

Transformation of Mean and Highest One-Tenth Wave Heights Using Representative Wave Approach

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ABSTRACT

Models were studied for computing the mean wave height (H_m) and highest one-tenth wave height ($H_{1/10}$) using a representative wave approach. Many researchers have pointed out that the use of a representative wave approach can give erroneous results in the computation of representative wave height transformations. However, the representative wave approach has great merit in its simple calculations. It would be useful for practical works, if this approach could be used to compute representative wave heights. Some researchers showed that the representative wave approach can be used to compute the transformation of the root-mean-square wave height and significant wave height with very good accuracy. However, it is not clear whether the approach is applicable for computing H_m and $H_{1/10}$. The present study investigated the accuracy of the calculation of the transformation of H_m and $H_{1/10}$ by using the representative wave approach. Laboratory data from small-scale and large-scale wave flumes were used to examine the models. The representative wave height transformation was computed from the energy flux conservation law. Seven energy dissipation models of regular wave breaking were directly applied to the irregular wave model to test their applicability. It was found that by using an appropriate energy dissipation model with new coefficients, the representative wave approach can also be used to compute H_m and $H_{1/10}$ with very good accuracy.

Keywords: representative wave approach, mean wave height, highest one-tenth wave height, energy dissipation, surf zone

INTRODUCTION

The representative wave height is one of the most essential parameters required for the study of coastal processes and the design of coastal structures. Several types of representative wave heights (H_{rep}) are usually defined, for example, the mean wave height (H_m), the root-mean-square wave height (H_{rms}), the significant wave height ($H_{1/3}$), the highest one-tenth wave height ($H_{1/10}$) and the maximum wave height (H_{max}). The

representative wave heights are usually available in deepwater, but not available in shallow water at the depths required. The representative wave heights in shallow water can be determined from a wave transformation model. Common methods to model the representative wave heights may be classified into three main approaches—the wave-by-wave approach, the conversion approach and the representative wave approach. The present study focused on the representative wave approach as it appears to be the simplest approach. It would

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be useful for practical works, if this approach could be used to compute the representative wave height transformations.

The representative wave approach considers only the propagation of representative wave height. The model of regular waves has been directly applied to irregular waves by using representative waves. The approach has the merits of easy understanding, simple application and it is not necessary to assume the shape of the probability function of the wave heights. Since the highest wave in an irregular wave train tends to break at the greatest distance from the shore, the initiation of a surf zone of irregular waves tends to occur at a greater distance from shore than that of regular waves. Therefore, the use of a regular wave model may give considerable errors in the surf zone. However, some researchers found that by using an appropriate energy dissipation model with new coefficients, the representative wave approach can be used to compute the transformation of H_{rms} (Rattanapitikon *et al.*, 2003) and $H_{1/3}$ (Rattanapitikon, 2008). Therefore, it may be possible to use the representative wave approach to predict the transformation of other representative wave heights. Nevertheless, it seems that no papers have pointed out that the representative wave approach is applicable for computing H_m and $H_{1/10}$. Consequently, engineers have been reluctant to use the representative wave approach for computing H_m and $H_{1/10}$. The present study was carried out to investigate the accuracy

of the calculation of the transformation of H_m and $H_{1/10}$ by using the representative wave approach.

COLLECTED LABORATORY DATA

Laboratory data of H_m and $H_{1/10}$ transformations in nearshore zones from four sources totaling 279 cases were collected for calibration and examination of the irregular wave models. A summary of the collected laboratory data is shown in Table 1. The collected data are separated into two groups based on the experimental scale, that is, small-scale and large-scale experiments. The experiments of Smith and Kraus (1990) and Ting (2001) were performed in small-scale wave flumes under fixed bed conditions, while the experiments of Kraus and Smith (1994) and Dette *et al.* (1998) were undertaken in large-scale wave flumes under movable bed (sandy bed) conditions. The data covered a range of deepwater wave steepness (H_{so}/L_o , where H_{so} is the deepwater significant wave height and L_o is the deepwater wavelength) from 0.002 to 0.070. A brief description of the experiments is given below.

The experiment of Smith and Kraus (1990) was conducted to investigate the macro-features of waves breaking over bars and artificial reefs using a small wave flume 45.70 m long, 0.46 m wide and 0.91 m deep. Both regular and irregular waves were employed in this experiment. Three test series (totaling 12 cases)

Table 1 Summary of collected experimental data.

| Source | No. of test series | No. of cases | No. of data | Measured H_{rep} | H_{so} / L_o |
|------------------------------|-----------------------|-----------------|----------------|-----------------------|----------------|
| Smith and Kraus (1990)* | 3 | 12 | 96 | H_m | 0.030-0.070 |
| Ting (2001)* | 1 | 1 | 7 | $H_m, H_{1/10}$ | 0.024 |
| Kraus and Smith (1994)** | 14 | 128 | 2,223 | $H_m, H_{1/10}$ | 0.002-0.064 |
| Dette <i>et al.</i> (1989)** | 8 | 138 | 3,561 | $H_{1/10}$ | 0.010-0.018 |
| Total | 26 | 279 | 5,887 | | 0.002-0.070 |

* = small-scale experiment; ** = large-scale experiment.

H_{rep} = representative wave height; H_m = mean wave height; $H_{1/10}$ = highest one-tenth wave height; H_{so} = deepwater significant wave height; L_o = deepwater wavelength.

were performed for irregular wave tests. Three irregular wave conditions were generated for three bar configurations as well as for a plane beach. A JONSWAP (Hasselmann *et al.*, 1973) computer signal was generated for a spectral width parameter of 3.3 and spectral peak periods of 1.07, 1.56 and 1.75 s with significant wave heights of 0.12, 0.15, and 0.14 m, respectively. Water surface elevations were measured at eight cross-shore locations using resistance-type gauges.

The experiment of Ting (2001) was conducted to study wave and turbulence velocities in a broad-banded, irregular, wave-surf zone. The experiment was performed in a small-scale wave flume, which was 37 m long, 0.91 m wide and 1.22 m deep. A false bottom with a 1/35 slope built of marine plywood was installed in the flume to create a plane beach. The irregular waves were developed from the TMA spectrum (Bouws *et al.*, 1985), with a spectral peak period of 2.0 s, a spectral significant wave height of 0.15 m and a spectral width parameter of 3.3. Water surface elevations were measured at seven cross-shore locations using capacitance-type gauges.

The SUPERTANK laboratory data collection project (Kraus and Smith, 1994) was conducted to investigate cross-shore hydrodynamic and sediment transport processes from 5 August to 13 September 1992 at Oregon State University, Corvallis, Oregon, USA. A 76 m-long sandy beach was constructed in a large wave tank 104 m long, 3.7 m wide and 4.6 m deep. Wave conditions included both regular and irregular waves. In all, 20 major tests were performed and each major test consisted of several cases. Most of the tests (14 test series) were performed under irregular wave actions. The wave conditions were designed to balance the need for repetition of wave conditions to move the beach profile toward equilibrium and to develop a variety of conditions for hydrodynamic studies. The TMA spectral shape (Bouws *et al.*, 1985) was used to design all irregular wave tests. The collected experiments for irregular waves

included 128 cases of wave and beach conditions, covering incident significant wave heights from 0.2 to 1.0 m, spectral peak periods from 3.0 to 10.0 s, and spectral width parameters between 3.3 (broad-banded) and 100 (narrow-banded). Sixteen resistance-type gauges were used to measure water surface elevations across shore.

Four SAFE Project (Dette *et al.*, 1998) activities were carried out to improve the methods of design and performance assessment of beach nourishment, one of which was experiments in a large-scale wave flume in Hannover, Germany. A 250 m-long sandy beach was constructed in a large wave tank 300 m long, 5 m wide and 7 m deep. The test program was divided into two major phases. The first phase (test series A, B, C and H) aimed to study the beach deformation of an equilibrium profile with different beach slope changes. The equilibrium beach profile ($h = 0.12x^{2/3}$) was adopted from the approach by Bruun (1954). In the second phase, the sediment transport behavior of dunes with and without structural aid was investigated (test series D, E, F and G). The TMA spectral shape (Bouws *et al.*, 1985) was used to design all irregular wave tests. The tests were performed under normal wave conditions ($H_{so}/L_o = 0.010$, water depth in the horizontal section = 4.0 m) and storm wave conditions ($H_{so}/L_o = 0.018$, water depth in the horizontal section = 5.0 m). In total, 27 wave gauges were installed over a length of 175 m along one wall of the flume. The experiments included 138 cases of wave and beach conditions.

REGULAR WAVE MODELS

The regular wave height transformation across-shore can be computed from the energy flux conservation (Equation 1):

$$\frac{\partial (Ec_g)}{\partial x} = -D_B \quad (1)$$

where $E = \rho g H^2 / 8$ is the wave energy density,

ρ is the water density, g is the acceleration due to gravity, H is the wave height, c_g is the group velocity, x is the distance in cross shore direction, and D_B is the energy dissipation rate due to wave breaking which is zero outside the surf zone. The energy dissipation rate due to bottom friction is neglected.

The wave height transformation can be computed from the energy flux conservation using Equation 1 by substituting the formula of the energy dissipation rate (D_B) and numerically integrating from offshore to shoreline. The difficulty in using Equation 1 is determining how to formulate the energy dissipation rate caused by the breaking waves.

During the past decades, various models have been developed for computing the energy dissipation of regular wave breaking. Widely used concepts for computing the energy dissipation rate (D_B) of regular wave breaking are the bore concept and the stable energy concept.

The bore concept is based on the similarity between a breaking wave and a hydraulic jump. Several models have been proposed based on slightly different assumptions on the conversion from the energy dissipation of a hydraulic jump to the energy dissipation of a breaking wave. Some existing D_B models, which were developed based on the bore concept, are listed below in Equations 2–4:

a) Battjes and Janssen (1978):

$$D_B = 0.47 \frac{\rho g H^2}{4T} \quad (2)$$

b) Thornton and Guza (1983):

$$D_B = 0.67 \frac{\rho g H^3}{4Th} \quad (3)$$

c) Deigaard *et al.* (1991):

$$D_B = 0.48 \frac{\rho g h H^3}{T(4h^2 - H^2)} \quad (4)$$

where h is the water depth, and T is the wave period, ρ is the water density and g is the acceleration due to gravity. The constants in the above models were calibrated by Rattanapitikon *et al.* (2003), based on a wide range of regular wave conditions.

The stable energy concept was introduced by Dally *et al.* (1985), based on an analysis of the measured breaking wave height on the horizontal slope of the study by Horikawa and Kuo (1966). When a breaking wave enters an area with a horizontal bed, the breaking continues (the wave height decreases) until some stable wave height is attained. The development of the stable energy concept was based on an observation of stable wave height on a horizontal slope. Dally *et al.* (1985) assumed that the energy dissipation rate was proportional to the difference between the local energy flux per unit depth and the stable energy flux per unit depth. Several models have been proposed on the basis of this concept. The main differences are in the formula for computing the stable wave height (for more detail, see Rattanapitikon *et al.*, 2003). Some existing D_B models, which were developed based on the stable energy concept, are listed in Equations 5–9:

a) Dally *et al.* (1985):

$$D_B = 0.15 \frac{\rho g c_g}{8h} \left[H^2 - (0.4h)^2 \right] \quad (5)$$

b) Rattanapitikon and Shibayama (1998):

$$D_B = 0.15 \frac{\rho g c_g}{8h} \left\{ H^2 - \left[h \exp \left(-0.36 - \frac{1.25h}{\sqrt{LH}} \right) \right]^2 \right\} \quad (6)$$

c) Rattanapitikon *et al.* (2003):

$$D_B = 0.15 \frac{\rho g c_g}{8h} \left(H^2 - 0.27 H_b^2 \right) \quad (7)$$

d) Rattanapitikon (2008):

$$D_B = \frac{\rho g H^2 c_g}{8h} \left[0.010 \left(\frac{H_b}{H} \right)^2 - 0.128 \left(\frac{H_b}{H} \right) + 0.226 \right] \quad (8)$$

in which the breaker height H_b is determined from the formula of Miche (1944) as:

$$H_b = 0.142L \tanh(kh) \quad (9)$$

where c is the phase velocity, L is the wavelength, and k is the wave number.

IRREGULAR WAVE MODELS

In the present study, for the representative wave approach, the regular wave model was applied directly to irregular waves by using the representative wave height (H_m and $H_{1/10}$) and the spectral peak period (T_p). The spectral peak period was used because it is the most commonly used parameter and typically is reported for irregular wave data.

Since the D_B formulas shown in Equations 2–8 were developed for regular waves, it is not clear which formula is the most suitable one for computing H_m and $H_{1/10}$. Therefore, all of them were used to investigate the accuracy of the calculation of the transformation of H_m and $H_{1/10}$.

Similar to the regular wave model, the irregular wave model based on the representative wave approach can be computed from the energy flux conservation using Equation 10:

$$\frac{\rho g}{8} \frac{\partial (H_{rep}^2 c_g)}{\partial x} = -D_B \quad (10)$$

where H_{rep} is the representative wave heights (H_m and $H_{1/10}$). The physical explanation of the process for using the representative wave approach is described in Rattanapitikon (2008).

Since the highest wave in an irregular wave train tends to break at the greatest distance from the shore, the initiation of a surf zone of irregular waves tends to occur at a greater distance from the shore than that of regular waves. Therefore, the use of a regular wave

model may give considerable errors in the surf zone. To overcome this problem, the coefficient in the dissipation model of regular waves should be changed to that used to model irregular waves (Rattanapitikon, 2008).

Applying regular wave dissipation models (Equations 2–8) for a representative wave height (H_{rep}) and spectral peak period (T_p), the dissipation models for irregular wave breaking can be expressed as seven models using Equations 11–17, respectively:

$$\text{model (1): } D_B = K_1 \frac{\rho g H_{rep}^2}{4T_p} \quad (11)$$

$$\text{model (2): } D_B = K_2 \frac{\rho g H_{rep}^3}{4T_p h} \quad (12)$$

$$\text{model (3): } D_B = K_3 \frac{\rho g h H_{rep}^3}{T_p (4h^2 - H_{rep}^2)} \quad (13)$$

$$\text{model (4): } D_B = 0.09 \frac{\rho g c_g}{8h} [H_{rep}^2 - (K_4 h)^2] \quad (14)$$

$$\text{model (5): } D_B = 0.09 \frac{\rho g c_g}{8h} \left[H_{rep}^2 - \left(K_5 h \exp \left(-0.36 - 1.25 \frac{h}{\sqrt{LH_{rep}}} \right) \right)^2 \right] \quad (15)$$

model (6):

$$D_B = 0.09 \frac{\rho g c_g}{8h} \left\{ H_{rep}^2 - [K_6 L \tanh(kh)]^2 \right\} \quad (16)$$

model (7):

$$D_B = \frac{\rho g H_{rep}^2 c_g}{8h} \left[0.095 \left(\frac{H_b}{H_{rep}} \right)^2 - 0.263 \left(\frac{H_b}{H_{rep}} \right) + 0.179 \right] \quad (17)$$

where $K_1 - K_6$ are the coefficients. The constants in Equations 14–17 were determined from the pre-calibration. The coefficients for $K_{1/3}$ (from Rattanapitikon, 2008) were used as initial values in the pre-calibration of the models. The pre-calibration revealed that only one coefficient had a substantial effect on the accuracy of each

model. Therefore, only one coefficient in each model was introduced as the adjustable coefficient to allow for the effect of the transformation of other representative wave heights, and the other coefficients were kept as constants. Hereafter, Equations 11–17 are referred to as MD1, MD2, MD3, MD4, MD5, MD6 and MD7, respectively. The variables, c_g , c , L , and k , in the models MD1–MD7 were calculated based on linear wave theory.

When a wave propagates toward a shore, its profile steepens and eventually it breaks. Once the wave starts to break, energy flux is dissipated to turbulence and causes a decrease in wave energy and wave height towards the shore. Hence the primary task is to consider the point where the wave starts to break (incipient wave breaking). Incipient wave breaking is used in an effort to provide the starting point to include the energy dissipation rate (D_B) in the equation of energy flux conservation. In the present study, the formula of Miche (1944) was used to compute the incipient wave breaking height. However, the formula of Miche (1944) was developed for regular wave breaking and so it requires modification before being applied to an irregular wave model. The modification used in the representative wave approach to compute the incipient wave breaking height (H_b) is shown in Equation 18:

$$H_b = K_7 L \tanh(kh) \quad (18)$$

where K_7 is the coefficient. The energy dissipation (D_B) of models MD1–MD7 occurs when $H_{rep} \geq H_b$ and is equal to zero when $H_{rep} < H_b$.

MODEL CALIBRATION

The coefficients in the models MD1–MD7 were calibrated with most of the measured data shown in Table 1 (except the three test series from three data sources) used to calibrate the coefficients ($K_1 - K_7$). The basic parameter for determination of the overall accuracy of the model was the average root-mean-square relative error

(ER_{avg}), which is defined in Equation 19:

$$ER_{avg} = \frac{\sum_{n=1}^m ER_{gn}}{tn} \quad (19)$$

where n is the data group number, ER_{gn} is the root-mean-square relative error of the group number n and tn is the total number of data groups. A small value of ER_{avg} indicates good overall accuracy of the wave model. The root-mean-square relative error of each data group (ER_g) is defined by Equation 20:

$$ER_g = 100 \sqrt{\frac{\sum_{i=1}^{nc} (H_{ci} - H_{mi})^2}{\sum_{i=1}^{nc} H_{mi}^2}} \quad (20)$$

where i is the wave height number, H_{ci} is the computed representative wave height of number i , H_{mi} is the measured representative wave height of number i and nc is the total number of measured representative wave heights in each data group.

The goodness of fit of a model is usually defined using a qualitative ranking (for example, excellent, very good, good, fair and poor). As the error of some existing irregular wave models is in the range 7–21% (see Table 5 of Rattanapitikon, 2007), the qualification of error ranges of an irregular wave model may be classified into five ranges—excellent ($ER_{avg} < 50\%$), very good ($5.0\% \leq ER_{avg} < 10.0\%$), good ($10.0\% \leq ER_{avg} < 15.0\%$), fair ($15.0\% \leq ER_{avg} < 20.0\%$), and poor ($ER_{avg} \geq 20.0\%$)—and the acceptable error should be less than 10.0%.

The transformation of each representative wave height was determined by substituting each dissipation model (MD1–MD7) into Equation 10 and replacing H_{rep} by each representative wave height (H_m and $H_{1/10}$). After that, numerical integration was taken from offshore to the shoreline. The energy dissipation was set to zero in the offshore zone. The incipient wave breaking height was computed from Equation 18. The

backward finite difference scheme was used to solve the differential equations. The input data were the beach profile (h and x), the incident wave height and the spectral peak period. The grid length (Δx) was set to be equal to the length between the measuring points of wave heights, except if $\Delta x > 5$ m, when $\Delta x = 5$ m. The length steps (Δx) used in the present study were 0.2–1.5 m for the small-scale experiments and 2.1–5.0 m for the large-scale experiments.

Most of the measured data shown in Table 1 (except for the three test series from the three data sources) were used to calibrate the models. The data were separated into two groups based on the experiment scale, that is, small-scale and large-scale experiments. The errors of the models were determined from Equations 19 and

20. Calibration of each model was conducted by gradually adjusting the coefficients in the formulas of D_B and H_b until the minimum value for ER_{avg} between the measured and computed representative wave heights was obtained. The calibration of K_7 was carried out simultaneously with the calibrations of K_1 – K_3 for the bore models (MD1–MD3), and with the calibrations of K_4 – K_6 for the stable wave models (MD4–MD7). The optimum coefficients of models MD1–MD7 for H_m and $H_{1/10}$ are shown in Table 2 together with the coefficients for $H_{1/3}$ which were calibrated by Rattanapitikon (2008). The errors of models MD1–MD7 in the simulation of H_m and $H_{1/10}$ are shown in Table 3. The results from Table 3 can be summarized in the following points:

Table 2 Calibrated coefficients (K_1 – K_7) of models MD1–MD7.

| Model | H_m | $H_{1/3}^*$ | $H_{1/10}$ |
|-------|-------------------------------|-------------------------------|-------------------------------|
| MD1 | $K_1 = 0.35$, $K_7 = 0.065$ | $K_1 = 0.34$, $K_7 = 0.098$ | $K_1 = 0.36$, $K_7 = 0.109$ |
| MD2 | $K_2 = 0.64$, $K_7 = 0.065$ | $K_2 = 0.53$, $K_7 = 0.098$ | $K_2 = 0.45$, $K_7 = 0.109$ |
| MD3 | $K_3 = 0.70$, $K_7 = 0.065$ | $K_3 = 0.40$, $K_7 = 0.098$ | $K_3 = 0.38$, $K_7 = 0.109$ |
| MD4 | $K_4 = 0.28$, $K_7 = 0.052$ | $K_4 = 0.42$, $K_7 = 0.076$ | $K_4 = 0.54$, $K_7 = 0.090$ |
| MD5 | $K_5 = 0.80$, $K_7 = 0.052$ | $K_5 = 1.07$, $K_7 = 0.076$ | $K_5 = 1.14$, $K_7 = 0.090$ |
| MD6 | $K_6 = 0.052$, $K_7 = 0.052$ | $K_6 = 0.076$, $K_7 = 0.076$ | $K_6 = 0.090$, $K_7 = 0.090$ |
| MD7 | $K_7 = 0.052$ | $K_7 = 0.076$ | $K_7 = 0.090$ |

* From Rattanapitikon (2008)

H_m = mean wave height; $H_{1/3}$ = significant wave height; $H_{1/10}$ = highest one-tenth wave height.

Table 3 Root-mean-square relative error of the group (ER_g) and the average root-mean-square relative error (ER_{avg}) of models MD1–MD7 in computing wave heights for small-scale and large-scale experiments.

| Mode | H_m | | | $H_{1/10}$ | | |
|------|-------------|-------------|------------|-------------|-------------|------------|
| | ER_g | | ER_{avg} | ER_g | | ER_{avg} |
| | Small-scale | Large-scale | | Small-scale | Large-scale | |
| MD1 | 12.6 | 12.0 | 12.3 | 4.9 | 8.8 | 6.8 |
| MD2 | 10.5 | 11.3 | 10.9 | 4.4 | 7.6 | 6.0 |
| MD3 | 10.5 | 10.6 | 10.5 | 4.3 | 7.9 | 6.1 |
| MD4 | 9.4 | 9.4 | 9.4 | 4.0 | 7.4 | 5.7 |
| MD5 | 8.7 | 10.4 | 9.6 | 4.2 | 6.7 | 5.4 |
| MD6 | 8.4 | 9.5 | 8.9 | 4.0 | 6.9 | 5.4 |
| MD7 | 6.9 | 9.2 | 8.1 | 4.1 | 6.6 | 5.3 |

H_m = mean wave height; $H_{1/10}$ = highest one-tenth wave height.

a) The ascending order for the average error (ER_{avg}) of the selected models in computing H_m was MD7, MD6, MD4, MD5, MD3, MD2 and MD1. The selected models were developed based on two concepts—namely, the bore concept and the stable energy concept. The average errors of the stable energy models (MD4–MD7) were in the range 8.1–9.6%, while the others (MD1–MD3) were in the range 10.5–12.3%. These results indicated that the representative wave approach with the stable energy concept is applicable for computing H_m transformation. The models that gave very good predictions ($ER_g < 10.0\%$) for either small-scale or large-scale experiments are MD4, MD6 and MD7.

b) The ascending order for the average error (ER_{avg}) of the selected models in computing $H_{1/10}$ was MD7, MD5, MD6, MD4, MD2, MD3 and MD1. All models can be used to compute $H_{1/10}$ with very good accuracy ($5.3\% \leq ER_{avg} \leq 6.8\%$). Nevertheless, the stable energy models (MD4–MD7) tended to give better predictions than those of the bore models (MD1–MD3). Among the stable energy models (MD4–MD7), no model had substantially better results than the others ($5.3\% \leq ER_{avg} \leq 5.7\%$).

c) Overall, the representative wave approach with a suitable dissipation model was applicable for computing H_m and $H_{1/10}$. The stable energy models (MD4–MD7) gave better predictions than the bore models (MD1–MD3). The main reason that the stable energy concept

gave better results than the bore concept was that the stable energy concept is able to calculate the wave reformation in the recovery zone while the bore concept gives a continuous dissipation due to wave breaking.

d) The models that gave very good predictions ($ER_g < 10.0\%$) for computing the transformation of H_m and $H_{1/10}$ on small-scale and large-scale experiments were MD4, MD6 and MD7.

e) Considering the overall accuracy of all models for computing H_m and $H_{1/10}$, model MD7 seemed to be the most suitable for computing the representative wave heights. The average errors of the best model (MD7) for computing H_m and $H_{1/10}$ were 8.1 and 5.3%, respectively. These numbers confirm in a quantitative sense the high degree of realism shown by the model outputs. This indicated that the representative wave approach is acceptable to use for computing the transformation of H_m and $H_{1/10}$.

MODEL VERIFICATION

Three test series from three data sources (which each had more than one test series) were used to verify the models. The first test series from each data source was selected for verifying the models. The experimental conditions of the selected data are shown in Table 4. Using the calibrated coefficients in the computations of H_m and $H_{1/10}$ for two level of experiment scale, the

Table 4 Selected experimental data for verifying models MD1–MD7.

| Source | Test series | No. of cases | No. of data | Measured H_{rep} | H_{so} / L_o |
|------------------------------|-------------|--------------|-------------|--------------------|----------------|
| Smith and Kraus (1990)* | 2xxx | 4 | 32 | H_m | 0.068-0.070 |
| Kraus and Smith (1994)** | ST10 | 26 | 416 | $H_m, H_{1/10}$ | 0.013-0.064 |
| Dette <i>et al.</i> (1989)** | A | 22 | 537 | $H_{1/10}$ | 0.010-0.018 |
| Total | | 52 | 985 | | 0.010-0.070 |

* = small-scale experiment; ** = large-scale experiment.

H_{rep} = representative wave height; H_m = mean wave height; $H_{1/10}$ = highest one-tenth wave height; H_{so} = deepwater significant wave height; L_o = deepwater wavelength.

errors of models MD1–MD7 in simulating H_m and $H_{1/10}$ are shown in Table 5. The results can be summarized as follows:

a) The ascending order for the average error (ER_{avg}) of the selected models in computing H_m was MD7, MD6, MD5, MD2, MD4, MD3 and MD1. There was only one model (MD7) that gave very good predictions ($ER_g < 10.0\%$) for either small-scale or large-scale experiments.

b) The ascending order of the average error (ER_{avg}) of the selected models in computing $H_{1/10}$ was MD7, MD6, MD5, MD2, MD3, MD4 and MD1. All models could be used to compute $H_{1/10}$ with very good accuracy ($5.5\% \leq ER_{avg} \leq 7.2\%$).

c) The model that gave very good predictions ($ER_g < 10.0\%$) for computing the transformation of H_m and $H_{1/10}$ in small-scale and large-scale experiments was MD7.

d) The errors in the verification were slightly different from those in the calibration because the number of data points that were used in the calibration and verification were different. However, overall, the results of the verification were similar to those of calibration, that is, the representative wave approach with a suitable dissipation model was applicable for computing H_m and $H_{1/10}$; the stable energy models (MD5–

MD7) gave overall better predictions than the bore models (MD1–MD3); and MD7 gave the best overall prediction.

Although, MD7 was quite realistic in simulating H_m and $H_{1/10}$, the model has certain limitations, which may restrict its use. The limitations of the model can be listed as follows.

a) As the swash zone processes are not included in the model, the model is limited to use in the nearshore zone (excluding swash zone).

b) Because the representative wave height is computed by a simple expression of energy flux conservation, the model is limited to use on open coasts away from river mouths and coastal structures.

c) As the model is an empirical model, its validity may be limited according to the range of experimental conditions which were employed in the calibration. The model should be applicable for deepwater wave steepness (H_{so} / L_o) ranging between 0.002 and 0.070.

d) It is not clear whether the model can be applied to real ocean situations or not because the model has not been verified with field data. However, there is a high possibility that it can be successfully applied to model real coasts or real oceans because the large-scale experiments had a scale approximately the same as the conditions

Table 5 Verification results of the models MD1–MD7 in computing wave heights for small-scale and large-scale experiments (using calibrated constants).

| Models | H_m | | | $H_{1/10}$ | | |
|--------|-------------|-------------|------------|-------------|-------------|------------|
| | ER_g | | ER_{avg} | ER_g | | ER_{avg} |
| | Small-scale | Large-scale | | Small-scale | Large-scale | |
| MD1 | 24.3 | 7.4 | 15.8 | - | 7.2 | 7.2 |
| MD2 | 14.6 | 6.4 | 10.5 | - | 6.4 | 6.4 |
| MD3 | 20.1 | 6.1 | 13.1 | - | 6.5 | 6.5 |
| MD4 | 16.8 | 4.7 | 10.8 | - | 6.8 | 6.8 |
| MD5 | 12.5 | 6.7 | 9.6 | - | 5.9 | 5.9 |
| MD6 | 10.9 | 4.8 | 7.9 | - | 5.8 | 5.8 |
| MD7 | 9.8 | 4.8 | 7.3 | - | 5.5 | 5.5 |

ER_g = root-mean-square relative error of the group; ER_{avg} = the average root-mean-square relative error; H_m = mean wave height; $H_{1/10}$ = highest one-tenth wave height.

in the ocean. Moreover, some researchers (for example, Wise *et al.*, 1996; and Rattanapitikon and Shibayama, 1998) have shown that models developed based on large-scale experiments could be applied directly to real ocean waves.

CONCLUSION

This study was carried out to investigate the accuracy of the calculation of the transformation of H_m and $H_{1/10}$ by using the representative wave approach. The representative wave height transformation was computed from the energy flux conservation law. The selected seven dissipation models of regular waves breaking were directly applied to the irregular waves by using the representative wave heights (H_m and $H_{1/10}$). The breaking criterion of Miche (1944) was applied to compute the incipient breaker height. In total, 279 cases from four sources of published experimental results were used to calibrate and verify the models. It was found that by using an appropriate dissipation model, the representative wave approach could be used to compute the transformation of H_m and $H_{1/10}$ with very good predictions. The best model (MD7) gave very good predictions ($ER_g < 10.0\%$) for computing the transformation of H_m and $H_{1/10}$ in small-scale and large-scale experiments. However, the model is limited to use in the nearshore zone (excluding the swash zone), open coasts and for deepwater wave steepness (H_{so} / L_o) ranging between 0.002 and 0.070.

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