Songklanakarin J. Sci. Technol.
30 (3), 333-341, May - Jun. 2008

Songklanakarin Journal
of Science and Technology

http://www.sjst.psu.ac.th

Original Article

Energy dissipation model for a parametric wave approach based on laboratory and field experiments

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Received 29 January 2007; Accepted 10 June 2008

Abstract

This study was undertaken to develop a simple energy dissipation model for computing the root mean square wave height transformation. The parametric wave approach of Battjes and Janssen (1978) was used as a framework for developing the energy dissipation model. In contrast to the common derivation, the fraction of breaking waves was not derived from the assumed probability density function of wave heights, but derived directly from the measured wave heights. The present model was verified extensively for a variety of wave and beach conditions (including small-scale, large-scale, and field experiments), and compared with four existing dissipation models. The present model gives very good accuracy for a wide range of wave and beach conditions and gives better predictions than those of existing models.

Keywords: irregular wave model, energy dissipation, parametric wave, surf zone

1. Introduction

Wave height is one of the most essential required factors for many coastal engineering applications such as the design of coastal structures and the study of beach morphodynamics. When waves propagate in shallow water, their profiles become steeper and they eventually break. Once the waves start to break, a part of the wave energy is transformed into turbulence and heat, and the wave height decreases towards the shore. The rate of energy dissipation of breaking waves is an essential requirement for computing wave height transformation in the surf zone. Several models have been proposed for computing the energy dissipation due to wave breaking, differing mainly in their formulation of the energy dissipation, and whether they were developed for regular (a single broken wave) or irregular waves.

Widely used models for computing the energy dissipation of a regular wave (a single broken wave) seem to be the bore model of Le Mehaute (1962) and the stable energy model of Dally *et al.* (1985). Brief reviews of these two models are described in the paper of Rattanapitikon and Leangruxa (2001). Aside from these two models, a number of alternative models for computing the energy dissipation have been presented. Horikawa and Kuo (1966) estimated the internal energy dissipation from the turbulent velocity fluctuations, which are assumed to decay exponentially with distance from the incipient wave breaking. Sawaragi and Iwata (1974) refined this approach by introducing the Prandt mixing length model to describe the turbulent velocity fluctuations. Mizuguchi (1980) applied an analytical solution for internal energy dissipation due to the viscosity, where the eddy viscosity replaces the molecular kinematic viscosity.

Irregular wave breaking is more complex than regular wave breaking. In contrast to regular waves, there is no well-defined breakpoint for irregular waves. The higher waves tend to break at a greater distance from the shore. Closer to the shore, more and more waves break, until almost all the waves break in the inner surf zone. The energy dissipation model developed for regular waves and extended to irregular waves introduces complexities, primarily with respect to the representation of the probability density function of wave

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heights. Common methods to model irregular wave height transformations can be classified into four main approaches, i.e. representative wave approach, spectral approach, probabilistic approach, and parametric wave approach. For computing beach morphodynamics, the wave model should be kept as simple as possible because of the frequent updating of wave fields to account for the change of the bottom morphology. The parametric and representative wave approaches appear to be simple methods and seem to be suitable for being incorporated in the beach morphodynamic model.

For the representative wave approach, the regular wave model has been directly applied to irregular waves by using representative (or equivalent) waves, while the parametric approach considers the random nature of the waves but describes the energy dissipation rate in terms of time-averaged parameters. The parametric wave models were developed based on the assumed probability density function (*pdf*) of wave heights inside the surf zone. The average rate of energy dissipation is described by integrating the product of energy dissipation of a broken wave and the probability of occurrence of breaking waves. The parametric wave approach is expected to be better than the representative wave approach because it includes the random nature of the waves into the model while the other does not. Therefore, the present study focuses on the parametric wave approach.

The parametric wave models are generally based on the work of Battjes and Janssen (1978). The model relies on the macroscopic features of breaking waves and predicts only the transformation of root-mean-square (*rms*) wave height. The wave height transformation is computed from the energy flux conservation law. It is:

$$\frac{\partial\left(Ec_g\cos\theta\right)}{\partial x}=-D_B \qquad (1)$$

where E is the wave energy density, c_g is the group velocity, θ is the mean wave angle, D_B is the distance in the cross shore direction, and is the energy dissipation rate due to wave breaking. The energy dissipation rate due to bottom friction is neglected. All variables are based on linear wave theory and Snell's law is employed to describe wave refraction.

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

$$\frac{\rho g}{8}\frac{\partial\left(H_{rms}^2 c_g\cos\theta\right)}{\partial x}=-D_B \qquad (2)$$

where ρ is the density of water, g is the gravitational acceleration, H_{rms} and is the *rms* wave height.

The *rms* wave height transformation can be computed from the energy flux balance equation (Equation 2) by substituting the model of energy dissipation rate (D_B) and numerically integrating from offshore to the shoreline. In the offshore zone, the energy dissipation rate is set to zero. The main difficulty of Equation 2 is how to formulate the energy dissipation rate caused by the breaking waves.

During the past decades, various energy dissipation models for the parametric wave approach have been proposed for computing H_{rms} in the surf zone. Because of the complexity of the wave breaking mechanisms, most of the energy dissipation models were developed based on an empirical or semi-empirical approach. It is well known that the validity of an empirical formula may be limited according to the range of experimental conditions that were employed in the calibrations and verifications. To make an empirical formula reliable, it is necessary to calibrate and verify the formula with a large amount of data and a wide range of experimental conditions. Since many energy dissipation models were developed based on data with limited experimental conditions, there is still a need for more data to confirm the underlying assumptions in order to make the model more reliable. It is the purpose of this study to develop a simple energy dissipation model for the parametric wave approach based on a wide range of experimental conditions.

Experimental data of *rms* wave height transformation from 13 sources, covering 1723 cases of wave and beach conditions, have been collected for verifying the dissipation models. The experiments cover a wide range of wave and bottom topography conditions, including small-scale, large-scale, and field experiments. The experiments cover a variety of beach conditions (i.e. plane, barred, and sandy beaches) and a range of deepwater wave steepnesses (H_{rmso}/L_o) from 0.0007 to 0.0588. A summary of the collected experimental data is given in Table 1. Excluding the introduction and the conclusions, this paper is divided into three main parts. The first part briefly reviews some existing dissipation models for the parametric wave approach. The second part describes the development of the present model. The last part is the verification of the present model in comparison with the existing models.

2. Existing energy dissipation models

During the past decades, various energy dissipation models have been developed based on a framework of the parametric wave approach of Battjes and Janssen (1978). Brief reviews of some existing dissipation models are described below.

a) Battjes and Janssen (1978), hereafter referred to as BJ78, proposed to compute D_B by multiplying the fraction of breaking waves (Q_B) by the energy dissipation of a single broken wave. The energy dissipation of a broken wave (D_{BS}) is determined from a simplified bore-type dissipation model and assumes that all broken waves have a height equal to the breaker height (H_b) as:

$$D_B=Q_{b1}\frac{\rho g H_b^2}{4T_p} \qquad (3)$$

where Q_{b1} is the fraction of breaking waves of BJ78, and T_p is the spectral peak period. The fraction of breaking waves (Q_{b1}) was derived based on the assumption that the prob-

Table 1. Summary of collected experimental data.

Sources	Total no. of cases	Total no. of data	Beach conditions	H_{rmso}/L_o	Apparatus
Hurue (1990)	1	7	plane beach	0.0259	small-scale
Smith and Kraus (1990)	12	96	plane and barred beach	0.0214-0.0588	small-scale
Sultan (1995)	1	12	plane beach	0.0042	small-scale
Grasmeijer and Rijn (1999)	2	20	sandy beach	0.0142-0.0168	small-scale
Hamilton and Ebersole (2001)	1	10	plane beach	0.0165	small-scale
Ting (2001)	1	7	plane beach	0.0161	small-scale
Kraus and Smith (1994): SUPERTANK project	128	2,223	sandy beach	0.0011-0.0452	large-scale
Roelvink and Reniers (1995): LIP 11D project	95	923	sandy beach	0.0039-0.0279	large-scale
Dette *et al.* (1998): MAST III – SAFE project	138	3,559	sandy beach	0.0061-0.0147	large-scale
Thornton and Guza (1986)	4	60	sandy beach	0.0012-0.0013	field
Kraus *et al.* (1989): DUCK85 project	8	90	sandy beach	0.0007-0.0018	field
Birkemeier *et al.* (1997): DELILAH project	745	5,033	sandy beach	0.0007-0.0254	field
Herbers *et al.* (2006): DUCK94 project	587	6,102	sandy beach	0.0009-0.0290	field
Total	1,723	18,142		0.0007-0.0588	

ability density function of wave heights could be modeled with a Rayleigh distribution truncated at the breaker height (H_b) and all broken waves have a height equal to the breaker height. The result is:

$$\frac{1-Q_{b1}}{-\ln Q_{b1}} = \left(\frac{H_{rms}}{H_b}\right)^2 \quad (4)$$

in which the breaker height (H_b) is determined from the formula of Miche (1951) with the additional coefficient (γ) in the tan-hyperbolic function as:

$$H_b = 0.14L\tanh(\gamma kh) \quad (5)$$

where L is the wavelength related to T_p, k is the wave number, and h is the water depth. Based on their small-scale laboratory data, the coefficient γ is determined at 0.91. As Equation 4 is an implicit equation, it has to be solved for Q_{b1} either by an iterative technique (e.g. Newton-Raphson technique), or by a 1-D look-up table (Southgate and Nairn, 1993), or by fitting Q_{b1} with a polynomial function as:

$$Q_{b1} = \sum_{n=0}^{7} a_n \left(\frac{H_{rms}}{H_b}\right)^n \quad (6)$$

where a_n is the constant of n^{th} term. A multiple regression analysis is used to determine the constants a_0 to a_7. The correlation coefficient (R^2) of Equation 6 is 0.99999999. The values of the constants a_0 to a_7 are shown in Table 2. Equation 6 is applicable for $0.3 < H_{rms}/H_b < 1.0$. For $H_{rms}/H_b \le$ 0.3, the value of Q_{b1} is very small (less than 10^{-4}) and thus is set as zero. The value of Q_{b1} is set to be 1.0 when $H_{rms}/H_b \ge 1.0$. It should be noted that the two main assumptions for deriving the model (i.e. the assumptions of the simplified bore-type dissipation model and the truncated-Rayleigh distribution of wave heights) are not supported by the experimental data. However, the model has been used successfully in many applications for computing H_{rms} transformation (e.g. Johnson, 2006; and Oliveira, 2007).

Table 2. Values of constants a_0 to a_7 for computing Q_{b1}.

Constants	Values
a_0	0.231707207858562
a_1	-3.609582722187040
a_2	22.594833612442000
a_3	-72.536799430847200
a_4	126.870449066162000
a_5	-120.567666053772000
a_6	60.741998672485400
a_7	-12.725062847137500

b) Battjes and Stive (1985), hereafter referred to as BS85, used the same energy dissipation model as BJ78 (Equation 3). They modified the model of BJ78 by recalibrating the coefficient γ in the breaker height formula (Equation 5). The coefficient γ was related to the deepwater wave steepness (H_{rmso}/L_o) . After calibration with small-scale and field experiments, the breaker height formula was modified to be:

$$H_b = 0.14L\tanh\left\{\left[0.57 + 0.45\tanh\left(33\frac{H_{rmso}}{L_o}\right)\right]kh\right\} \quad (7)$$

where H_{rmso} is the deepwater *rms* wave height, and L_o is the deepwater wavelength. Hence, the main difference between the models of BJ78 and BS85 is only the formula for computing H_b.

c) Baldock *et al.* (1998), hereafter referred to as BHV98, proposed to compute D_B by integrating from H_b to ∞ the product of the dissipation for a single broken wave and the *pdf* of the wave heights. The energy dissipation of a single broken wave is described by the bore model of BJ78. The *pdf* of wave heights inside the surf zone was assumed to be a Rayleigh distribution. The result is:

$$D_B = \begin{cases} \exp\left[-\left(\dfrac{H_b}{H_{rms}}\right)^2\right]\dfrac{\rho g\left(H_b^2 + H_{rms}^2\right)}{4T_p} & for \quad H_{rms} < H_b \\ \exp[-1]\dfrac{2\rho g H_b^2}{4T_p} & for \quad H_{rms} \geq H_b \end{cases} \quad (8)$$

in which the breaker height (H_b) is determined from the formula of Nairn (1990) as:

$$H_b = h\left[0.39 + 0.56\tanh\left(33\frac{H_{rmso}}{L_o}\right)\right] \quad (9)$$

Although the model of BHV98 (Equation 8) seems to be quite different from the D_B model of BJ78, it can be rewritten in the similar form as that of BJ78 as:

$$D_B = Q_{b2}\frac{\rho g H_b^2}{4T_p} \quad (10)$$

in which Q_{b2} is a function of H_{rms}/H_b as:

$$Q_{b2} = \begin{cases} \left[1 + \left(\dfrac{H_{rms}}{H_b}\right)^2\right]\exp\left[-\left(\dfrac{H_{rms}}{H_b}\right)^{-2}\right] & for \quad \dfrac{H_{rms}}{H_b} < 1 \\ 2\exp[-1] & for \quad \dfrac{H_{rms}}{H_b} \geq 1 \end{cases} \quad (11)$$

Comparing with the model of BJ78, the parameter Q_{b2} may be also considered as the fraction of breaking waves. The main difference between the models of BJ78 and BHV98 are the formulas for computing H_b and Q_b.

d) Ruessink *et al.* (2003), hereafter referred to as RWS03, used the same energy dissipation model as BHV98 (Equation 8), but a different breaker height formula. The breaker height formula of BJ78 (Equation 5) is modified by adding the term *kh* into the formula. After calibration with field experiments, the breaker height formula was modified to be:

$$H_b = 0.14L\tanh[(0.86kh + 0.33)kh] \quad (12)$$

3. Model Development

In this study, the energy dissipation model of BJ78 is used as a framework for developing the present energy dissipation model. Similar to the model of BJ78, the present model is expressed as:

$$D_B = Q_{b3}\frac{\rho g H_b^2}{4T_p} \quad (13)$$

where Q_{b3} is the fraction of breaking waves of the present study, which is a function of H_{rms}/H_b.

It can be seen from Section 2 that the main difference among the existing models are the formulas for computing Q_b and H_b. It is not clear, which formulas of H_b and Q_b are suitable for modeling D_B (or computing H_{rms}). The objective of this section is to determine suitable formulas of H_b and Q_b for computing the *rms* wave height transformation.

The model of BJ78 was derived based on two main assumptions, the assumptions of truncated-Rayleigh distribution of wave heights and a simplified bore-type dissipation model. It should be noted that the assumption of a truncated-Rayleigh distribution, which is used to derive the formula of Q_b, is not supported by laboratory and field data (Dally, 1990). Some researchers (e.g. Southgate and Nairn, 1993; and Baldock *et al.*, 1998) demonstrated that Equation 4 gives a large error in predicting the fraction of breaking waves (Q_b). Moreover, the simplified bore-type dissipation model for estimating energy dissipation of a single breaking wave ($D_{BS} = \rho g H^2/4T$) is also not supported by laboratory data (Rattanapitikon *et al.*, 2003). Surprisingly, the D_B model of BJ78 seems to give good results in predicting H_{rms} and has proven to be a popular framework for estimating H_{rms} (Ruessink *et al.*, 2003). Because the assumptions for deriving the model are not valid, but the model gives good results in predicting H_{rms}, the D_B model of BJ78 may be considered as an empirical model for computing only H_{rms} (not for computing Q_b and a single breaking wave). As the model is an empirical model, it may not be necessary to derive the formula of Q_b by assuming the *pdf* of wave heights inside the surf zone (as done by BJ78 and BHV98). Moreover, the acceptable *pdf* of wave heights inside the surf zone is not available (Demerbilek and Vincent, 2006). It may not be suitable to derive formulas of Q_b from the assumed *pdf* of wave heights. Alternatively, the formula of Q_b can be derived directly from the measured wave heights by inverting the energy dissipation model (Equation 13) and the wave model (Equation 2). Therefore, in the present study, the formula of Q_b will be newly derived from the measured wave heights.

As Q_b is the function of H_{rms}/H_b, the formula of Q_b can be determined by plotting a relationship between measured Q_b versus H_{rms}/H_b. The required data for determining the formula are the measured data of Q_b and H_{rms}/H_b. The measured Q_b can be determined from the measured wave heights as the following.

Substituting Equation 2 into Equation 13 and using a backward finite difference scheme to describe the differential equation, the variable Q_{b3} is expressed as:

$$Q_{b3i} = \frac{T_p}{2H_b^2} \frac{\left(H_{rmsi-1}^2 c_{gi-1} \cos\theta_{i-1} - H_{rmsi}^2 c_{gi} \cos\theta_i\right)}{x_i - x_{i-1}} \tag{14}$$

where i is the grid number and the originate of i is at the offshore boundary. Hereafter, the variable Q_{b3} determined from Equation 14 is referred to as measured Q_{b3}.

For determining Q_{b3} from Equation 14, a formula of H_b must be given. As there are four existing breaker height formulas (Equations. 5, 7, 9, and 12), four Q_{b3} can be determined and consequently four relationships between measured Q_{b3} and H_{rms}/H_b are considered in this study. The required data set for determining the measured Q_{b3} are the measured values of h, T_p, H_{rms}, θ, and x. Other related variables (e.g. H_{rmso}, L_o, L, k, and c_g) are computed based on linear wave theory. To avoid a large fluctuation in the relationships, the wave heights variation across the shore should have a small fluctuation.

Because of a variety of wave conditions and a small fluctuation of wave heights variation across the shore, the data from Dette *et al.* (1998) are used for deriving the formulas of Q_{b3} for the four H_b formulas. An example of measured wave height transformation across-shore is shown in Figure 1. However, all collected data shown in Table 1 are used for verification of the models.

The four relationships between measured Q_{b3} versus H_{rms}/H_b (using Equations 5, 7, 9, and 12 for computing H_b) have been plotted to determine a suitable formula of Q_{b3} (see Figures 2 to 5). It can be seen from Figures 2 to 5 that all relationships are fitted well with a quadratic equation as:

$$Q_{b3} = C_1 + C_2\left(\frac{H_{rms}}{H_b}\right) + C_3\left(\frac{H_{rms}}{H_b}\right)^2 \quad \text{for} \quad \frac{H_{rms}}{H_b} > C_4 \tag{15}$$

where C_1 to C_4 are constants. The fraction of breaking waves

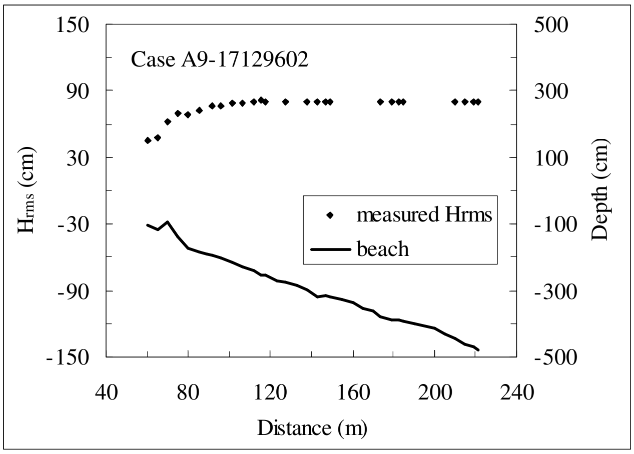

Figure 1. Example of measured wave height transformation across-shore (measured data from Dette *et al.'*, 1998, case A9-17129602).

(Q_{b3}) is set to be zero when $H_{rms}/H_b \le C_4$ (in the offshore zone). The constants C_1 to C_3 can be determined by fitting the curves in Figures 2 to 5. As the constant C_4 is the point where Q_{b3}= 0 (x-intercept), it can be determined from the known constants C_1 to C_3 by solving the quadratic equation. The constants C_1 to C_4 and correlation coefficients (R^2) of

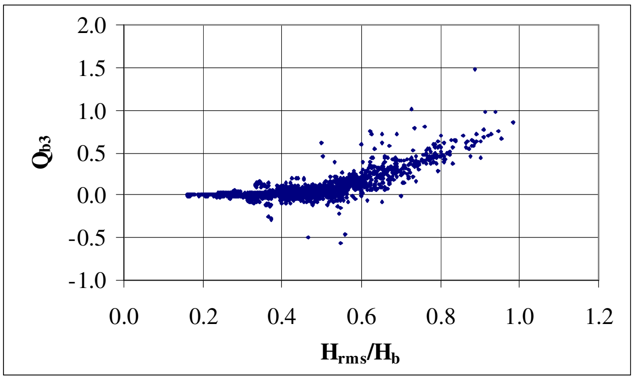

Figure 2. Relationship between measured Q_{b3} versus H_{rms}/H_b in which Equation 5 is used for computing H_b (measured data from Dette *et al.*, 1998).

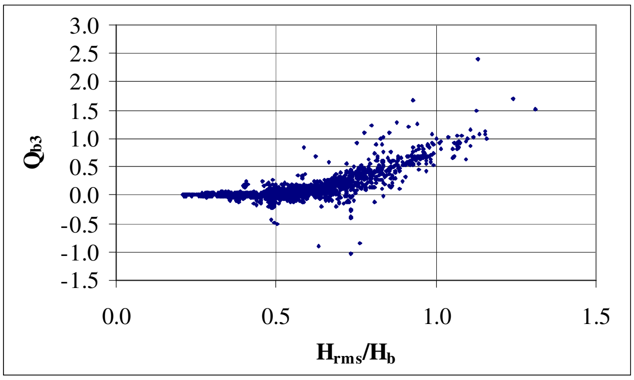

Figure 3. Relationship between measured Q_{b3} versus H_{rms}/H_b in which Equation 7 is used for computing H_b (measured data from Dette *et al.*, 1998).

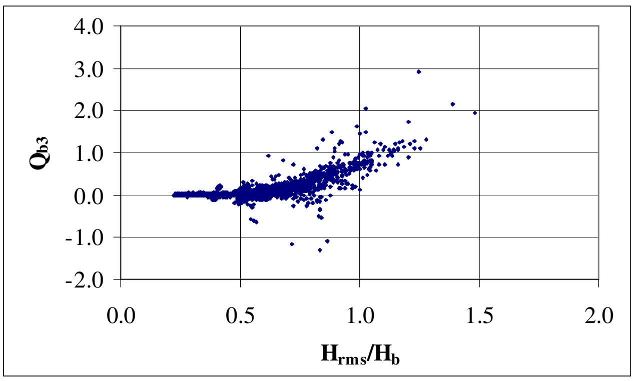

Figure 4. Relationship between measured Q_{b3} versus H_{rms}/H_b in which Equation 9 is used for computing H_b (measured data from Dette *et al.*, 1998).

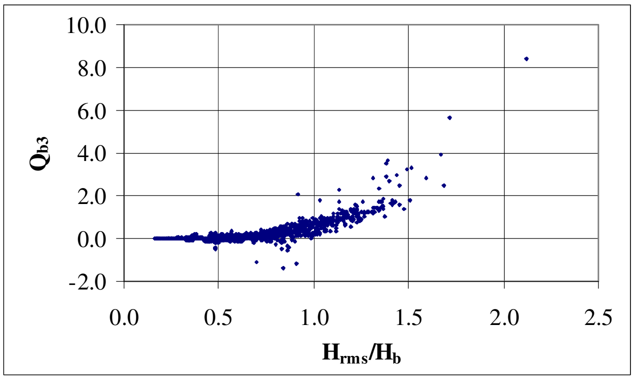

Figure 5. Relationship between measured Q_{b3} versus H_{rms}/H_b in which Equation 12 is used for computing H_b (measured data from Dette *et al.*, 1998).

Equation 15 for four H_b formulas are shown in Table 3. The correlation coefficients (R^2) of the fitting vary between 0.73 to 0.83, which indicates a reasonably good fit.

It should be noted that an attempt is also made to fit the measured Q_{b3} with a cubic equation. However, it is found that the correlation coefficients (R^2) of all models did not significantly improve. Therefore, the quadratic equation is used in this study.

Substituting the formula of Q_{b3} for each H_b formula into Equation 13, the present D_B models (MD1-MD4) can be expressed as:

MD1:

$$D_B = \frac{\rho g H_b^2}{4T}\left[0.189 - 1.282\left(\frac{H_{rms}}{H_b}\right) + 2.073\left(\frac{H_{rms}}{H_b}\right)^2\right]$$

$$\text{for } \frac{H_{rms}}{H_b} > 0.37 \qquad (16)$$

in which H_b is determined from the breaker height formula of BJ78 (Equation 5).

MD2:

$$D_B = \frac{\rho g H_b^2}{4T}\left[0.293 - 1.601\left(\frac{H_{rms}}{H_b}\right) + 2.096\left(\frac{H_{rms}}{H_b}\right)^2\right]$$

$$\text{for } \frac{H_{rms}}{H_b} > 0.46 \qquad (17)$$

in which H_b is determined from the breaker height formula of BS85 (Equation 7).

MD3:

$$D_B = \frac{\rho g H_b^2}{4T}\left[0.309 - 1.614\left(\frac{H_{rms}}{H_b}\right) + 2.013\left(\frac{H_{rms}}{H_b}\right)^2\right]$$

$$\text{for } \frac{H_{rms}}{H_b} > 0.49 \qquad (18)$$

in which H_b is determined from the breaker height formula of Nairn (1990) (Equation 9).

MD4:

$$D_B = \frac{\rho g H_b^2}{4T}\left[0.342 - 1.776\left(\frac{H_{rms}}{H_b}\right) + 2.087\left(\frac{H_{rms}}{H_b}\right)^2\right]$$

$$\text{for } \frac{H_{rms}}{H_b} > 0.56 \qquad (19)$$

in which H_b is determined from the breaker height formula of RWS03 (Equation 12).

4. Model Examination

In the beach morphodynamics model, the wave model has to be run several times to account for the change of beach morphology. It is necessary to estimate the wave height with a high accuracy, because the error of the estimation may be accumulate over time. The objective of this section is to examine the applicability of the present dissipation models on simulating *rms* wave heights (H_{rms}) and to select the best one. To confirm the ability of the present models, the accuracy of the present models was also compared with that of four existing models (shown in Section 2). The measured *rms* wave heights from 13 sources (1723 cases) of collected experimental results (shown in Table 1) are used to examine the models. The collected data are separated into three groups according to the experiment scales, i.e. small-scale, large-scale, and field experiments. It is expected that a good model should be able to predict well for the three groups of experimental scales and well for all collected data.

The basic parameter for determination of the accuracy of a model is the average relative error (ER), which is defined as:

Table 3. Calibrated constants (C_1 to C_4) and correlation coefficients (R^2) of Q_{b3} formula (Equation 15) for the four H_b formulas.

No.	Q_{b3} Formulas	H_b Formulas	Calibrated constants C_1	C_2	C_3	C_4	R^2
1	Eq. (15)	Eq. (5)	0.189	-1.282	2.073	0.37	0.77
2	Eq. (15)	Eq. (7)	0.293	-1.601	2.096	0.46	0.75
3	Eq. (15)	Eq. (9)	0.309	-1.614	2.013	0.49	0.73
4	Eq. (15)	Eq. (12)	0.342	-1.776	2.087	0.56	0.83

Table 4. The average relative errors (ER) of the existing and the present models for 3 experiment scales and all collected data (measured data from Table 1).

Models	D_B Formulas	H_b Formulas	ER			
			Small-scale (152 data)	Large-scale (6705 data)	Field (11285 data)	All data (18142 data)
BJ78	Eq. (3)	Eq. (5)	8.80	10.05	18.68	15.41
BS85	Eq. (3)	Eq. (7)	6.98	6.68	10.69	9.18
BHV98	Eq. (8)	Eq. (9)	9.93	6.72	11.47	9.70
RWS03	Eq. (8)	Eq. (12)	11.65	8.06	10.73	9.75
MD1	Eq. (16)	Eq. (5)	24.06	8.17	11.56	10.41
MD2	Eq. (17)	Eq. (7)	6.96	6.62	9.77	8.58
MD3	Eq. (18)	Eq. (9)	9.24	7.70	10.24	9.29
MD4	Eq. (19)	Eq. (12)	9.93	9.08	10.94	10.24

$$ER = \frac{100}{N}\sum_{j=1}^{N}\left(\frac{\left|H_{mj} - H_{cj}\right|}{H_{mj}}\right) \qquad (20)$$

where j is the wave height number, H_{cj} is the computed wave height of number j, H_{mj} is the measured wave height of number j, and N is the total number of data of measured wave heights. A small value of ER indicates a high level of accuracy of the model.

The *rms* wave height transformation is computed by numerical integration of the energy flux balance equation (Equation 2) with the energy dissipation rate of the existing and the present models (i.e. the models of BJ78, BS85, BHV98, RWS03, and MD1 to MD4). A backward finite difference scheme is used to solve the energy flux balance equation (Equation 2). The ER of each dissipation model for three experimental scales and all collected data have been computed and shown in Table 4. The results can be summarized as follows:

a) The ER of the models for small-scale experiments varies between 7.0% and 24.1%. The accuracy of the models for small-scale experiments in descending order are MD2, BS85, BJ78, MD3, BHV98, MD4, RWS03, and MD1.

b) The ER of the models for large-scale experiments varies between 6.6% and 10.1%. The accuracy of the models for large-scale experiments in descending order are MD2, BS85, BHV98, MD3, RWS03, MD1, MD4, and BJ78.

c) The ER of the models for field experiments varies between 9.8% and 18.7%. The accuracy of the models for field experiments in descending order are MD2, MD3, BS85, RWS03, MD4, BHV98, MD1, and BJ78.

d) The ER of the models for all collected data, which is used to indicate the overall accuracy, varies between 8.6% and 15.4%. The overall accuracy of the models for all collected data in descending order are MD2, BS85, MD3, BHV98, RWS03, MD4, MD1, and BJ78.

e) Comparing the overall accuracy of the existing models (BJ78, BS85, BHV98, and RWS03), the model of BS85 gives the best prediction.

f) Comparing the overall accuracy of the present models (MD1-MD4), the model of MD2 gives the best prediction.

g) Considering the overall performance of all models, the model MD2 seems to be the best one. Therefore, MD2 is recommended to use for computing the transformation of H_{rms}.

It can be seen that the model MD2 is similar to the model of BS85. The main difference between the models MD2 and BS85 is the formula of Q_b which makes the model MD2 simpler than the model BS85. Although the model MD2 is simpler than BS85, the accuracy is better.

5. Conclusions

A simple energy dissipation model for computing the *rms* wave height transformation was developed. The *rms* wave height transformation is computed from the energy flux conservation law. The dissipation model of Battjes and Janssen (1978) was used as a framework for developing the present model. The model of Battjes and Janssen (1978) consists of three main formulas, (a) the formulas of energy dissipation of a single broken wave, (b) the breaker height (H_b), and (c) the fraction of breaking waves (Q_b). The present study focuses mainly on the new derivation of the Q_b formula. Unlike the common derivation, the formula of Q_b was derived directly from the measured wave heights by inverting the wave model together with the dissipation model. Based on the four existing breaker height formulas, four Q_b formulas were developed and consequently yielded four dissipation models.

A wide range and large amount of collected experimental data (1723 cases collected from 13 sources) were used to examine the applicability of the present dissipation models on simulating H_{rms} and to select the best one. To confirm the ability of the proposed models, their accuracy was also compared with that of four existing dissipation models. The examination results were presented in terms of average relative error. The examination shows that the model

MD2 gives very good accuracy for a wide range of wave and beach conditions (with *ER* for all collected data of 8.6%) and gives better predictions than that of existing models.

Acknowledgements

This research was sponsored by the Thailand Research Fund and the Commission on Higher Education, Ministry of Education, Thailand. The data collection of the DELILAH and DUCK94 Projects were funded by the US Office of Naval Research and the US National Science Foundation, U.S.A.

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