CHAPTER 30

DYNAMIC CHARACTERISTICS IN THE NEARSHORE AREA

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ABSTRACT

A detailed discussion is made on the dynamic characteristics of waves and wave-induced currents in the nearshore area by using the laboratory and field investigation data collected during the last few years. The main purposes of this paper are to get the insight on the precise mechanism of the nearshore dynamic phenomena and to evaluate critically the applicability of the various assumptions commonly applied by the previous researchers.

INTRODUCTION

During the last several years, the research group supervised by the senior author have carried out the series of field and laboratory investigations on the nearshore dynamic phenomena. The final target of the research works is to undersatnd precisely and more deeply the coastal sediment processes, which must be governed by the nearshore dynamics. However, in the present paper, the authors would like to focus their discussions on the several subjects which are closely related to the detailed mechanism of nearshore dynamics.

Since the radiation stress concept was presented by Longuet-Higgins and Stewart (1960, 1964), various important phenomena in the nearshore area have been analyzed extensively. Wave set-down and wave set-up, longshore current velocity distribution, and nearshore circulation must be typical examples in these phenomena.

Generally speaking, the phenomena in the nearshore area are extremely complex due to the complicated action of breaking waves. Therefore, in the previous treatments, some appropriate assumptions have been introduced to formulate the dynamical equations. These assumptions are that, for example, the small amplitude wave theory is applicable to the wave motion in the nearshore area, the wave height in the surf zone is proportional to the local water depth, and the bottom and lateral frictional terms are expressed in specified forms.

These previous works contributed very much to the advancement of coastal engineering research in the 1970s. On the other hand the instrumentation techniques have been developed extensively during these days. These facts encourage the scientists to carry out the detailed investigations to clarify the fine structures of nearshore phenomena, such as wave characteristics and current fields in the nearshore area.

Reflecting the above fortunate circumstances, the staffs at the Coastal Engineering Loboratory, University of Tokyo, have continued the extensive field and laboratory investigations during the last three years. Based on the data obtained up to the present stage, the authors' concept or understanding on the dynamic characteristics of waves and wave-induced currents in the nearshore area will be introduced in the following sections.

GOVERNING EQUATIONS

Figure 1 indicates the difinition sketch. By using these terms, the dynamic equations, such as the total mass conservation equation, and the total momentum conservation equation, can be written down as shown in the following forms after Phillips (1977).

1) Conservation of total mass:

$$\frac{\partial}{\partial t}[\rho(h+\overline{\zeta})] + \frac{\partial}{\partial x_\alpha}\tilde{M}_\alpha = 0 \tag{1}$$

2) Conservation of total momentum:

$$\frac{\partial}{\partial t}\tilde{M}_\alpha + \frac{\partial}{\partial x_\beta}[\tilde{U}_\alpha \tilde{M}_\beta + S_{\alpha\beta}] = T_\alpha + R_\alpha \tag{2}$$

where $\tilde{u}_\alpha = \tilde{M}_\alpha / \rho(h+\overline{\zeta}) = U_\alpha + M_\alpha / \rho(h+\overline{\zeta})$, $S_{\alpha\beta} = \overline{\int_{-h}^{\zeta}(\rho u'_\alpha u'_\beta + P\delta_{\alpha\beta})dz}$

$- \frac{1}{2}\rho g\,(h+\overline{\zeta})^2\delta_{\alpha\beta} - M_\alpha M_\beta / \rho(h+\overline{\zeta})$, $T_\alpha = -\rho g\,(h+\overline{\zeta})\frac{\partial}{\partial x_\alpha}\overline{\zeta}$, and

$$R_\alpha = \overline{\int_{-h}^{\zeta}\frac{\partial}{\partial x_\beta}\tau_{\beta\alpha}dz} + \overline{\tau_{\zeta\alpha}} - \overline{\tau_{h\alpha}} = -\frac{\partial}{\partial x_\beta}(S'_{\alpha\beta}) + \overline{\tau_{\zeta\alpha}} - \overline{\tau_{h\alpha}}$$

Here t is the time, x_α the horizontal axis, z the vertical axis taken above the still water level, p the pressure intensity, u'_α the horizontal component of wave orbital velocity, ρ the fluid density, g the acceleration due to gravity, $\delta_{\alpha\beta}$ the Kronecker delta, $\tau_{\beta\alpha}$ the Reynolds stress and $\overline{\tau_{\zeta\alpha}}$, $\overline{\tau_{h\alpha}}$, are the mean shear stresses at the free surface and at the bottom respectively. The term $S_{\alpha\beta}$ is the so-called radiation stress which corresponds to the excess momentum flux tensor, T_α the horizontal force per unit surface area induced by the free surface gradient, and R_α the frictional term consisting of the lateral and boundary frictional terms. The term $S'_{\alpha\beta}$ introduced here may be expressed by $\int_{-h}^{\zeta}\overline{\rho u''v''}dz$, where u'' and v'' are the horizontal components of turbulent velocity.

As stated previously, it is very common to apply the small amplitude wave theory in evaluating the radiation stress tensor $S_{\alpha\beta}$ which is given by

$$S = \overline{E}\begin{pmatrix} \frac{c_g}{c}\cos\theta^2 + \frac{1}{2}\left(\frac{2c_g}{c} - 1\right) & \frac{1}{2}\frac{c_g}{c}\sin 2\theta \\ \frac{1}{2}\frac{c_g}{c}\sin 2\theta & \frac{c_g}{c}\sin\theta^2 + \frac{1}{2}\left(\frac{2c_g}{c} - 1\right) \end{pmatrix} \tag{3}$$

where the wave profile ζ is assumed to be expressed by $\zeta = \frac{H}{2}\cos(x_1 k\cos\theta + x_2 k\sin\theta - \sigma t)$, in which H is the wave height, k the wave number, σ the angular frequency, θ the wave direction angle, and $\bar{E} = \frac{1}{8}\rho g H^2$ the average wave energy per unit water surface.

TWO DIMENSIONAL CASE

WAVE SET-DOWN AND WAVE SET-UP

As a first step of the present discussion, the following simple case will be taken. That is to say, the waves are coming perpendicularly to the shoreline, hence the wave direction angle θ is equal to zero. In addition to the above it is assumed that the phenomenon is in the steady state, and the bottom contour lines are parallel to the shoreline. In such a case, the basic equation is simply expressed by

$$\frac{d}{dx} S_{xx} = - g(h+\bar{\zeta})\frac{d}{dx}\bar{\zeta} + R_x \tag{4}$$

where x is taken in the onshore-offshore direction.

The nearshore area is usually separated into two regions; the first one is the outside of the surf zone, and the other one is the inside of the surf zone. The reason is that there exists a remarkable difference in wave characteristics in these two regions. The treatments given by Eqs. (5) and (6) in the following are the very common ways to evaluate the amount of wave set-down as well as that of wave set-up.

1) Outside the surf zone:

$$\bar{\zeta} = -\frac{H^2}{8}\frac{k}{\sinh 2kh} \tag{5}$$

under the conditions of $R_x \approx 0$ and $\bar{\zeta} << h$.

2) Inside the surf zone:

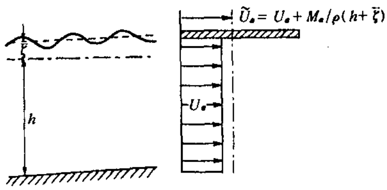
$$\bar{\zeta} = K(h_b - h) + \bar{\zeta}_b$$

$$K = [1 + (8/3\gamma^2)]^{-1} \tag{6}$$

under the conditions of $R_x \approx 0$ and $H \approx \gamma(h+\bar{\zeta})$, where the subscript b indicates the value at the breaking point.

It has been realized that these equations give the curves of mean water level which agree well with the laboratory data except in the vicinity of the breaking point.

Figure 2 demonstrates a result of comparison among the mean water level measured in a wave flume and those calculated by using any one of the small amplitude wave theory, the linear long wave theory, the stream function theory (Dean, 1967), and the radiation stress S_{xx} obtained from the measured velocity field through an approximate expression (Isobe, Fukuda & Horikawa, 1979). Here it should be mentioned that these calculations except the last one were made by using the measured wave profile at each location. That is to say, in the case of the small amplitude wave theory the measured wave height only



$$u_\alpha = U_\alpha + u'_\alpha$$

$$\tilde{M}_\alpha = \overline{\int_{-h}^{\zeta} \rho u_\alpha dz} = \hat{M}_\alpha + M_\alpha$$

$$\hat{M}_\alpha = \overline{\int_{-h}^{\zeta} \rho U_\alpha dz} = \rho(h+\bar{\zeta})U_\alpha$$

$$M_\alpha = \overline{\int_{-h}^{\zeta} \rho u'_\alpha dz}$$

Fig. 1 Definition sketch (adapted from Phillips, 1977).

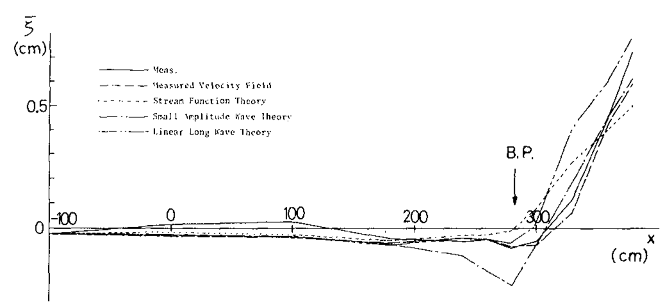


Fig. 2 Comparison between the measured and predicted wave set-down and wave set-up curves.

was used for the computation, while in the case of the linear long wave theory the instant horizontal velocity component was calculated by using the well-known relationship of $u = \sqrt{g/h}\,\zeta$, where u is the horizontal velocity component and ζ is the surface wave elevation above the mean water level. On the other hand, the stream function theory containes in it the non-linear effect of wave characteristics.

From this diagram, it is realized that the curve calculated by using the values of S_{xx} stated above fits best in the measured mean water level. However the curve based on the small amplitude wave theory deviated extremely from the measured one especially in the vicinity of breaking point.

EVALUATION OF RADIATION STRESS

The fact stated above indicates that the radiation stress S_{xx} outside the surf zone evaluated here on the basis of the small amplitude wave theory seems to be inadequate for the present purpose. Figure 3 demonstrates the above surmise; that is to say, the small amplitude wave theory seems to have a tendency to overestimate the value of $S_{xx}/\rho g$ especially near the breaking point. This conclusion is quite natural, because the non-linearity of waves is normally intensified in the shallow water region. In addition to the above, it should be mentioned that the actual wave height change on the gently sloping beach up to the breaking point differs from the curve calculated by using the small amplitude wave theory as shown in Fig. 4. Here the predicted curve is based on the simple rule of energy flux conservation, and only the wave height in deep water is given in the present computation. Due to the double fault stated above, it is quite possible that the onshore-offshore distribution curve of $S_{xx}/\rho g$ outside the surf zone can be predicted a little more closer to the reference curve from the deep water wave height on the basis of the small amplitude wave theory.

On the other hand, the wave height inside the surf zone, H, is well expressed by the relationship of $H = \gamma(h + \bar{\zeta})$, where h is the still water depth, $(h + \bar{\zeta})$ is the local water depth, and γ is a proportionality constant. However, the field and laboratory data indicate that the above proportional relationship between the wave height and the local water depth holds good only on a uniformly gently sloping beach (Hotta & Mizuguchi, 1978, Mizuguchi, Tsujioka & Horikawa, 1978, and Mizuguchi & Horikawa, 1978).

The wave set-down and wave set-up are closely related to the gradient of radiation stress, while the radiation stress has a close connection with the local wave pattern. That is why the stream function theory predicts well the radiation stress, thus the mean water level, at least outside the surf zone.

WAVE CELERITY

From the above discussion, it is clear that the small amplitude wave theory is not powerful to predict the wave height change on a gently sloping beach. However the wave celerity is in a little different situation from the wave height. Figure 5 show the comparison between the measured wave celerity curve and the theoretical curves based either on the small amplitude wave theory or on the solitary wave thoery. From this diagram it is realized that the discrepancy between the measured one and the theoretical one based on the small amp-

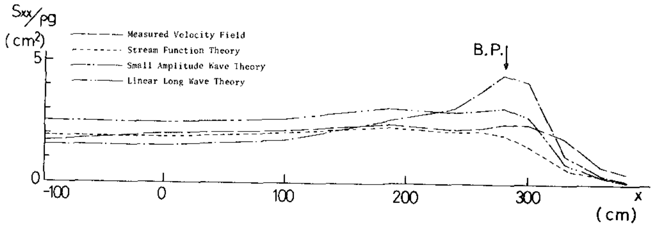


Fig. 3 Radiation stress curves predicted by the various methods.

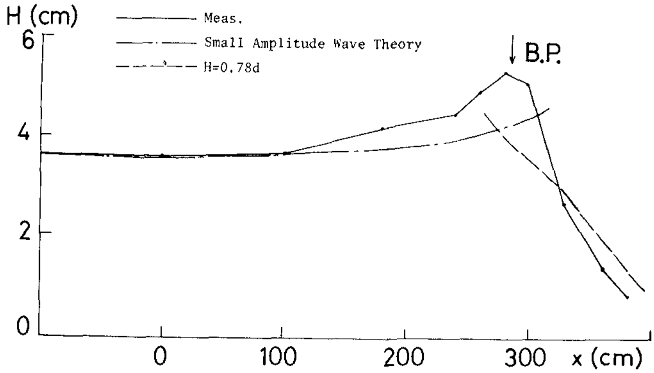


Fig. 4 Comparison between the measured and predicted wave height change.

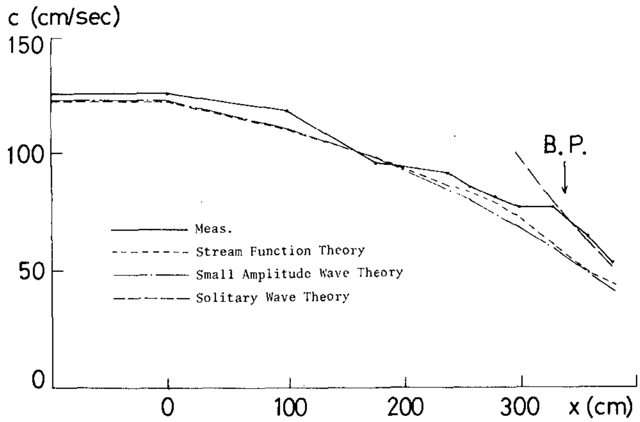


Fig. 5 Comparison between the measured and predicted wave celerity change.

litude wave theory is not large in the offshore region, but becomes large in the nearshore region. However in the surf zone, the wave celerity can be predicted fairly well by the solitary wave theory.

CORRELATION BETWEEN SURFACE PROFILE AND VELOCITY FIELD

In order to investigate the detailed mechanism of wave-induced velocity field, the surface fluctuation and the fluid velocity components were measured at numerious locations in a laboratory flume (Fig. 6). Table 1 gives the conditions of laboratory experiments carried out for the present investigation. Figure 7 shows sample records of wave profile and the horizontal velocity component taken simultaneously. For the comparison, the stream function method and the 5th order Stokes wave theory were applied to the wave profile, and the time history of velocity components were calculated by these methods. In addition to these, the linear filter method was applied to calculate the velocity component from the wave profile. As for the wave profile, it is quite natural that the curves based on the stream function method agree well with the measured ones both outside and inside the surf zone. The 5th order Stokes wave theory gives fairly good results in the offshore region. As for the velocity component, the curves obtained outside the surf zone agree well with those based on either the Stokes wave theory or the stream function method. The linear filter is also applicable to calculate the velocity component near the bottom from the surface profile. On the other hand, the velocity component inside the surf zone has the following remarkable tendency. The velocity near the free surface measured at the location just after breaking differs largely from the predicted one, but the velocity near the bottom agrees well with the one predicted by using the stream function theory.

That is to say, in the region just after the breaking the turbulent fluctuation is very strong, therefore the simple prediction methods stated above are not powerful for our purposes, but the turbulent fluctuation does not penetrate down to the sea bottom. Off course, such situation is strongly dependent on the breaking type and the distance to the questioned point measured shoreward from the breaking point. The above fact indicates that the Reynolds stress of the turbulent fluctuation induced by breaking phenomenon should play an important role in the nearshore dynamics.

In the ordinary treatment on the wave set-up in the surf zone, the frictional term is conventionally neglected as shown in Eqs. (5) and (6). The frictional term consists of the bottom frictional and the lateral frictional terms, in which the latter term is the depth integral of the Reynolds stress. Based on the laboratory investigation data, the authors have the insight that the bottom frictional term averaged over many wave cycles does not contribute significantly to the wave set-up phenomenon due to the time-dependent oscillatory motion, while the lateral frictional term must have an important influence on the stated phenomenon. At the present stage, the data on this subject are extremely scarce, hence the further effort to accumulate laboratory and field data seems to be of essential importance.

FIELD OBSERVATION

In the foregoing discussion, the laboratory data were only used. In order to confirm the stated results, a part of the field observation data will be presented in the following.

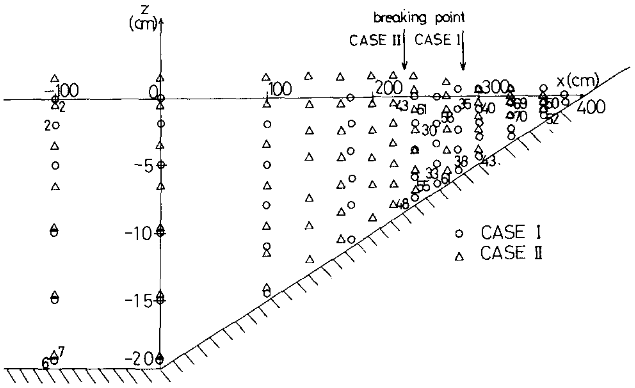


Fig. 6 Location diagram of the measuring points.

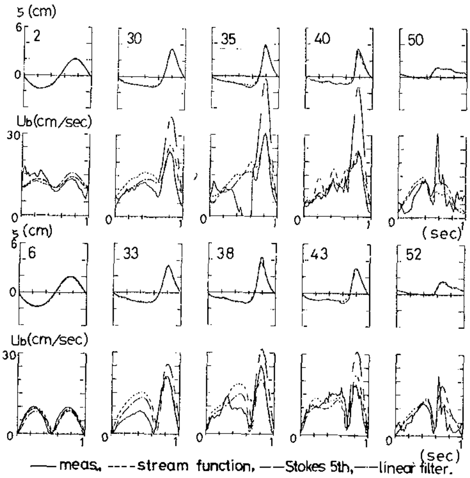


Fig. 7 Comparison of the measured time histories of wave profile and of corresponding absolute velocity with those predicted by the various methods (Case I).

A number of poles were installed closely in a raw perpendicular to the shoreline inside the surf zone on Ajigaura coast, Ibaragi Prefecture, Japan, and the data of sea surface fluctuations at these poles were collected by using simultaneously operated 16mm memo-motion cameras. In some cases a frame was set in the surf zone. On this frame a certain number of electromagnetic current meters were attached in order to measure the vertical distribution of wave-induced current velocities. Hence the surface fluctuation and the corresponding velocity fluctuations were measured simultaneously.

Two records of surface fluctuations obtained at two points 2m apart in the direction perpendicular to the shoreline in the surf zone were picked up. The wave direction angle was negligibly small, hence the wave celerity could be calculated by the phase shift between these two records. The abscissa of the diagram shown in Fig. 8 is the frequency in Hz and the ordinate is the phase shift. Therefore the wave celerity is proportional to the slope of the curve. The plotted points fall on the theoretical curve based on the solitary wave theory, and this fact confirms the conclusion obtained in the loboratory investigations.

Figures 9 (a), (b), and (c) show the serial comparison between the time history of measured velocity components and those predicted by the various methods using the corresponding surface profiles. From these figures, it can be said in general that the stream function method is useful in field also for the prediction of velocity components outside the surf zone. However, the predicted velocity curves by the various methods are not always fit to the measured ones inside the surf zone. Especially it is remarkable that there is time lag between the calculated and measured velocity components.

Figures 10 (a) and (b) give the power spectra of water surface fluctuaions at two points, one is located outside and the other is inside the surf zone. Figures 11 (a) and (b) indicate the power spectra of wave induced velocity components at the corresponding locations in Figs. 10 (a) and (b), where u_2 and v_2 are the onshore-offshore and alongshore components of velocity measured near the water surface, while u_4 and v_4 are near the sea bed. From these diagrams it can be observed that the turbulent velocity fluctuation is very weak outside the surf zone, but it is strong just after the breaking point especially near the surface. Looking at these data, the authors have tried to construct the following conceptual model of turbulent fluctuation in the nearshore area.

The turbulent fluctuation in the nearshore area is primarily generated by the wave breaking, therefore the turbulence outside the surf zone is negligibly small but that inside the surf zone is remarkably strong especially in the vicinity of the breaking point. The disturbance induced by the breaking waves penetrates into the body of water, and reaches slightly to the bottom. Therefore the distribution of the Reynolds stresses is negligibly small outside the surf zone, but is large enough to be considered inside the surf zone. It is needless to say that the wave-induced turbulence depends upon the breaker type, the running distance of breakers, and the depth below the water surface.

In addition to the above, it should be mentioned that the power spectra of velocity fluctuation inside the surf zone contain tremendously big spectral density in the low frequency part as shown in Fig. 11 (b) comparing with

Table 1 Experimental conditions.

Case	Incid. Wave Height Hi(cm)	Wave Period T(s)	Ho Io	Breaker Type
I	3.5	1.0	0.025	Plunging
II	5.5	1.0	0.039	Plunging

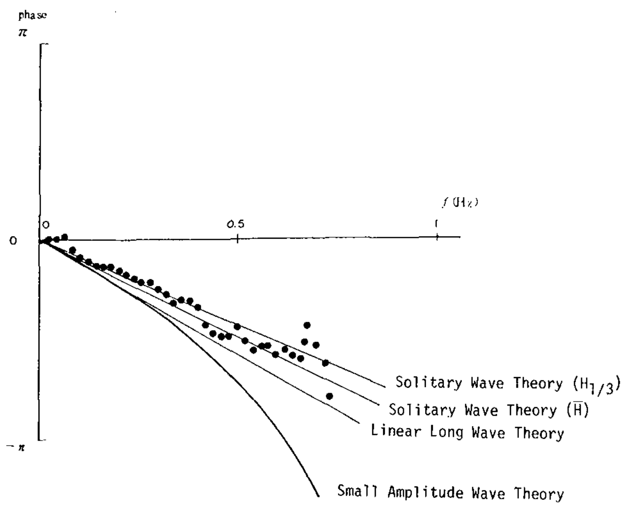
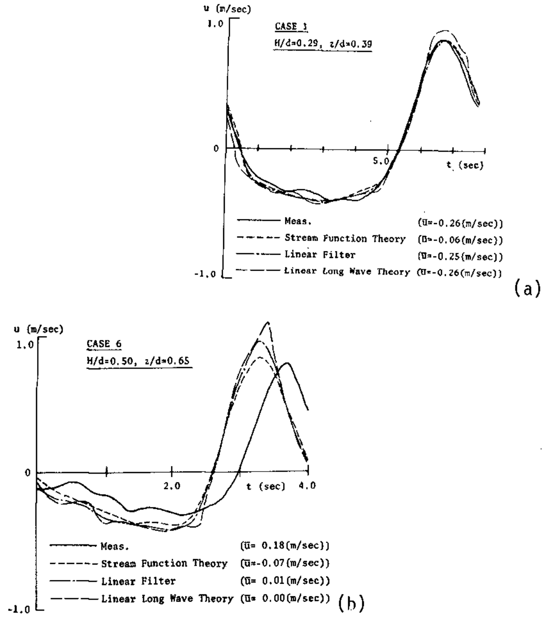


Fig. B Wave celerity in the surf zone observed in field.



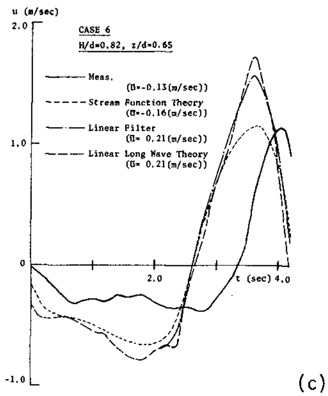
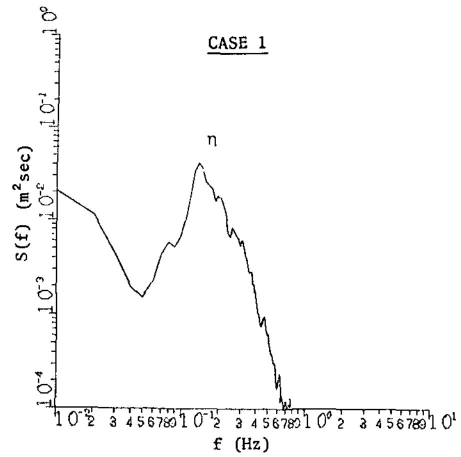
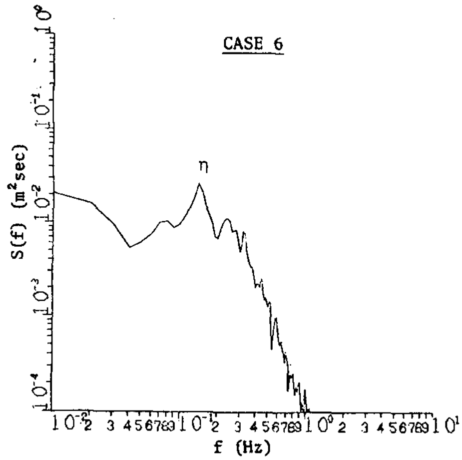


Fig. 9 Time history of horizontal velocity component. Comparizon between the measured and predicted curves, where z is taken upward from the sea bottom, d the mean water depth at the measuring site, and $\overline{u}$ the shoreward mean constant velocity. Thus u is the value subtracted the $\overline{u}$ value from the actual velocity.

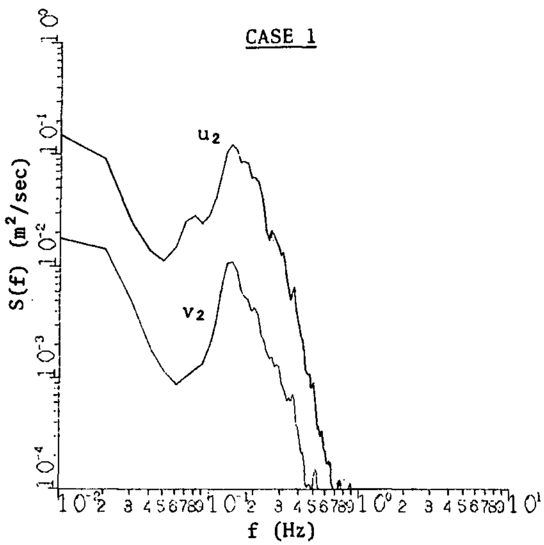


(a) Outside the surf zone.



(b) Inside the surf zone.

Fig. 10 Spectra of surface fluctuation at the two measuring points, where η is the surface elevation measured upward from the mean sea level.



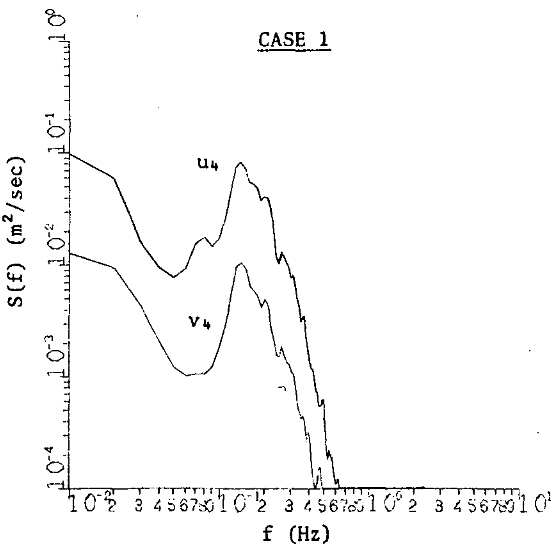
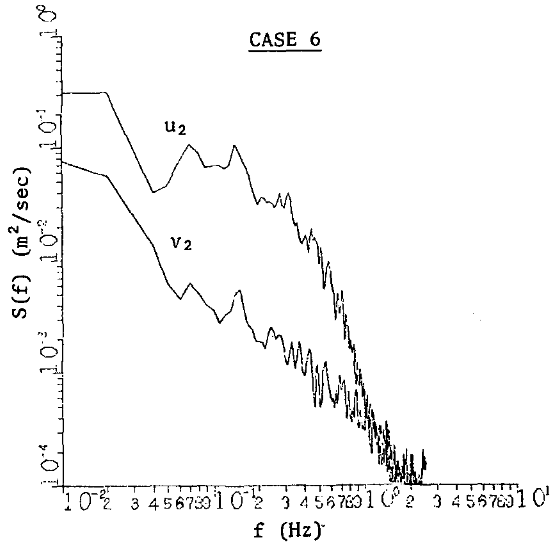


Fig. 11 (a) Spectra of velocity components outside the surf zone.



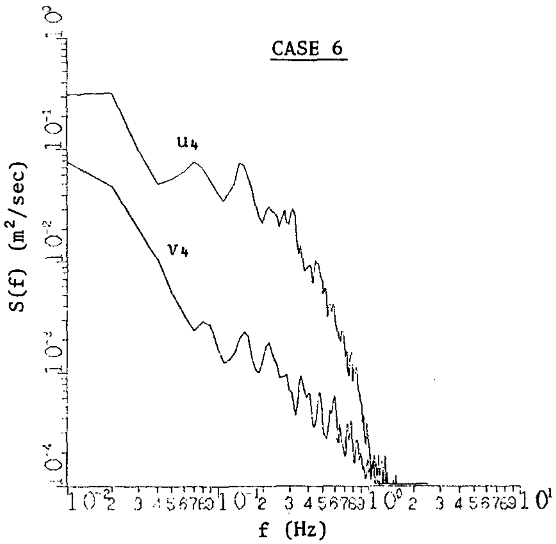


Fig. 11 (b) Spectra of velocity components inside the surf zone.

those for the outside of the surf zone as shown in Fig. 11 (a). This fact indicates that the low frequency (that is, long period) oscillation is predominant inside the surf zone as reported by Sasaki and Horikawa (1978).

THREE DIMENSIONAL CASE

LONGSHORE CURRENT VELOCITY DISTRIBUTION

In order to proceed the present discussion to the three dimensional case, longshore current velocity distribution will be treated. As Longuet-Higgins (1970) pointed out in his paper, the longshore current velocity is used to have its maximum at a certain point located between the shoreline and the breaker line. The velocity distributions in a wave basin have so far been measured under the various conditions of bottom slope, wave approaching angle, and wave characteristics. Through the analysis of these data, it was realized that the shoreward pattern of velocity distribution in the surf zone on a uniformly sloping beach fits very well with the one calculated under an appropriate value of P on the basis of the Longuet-Higgins analytical result. Here P is defined by Longuet-Higgins as a non-dimensional parameter representing the relative importance of horizontal mixing and lateral friction. However, the seaward pattern of the measured velocity distribution curve drops abruptly comparing with the theoretical one. One example is shown in Fig. 12. The above discrepancy is presumably caused by the following two reasons. The first reason is that the value of S_{xy} used for the calculation was derived by using the small amplitude wave theory. The second reason is that the expression for the lateral friction outside the surf zone was estimated to be too large comparing with the actual one. In addition to these, the effect of wave approaching angle can be pointed out as discussed independently by Liu & Darlimple (1978) and Kraus & Sasaki (1979).

INTERNAL CHARACTERISTICS OF SURF ZONE

Izumiya, Isobe, Watanabe & Horikawa (1980) reported recently a detailed laboratory measurement of the internal characteristics of waves and wave-induced current in the surf zone. Their measurement was performed under such a simple condition as the longshore current being predominant on a fixed uniform slope of 1/20 in a wave basin. The characteristic conditions of the waves are as follows: the wave height at the uniform water depth h=25cm is 4.1cm, the wave period is 0.87s and the wave angle at the breaker line is 15°.

The fluctuation of velocity components were measured directly by using hot-film anemometers. Based on these laboratory data, they tried to evaluate how well the radiation stresses outside and inside the surf zone can be evaluated by using the appropriate theory, and to find out how much the lateral frictional term contributes to the balance in the dynamical equation.

The governing equation of the present case is expressed by

$$\frac{d}{dx} S_{xy} = R_y = -\frac{d}{dx} S_{xy}' + \overline{\tau_{\zeta y}} - \overline{\tau_{hy}} \tag{7}$$

where x and y are taken perpendicular and parallel to the shoreline respectively. In order to predict precisely the spatial velocity distribution of longshore current, the characteristics of the two terms S_{xy} and R_y should be clarified in more detail. Equation (7) can be rewritten in the next form;

$$\frac{d}{dx}(S_{xy} + S_{xy}') = \overline{\tau_{\zeta y}} - \overline{\tau_{hy}} \tag{8}$$

Here the new term $\tilde{S}_{xy} = S_{xy} + S_{xy}'$ will be difined for the convenience of the following discussion.

It is quite natural that the record of current velocity components taken inside the surf zone is the superposition of the turbulent fluctuation generated by the breaking wave action on the wave orbital and steady current velocity components. In the forgoing treatment, the vertically uniform steady current is assumed, however the actual current must have a certain vertical distribution which is not yet clearly known. Considering the above fact, it should be noticed that the term S_{xy} in the paper reported by Izumiya, Isobe, Watanabe & Horikawa (1980) is not exactly equal to the radiation stress or the excess momentum flux defined by Longuet-Higgins & Stewart (1964). However, they reported that the caluculated term S_{xy} is well expressed by the 5th order Stokes wave theory outside the surf zone.

Figure 13 indicates the variations of $\tilde{S}_{xy}$ and S_{xy} from offshore to onshore. From this diagram, it is clearly seen that the $S_{xy}' = \tilde{S}_{xy} - S_{xy}$ is zero outside the surf zone but is large enough to be considered inside the surf zone. In Eq. (8) the shear stress along the water surface $\tau_{\zeta y}$ is negligibly small, therefore the gradient of $\tilde{S}_{xy}$ must be balanced with the bottom shear stress τ_{hy}.

The lateral frictional stress is used to be expressed simply to be proportional to the gradient of the longshore current velocity. However, it seems to be unreasonable that the proportionality constant becomes negative just after breaking as seeing from Figs. 12 and 13.

Here it should be noticed that the term S_{xy} takes its maximum at the location a little offshoreward from the breaking point. That is to say, the gradient of S_{xy} between that point and the breaking point determines the velocity destribution of longshore current outside the surf zone. The above mechanism is quite important to understand the real longshore current pattern.

Figure 14 demonstrates the spatial distribution of Reynolds stress $-\overline{\rho u''v''}$ from which the statement made in the previous section can be confirmed.

CONCLUSIONS

The main conclusions of the present paper are summarized in the following:

(1) It is quite naturally true that the small amplitude wave theory is not powerfull to take the insight of the detailed mechanism of nearshore dynamics.

(2) Therefore some appropriate theory or method should be applied to evaluate the dynamic characteristics of waves outside and inside the surf zone.

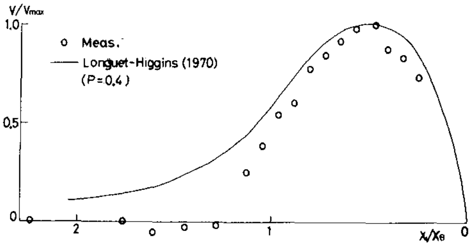


Fig. 12 Longshore current velocity distribution ($\tan\beta = 1/20$) (adapted from Izumiya, Isobe, Watanabe & Horikawa, 1980).

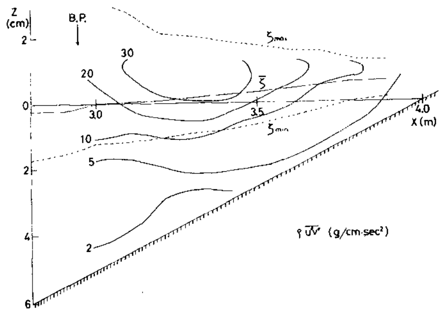


Fig. 13 Distribution curves of $\tilde{S}_{xy}$ and S_{xy} (adapted from Izumiya, Isobe, Watanabe & Horikawa, 1980).

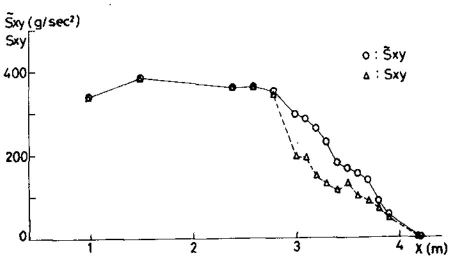


Fig. 14 Distribution pattern of $\rho\overline{u''v''}$ (adapted from Izumiya, Isobe, Watanabe & Horikawa, 1980).

(3) The precise caluculation of radiation stresses is of essential importance to predict the phenomena actually happening in the nearshore area.

(4) The Reynolds stresses are negligibly small outside the surf zone, but is large enough to be taken into consideration inside the surf zone due to the strong breaking wave disturbance. Therefore the evaluation of Reynolds stresses in the surf zone is also needed to understand the various phenomena in the surf zone.

(5) In order to clarify the detailed mechanism of nearshore phenomena, more data should be accumulated in laboratory as well as in field.

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REFERENCE

Dean R. G. (1965): Stream function representation of nonlinear ocean waves, J. Geophy. Res., Vol. 70. No. 18, pp.4516-4572.

Hotta, S, and M. Mizuguchi (1978): Field observations of broken wave characteristics, Proc. 25th Conf. on Coastal Eng. in Japan, pp.151-154 (in Japanese).

Isobe, M., N. Fukuda and K Horikawa (1979): Two-dimensional laboratory experiments on the velocity field inside the surf zone, Proc. 26th Conf. on Coastal Eng. in Japan, pp.41-45 (in Japanese).

Izumiya, T., M. Isobe, A. Watanabe and K. Horikawa (1980): Laboratory investigation on the internal velocity and the frictional stress coefficient in the wave and wave induced current field, Proc. 27th Conf. on Coastal Eng. in Japan (in Japanese, in press).

Kraus, N. C. and T. O. Sasaki (1979): Influence of wave angle and lateral mixing, Cmmu. of Marine Sci., Vol. 5, No. 2, pp.91-126.

Liu, P. L - F. and R. A. Oarlymple (1978): Bottom frictional stresses and longshore currents due to waves with large angle of incidence, J. Marine Res., Vol. 36, No. 2, pp.357-375.

Longuet-Higgins, M. S. (1970): Longshore currents generated by obliquely incident sea waves, 1 & 2, J. Geophys. Res., Vol. 75, No. 33, pp.6778-6789 & pp.6790-6801.

Longuet-Higgins, M. S. and R. W. Stewart (1960): Changes in the form of short gravity waves on long waves and tidal currents, J. Fluid Mech., Vol. 8, pp.565-583.

Longuet-Higgins, M. S. and R. W. Stewart (1964): Radiation stresses in water waves; a physical discussion, with application, Deep Sea Res., Vol. 11, pp.529-562.

Mizuguchi, M., K. Tsujioka and K. Horikawa (1978); A consideration on wave height variation after breaking, Proc, 25th Con-on Coastal Eng, in Japan, pp.155-159 (in Japanese),

Mizuguchi, M. and K. Horikawa (1978): Experimental study on longshore current velocity distribution, Bull. Faculty of Science and Eng., Chuo Univ,, Vol, 21, pp.123-149.

Phillips. O. M. (1977): The Dynamics of the Upper Ocean, Cambridge Univ. Press, 336p.

Sasaki, O. T. and K. Horikawa (1978): Observation of nearshore current and edge waves, Proc 16th Int. Conf. on Coastal Eng., Hamburg, pp.791-809,