CHAPTER 42

ON THE ATTENUATION OF WAVES PROPAGATING WITH A CURRENT

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Abstract

In this paper, the mechanisms which dissipate the energy of waves propagating on a current are considered. It is shown that the surface slope of an actual uniform current plays an important part for the variation of wave height attenuation rates with the intensity of the current. The surface slope enhances the attenuation of waves propagating on an opposing current and weakens it for a following current. It is also shown that, as the wave attenuation rate increases in stronger opposing currents, it affects the change in height of waves on a gradually varying opposing current to such an extent that we can not ignore the effect.

1 INTRODUCTION

When waves propagate on an opposing uniform current, the rate of wave height attenuation increase with the current velocity. Iwasaki and Sato(1972; hereafter referred to as IS) attempted to explain the increase of the wave height attenuation through the dissipation of wave energy due to the work done by internal and boundary shear stresses.

On the other hand, it has been pointed out that, when waves propagate on a following current, the wave attenuation rate decreases as the strength of the superimposed following current increases. Kemp and Simons(1983) and Simons et al. (1988) provided experimental results which showed the reduction of wave height attenuation rates on following currents.

The objective of this paper is to provide a theoretical explanation for the reduction of the wave attenuation rates on following currents together with the increase of ones on opposing currents.

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2 WAVE HEIGHT CHANGE ON A UNIFORM CURRENT

Problems on coexisting system of waves and currents have been treated frequently in an unrealistic situation of horizontal bed and uniform depth. However, when the bottom is horizontal, the depth of a flow changes in the flow direction and a uniform flow is not possible in real fluid.

Before going to the main subject, we consider the role of the mean surface slope in somewhat intuitive fashion through a thought experiment.

When waves propagate on still water of constant depth with a horizontal bottom, the wave energy fluxes and the wave heights at the sections I and II in figure 1(a) are equal unless the wave energy dissipates due to viscosity. Then, we consider the situation like (b) in figure 1 where waves go uphill assuming no wave energy dissipation due to viscosity. If waves propagate without change in height, there must be mass transports of the same intensity through the sections I and II. However, the potential energy of the mass transported through the section I is greater than the one transported through the section II by the quantity of the mass times the gravitational accelation times the difference of mean surface elevations, and there are no energy sources which supply the potential energy other than wave energy. Therefore, the constant wave energy flux does not hold and wave height is expected to decrease as the waves propagate.

In the situation like (c) in figure 1, we can deduce that the wave height will increase as the waves propagate. This thought experiment suggests that the effect of surface slope be taken into consideration for the discussion of wave height change on a uniform current.

WAVE ENERGY BALANCE Now, we consider a two dimensional situation in which waves propagate on a current with uniforn depth. The mean surface has the same inclination as the bottom slope. Choosing space coordinates x and y to be along and perpendicular to the mean water surface respectively (figure 2), equations of motion and continuity are

$$\frac{\partial u}{\partial t} + (U+u)\frac{\partial u}{\partial x} + v\frac{\partial (U+u)}{\partial y} = g\sin\theta - \frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{1}{\rho}\frac{\partial \tau}{\partial y}$$
(1)

$$\frac{\partial v}{\partial t} + (U+u)\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -g\cos\theta - \frac{1}{\rho}\frac{\partial p}{\partial y}$$
(2)

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{3}$$

In IS, the term $g \sin \theta$ in equation(1) was omitted on the assumption that the gradient of τ_c , which was a part of τ due to pure current, in y direction was compensated with this term when flow was uniform without waves. However, the mean surface slope of wave-current co-existing system differs from the surface slope of



Figure 1: Energy balance of waves propagating over a still water with inclined surface



Figure 2: Definition sketch

pure current and this has been confirmed experimentally by Asano et al. (1986). The boundary conditions at the free surface $y = h + \eta$ and at the bottom y = 0 are

$$v = \frac{\partial \eta}{\partial x} + (U+u)\frac{\partial \eta}{\partial x}$$
 at $y = h + \eta$ (4)

0 at
$$y = h + \eta$$
 (5)

$$v = 0 \qquad \text{at} \quad y = 0 \tag{6}$$

where u and v are the velocity components of wave motion in x and y direction, U is the current velocity and assumed to be a function of y; ρ , p, g, τ and η are density, pressure, gravitational acceleration, Reynolds stress and surface elevation.

p =

Integrating the sum of equation (1) multiplied by ρu and equation (2) multiplied by ρv over the depth with respect to y, and making use of equations (3) to (6) together with the Leibnitz's rule, an equation for the balance of wave energy is obtained as follows after averaging over a wave period.

$$\frac{\partial}{\partial t} \left[\int_{0}^{h+\eta} \frac{\rho}{2} (u^{2} + v^{2}) dy + \frac{1}{2} \rho g \overline{\eta^{2}} \cos \theta \right] \\
+ \frac{\partial}{\partial x} \left[\int_{0}^{h+\eta} \left\{ \frac{\rho}{2} (u^{2} + v^{2}) + p + \rho g (y - h) \cos \theta \right\} u dy \\
+ \int_{0}^{h+\eta} \frac{\rho}{2} (u^{2} + v^{2}) U dy + \frac{1}{2} \rho g \cos \theta \overline{\eta^{2} U_{h+\eta}} \right] \\
= \frac{1}{2} \rho g \cos \theta \overline{\eta^{2} \frac{\partial U_{h+\eta}}{\partial x}} + \int_{0}^{h+\eta} u \frac{\partial \tau}{\partial y} dy + \int_{0}^{h+\eta} (-\rho uv) \frac{dU}{dy} dy \\
+ \rho g \sin \theta \overline{\int_{0}^{h+\eta} u dy} \tag{7}$$

Assuming that the slope is small enough for the following approximation to be valid

$$\cos \theta pprox 1$$
 and $\sin \theta pprox \tan \theta = I$

and confining ourselves to the second order approximation of wave motion in the following discussion for the sake of simplicity, the wave energy ballance equation becomes as follows

$$\frac{\partial E}{\partial t} + \frac{\partial F}{\partial x} = \int_0^h \overline{u} \frac{\partial \tau}{\partial y} \, dy + \int_0^h (-\rho \overline{u} \overline{v}) \, \frac{dU}{dy} \, dy + \rho g I \overline{\int_0^{h+\eta} u \, dy} \tag{8}$$

where E is the wave energy density and F is the wave energy flux given by

$$E = \int_{0}^{h} \frac{\rho}{2} \left(\overline{u^{2} + v^{2}} \right) dy + \frac{1}{2} \rho g \overline{\eta^{2}}$$
(9)

$$F = \int_0^h \overline{pu} \, dy + \int_0^h \frac{\rho}{2} \left(\overline{u^2 + v^2} \right) U \, dy + \frac{1}{2} \rho g \overline{\eta^2} U_h \tag{10}$$

There appear three sources of wave energy in the righthand side of equation (8).

The first term gives energy dissipation due to viscosity. The second term shows the possibility of energy transfer between waves and a current through the mechanism similar to the energy transfer through the work done by Reynolds stress against flow strain in turbulent flow. This term vanishes for inviscid wave motion because of the phase difference of $\pi/2$ between u and v. However, the existence of bottom wave boundary layer is expected, this term should be examined.

The last term stems from the existence of the inclination of surface on an actual uniform flow. As was mentioned previously, waves must do work against the gravity in order to maintain the mass transport over the inclined surface.

WAVE HEIGHT CHANGE Putting each terms of the righthand of the equation (8) as follows

$$\int_0^h \overline{u \frac{\partial \tau}{\partial y}} \, dy = -2\alpha_1 F \tag{11}$$

$$\int_0^h (-\rho \overline{u} \overline{v}) \frac{dU}{dy} dy = -2\alpha_2 F \tag{12}$$

$$\rho g I \overline{\int_0^{h+\eta} u \, dy} = -2\alpha_3 F \tag{13}$$

For monochromatic waves, $\partial/\partial t = 0$ and equation (8) reduces to

$$\frac{d}{dx}F = -2\left(\alpha_1 + \alpha_2 + \alpha_3\right)F$$

Integrating this with respect to x

$$\frac{\dot{F}}{F_0} = \exp\{-2\left(\alpha_1 + \alpha_2 + \alpha_3\right)x\}$$

where the subscript $_0$ denotes the quantities at x = 0, and the wave energy flux F is expressed using wave height H and wave energy transfer velocity C_q^{1} as

$$F = EC_g = \frac{1}{8}\rho g H^2 C_g \tag{14}$$

For the uniform current under consideration, $C_g = C_{g_0}$. Therefore, the change in height of the waves on a uniform current is given by

$$\frac{H}{H_0} = \exp\{-(\alpha_1 + \alpha_2 + \alpha_3)x\} = \exp(-\alpha x)$$
(15)

In order to obtain the attenuation coefficients α , expressions relevant to the quantities on waves and currents must be given. In the following analysis, expressions in IS were used. They were derived on the assumption that the mean velocity profile was logarithmic for smooth bed and the prevailing part of eddy viscosity was due to the current and the contribution of waves to the eddy viscosity was small.

Examples of calculated results of the wave height attenuation rates are shown in figure 3. These results show that α_1 , defined by equation (11) and discussed in IS is positive and makes the base of the wave attenuation; α_2 , which is the part due to the Reynold's stress like stress induced by the wave orbital velocity components u and v, is small for a following current compared to the others, but this enhances the wave attenuation for a strong opposing current; α_3 , which is related to the slope of the mean water surface, is negative for a following current and positive for an opposing current and the absolute value increase with the current velocity.

Hence, the wave attenuation rate α decreases with the velocity of the following current, and this seems to give a possible physical explanation for the experimental results of Simons et al. (1988).

When the velocity of a following current is small, α_3 is smaller than α_1 and the resultant α gives wave attenuation. For a certain velocity of the following current, α_1 and α_3 cancel out and waves are expected to propagate without changing the height. And when the velocity exceeds the critical one, α_3 overcomes α_1 . In such situation as this, the resultant attenuation rate α becomes negative and gives waves the growth in height.

On the other hand, α_1, α_2 and α_3 all enhance the attenuation of wave height on opposing currents.

¹To be exact, E is not necessarily equal to $(1/8)\rho g H^2$ and wave energy transport velocity also does not necessarily coincide with group velocity defined by $d\sigma/dk(k:wave number,\sigma:radian$ frequency) except the case in which the vertical velocity distribution is uniform. But thedifferences for the logarithmic flow are small.



Figure 3: Calculated results of wave attenuation rete

The comparison between the calculated results and some experimental data is shown in figure 4. The agreement of the calculation with the experimental data is improved compared to IS. The experiment were conducted only for opposing currents since the experimental facilities were not available for following currents.

WAVES ON NON-UNIFORM CURRENTS 3

Next, the case in which both of water depth and velocity change along the direction of a current is considered (figure 5). In this case we choose space coordinates x and y along and perpendicular to a horizontal plane taken near the mean surface, respectively. Then, the basic equations and the boundary conditions are given by

$$\frac{\partial u}{\partial t} + (U+u)\frac{\partial (U+u)}{\partial x} + (V+v)\frac{\partial (U+u)}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{1}{\rho}\left(\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{yx}}{\partial y}\right) \quad (16)$$

$$\frac{\partial v}{\partial t} + (U+u)\frac{\partial (V+v)}{\partial x} + (V+v)\frac{\partial (V+v)}{\partial y} = -g - \frac{1}{\rho}\frac{\partial p}{\partial y} + \frac{1}{\rho}\left(\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y}\right)$$
(17)

$$\frac{\partial (U+u)}{\partial x} + \frac{\partial (V+v)}{\partial y} = 0$$
(18)

$$V + v = \frac{\partial \eta}{\partial t} + (U + u) \frac{\partial \eta}{\partial x} \quad \text{at} \quad y = \eta \tag{19}$$
$$v = 0 \qquad \qquad \text{at} \quad y = n \tag{20}$$

$$V + v = -(U + u)\frac{dh}{dr} \qquad \text{at} \quad y = -h \tag{21}$$

at

u = n



Figure 4: Comparison with experimental results for opposing currents



Figure 5: Definition sketch

where V is the vertical velocity component of the current and $\sigma_x, \sigma_y, \tau_{xy}, \tau_{yx}$ denote stress component due to turbulence.

WAVE ENRGY BALANCE Based on these equations, we obtain an equation for wave energy balance in the same way as the case of uniform currents as

$$\frac{\partial}{\partial t} \left[\overline{\int_{-h}^{\eta} \frac{\rho}{2} (u^{2} + v^{2}) dy} + \frac{1}{2} \rho g \overline{(\eta - \overline{\eta})^{2}} \right]
+ \frac{\partial}{\partial x} \left[\overline{\int_{-h}^{\eta} \left\{ \frac{\rho}{2} (u^{2} + v^{2}) + p + \rho g (y - \overline{\eta}) \right\} u dy} \right]
+ \frac{\partial}{\partial x} \left[\overline{\int_{-h}^{\eta} \left\{ \frac{\rho}{2} (u^{2} + v^{2}) + p + \rho g (y - \overline{\eta}) \right\} u dy} \right]
= \frac{1}{2} \rho g \overline{(\eta - \overline{\eta})^{2} \frac{\partial U_{h+\eta}}{\partial x}} - \overline{\int_{-h}^{\eta} \rho (U + u) u \frac{\partial U}{\partial x} dy} - \overline{\int_{-h}^{\eta} \rho (U + u) v \frac{\partial V}{\partial x} dy}
- \frac{\partial}{\partial u} \overline{\int_{-h}^{\eta} \rho (V + v) u \frac{\partial U}{\partial y} dy} - \overline{\int_{-h}^{\eta} \rho (V + v) v \frac{\partial V}{\partial y} dy} + \rho g \overline{(\eta - \overline{\eta})} \left[V - U \frac{\partial \overline{\eta}}{\partial x} \right]_{\eta}
+ \frac{\partial}{\partial u} \left(\frac{\partial \sigma_{x}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} \right) dy + \overline{\int_{-h}^{\eta} v \left(\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_{y}}{\partial y} \right) dy} - \rho g \frac{\partial \overline{\eta}}{\partial x} \overline{\int_{-h}^{\eta} u dy}$$
(22)

where $\overline{\eta}$ denotes mean water level.

In the righthand side of this equation, lots of sources of wave energy appear and rather complicated. For the sake of simplicity, we assume gradually varing flow. Then, $(\partial U/\partial x)^2$ and V^2 are small, and we may put $-\rho v^2 = p - \rho g(\overline{\eta} - y)$. Besides, we assume that $(\partial \tau_{yx}/\partial y) \gg (\partial \sigma_x/\partial x), (\partial \sigma_y/\partial y), (\partial \tau_{xy}/\partial x)$ and $(\partial U/\partial y) \gg (\partial V/\partial x)$. To the second order approximation, equation (22) reduces to

$$\frac{\partial E}{\partial t} + \frac{\partial F}{\partial x} = -\left[\frac{\int_{-h}^{\eta} (\rho u^2 + p) \frac{\partial U}{\partial x} dy - \int_{-h}^{\overline{\eta}} p_0 \frac{\partial U}{\partial x} dy\right] \\ + \int_{0}^{h} \overline{u \frac{\partial \tau}{\partial y}} dy + \int_{0}^{h} (-\rho \overline{u} \overline{v}) \frac{dU}{dy} dy - \rho g \overline{\int_{0}^{h+\eta} u dy} \frac{d}{dx} \left(\overline{\eta} + \frac{U_{\overline{\eta}}^2}{2g}\right)$$
(23)

where E and F have been given by equations (9) and (10).

When U is independent on y, the part in the bracket of equation (23) becomes as follows

$$[\cdots\cdots] = \left[\frac{\int_{-h}^{\eta} (\rho u^2 + p) \, dy - \int_{-h}^{\overline{\eta}} p_0 \, dy \right] \frac{dU}{dx} = S_x \frac{dU}{dx} \tag{24}$$

where S_x is the radiation stress introduced by Longuet-Higgins and Stewart (1960). Therefore, the bracket can be considered to correspond to the radiation stress term in the case where current velocity varies not only horizontally but also vertically.

The last term of the righthand side corresponds to the one in equation (7). When we consider the head loss of the mean flow, we should take this term into consideration.

WAVE HEIGHT CHANGE Considering monochromatic waves and defining α^* and α as

$$-2\alpha^* F = \left[\frac{\int_{-h}^{\eta} (\rho u^2 + p) \frac{\partial U}{\partial x} dy - \int_{-h}^{\overline{\eta}} p_0 \frac{\partial U}{\partial x} dy \right]$$
(25)

$$-2\alpha F = \int_0^h \overline{\frac{\partial \tau}{\partial y}} \, dy + \int_0^h (-\rho \overline{uv}) \, \frac{dU}{dy} \, dy - \rho g \overline{\int_0^{h+\eta} u \, dy} \frac{d}{dx} \left(\overline{\eta} + \frac{U_{\overline{\eta}}^2}{2g} \right)$$
(26)

Equation (23) reduces to

$$\frac{d}{dx}F = 2\alpha^* F - 2\alpha F \tag{27}$$

Integrating this from x = 0 to x with respect to x

. ..

$$\frac{F}{F_0} = \frac{C_{g_0}}{C_g} \exp\left(2\int_0^x \alpha^* dx\right) \exp\left(-2\int_0^x \alpha dx\right)$$
(28)

Thus, wave height change is given by

$$\frac{H}{H_0} = \left(\frac{C_{g_0}}{C_g}\right)^{1/2} \exp\left(\int_0^x \alpha^* dx\right) \exp\left(-\int_0^x \alpha dx\right) \tag{29}$$

We could calculate the change of wave height on non-uniform currents using this equation. However, it is rather complicated and laborious job to carry out the calculation.

When wave motion and currents are inviscid and vertical velocity distribution of the current is independent on y, equation (29) reduces to

$$\frac{H}{H_0} = \left(\frac{C_{g_{u_0}}}{C_{g_u}}\right)^{1/2} \exp\left(\int_0^x \alpha_u^* dx\right) \tag{30}$$

where subscript u denotes the expressions for waves on vertically uniform currents. So, equation(30) corrected by the factor $\exp\left(-\int_0^x \alpha dx\right)$ was used in the following calculation.

The integrals in equation(30) were approximated using trapezoidal approximation for equally divides intervals of Δx . Then

$$\frac{H_n}{H_0} = \prod_{i=0}^{n-1} \frac{H_{i+1}}{H_i} = \prod_{i=0}^{n-1} \left(\frac{C_{g_{ui}}}{Cg_{ui+1}} \right)^{\frac{1}{2}} \exp\left\{ \frac{1}{2} \left(\alpha_i^* + \alpha_{i+1}^* \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \left(\alpha_i + \alpha_{i+1} \right) \Delta x \right\} \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \exp\left\{ \frac{1}{2} \left(\alpha_i + \alpha_{i+1} \right) \left(\alpha_i +$$

Prior to the calculation of wave height, the depth and the velocity of the current and dU/dx were calculated at points *i* and *i* + 1 by a conventional calculation method for a non-uniform current. Then, the wave height at each *i* was calculated.

Figure 6 is an example of calculated results for opposing currents. In this figure, subscript $_0$ denotes the quantities at x = 0.

As the bottom slope becomes smaller, the factor $\exp(-\int_0^x \alpha dx)$ weaken the amplification effects due to the shoaling effect and the energy transfer through $S_x (dU/dy)$ for the waves traveling over an opposing current. Figure 7 shows the comparison between experimental results and calculated ones. These results show that the dissipative effect of the factor $\exp(-\int_0^x \alpha dx)$ plays an important role for the wave height change on a gradually varying opposing current.



Figure 6: A model calculation results



Figure 7: Comparison between measurements and calculated results

4 CONCLUSION

Waves propagating on a uniform current attenuate their height due to the effects of 1) viscosity, 2)Reynolds stress like wave stress induced by the orbital velocity in bottom wave boundary layer and 3)the existence of the inclination of the mean surface.

The effect of 1) makes the base of the wave attenuation rate. The effect of 2) is small for a following current, but this enhances the wave attenuation for a strong opposing current. And the effect of 3) gives positive attenuation rate for an oppsing current and negative attenuation rate for a following current.

The combined effect of them increases the wave attenuation rate for an opposing current. But it decreases the attenuation rate as the velocity of a following current increases, and this seems to give a possible physical explanation for the experimental results of Simon et al.(1988).

As the wave attenuation rate increases with the velocity of an opposing current, it affects the change in height of waves on a gradually varying opposing current to such an extent that we can not ignore the effect.

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