ_B in the breaking wave height formula (Eq. 6). The coefficient γ_B was related to the deepwater wave steepness (H_{rmso}/L_o). After calibration, the breaking wave height was modified to be

$$H_b = 0.14L \tanh\left\{\left[0.57 + 0.45\tanh\left(33\frac{H_{rmso}}{L_o}\right)\right]\frac{2\pi \mathrm{h}}{L}\right\}, \tag{11}$$

where H_{rmso} is the deepwater *rms* wave height, and L_o is the deepwater wavelength. Hence the model of BS84 is similar to that of BJ78, except for the formula of H_b.

d) Southgate and Nairn (1993), hereafter referred to as SN93, modified the model of BJ78 by changing the expression of energy dissipation of a single broken wave from the bore model of BJ78 to be the bore model of TG83 as

$$D_B = K_5 Q_b \frac{\rho g H_b^3}{4 T_p h} , \tag{12}$$

where K_5 is the coefficient. The published value of K_5 is 1.0 and Q_b is computed from Eq. (7). The breaking wave height is determined from a formula of Nairn (1990) as

$$H_b = h\left[0.39 + 0.56 \tanh\left(33 \frac{H_{rmso}}{L_o}\right)\right] . \tag{13}$$

e) Baldock *et al.* (1998), hereafter referred to as BA98, proposed to compute D_B by integrating from H_b to ∞ of the product of the dissipation for a single broken wave and the *pdf* of the wave height. The energy dissipation of a single broken wave is described by the bore analogy of BJ78. The *pdf* of wave height inside the surf zone was assumed to be the Rayleigh distribution.

$$D_B = K_6 \exp\left[-\left(\frac{H_b}{H_{rms}}\right)^2\right] \frac{\rho g (H_b^2 + H_{rms}^2)}{4 T_P} , \qquad \text{for } H_{rms} < H_b . \tag{14}$$

In the saturated surf zone ($H_{rms} \geq H_b$) , H_{rms} is set to be equal to H_b. The published coefficient K_6 is 1.0. The breaking wave height (H_b) is determined from the formula of Nairn (1990) as shown in Eq. (13).

f) Rattanapitikon and Shibayama (1998), hereafter referred to as RS98, modified the model of BJ78 by changing the expression of energy dissipation of a single broken wave from the bore concept to the stable energy concept,

$$D_B = K_7 Q_b \frac{c_g \rho g}{8h}\left[H_{rms}^2 - \left(h\, exp(-0.58 - 2.00 \frac{h}{\sqrt{L H_{rms}}})\right)^2\right] , \tag{15}$$

where K_7 is the coefficient. The published value of K_7 is 0.1 , Q_b is computed from Eq. (7). The breaking wave height (H_b) is computed by using the breaking criteria of Goda (1970) as

$$H_b = 0.1 L_0 \left\{1 - \exp\left[-1.5 \frac{\pi h}{L_0}(1 + 15 m^{4/3})\right]\right\} , \tag{16}$$

where m is the average bottom slope.

The main difference between RS98 and other models is the concept used to describe the energy dissipation of a single breaking wave. The RS98's model uses a stable energy concept while other models use a bore concept. A brief review of these two concepts can be found in the paper of Rattanapitikon and Leangruxa (2001).

Model comparison

In order to make the verification reliable, the performances of the 7 above-presented models are verified against a wide range and large amounts of experimental data. However, the energy dissipation rate D_B could not be measured directly from the experiment. The comparison of the selected models is, therefore, performed by using the measured *rms* wave height. The measured *rms* wave heights from 9 sources (totally 385 cases) of published experimental results have been used in this study. The experiments cover a wide range of wave and bottom topography conditions, including small-scale, large-scale, and field experiments. The use of these independent data sources and a wide range of experimental conditions are expected to clearly demonstrate the applicability of the models. A summary of the collected experimental data is shown in Table 1.

The *rms* wave height transformation is computed by numerical integration of the energy flux balance equation (Eq. 3) with the energy dissipation rate of the 7 models (Eqs. 4, 8, 9, 10, 12, 14, and 15). The backward finite difference scheme is used to solve the energy flux balance equation (Eq. 3). The grid length (Δx) is set to be equal to the length between the point of measured wave height, except if Δx > 5m, Δx is set to be 5m.

The basic parameter for determination of the overall accuracy of a model is the average *rms* relative error (ER_{avg}), which is defined as

$$ER_{avg} = \frac{\sum_{j=1}^{tn} ER_{gj}}{tn} , \qquad (17)$$

where ER_{gj} is the root mean square relative error of the data group j , j is the group number, and tn is the total number of groups. The small value of ER_{avg} represents a good overall accuracy of the model.

The *rms* error of each data group (ER_g) is defined as

$$ER_g = 100\sqrt{\frac{\sum_{i=1}^{ng}(H_{ci} - H_{mi})^2}{\sum_{i=1}^{ng} H_{mi}^2}} , \qquad (18)$$

where, i is the wave height number, H_{ci} is the computed wave height of number i , H_{mi} is the

Table 1. Summary of collected experimental data used in this study.

Sources	Total No. of cases	Total No. of data points	Bed condition	Apparatus
Smith and Kraus (1990)	12	96	plane and barred beach	small-scale
Hurue (1990)	1	6	plane	small-scale
Sultan (1995)	1	12	plane	small-scale
Grasmeijer and Rijn (1999)	2	20	sandy beach	small-scale
SUPERTANK project (Kraus and Smith, 1994)	128	2223	sandy beach	large-scale
LIP 11D project (Roelvink and Reniers, 1995)	95	923	sandy beach	large-scale
MAST III - SAFE project (Dette *et al.*,1998)	138	3561	sandy beach	large-scale
Thornton and Guza (1986)	4	60	sandy beach	field
DELILAH Project (Smith *et al.*, 1993)	4	32	sandy beach	field
Total	**385**	**6933**		

measured wave height of number i , and ng is the total number of measured wave heights in each data group.

Using the default coefficients (K), the error for three groups of experiment scales (ER_g) and the average error (ER_{avg}) is shown in Table 2. It can be seen that the model of RS98 gives the best prediction for general cases. However the errors in Table 2 are not used to judge the applicability of the 7 models. Because some dissipation models were developed with limited experimental conditions, the coefficients in each model may not be the optimal values for a wide range of experimental conditions. Therefore the re-calibrations of the coefficients in the 7 models are performed before examining the validity of the models.

The calibration of each dissipation model is conducted by varying the empirical coefficient K in each dissipation model until the minimum error (ER_{avg}) , between the measured and computed wave height, is obtained. The sensitivity of the average error (ER_{avg}) to the selection of coefficient (K) for the 7 models is shown in Figures. 1-7.

The calibrated coefficients K_1 to K_7 are summarized in the second column of Table 3. It can be seen from Tables 2 and 3 that the calibrated coefficients of the most models (except BS84 and RS98) had to be changed. This is mainly because these models were developed based on limited experimental conditions.

Using the calibrated coefficients, the errors ER_g and ER_{avg} of each model have been computed

Table 2. The error ER_g for 3 groups of experiment scales, and ER_{avg} (using the default coefficients).

Models	Default Coeff. K	ER_g			ER_{avg}
		Small scale	Large scale	Field	
Battjes and Janssen (1978)	$K_1 = 1.0$	9.5	10.7	19.1	13.1
Thornton and Guza (1983), model 1	$K_2 = 0.51$	29.3	17.1	29.4	25.3
Thornton and Guza (1983), model 2	$K_3 = 0.51$	23.4	8.9	15.8	16.0
Battjes and Stive (1984)	$K_4 = 1.0$	8.7	7.1	18.8	11.6
Southgate and Nairn (1993)	$K_5 = 1.0$	12.6	10.0	20.6	14.4
Baldock *et al*. (1998)	$K_6 = 1.0$	11.5	7.0	23.5	14.0
Rattanapitikon and Shibayama (1998)	$K_7 = 0.1$	10.1	7.4	14.5	10.7

Table 3. The error ER_g for 3 groups of experiment scales, and ER_{avg} (using the calibrated coefficients).

Models	Calibrated Coeff. K	ER_g			ER_{avg}
		Small scale	Large scale	Field	
Battjes and Janssen (1978)	$K_1 = 1.2$	11.0	10.0	17.6	12.9
Thornton and Guza (1983), model 1	$K_2 = 0.3$	26.0	16.6	23.1	21.9
Thornton and Guza (1983), model 2	$K_3 = 0.3$	16.2	10.1	16.6	14.3
Battjes and Stive (1984)	$K_4 = 1.0$	8.7	7.1	18.8	11.6
Southgate and Nairn (1993)	$K_5 = 1.4$	9.8	8.0	19.8	12.5
Baldock *et al*. (1998)	$K_6 = 0.9$	12.0	7.3	21.1	13.5
Rattanapitikon and Shibayama (1998)	$K_7 = 0.1$	10.1	7.4	14.5	10.7

Figure 1. Average error of Battjes and Janssen (1978) for various values of coefficient K_1.

Figure 2. Average error of Thornton and Guza (1983), model 1 for various values of coefficient K_2.

Figure 3. Average error of Thornton and Guza (1983), model 2 for various values of coefficient K_3.

Figure 4. Average error of Battjes and Stive (1984) for various values of coefficient K_4.

Figure 5. Average error of Southgate and Nairn (1993) for various values of coefficient K_5.

Figure 6. Average error of Baldock *et al*. (1998) for various values of coefficient K_6.

Figure 7. Average error of Rattanapitikon and Shibayama (1998) for various values of coefficient K_7.

and are shown in Table 3. The results can be summarized as follows:

a) It can be seen from the last column of Table 3 that most models (except TG83-1) give nearly the same overall accuracy. The overall accuracies of the models in descending order are RS98, BS84, SN93, BJ78, BA98, TG83-2, and TG83-1. The model of TG83-1 gives quite large average error (ER_{avg}). It may not be suitable.

b) Most models (except TG83-1) give very good predictions for the experiment in small-scale and large-scale wave flumes. However, the accuracies of these models are reduced in the field experiments. These facts indicate that the assumptions made in the derivation of these models may be true only under certain circumstances. All models should be used with care in the field applications.

c) The model of RS98 gives the best prediction for general cases (ER_{avg} = 10.7). However, it is not superior to other models under all conditions. The main difference between RS98 and other models is that RS98 uses a stable energy concept to describe the energy dissipation of a single breaking wave while other models use a bore concept. It is concluded that the stable energy concept gives a better prediction than that of a bore concept.

Conclusions

A total of 385 cases from 9 sources of published experimental results were used to calibrate and compare the accuracy of the 7 existing dissipation models. The experimental data cover a wide range of wave and beach conditions. The basic parameter used for determination of the overall accuracy of the models is the average *rms* relative error (ER_{avg}) . The calibration of each model was conducted by varying the empirical coefficients (K_1 to K_7) in each model until the minimum error (ER_{avg}) , between the measured and computed wave height, is obtained. Using the calibrated K_1 to K_7 , the errors ER_{avg} of the selected models were computed and compared. The comparisons show that the model of Rattanapitikon and Shibayama (1998) gives the best prediction for general cases.

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