

CHAPTER 162

Numerical Model for Longshore Current Distribution on a Bar-Trough Beach

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Abstract

A numerical model for the time-averaged nearshore current in the surf zone is developed to simulate the longshore current distribution on a bar-trough beach that has a peak velocity shoreward of the bar crest. Momentum fluxes due to mass transport under broken waves, which are ignored in other models, are included in the present model. The validity of the model is verified with field data.

1. Introduction

There are two patterns of the time-averaged longshore current distribution on a bar-trough beach. One has a peak velocity seaward of the bar crest, and the other has the peak shoreward of the bar crest. Kuriyama and Ozaki (1993) measured longshore current velocities in the field when a single bar-trough system was formed and waves broke over the bar. They showed that eighty-five percent of the measured longshore current distributions have peak velocities shoreward of the bar crests, whereas fifteen percent have peaks seaward of the bar crests.

The seaward peak can be reproduced by one-dimensional models of the longshore current where the driving force of the longshore current is the cross-shore gradient of radiation stress (Ebersole and Dalrymple, 1980; Larson and Kraus, 1991) because the gradient is largest seaward of a bar crest owing to the large dissipation of wave energy due to wave breaking. On the other hand, the shoreward peak cannot be reproduced by the one-dimensional models. Church and Thornton (1993) and Smith et al. (1993) have recently developed one-dimensional numerical models for the longshore current that include the effect of turbulence due to wave breaking on the driving force through consideration of the surface roller. Although the peak velocities predicted by their models are located shoreward of the peaks predicted by previous

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models, the peaks predicted by their models are still located seaward of the peaks measured in the field. Symonds and Huntley (1980) showed that the longshore gradient of wave setup can cause a shoreward peak. The shoreward peak, however, was sometimes observed when the longshore gradient of the wave setup was small.

The objective of this study is to develop a numerical model that reproduces the shoreward peak in the longshore current even when the longshore gradient of the wave setup is small. It is assumed that the momentum fluxes due to mass transport under broken waves generate the shoreward peak, and the resultant momentum fluxes are introduced into a previous nearshore current model. Longshore current distributions predicted by the present model are compared with those measured in the field.

2. Numerical Model

The present model consists of two computationally distinct numerical models: a wave height transformation model and a nearshore current model.

2.1 Wave height transformation model

The present model for wave height transformation is based on the Karlsson's model (1969) for directional random waves, which is based on the balance of wave energy. I introduce a wave energy dissipation term as Takayama et al. (1991) did. The energy equation of a wave component with the frequency of f and the direction of θ is expressed as

$$\begin{aligned} \frac{\partial(D_s V_x)}{\partial x} - \frac{\partial(D_s V_y)}{\partial y} + \frac{\partial(D_s V_\theta)}{\partial \theta} &= -D, \\ D_s &= S(f, \theta) \delta f \delta \theta, \\ V_x &= C_g \sin \theta, V_y = C_g \cos \theta, \\ V_\theta &= \frac{C_g}{C} (-\cos \theta \frac{\partial C}{\partial x} - \sin \theta \frac{\partial C}{\partial y}), \end{aligned} \quad (1)$$

where D_s is the wave energy, S is the directional wave spectral density, δf is the frequency band width, $\delta \theta$ is the directional band width, C_g is the group velocity, C is the celerity, and D is the wave energy dissipation rate. The values of D_s , C_g , C and D are defined for a wave component. The co-ordinate system used in this paper is shown in Figure 1. The positive direction of the y -axis is seaward. The wave direction is defined relative to the shoreward direction and positive counterclockwise. The vertical axis extends upward.

The principle of the dissipation term proposed by Dally et al. (1985) is used in the present model because the dissipation term can reproduce the wave height stabilization in a uniform depth, which is like the wave transformation over a trough.

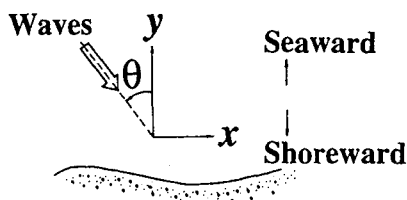


Figure 1 Definition sketch of co-ordinate system.

Modification of the dissipation term by Dally et al., which is for one-dimensional monochromatic waves, yields Eq. (2) for a wave component of directional random waves.

$$D = \frac{K}{h} (D_s C_g - D_s \frac{E_s}{E} C_g), \quad (2)$$

$$E_s = \frac{1}{16} \rho g (H_{1/3})_s^2, \quad (H_{1/3})_s = \Gamma h.$$

where $(H_{1/3})_s$ is the stable significant wave height, h is the still water depth, E is the total wave energy, the sum of D_s , E_s is the total energy where the wave height is stable after wave breaking, and K and Γ are dimensionless empirical coefficients.

I assume that K and Γ are functions of the beach slope, $\tan \beta$, and express them with Eqs.(3) and (4) because the wave energy dissipation in the surf zone is affected by the beach slope. These functions were obtained on the basis of the calculations of the wave height transformation in the surf zone for offshore wave steepness of 0.02 by Goda (1975).

$$K = 1.7 \times 10^\alpha, \quad \alpha = -0.857 \log_{10}(1/\tan \beta) + 0.219. \quad (3)$$

$$\Gamma = -0.14 \log_{10}(1/\tan \beta) + 0.56. \quad (4)$$

The significant wave height, $H_{1/3}$, and the principal wave direction, θ_p , are calculated by

$$H_{1/3} = 4.0 \sqrt{m_0}, \quad m_0 = \int_0^\infty \int_{-2\pi}^{2\pi} D_s d\theta df. \quad (5)$$

$$\theta_p = \int_0^\infty \int_{-2\pi}^{2\pi} \theta D_s d\theta df / m_0. \quad (6)$$

The significant wave period, $T_{1/3}$, is assumed to be equal to that in deep water.

2.2 Nearshore current model

a. Momentum equation

The movements of water particles, which have the maximum orbital velocity of v_m due to waves, are assumed as shown in Figure 2. Water particles above the wave trough level, d_w , are transported by the depth and time-averaged nearshore current; U and V are the longshore and cross-shore components of the nearshore current velocity. The particles are also transported shoreward by mass transport due to waves at the angle of θ and the velocity of V_u . Water particles below the wave trough level are transported by the nearshore current, and transported seaward at the velocity of V_l of the return flow, which is perpendicular to the shore. The mass of water transported shoreward by the mass transport is assumed to be equal to that transported seaward by the return flow.

Under the assumptions, the cross-shore flux of the longshore momentum in the surf zone, M_w , is expressed as

$$\begin{aligned}
 M_w = & \frac{\rho}{T} \int_0^T \int_{d_w}^{\eta} \{ [U + (V_u + v_m \cos \sigma t) \sin \theta_p] \\
 & \{ V + (V_u + v_m \cos \sigma t) \cos \theta_p \}] dz dt \\
 & + \frac{\rho}{T} \int_0^T \int_{-h}^{d_w} [(U + v_m \cos \sigma t \sin \theta_p) \\
 & (V + V_l + v_m \cos \sigma t \cos \theta_p)] dz dt,
 \end{aligned} \tag{7}$$

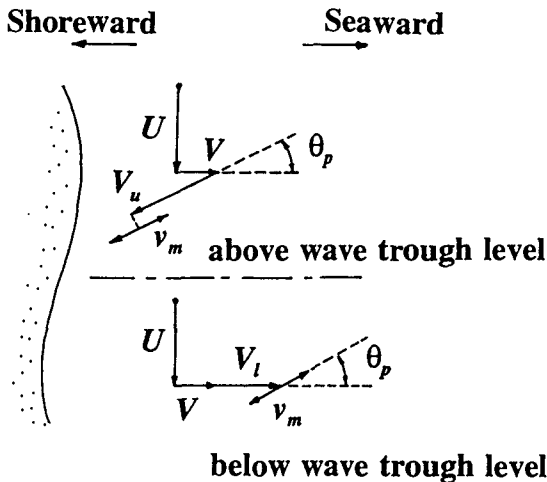


Figure 2 Definition sketch of the assumed movements of water particles above and below the wave trough level.

where ρ is the density of sea water, T is the wave period, η is the elevation of water surface, z is the upward elevation relative to the mean water level, σ is the angular frequency. The value of $T_{1/3}$ is used as T in the calculation.

Equation (7) becomes

$$\begin{aligned} M_w = & \frac{\rho}{T} \int_0^T \left\{ \int_{-h}^{\eta} U V dz \right. \\ & + \int_{-h}^{\eta} v_m^2 \cos^2 \sigma t \sin \theta_p \cos \theta_p dz \\ & + U \left(\int_{d_r}^{\eta} V_u \cos \theta_p dz + \int_{-h}^{d_r} V_l dz \right) \\ & \left. + \int_{d_r}^{\eta} (V_u^2 + V V_u) \sin \theta_p \cos \theta_p dz \right\} dt. \end{aligned} \quad (8)$$

The first and second terms on the right-hand side of Eq.(8) represent the momentum flux due to the nearshore current and a radiation stress, respectively. The third term is equal to zero because the mass of water transported shoreward is assumed to be equal to that transported seaward. The fourth term is the cross-shore flux of the longshore momentum due to mass transport by waves.

In most previous models for the nearshore current, the fourth term is neglected because the effect of the mass transport due to unbroken waves on the nearshore current is small. However, the mass flux under broken waves is several times of that calculated with a formula for unbroken waves (Nadaoka and Kondoh, 1982). This means that a momentum flux due to mass transport under broken waves is much greater than that under unbroken waves. Therefore I consider that the momentum fluxes due to mass transport under broken waves are significant for the prediction of the longshore current distribution on a bar-trough beach, and introduce the fluxes into a previous model.

The fourth term, M_{bl} , becomes Eq.(9) with a surface roller model proposed by Svendsen (1984) as shown in Figure 3; in his model, a water particle in the surface roller is transported shoreward with the celerity, C ,

$$M_{bl} = \rho P_b e (-C \cos \theta_p + V) C \sin \theta_p, \quad (9)$$

where e is the time-averaged thickness of the surface roller, and P_b is the fraction of breaking waves, which is introduced for random waves. The value of e is assumed as

$$e = C_A H_{1/3}^2 / L, \quad (10)$$

in which C_A is a dimensionless coefficient, and L is the wavelength for the wave period of T .

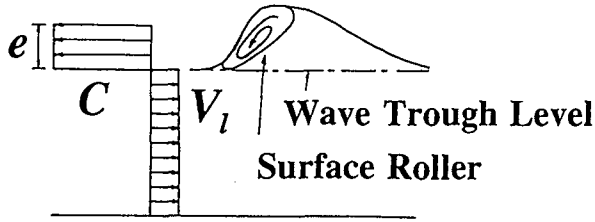


Figure 3 Definition sketch of the vertical distribution of time-averaged cross-shore velocity in a surface roller model by Svendsen (1984).

The cross-shore flux of the cross-shore momentum due to broken waves, M_{b2} , and the longshore flux of the longshore momentum, M_{b3} , are obtained in a similar way for the value of M_{b1} ; these are described by

$$M_{b2} = \rho P_b e C^2 \cos^2 \theta_p + (d_r + h) V_i^2. \quad (11)$$

$$M_{b3} = \rho P_b e (C \sin \theta_p + 2U) C \sin \theta_p. \quad (12)$$

The value of V_i is expressed as Eq.(13), which is derived by Kuriyama(1991) on the basis of Svendsen's model (1984).

$$V_i = \left(C \frac{m_0}{h^2} + P_b C_A \frac{H_{1/3}^2}{hT} \right) \cos \theta_p. \quad (13)$$

Finally, the horizontal momentum equations in the present model for the nearshore current, which contains the momentum fluxes due to surface rollers, are represented by

$$\begin{aligned} \frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} + F_x - L_x + R_x + g \frac{\partial \bar{\eta}}{\partial x} + M_x &= 0, \\ \frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + F_y - L_y + R_y + g \frac{\partial \bar{\eta}}{\partial y} + M_y &= 0, \end{aligned} \quad (14)$$

$$\begin{aligned}
 L_x &= \frac{\partial}{\partial x} \left(\epsilon \frac{\partial U}{\partial x} \right) + \frac{\partial}{\partial y} \left(\epsilon \frac{\partial U}{\partial y} \right), L_y = \frac{\partial}{\partial x} \left(\epsilon \frac{\partial V}{\partial x} \right) + \frac{\partial}{\partial y} \left(\epsilon \frac{\partial V}{\partial y} \right), \\
 R_x &= \frac{1}{\rho(h+\bar{\eta})} \left(\frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{yx}}{\partial y} \right), R_y = \frac{1}{\rho(h+\bar{\eta})} \left(\frac{\partial S_{xy}}{\partial x} + \frac{\partial S_{yy}}{\partial y} \right), \\
 M_x &= \frac{1}{\rho(h+\bar{\eta})} \left(\frac{\partial M_{bx}}{\partial x} + \frac{\partial M_{by}}{\partial y} \right), M_y = \frac{1}{\rho(h+\bar{\eta})} \left(\frac{\partial M_{bx}}{\partial x} + \frac{\partial M_{by}}{\partial y} \right),
 \end{aligned} \tag{15}$$

where $\bar{\eta}$ is the elevation of the mean water level, F_x and F_y are the bottom friction terms, L_x and L_y are the lateral mixing terms, S_{xx} , S_{xy} , and S_{yy} are the radiation stress components, and ϵ is a lateral mixing coefficient. The subscripts x and y denote the values in the x -direction and y -direction.

b. Fraction of breaking waves

Seaward of a bar crest, I assume that the fraction of breaking waves is a function of wave height-water depth ratio as Thornton and Guza (1983) did, and represent it by Eq.(16) with a dimensionless coefficient, γ , which is the wave height-water depth ratio in the surf zone, where all waves are broken.

$$P_b = (H_{1/3} / (\gamma h))^4. \tag{16}$$

I introduce the effect of beach slope into the calculation of γ because the wave energy dissipation in the surf zone depends on beach slope. The value of γ is assumed as Eq.(17) on the basis of the calculations of the wave height in the surf zone for offshore wave steepness of 0.02 by Goda (1975).

$$\gamma = 0.68 \exp(4.2 \tan \beta). \tag{17}$$

Shoreward of a bar crest, the fraction of breaking waves is assumed as

$$\begin{aligned}
 P_b &= (P_b)_{bar}, & y_{bar} - 10 < y \leq y_{bar}, \\
 P_b &= (P_b)_{bar} - 0.014(y - y_{bar} + 10)^2, & y \leq y_{bar} - 10,
 \end{aligned} \tag{18}$$

where $(P_b)_{bar}$ is the fraction of breaking waves at the bar crest, and y_{bar} is the offshore distance at the bar crest. According to visual observations, waves break even shoreward of a bar crest. This means that the fraction of breaking waves does not decrease rapidly from a bar crest although the value predicted by Eq.(16) decreases rapidly from the bar crest. Thus, the fraction of breaking waves shoreward of a bar crest is assumed to be constant near the bar crest and to decrease shoreward proportionally to the square of the distance from the shoreward limit of the constant

P_b zone. The coefficients of Eq.(18) were determined on the basis of visual observation data (Kuriyama and Ozaki, 1993); the units of y and y_{bar} are meters.

Near the surf zone shoreward of a trough, Eq.(16) is used again where P_b estimated by Eq.(16) is larger than that by Eq.(18).

c. Surface roller area parameter, C_A

I assume that C_A changes according to the development and decay of the surface roller although it is treated as a constant value by Svendsen (1984), because a constant C_A cannot represent the disappearance of the surface roller in a trough. The development and decay of the surface roller are assumed to be proportional to the fraction of wave breaking; the maximum value of C_A is determined to be 4.0 on the basis of the field data obtained by Kuriyama (1991). Finally, C_A is expressed as

$$C_A = 4.0 P_b. \quad (19)$$

d. Radiation stress, bottom shear stress and lateral mixing

The radiation stresses of directional random waves are calculated by Eq.(20) proposed by Yamaguchi(1988).

$$\begin{aligned} S_{xx} &= \int_0^\infty \int_{-\pi/2}^{\pi/2} \rho g \left\{ \frac{C_g}{C} \sin^2 \theta + \left(\frac{C_g}{C} - \frac{1}{2} \right) \right\} D_s d\theta df, \\ S_{xy} &= S_{yx} = \int_0^\infty \int_{-\pi/2}^{\pi/2} \rho g \frac{C_g}{C} \cos \theta \sin \theta D_s d\theta df, \\ S_{yy} &= \int_0^\infty \int_{-\pi/2}^{\pi/2} \rho g \left\{ \frac{C_g}{C} \cos^2 \theta + \left(\frac{C_g}{C} - \frac{1}{2} \right) \right\} D_s d\theta df. \end{aligned} \quad (20)$$

Equation (21) (Nishimura, 1982; Nishimura, 1988) is used for the calculation of the bottom shear stresses, F_x and F_y . The value of 0.005 is used as the friction coefficient, C_f .

$$\begin{aligned} F_x &= \rho C_f \left\{ \left(W + \frac{w_b^2}{W} \sin^2 \theta_p \right) U - \frac{w_b^2}{W} \sin \theta_p \cos \theta_p V \right\}, \\ F_y &= \rho C_f \left\{ \frac{w_b^2}{W} \sin \theta_p \cos \theta_p U - \left(W + \frac{w_b^2}{W} \cos^2 \theta_p \right) V \right\}, \\ W &= \left\{ \sqrt{U^2 + V^2 + w_b^2} + 2(U \sin \theta_p - V \cos \theta_p) w_b \right. \\ &\quad \left. + \sqrt{U^2 + V^2 + w_b^2} + 2(U \sin \theta_p - V \cos \theta_p) w_b \right\} / 2, \\ w_p &= 2(v_m)_b / \pi, \quad (v_m)_b = \frac{\pi H_{1/3}}{T \sin(2\pi h/L)}. \end{aligned} \quad (21)$$

The lateral mixing coefficient proposed by Battjes (1975) is used in the present model. This coefficient is given by

$$\epsilon = Mh\left(\frac{D_{total}}{\rho}\right)^{1/3}, \quad (22)$$

where D_{total} is the total wave energy dissipation rate and M is a dimensionless coefficient. Lateral mixing is probably related to turbulence; the turbulence due to breaking waves is much larger than that due to non-breaking waves. Hence, the degree of the lateral mixing in a trough is expected to be smaller than that in the surf zone located shoreward of the trough. Although the lateral mixing coefficient proposed by Longuet-Higgins (1970) is widely used, it seems to be inappropriate for the prediction of the longshore current on a bar-trough beach because the coefficient proposed by Longuet-Higgins, which is proportional to the distance from the shoreline, does not reproduce the difference between the lateral mixing in a trough and that in the shoreward surf zone. On the other hand, the lateral mixing coefficient proposed by Battjes reproduces the difference because it is based on the wave energy dissipation due to wave breaking. Thus, in the present model, I adopt the lateral mixing coefficient proposed by Battjes.

3. Model Comparisons with Measurements

The significant wave heights and the longshore current velocities predicted by the present model are compared with the values measured at Hazaki Oceanographical Research Facility (HORF), which is a field observation pier of 427m in length on the Kashima-nada coast of Japan facing to the Pacific Ocean. Water surface elevations were measured with ultrasonic wave gages before and after the measurement of the longshore current. A spherical float having a diameter of 0.2m was used to measure time-averaged longshore current velocities 1m below the water surface. This method with the float was confirmed to be useful for the measurement of the time-averaged longshore current velocity by calibrations with an electromagnetic current meter; there is a strong correlation between the time-averaged longshore current velocity measured by the float and that measured by the current meter (Kuriyama and Ozaki, 1993).

3.1 Calculation conditions

The calculation results for three cases, on March 24, 28 and April 4, 1989, are compared with the measurements. Figure 4 shows the topographic map of the vicinity of the HORF on March 31; this topography is used in the calculations for the three cases because the beach profile changes from March 24 to April 4 were small. The topography was almost uniform alongshore although scour occurred around the tip and the middle of the HORF, $y=380\text{m}$ and $y=200\text{m}$, where piles are concentrated. The calculation areas extend from the shorelines to $y=650\text{m}$, and alongshore from $x=-320\text{m}$ to $x=320\text{m}$.

In the calculations of wave height transformation, the grid distances in x -direction and y -direction are 10m. The numbers of frequency components and directional components are 10 and 35, respectively. The wave heights, $(H_{1/3})_{obs}$, the wave periods,

$(T_{1/3})_{ob}$, the principal wave directions, $(\theta_p)_{1/3}$, and the spreading parameters, $(s_{max})_{ob}$, input at the offshore boundaries are listed in Table 1. The Bretschneider-Mitsuyasu frequency spectrum and the Mitsuyasu-type spreading function are given at the offshore boundaries.

In the calculations of wave energy dissipation, a beach slope below 1/100 and that over 1/10 are replaced by values of 1/100 and 1/10, respectively, because Eqs.(3) and (4) are valid for the beach slopes from 1/100 to 1/10.

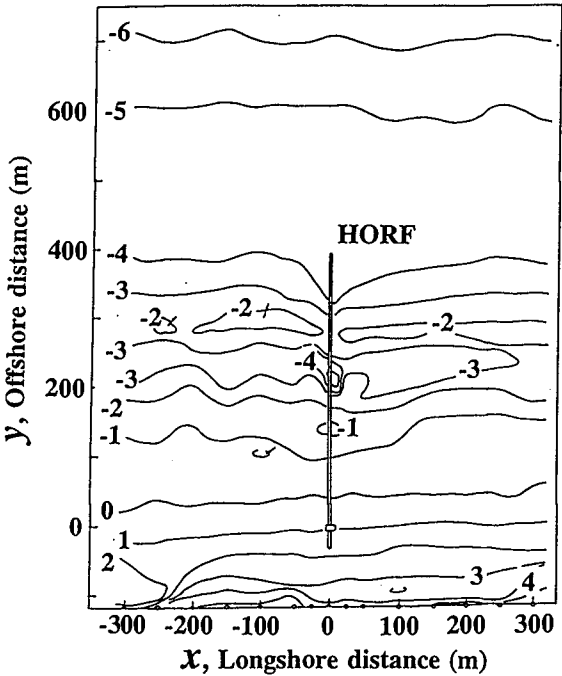


Figure 4 Topographic map of the vicinity of the HORF.

Table 1 Offshore boundary conditions

Case	Date	$(H_{1/3})_{ob}$	$(T_{1/3})_{ob}$	$(\theta_p)_{ob}$	$(s_{max})_{ob}$
1	March 24	3.20m	11.20s	-20.0°	90
2	March 28	2.47m	8.86s	-25.0°	40
3	April 4	2.03m	8.40s	-10.0°	45

The nearshore currents are calculated with the horizontal momentum equations, Eqs.(14) and (15), and the continuity equation by the ADI (Alternating Direction Implicit) method. The calculations are done for 4000 time step with a step length of 0.4s; the grid distances are 10m.

The nearshore current velocities are assumed to be equal to zero at the offshore boundaries and at the shorelines. The nearshore current velocities and the mean water levels at the side boundaries are assumed to be equal to the values at internal grid points next to the side boundaries.

The longshore flux of the longshore momentum, M_{bs} , is neglected in the calculations of the nearshore current because the nearshore currents preliminarily calculated by a previous model are almost uniform alongshore.

3.2 Wave height

Figures 5 shows the predicted significant wave heights and the values measured at the HORF. The solid lines show the values predicted by the present model, and the closed circles show the values measured before and after the measurements of the longshore current. The predicted values agree well with the measured values except for the data near the shorelines.

Causes of the small disagreement of calculated and measured values near the shorelines are supposed to be infragravity waves and the increase of water depth due to wave setup. When an offshore wave height is large, the amount of wave setup and the infragravity wave height are large near the shoreline. Infragravity waves and the increase of water depth due to wave setup, however, are not taken into account in the present model although the gradient of mean water level is considered in the nearshore current model. Disregard of the two factors results in the disagreement of calculated and measured values near the shorelines.

3.3 Nearshore current

Figure 6 shows a comparison of the longshore current velocities measured at the HORF with those predicted by the present model and by a previous model, which does not include momentum fluxes due to mass transport under broken waves; the velocities on March 24 and 28 were predicted with $M=5$ and those on April 4 were predicted with $M=10$. Seaward of the bar crests, the values predicted by the present model and by the previous model increase shoreward; both agree with the measured values. Shoreward of the bar crests, however, the values predicted by the present model and the measured values increase toward shore whereas the values predicted by the previous model decrease. Consequently the longshore current velocities over the troughs predicted by the present model agree well with the measured values whereas the values predicted by the previous model do not.

The Longshore current velocities predicted by a quasi-present model where the fraction of breaking waves shoreward of the bar crest is estimated with Eq.(16) are also shown in Figure 6. The peaks in velocity predicted by the quasi-present model are located at the bar crests, shoreward of the peaks predicted by the previous model and seaward of the peaks measured at the HORF and predicted by the present model.

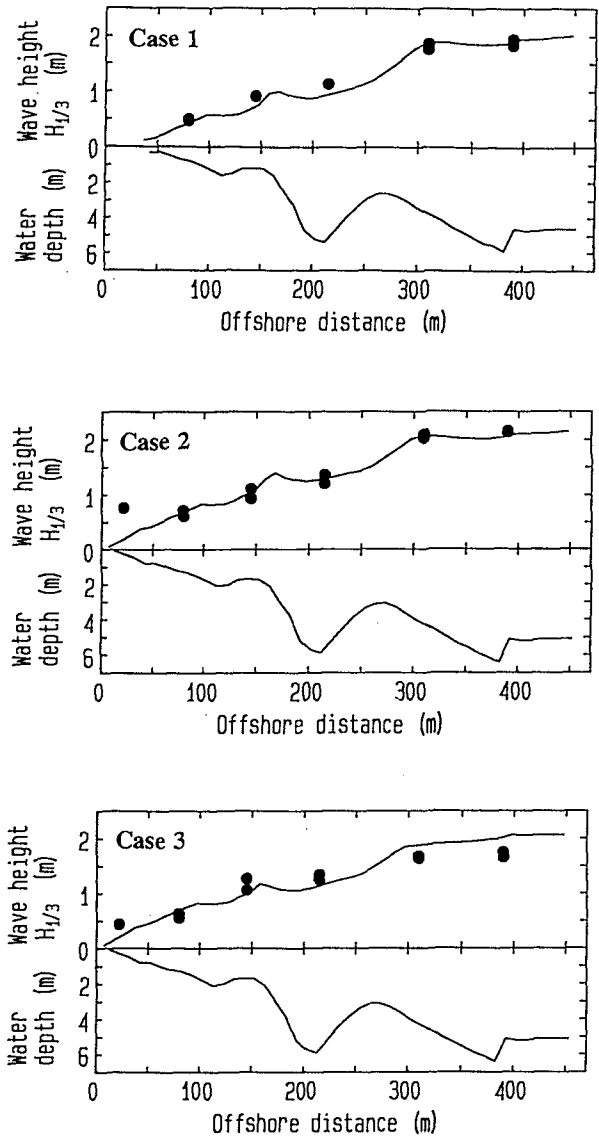


Figure 5 Comparison of the significant wave heights measured at the HORF (circles) with those predicted by the present model.

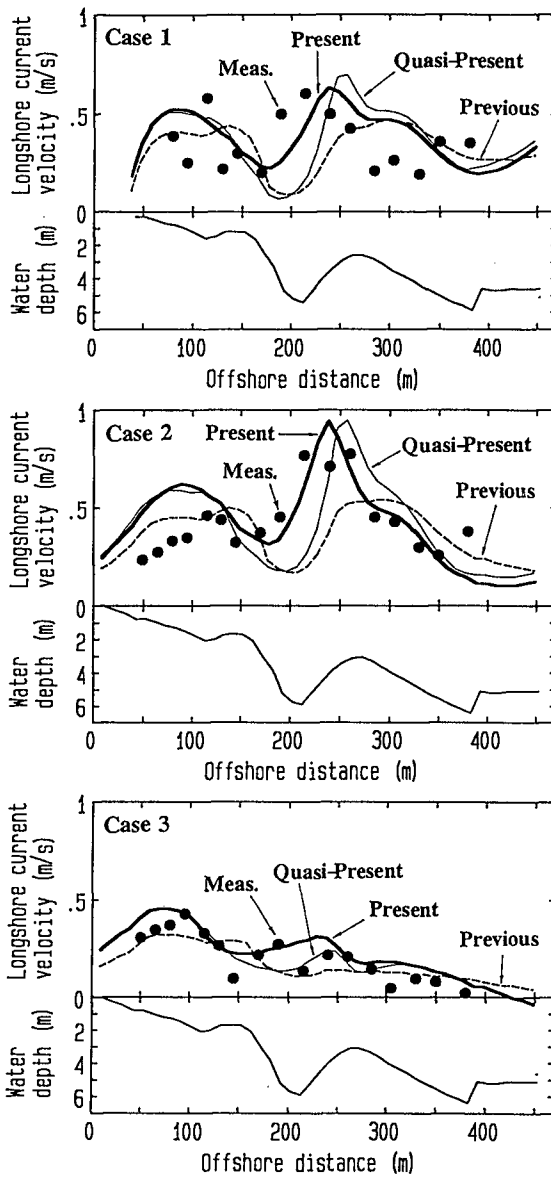


Figure 6 Comparison of the longshore current velocities measured at the HORF (circles) with those predicted by the previous model (broken lines), by the quasi-present model (thin solid lines), and by the present model (thick solid lines).

4. Discussion and Conclusions

Let us assume that an incident wave angle and the longshore current velocity are positive. Shoreward of a bar crest, the cross-shore flux of the longshore momentum due to the surface roller decreases with travel shoreward owing to the decay of the roller. This decrease means that the cross-shore flux of the longshore momentum transported into a unit volume is larger than that transported out of the volume. Consequently the longshore current velocities calculated by the present model are larger than those calculated by the previous model.

On the other hand, seaward of the bar crest, the cross-shore flux of the longshore momentum due to the surface roller increases with travel shoreward owing to the development of the surface roller. Thus the longshore current velocities calculated by the present model are smaller than those calculated by the previous model. As a result, the longshore current distribution calculated by the present model has a peak velocity shoreward of the bar crest.

The longshore current distributions predicted by the quasi-present model have peaks at the bar crests, seaward of the peaks predicted by the present model because the surface roller calculated by the quasi-present model with Eq.(16) decays rapidly from the bar crest whereas the roller calculated by the present model with Eqs.(16) and (18) propagates without decay near the bar crest, and then gradually decays.

The longshore current distributions on a bar-trough beach predicted by the present model agree with the field measurements, which have peaks in velocity shoreward of the bar crests, better than the distributions predicted by the other two models. The agreement shows that the fraction of breaking waves predicted by Eq.(18) is reasonable shoreward of a bar crest and the momentum fluxes due to mass transport under broken waves are significant for the prediction of the longshore current.

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