Coastal Engineering, 16 (1992) 165–179
Elsevier Science Publishers B.V., Amsterdam

An evaluation of expressions for wave energy dissipation due to bottom friction in the presence of currents

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(Received 4 April 1990; revised and accepted 27 February 1991)

ABSTRACT

Tolman, H.L., 1992. An evaluation of expressions for wave energy dissipation due to bottom friction in the presence of currents. *Coastal Eng.*, 16: 165–179.

The effects of a mean current on wave energy dissipation due to bottom friction is investigated. A re-analysis of published measurements shows that current influences on wave energy dissipation are much smaller than suggested by the current-induced variations of the friction factor for the combined wave-current motion. Available models for the combined wave-current boundary layer predict effects of currents on wave energy dissipation with the wrong trend (in contrast with previous conclusions, based on the behaviour of the above friction factor). It follows that, surprisingly, the (presently) most suitable way to describe the effects of currents appears to be to neglect the explicit effects of them on wave energy dissipation.

INTRODUCTION

Generation and dissipation of random, short-crested wind waves is commonly described in terms of a spectral energy or action balance equation. This study deals with the corresponding source term for wave energy dissipation due to bottom friction. For many practical conditions friction is the major source of wave energy dissipation due to wave bottom interactions (e.g., Shemdin et al., 1978; Weber, 1989). Several expressions for such a source term are available for cases without mean currents (e.g., Hasselmann and Collins, 1968; Collins, 1972; Graber, 1984; Madsen et al., 1988; Weber, 1989), but not for cases with mean currents. Such currents are potentially important for wind wave propagation and generation, as is illustrated by Tolman (1988, 1990) for wind waves on tides in shelf seas.

Because theoretical models and laboratory observations for current-in-

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duced variations of wave energy dissipation for monochromatic waves are available, such waves are considered here. Theories have been published by Grant and Madsen (1979), Christoffersen (1982) and Christoffersen and Jonsson (1985). However, they have not been validated thoroughly due to a shortage of high-quality experimental data.

In this study some published laboratory measurements for monochromatic unidirectional waves are re-analyzed with respect to the effects of currents on the (local) wave energy dissipation. Only those data are considered, which directly interrelate bottom friction and wave height attenuation/wave energy dissipation. Measurements of the near-bottom velocity field only will not be used, because the derivation of wave height attenuation rates from the boundary flow field incorporates assumption, the effects of which cannot be verified. The re-analysis suggests that the effects of currents appear to be opposite to the effects as predicted by the theoretical models considered here. Furthermore, effects of currents on wave energy dissipation seem to be much smaller than the potential effects of dynamic variation of the roughness length scale of movable beds. It is therefore presently not useful to consider wave-current bottom boundary layer models for irregular, short-crested waves.

GENERAL FORMULATION

Bottom shear stress parameterizations

Bottom friction is commonly formulated in terms of a quadratic friction law. For pure waves (no current) and pure currents (no waves) the following formulations are often used:

$$\vec{\tau}_w = \frac{1}{2}\rho f_w \vec{u}_b \,|\vec{u}_b| \tag{1}$$

$$\vec{\tau}_c = \frac{1}{2}\rho f_c \vec{U}\,|\vec{U}| \tag{2}$$

where $\vec{\tau}_w$ is the instantaneous bottom shear stress for waves only, $\vec{\tau}_c$ is the bottom shear stress for current only, f_w and f_c are the corresponding friction factors, $\vec{u}_b$ is the near-bottom orbital velocity of the waves just outside the wave boundary layer and $\vec{U}$ is the mean current velocity, averaged over depth.

If waves on currents are considered, two different parameterizations of the instantaneous bottom shear stress are frequently used. In the first, the instantaneous bottom friction vector is related to the velocity due to both the current ($\vec{U}$) and the waves ($\vec{u}_b$), using a friction factor f_{cw}:

$$\vec{\tau} = \frac{1}{2}\rho f_{cw}(\vec{U}+\vec{u}_b)\,|(\vec{U}+\vec{u}_b)| \tag{3}$$

The friction factor f_{cw} is a function of both wave and current parameters (e.g., Grant and Madsen, 1979). In the second parameterization the instantaneous bottom friction vector consists of a mean friction, determined by the average current velocity, and a fluctuating component, determined by the near-bottom orbital velocity (Christoffersen, 1982):

$$\vec{\tau}=\frac{1}{2}\rho f_c^* \vec{U}|\vec{U}|+\frac{1}{2}\rho f_w^* \vec{u}_b|\vec{u}_b| \tag{4}$$

In this equation f_c^* and f_w^* are friction factors for the mean and the fluctuating motion, respectively. Both friction factors incorporate wave and current influences. In the following, the approached leading to the first parameterization for the instantaneous bottom friction will be denoted as the integral approach; the second one will be denoted as the separate approach. Note that $f_c=f_c^*=f_{cw}$ in cases with currents only and that $f_w=f_w^*=f_{cw}$ in cases with waves only.

Energy dissipation

Independent of the parameterization of the bottom shear stress, the average dissipation of energy D (per unit time and unit bed area) of the combined wave-current system is given as (e.g., Kajiura, 1968; Hasselmann and Collins, 1968):

$$D=\langle\vec{\tau}\cdot(\vec{U}+\vec{u}_b)\rangle \tag{5}$$

where $\langle..\rangle$ denotes an average over time. Because $\langle\vec{u}_b\rangle\equiv0$, the total dissipation can be divided in a mean current energy dissipation D_c, and a wave energy dissipation D_w (Christoffersen, 1982):

$$D=\langle\vec{\tau}\rangle\cdot\vec{U}+\langle\vec{\tau}\cdot\vec{u}_b\rangle\equiv D_c+D_w \tag{6}$$

Whereas the above division of the total energy dissipation into wave and current energy dissipation is generally applicable, expressions for D_w (and D_c) depend on the parameterization of the bottom shear stress as is shown below. For a later comparison with expressions for a case without currents, such a case is considered first.

For cases without currents the mean wave energy dissipation can be determined directly from Eqs. 1 and 6 as (Putman and Johnson, 1949):

$$D_w=\frac{2}{3}\pi^{-1}\rho f_w u_{bm}^3 \tag{7}$$

where u_{bm} is the maximum near-bottom orbital velocity of the waves. This equation has been derived assuming that the orbital velocity $\vec{u}_b$ varies sinusoidally in time and that $\vec{u}_b$ and the fluctuating part of the bottom friction $\vec{\tau}$ are in phase. The same assumptions will be used below.

Using a separate approach for waves on currents, the mean wave energy dissipation can be determined directly froms Eqs. 4 and 6 (Christoffersen, 1982):

$$D_{\mathrm{w}} = \frac{2}{3}\pi^{-1}\rho f^{*}_{\mathrm{w}} u^{3}_{\mathrm{bm}} \tag{8}$$

This expression is similar to that for waves only (Eq. 7), the only difference being the friction factor (f^{*}_{w} or f_{w}). Because all current influences on D_{w} are gathered in the friction factor f^{*}_{w}, the effects of currents on wave energy dissipation can be assessed simply by comparing the friction factors f^{*}_{w} for cases with currents with the friction factor f_{w} for cases without currents.

In the integral approach the wave energy dissipation D_{w} has to be calculated indirectly as $D_{\mathrm{w}} = D - D_{\mathrm{c}}$ (Eq. 6) using Eqs. 3 and 5. Following Brevik and Aas (1980) and Brevik (1980), the wave energy dissipation becomes:

$$D_{\mathrm{w}} = \frac{1}{2}\rho f_{\mathrm{cw}} U^{3} f(\gamma), \qquad \gamma = \frac{U}{u_{\mathrm{bm}}} \tag{9}$$

where $f(\gamma)$ accounts for the time averaging (see e.g., Brevik and Aas, 1980, p. 168). Expressions for $f(\gamma)$ depend on the value of γ:

$$f(\gamma) = \frac{4}{3}\pi^{-1}\gamma^{-3} \qquad \text{for } \gamma\downarrow 0 \tag{10a}$$

$$f(\gamma) = \pi^{-1}\left[\gamma^{-2}\arccos(1-2\gamma^{2}) + \frac{2}{3}(\gamma^{-1}+2\gamma^{-3})\sqrt{1-\gamma^{2}}\right] \qquad \text{for } 0<\gamma<1 \tag{10b}$$

$$f(\gamma) = \gamma^{-2} \qquad \text{for } \gamma>1 \tag{10c}$$

For cases without currents (i.e. $\gamma=0$) Eqs. 9 and 10a are equivalent to Eq. 7, because $f_{\mathrm{cw}} = f_{\mathrm{w}}$ in such cases. In cases with current, effects of currents arise both explicitly in Eq. 9 through U and $f(\gamma)$ and implicitly through f_{cw}. Using the integral approach, the effects of currents on wave energy dissipation can only be assessed by considering the ratio of D_{w} of Eqs. 9 and 7, which equals:

$$\frac{\frac{3}{4}\pi\gamma^{3} f(\gamma) f_{\mathrm{cw}}}{f_{\mathrm{w}}} \tag{11}$$

In several publications (e.g., Grant and Madsen, 1979; Simons et al., 1988), however, only the relation between f_{cw} and f_{w} is assessed instead of the ratio (11). This is obviously misleading with respect to the influence of currents on wave energy dissipation. Note that the ratio (11) simply equals $f^{*}_{\mathrm{w}}/f_{\mathrm{w}}$ because Eqs. 8 and 9 show that:

$$f_{\mathrm{w}}^{*}=\frac{3}{4}\pi\gamma^{3}f(\gamma)f_{\mathrm{cw}} \tag{12}$$

FRICTION FACTORS FOR MONOCHROMATIC WAVES

Extensive research on friction factors for monochromatic waves has been reported in the literature. Situations with and without currents are considered, both from a theoretical and an experimental point of view. In the following the theory for waves without currents is reviewed first to illustrate the behaviour of f_{w} as a function of wave conditions. Secondly, available theories for boundary layers and friction factors for monochromatic waves on currents are reviewed briefly. In papers on laboratory experiments for such cases, the friction factor f_{cw} of the integral approach is usually assessed. As shown in the previous section this is misleading in the present context. Therefore available measurements are re-analyzed to obtain friction factors f_{w}^{*} of the separate approach.

Theories for wave bottom boundary layers

The nature of the flow in a wave bottom boundary layer depends on the near-bottom amplitude Reynolds number and the relative amplitude $a_{\mathrm{b}}/k_{\mathrm{N}}$, where a_{b} is the near-bottom excursion amplitude and k_{N} is the roughness length scale of the bottom. For most practical conditions the type of flow is usually assumed to be rough turbulent (e.g., Kamphuis, 1975, 1978; Jonsson, 1966a, 1978, 1980), in which case the wave friction factor is independent of the Reynolds number and is a function of the relative amplitude $a_{\mathrm{b}}/k_{\mathrm{N}}$ only. Many theoretical and empirical expressions for the relation between the relative amplitude and the friction factor have been presented. Reviews of early work are given by Kamphuis (1975, 1978) and Jonsson (1966a, 1978, 1980). Early expressions for friction factors were mainly empirical, or based on time-invariant eddy viscosity models. The most consistent and detailed theory of this sort is probably given by Kajiura (1968), who used a time-invariant three layer eddy viscosity model. For rough beds Kajiura obtained:

$$\frac{1}{4.05\sqrt{f_{\mathrm{w}}}}+\log_{10}\frac{1}{4\sqrt{f_{\mathrm{w}}}}=-0.254+\log_{10}\frac{a_{\mathrm{b}}}{k_{\mathrm{N}}} \tag{13}$$

This expression is similar to the commonly used semi-empirical expression of Jonsson (1963, 1966a) and Jonsson and Carlsen (1976):

$$\frac{1}{4\sqrt{f_{\mathrm{w}}}}+\log_{10}\frac{1}{4\sqrt{f_{\mathrm{w}}}}=-0.08+\log_{10}\frac{a_{\mathrm{b}}}{k_{\mathrm{N}}} \tag{14}$$

For the above theories to be valid, a velocity overlap layer has to exist, so that a_b/k_N has to be larger than approximately 30 (Kajiura, 1968). In practice however, the results are reasonably accurate for smaller relative amplitudes, i.e., down to approximately 1. If a_b/k_N becomes smaller than some critical value ($\cong 1$), the application of a constant value of f_w is suggested by several authors ($f_{w,max}=0.30$ by Jonsson, 1978; $f_{w,max}=0.25$ by e.g., Kajiura, 1968 and Grant and Madsen, 1982). The critical value of a_b/k_N then is determined from $f_{w,max}$ and the actual expression for $f_w(a_b/k_N)$.

Equations 13 and 14 (and similar semi-empirical relations) show a reasonable agreement with measurements, as illustrated in many papers (e.g. Kamphuis, 1975, Fig. 8; Jonsson, 1980, Fig. 7; Myrhaug, 1989, Fig. 1). For small values of a_b/k_N (e.g., <10), Eq. 13 generally gives smaller friction factors than observed, whereas Eq. 14 results in larger values. Note that the above rough turbulent approach is not valid for sheet flow conditions, as recently found by Wilson (1989), making the above approach not valid for rough wave conditions over sandy bottoms in shallow water.

In spite of the good agreement between measured and theoretical friction factors, the physics of the wave bottom boundary layer are still not completely understood. Recently, more sophisticated models have been proposed including time varying eddy viscosity models (e.g., Fredsøe, 1984; Justesen, 1988). Such models, however, lead to qualitatively similar relations between the friction factor and the relative amplitude, as is shown by e.g. Justesen (1988, Fig. 4).

Because reasonably accurate expressions for the wave friction factor f_w are available, the major problem in obtaining values of friction factors for practical situations is the estimation of the roughness length scale k_N, in particular for movable beds. Due to ripple formation the bottom roughness k_N varies dramatically and the friction factor f_w can vary by an order of magnitude or more (Grant and Madsen, 1982; Graber and Madsen, 1988). The estimation of the bottom roughness has therefore a potentially much larger impact on the calculated friction factors than the selection of the actual expression to calculate f_w from a_b/k_N.

Theories for wave-current bottom boundary layers

Bottom boundary layers, friction factors and energy dissipation for a combined wave-current system have been studied extensively in the last decades. A review of early publications is given by Peregrine and Jonsson (1983, their section II.6). The most elaborate theories are those of Grant and Madsen (1979) (integral approach), Christoffersen (1982) and Christoffersen and Jonsson (1985) (separate approach). These theories are based on time-invariant two-layer eddy viscosity models. The two layers represent a highly turbulent wave boundary layer, which is relatively thin compared to the depth, and a less turbulent current boundary layer over the entire depth. The above theories use different sets of expressions to describe the eddy viscosity distribution over the depth, resulting in slightly different friction factors. The theories in general result in a set of approximately ten equations which can be solved iteratively using simple algorithms.

The behaviour of wave friction factors for such models is illustrated by Christoffersen and Jonsson (1985). In these theories a significant increase of the current friction factor f_c^* (Eq. 4) occurs if waves are superimposed on currents. Furthermore these theories show an increase of the wave friction factor f_w^* with increasing relative current velocity γ (for following currents) and with increasing relative amplitude a_b/k_N.

In addition to these rather complex theories, a simple interpolation formula for the wave-current friction factor f_{cw} of the integral approach has been suggested by Jonsson (1966b):

$$f_{cw} = \frac{f_w + \gamma f_c}{1+\gamma} \tag{15}$$

in which f_w is determined ignoring the current using e.g., Eq. 14 and f_c is determined ignoring the waves using e.g.:

$$\sqrt{\frac{2}{f_c}} = \frac{1}{\kappa} \ln \frac{11d}{k_N} \tag{16}$$

where κ ($\cong 0.4$) is the von Kármán constant and d is the mean water depth (average over the wave period). Using Eqs. 12 and 10 the corresponding friction factor f_w^* of the separate approach can be determined.

The above theories have not been validated thoroughly, due to the limited availability of boundary layer data for waves on currents. Furthermore, to the knowledge of the present author, the validity of the models has been checked using friction factors f_{cw} of the integral approach only. As discussed above, the effects of currents on wave energy dissipation and the validity of expressions for friction factors are more correctly assessed using ratio (11) or simply the friction factor f_w^* of the separate approach. Therefore the available data have been re-analyzed to obtain friction factors f_w^* of the separate approach.

Measurements of attenuation of waves on currents

Wave friction factors in experiments are usually determined using measured wave height attenuation rates. Several problems occur in such measurements. Usually attenuation rates are small, which makes the relative uncertainty (and therefore the scatter) in the results large. This uncertainty is enhanced by the occurrence of reflected waves and by side wall friction. Finally most available measurements consider conditions for which the Reynolds number is in the transition zone from smooth turbulent to rough turbulent flow, which also hampers the interpretation of the results.

Wave friction factors can be derived from the wave height attenuation rates by applying the linear wave theory in a wave energy balance equation assuming a stationary and homogeneous current and depth (and small Froude number), as in:

$$D_{\mathrm{w}}=\frac{2}{3}\pi^{-1}\rho f_{\mathrm{w}}^{*}u_{\mathrm{bm}}^{3}=-\frac{\mathrm{d}}{\mathrm{d}x}\left[(c_{\mathrm{g}}+U)\frac{1}{8}\rho gH^{2}\right] \tag{17}$$

which gives:

$$f_{\mathrm{w}}^{*}=-\frac{3}{8}\pi g(c_{\mathrm{g}}+U)u_{\mathrm{bm}}^{-3}H\frac{\mathrm{d}H}{\mathrm{d}x} \tag{18}$$

In these equations c_{g} is the energy propagation velocity in a frame of reference moving with the current, k is the wavenumber and σ is the relative or intrinsic angular frequency (observed in a frame of reference which moves with the mean current velocity). In the linear (uniform-) wave theory these parameters are related as:

$$\sigma=\sqrt{gk\tanh kd}=\omega-\vec{k}\cdot\vec{U} \tag{19}$$

$$c_{\mathrm{g}}=\frac{\sigma}{k}n,\qquad n=\frac{1}{2}+\frac{kd}{\sinh 2kd} \tag{20}$$

where ω is the absolute angular frequency, as observed in a fixed frame of reference. Some authors (e.g., Simons et al., 1988) have calculated values for f_{w} and f_{cw} using an approach equivalent to the use of Eqs. 18, 12 and 10 and using measured values of $H\,(\mathrm{d}H/\mathrm{d}x)$ and u_{bm}. Another approach (e.g., Brevik, 1980) is to substitute the linear theory expression for u_{bm} in Eq. 18, which after further elaboration results in:

$$f_{\mathrm{w}}^{*}=3\pi g(c_{\mathrm{g}}+U)\left[\frac{\sinh kd}{\sigma}\right]^{3}\frac{\mathrm{d}}{\mathrm{d}x}H^{-1} \tag{21}$$

The latter approach is more suitable for use in this study than the former, because the friction factor is thus calculated using a method which is analogous to the method used in predictive wave models. Therefore observed friction factors presented below have been calculated using Eq. 21 from observed wave height attenuation rates.

Measurements of attenuation of waves on currents are presented by Brevik and Aas (1980), Brevik (1980), Kemp and Simons (1982, 1983) and Simons et al. (1988). Of these data the smooth bed results of Brevik and Aas (1980) are not of interest in this study, because smooth beds are not expected to occur in natural conditions. The remaining publications consider friction factors f_{cw} for rough beds. Before the data are re-analyzed, the quality of these data will be discussed.

Brevik (1980) presents friction factors (f_{cw}) for four cases, including cases with waves propagating with or against the current. Brevik (1980) claims that the observational error in the friction factors is less than 10% to 20%. However, the large scatter in the observed wave heights (Brevik, 1980, Fig. 8) makes the determination of wave height attenuation rates rather arbitrary. Kemp and Simons (1982, 1983) consider three current conditions, with waves on following currents, on opposing currents or without currents. The cases with following current show a large scatter in observed wave heights compared to the wave height decay. The cases with opposing current show good quality results (i.e., small scatter in observed wave heights, see, e.g., Kemp and Simons, 1983, Fig. 5). Simons et al. (1988) present data for several cases with waves on following currents ($T_a = 2\pi/\omega = 0.7$ s or 1.0 s). The quality of these data for $T_a = 0.7$ s deteriorates with the increase of the current velocity (see Simons et al., 1988, Fig. 4). The quality of the data for $T_a = 1.0$ s cannot be assessed from data presented in the paper. Simons et al. find extremely high wave friction factors [$f_w = O(10)$] for small relative amplitude [$a_b/k_N = O(0.1)$] for cases without currents. Whereas these factors show good agreement with Jonsson's formula (Eq. 14), they are suspect because they are far out of the range of applicability of Jonsson's formulation as discussed above and because they are in conflict with previous data of e.g., Bagnold (1946, no currents). They are also suspect because their (measured) velocities u_{bm} deviate strongly from the linear theory. For the above reasons the re-analysis will be limited to the cases with opposing currents Kemp and Simons (1982, 1983) (henceforth denoted as KS), the cases with following currents of Simons et al. (1988) (henceforth denoted as SGK) and all corresponding cases without currents. Friction factors for the experiments of KS and SGK are (re-)calculated to assess the influence of currents on wave energy dissipation and to assess the quality of theoretical models for the wave-current boundary layer with respect to wave energy dissipation. The wave friction factor f_w^* is calculated using Eq. 21 and measured wave heights and attenuation rates as tabulated by KS and SGK. The wave-current friction factor f_{cw} is (re-)calculated for a comparison with f_w^*, using the recalculated value of f_w^* and Eqs. 12 and 10.

In Fig. 1 friction factors f_{cw} and f_w^* for the experiments of KS and SGK are presented. The behaviour of the friction factor f_{cw} of the integral approach (Fig. 1a) might suggest a strong influence of currents on wave energy dissipation (as concluded by SGK). However, as discussed above, this friction factor does not incorporate all of the effects of currents on the local wave energy dissipation, unlike f_w^* of the separate approach. Values of f_w^* as presented in Fig. 1b show much smaller spread (for given a_b/k_N) than f_{cw}. Con-

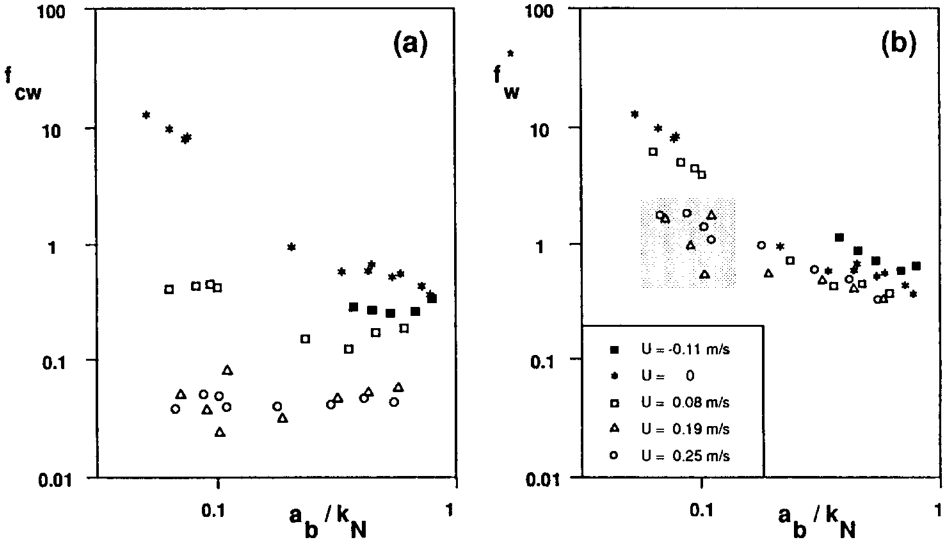

Fig. 1. Friction factors as recalculated from the data of Kemp and Simons (1982, 1983) and Simons et al. (1988). (a) f_{cw} of the integral appraoch; (b) f^*_w of the separate approach. The shaded area in (b) shows results of Simons et al. for $T_a = 0.7$ s and $U > 0.08$ m/s.

sequently, the effect of the currents on wave energy dissipation are much smaller than suggested by f_{cw}.

Nevertheless, the friction factor f^*_w of Fig. 1b still shows a considerable spread which appears to be current related. Compared to the zero-current case, f^*_w is larger for opposing currents and smaller for following currents (for a given relative amplitude a_b/k_N). The no-current data shows little scatter and shows reasonable agreement with Eqs. 13 and 14 (as concluded by KS and SGK). However, in particular the friction factors for relative amplitudes a_b/k_N of O(0.1) are suspect, as discussed above. The observed friction factors for opposing currents seem to have a clear trend without much scatter (note that the small data sample might be responsible for this). For the following current cases with $a_b/k_N > 0.12$ (corresponding to the experiment of SGK with $T_a = 1.0$ s) the scatter in the friction factors for a given current velocity seems small, suggesting that the data is of good quality (note that the quality of this data could not be assessed from the original paper). This data does not present any proof of increasing effects of currents with increasing current velocities, as would be expected. For the following current cases with $a_b/k_N < 0.12$ (corresponding to the experiment of SGK with $T_a = 0.7$ s) there is a considerable spread in friction factors, in particular for $U = 0.19$ m/s (triangles). This is probably related to the large spread in wave heights along the flume for the experiments of SGK with $T_a = 0.7$ s and $U > 0.08$ m/s (Simons et al., 1988, Fig. 4). On the one hand, the rejection of this potentially poor quality data (shaded area in Fig. 1b) would remove all proof of an increase in current effects with increasing current velocity and of large effects of currents on wave energy dissipation. On the other hand the shaded area shows friction factors which are nearly an order of magnitude smaller than the (presumably good quality) data for cases with $U=0.08$ m/s. Inspection of Fig. 4 of Simons et al. (1988) shows that it is unlikely that such a difference is caused by the observed scatter of wave heights only [note that the friction factor is linearly related to $H(\partial H/\partial x)$].

From these considerations it is nearly impossible to draw any firm conclusions from the data in Fig. 1b; there seems to be a consistent increase of friction factors for opposing current and a decrease with following currents. However, the data does not seem to allow conclusions on the expected increase of effects with increasing current velocities.

To assess the quality of theoretical models for wave-current boundary layers with respect to wave energy dissipation, the friction factors f^*_w have been predicted using two models. The first is the model of Grand and Madsen (1979), re-formulated by Christoffersen (1982) (Fig. 2b, expressions not given here). This model is fairly representative for two-layer, time-invariant eddy viscosity models (see e.g., Christoffersen and Jonsson, 1985); it results in friction factors f^*_w. The second model is the simple interpolation formula of Jonsson (1966b, see Eq. 15 and Fig. 2b), resulting in friction factors f_{cw}. Values of f^*_w for the second model are calculated using Eqs. 12 and 10. Note that both models reduce to Eq. 14 for cases without currents.

Figure 2 shows that both models considered here predict an increase of the friction factor f^*_w compared to the zero-current cases (f_w, dotted line) for following currents. The observed friction factors of Fig. 1b show exactly the opposite behaviour; the models seem to predict influences of following currents on wave energy dissipation with a wrong trend. The same applies to the Grant and Madsen (1979) model for opposing currents, whereas the interpolation formula 15 shows good results for opposing currents. Note that several authors (e.g., SGK) conclude that similar models describe the observed effects of currents qualitatively correct by comparing friction factors f_{cw} of the integral approach (cf. Fig. 1a). This is misleading with respect to the quality of models if wave energy dissipation is considered.

Because the theoretical models mentioned above show a systematically wrong trend of the effects of the currents on wave energy dissipation, better results are obtained by calculating f^*_w according to Eq. 14, which does not contain explicit contributions of the current (or any similar formulation, e.g., Myrhaug, 1989). Note that if the explicit effects of currents on the wave boundary layer are neglected, the dynamic variation of f_w as a function of wave conditions still incorporates implicit current effects, through current-induced variations of the relative amplitude a_b/k_N. The wave height attenuation rate dH/dx is furthermore influenced by current-induced variations

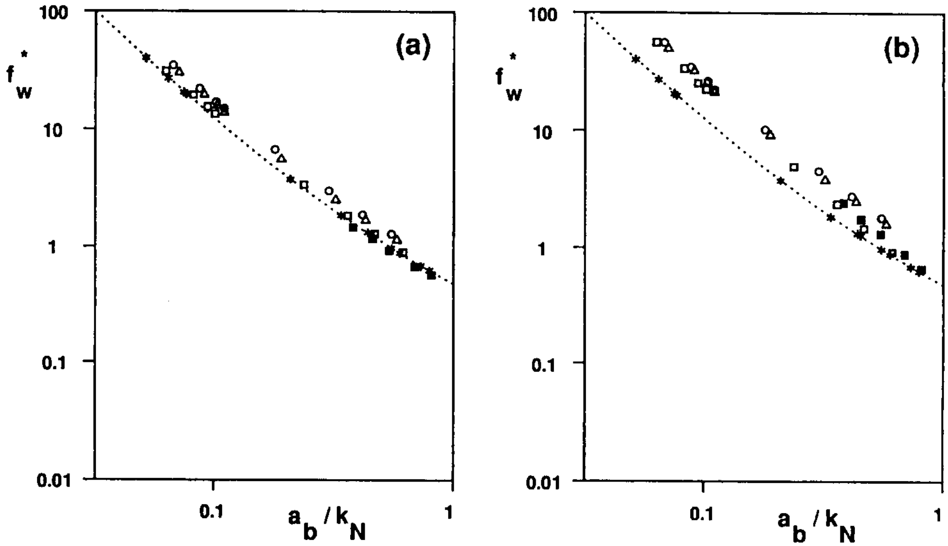

Fig. 2. Friction factors of the separate approach for the experimental conditions of Kemp and Simons (1982, 1983) and Simons et al. (1988) as predicted by (a) the model of Grant and Madsen, 1979, (Christoffersen, 1982) and by (b) Jonsson's (1966b) interpolation formula (15). Symbols as in Fig. 1; dotted line = Eq. 14 (no currents).

of the convection velocity $c_g + U$, the near-bottom orbital velocity u_{bm} and the wave height H (see Eq. 18).

DISCUSSION

Wave energy dissipation due to bottom friction has been investigated extensively, but it is still poorly understood, in particular when waves on currents are considered.

A re-analysis of some published (laboratory) measurements for monochromatic waves on homogeneous and stationary currents indicate that opposing currents increase friction factors and that following currents decrease friction factors. It is, however, difficult to assess the magnitude of current influence on friction factors from data; conclusions are strongly influenced by data selection criteria. If the data in the shaded area of Fig. 1b are rejected, the current-induced effects on friction factors are moderate. For a given relative amplitude the difference between friction factors for the strongest following and opposing currents is no more than a factor of 2 to 3. Adding the data from the shaded area, however, results in an order of magnitude difference in friction factors for $a_b/k_N = O(0.1)$. These relative amplitudes, however, represent a very extreme range of this non-dimensional parameter. The least extreme data at the right hand side of Fig. 1b suggest that one might expect relatively small effects of currents on wave energy dissipation in more practical conditions. Furthermore the data used here considered extremely current dominated conditions ($1 < |U/u_{bm}| < 20$, SGK). If currents have a small influence on the wave boundary layer in current-dominated conditions, this can be expected to be even more so for wave-dominated conditions. In practical conditions the bottom-induced wave energy dissipation will be important only in such wave-dominated (i.e. shallow water) conditions.

Observed current-induced variations of the wave friction factor cannot be predicted by the available theories. In fact, theories like those of Grant and Madsen (1979) appear to predict current influences that are systematically opposite to observed influences. Consequently, wave energy dissipation in a combined wave-current system is better described by neglecting explicit effects of the current on the wave boundary layer altogether (i.e. $f_w^* = f_w$), than by using one of the presently available theoretical models as discussed here. The fact that such an approach is feasible indicates that the low-intensity turbulence of the mean current has only a small effect on the highly turbulent wave boundary layer.

The poor performance of models for the combined wave-current bottom boundary layer obviously calls for detailed investigations. However, because effects of currents on wave energy dissipation appear to be relatively small (at least model predictions), the major problem in the estimation of friction factors remains the determination of the bottom roughness length scale, in particular where ripple formation (or sheet flow) is expected to occur. In view of its large impact, the latter subject is deemed to deserve the main attention in future research.

Considering the above results for monochromatic waves, it appears presently neither necessary nor feasible to incorporate explicit effects of currents on the wave boundary layer in spectral wave models.

CONCLUSIONS

Re-analysis of available for wave energy dissipation on current show that (a) such an analysis is difficult and that several results are sensitive to data selection, (b) effects of currents on wave energy dissipation appear to be much smaller than suggested by previously published friction factors f_{cw} of the combined wave-current field and (c) opposite currents tend to increase wave friction factors whereas following currents decrease it. Sophisticated wave-current boundary layer models predict current effects on wave energy dissipation opposite to the above trends, contrary to what might be concluded from an analysis of f_{cw} only. In view of the apparent magnitude of interactions and the behaviour of available models it seems presently feasible nor necessary to incorporate effects of current on the wave boundary layer in wind wave prediction models.

ACKNOWLEDGEMENTS

The author wishes to thank J.A. Battjes and L.H. Holthuijsen of the Delft University of Technology, I.G. Jonsson of the ISVA (Technical University of Denmark), R.R. Simons of University College London and D.G. Duffy of NASA/GSFC for their useful comments and discussion. Part of this manuscript has been written while the author held a National Research Council-NASA Research Associateship.

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