

CHAPTER 184

Effect of Breaking Waves on Dissolved Oxygen and Organic Matter

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Abstract

Water pollution in the near shore area has become a serious problem in coastal engineering. In such a situation, not only wave dissipation but also the functioning of water pollution control is expected from the coastal structure. Since breaking waves are accompanied by many bubbles and intense water turbulence, they promote the contact between organic matter and bacteria and between water and air. Therefore the water quality related to organic matter seems to change under the effect of breaking waves. In this study the variation of the dissolved oxygen and the organic matter near the surf zone were considered. First, a self purification model in the surf zone was developed. Second, the efficiency of breaking waves on reaeration and organic matter decomposition was estimated by an experiment in the laboratory flume and numerical simulation.

1. Introduction

With the expansion of human activities, water pollution in the nearshore area has increased. Organic contaminants discharged into water are decomposed by aerobic bacteria through their metabolic process, which results in the utilization of the dissolved oxygen. The deficit oxygen is compensated for by reaeration which occurs through the water surface exposed to the atmosphere. When the rate of oxygen utilization in the decomposition of organic contaminants is within the limit recoverable by the reaeration, the water environment is maintained under desirable conditions. In that sense, the evaluation of natural purification is important in water quality control. Many studies concerning this have been made in rivers.(O'Connor and Dobbins(1956), Churchill et al.(1962), Dobbins(1964)) However, studies of this kind in the sea are few, because the great dilution within a large amount of water plays a principal role in sea water purification.

In general, water turbulence accelerates the contact between the organic matter and bacteria and also between water and air. Therefore it promotes the decomposition of organic matter and the oxygen absorption. Breaking waves produce many bubbles and intense water turbulence. Thus they seem to play a significant role in water purification near the coast, particularly in a bay or water enclosed by breakwaters, where the water exchange with the outer ocean is relatively limited.

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Therefore, if we know the characteristics of the natural water purification caused by breaking waves, we can design artificial coasts or coastal structures from the viewpoint of water quality control.

In this study, in order to examine the effect of breaking waves on water quality, we considered the changes of water quality related to organic pollution near the surf zone.

2. Self purification in the nearshore area

As for the decomposition of organic contaminants in a river, the attached bacteria on the bed are considered to play a more significant role than suspended ones. In the case of the coastal area, there are many sites where attached bacteria can grow, for example beaches, breakwaters and so forth. Therefore we can suppose that organic matter is decomposed there by the activity of attached bacteria. Here we propose a model of self purification near the coast as shown in Fig.1.

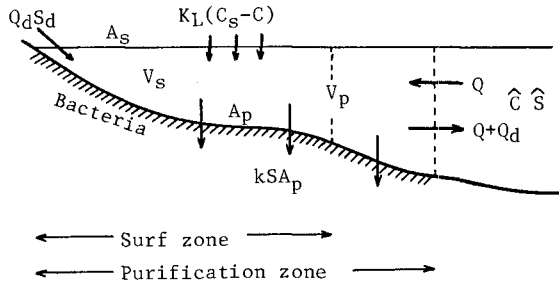


Fig.1 Model of self-purification in nearshore area

The volume of discharged water is represented by Q_d , which includes organic matter whose concentration is S_d . The organic matter is decomposed by the biofilm with the rate of kSA_p . The water volume per unit width in this decomposition zone (which we call in this paper the purification zone) is described by V_p .

The oxygen is supplied through the water surface. As we will describe later, the reaeration efficiency in the surf zone is still greater than that in other areas. Therefore we assume the oxygen is absorbed only at the surf zone whose surface area is A_s .

The mass conservation equations describing the dissolved oxygen and the organic matter are as follows, respectively,

$$d(CV_p)/dt = -kSA_p + K_L(C_s - C)A_s + Q_d C_d + Q\hat{C} - (Q + Q_d)C \quad (1)$$

$$d(SV_p)/dt = -kSA_p + Q_d S_d + Q\hat{S} - (Q + Q_d)S \quad (2)$$

where C and S are the dissolved oxygen concentration and the organic matter concentration, respectively. $\hat{C}$ and $\hat{S}$ represent the quantities of the outside of the purification zone and C_s the saturated dissolved oxygen concentration. C_d represents the dissolved oxygen in the

discharged water.

We introduce the nondimensional form:

$$C^* = C/C_s, \quad S^* = S/S_r, \quad t^* = t/T \quad (3)$$

where S_r and T are the representative concentration of organic matter and the wave period, respectively.

We rewrite Eqs.(1) and (2) by Eq.(3) as follows,

$$dC^*/dt^* = -k_1 T S^* S_r / C_s + k_2 T (1 - C^*) + T Q_d C_d^* / V_p + T Q \hat{C}^* / V_p - T (Q + Q_d) C^* / V_p \quad (4)$$

$$dS^*/dt^* = -k_1 T S^* + T Q_d S_d^* / V_p + T Q \hat{S}^* / V_p - T (Q + Q_d) S^* / V_p \quad (5)$$

where $k_1 = k A_p / V_p$ (6), $k_2 = K_L A_s / V_p$ (7)

k_1 and k_2 stand for the overall rate constants of decomposition and reaeration in the purification zone, respectively. When the role of suspended bacteria cannot be disregarded, we can include their effects in k_1 .

The initial condition is given as follows,

$$t^* = 0 : S^* = S_0^*, \quad C^* = C_0^* \quad (8)$$

We solve Eqs.(4) and (5) and obtain the following equations.

$$S^* = S_\infty^* + (S_0^* - S_\infty^*) \exp(-\alpha t^*) \quad (9)$$

$$C^* = C_\infty^* - \gamma \exp(-\alpha t^*) + (C_0^* - C_\infty^* + \gamma) \exp(-\beta t^*) \quad (10)$$

$$\gamma = (k_1 S_r / C_s) (S_0^* - S_\infty^*) / (k_2 - k_1)$$

α shows water purification efficiency by bacterial decomposition and the water exchange with the outer region, and β shows the efficiency of oxygen supply in reaeration and the water exchange. Each of them are written as follows, respectively.

$$\alpha = k_1 T + T (Q + Q_d) / V_p \quad (11)$$

$$\beta = k_2 T + T (Q + Q_d) / V_p \quad (12)$$

The steady state solutions, S_∞^* and C_∞^* , are given as follows, respectively,

$$S_\infty^* = F / \alpha = (Q_d S_d^* + Q \hat{S}^*) / (k_1 V_p + Q + Q_d) \quad (13)$$

$$C_\infty^* = (F + k_2 T - k_1 T S_\infty^* S_r / C_s) / \beta = \frac{Q_d C_d^* + Q \hat{C}^* + k_2 V_p - k_1 V_p S_\infty^* S_r / C_s}{k_2 V_p + Q + Q_d} \quad (14)$$

F is the total discharged contaminant load written as

$$F = (Q_d S_d^* + Q \hat{S}^*) T / V_p \quad (15)$$

The oxygen sag curve obtained by Eq.(10) is shown in Fig.2 and t_1^* , t_2^* and $C_{\min}^*$ are given as follows, respectively.

$$t_1^* = \frac{1}{\beta - \alpha} \ln \frac{\beta(F + C_{\infty}^* - C_0^*)}{\alpha F} \quad (16)$$

$$t_2^* = \frac{1}{\beta - \alpha} \ln \frac{\beta^2(F + C_{\infty}^* - C_0^*)}{\alpha^2 F} \quad (17)$$

$$C_{\min}^* = C_{\infty}^* - \gamma \left\{ \frac{\beta(C_0^* - C_{\infty}^* + \gamma)}{\alpha \gamma} \right\}^{\frac{\alpha}{\alpha - \beta}} + (C_0^* - C_{\infty}^* + \gamma) \left\{ \frac{\beta(C_0^* - C_{\infty}^* + \gamma)}{\alpha \gamma} \right\}^{\frac{\beta}{\alpha - \beta}} \quad (18)$$

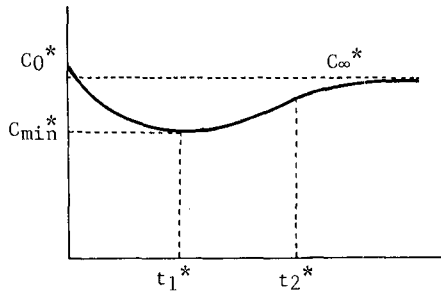


Fig.2 Oxygen sag curve in nearshore area

When $C_{\min}^*$ is greater than the critical concentration in which the self purification is possible, the desirable water environment can be recovered. Generally, the minimum DO concentration where aerobic decomposition takes place is said to be 2 mg/l. Thus $C_{\min}^*$ must be greater than 0.15-0.3 (C_s depends on the water temperature and salinity).

In the steady state case, the amount of discharged contaminants into the purification zone is $Q_d S_d^*$ and the amount going out from the purification zone toward the offing is $(Q + Q_d) S_{\infty}^*$. When we can regard $Q\hat{S}$ as negligibly small compared with $Q_d S_d^*$, the ratio of both amounts, which gives the purification efficiency, is shown as

$$\frac{(Q + Q_d) S_{\infty}^*}{Q_d S_d^*} = \frac{1}{1 + (k_1 V_p) / (Q + Q_d)}$$

Thus $k_1 V_p / (Q + Q_d)$ is the index which indicates the purification capacity when $C_{\min}^*$ satisfies the condition mentioned above.

3. Experimental apparatus and procedure

We examined the behavior of water quality in and near the

purification zone by experiments.

The experiments were performed in a two dimensional wave flume, 14.8 m long, 18.5 cm wide. The water depth was 15.0 cm. The model beach with a plane slope 1/20 was placed in it. Two kinds of experiment were performed as follows.

1) The experiments on reaeration

After the dissolved oxygen (DO) concentration in the flume was reduced with sodium sulfite, waves were generated and broken on the beach. The spatial-temporal DO distribution was observed. The detailed method was reported in Hosoi et al.(1984).

2) The experiments on the decomposition of the organic matter

The aerobic bacteria were added to the water in the flume and waves were generated. Under the presence of waves they were cultured for about 20 days with skim milk fed as a substrate. After the bacteria had grown attached to the sloping bottom, the experiment on the oxidization was conducted as follows.

The initial concentration of organic matter was promoted by skim milk, and waves were generated. The water samples were collected at fixed intervals to capture the spatial-temporal change of DO and the organic matter. The amount of the organic matter was estimated by the chemical oxygen demand (COD) using potassium dichromate.

One series of experiments continued for not longer than 3 days to avoid the influence of the change of biofilm condition.

After one series of experiments was finished, we collected the attached bacteria and observed the biomass and the bacterial activity. The bacterial activity was examined as follows. We put the collected bacteria into a beaker of water which contained organic matter. The water was stirred to suspend bacteria and the temporal changes of COD were observed.

The experiments of 1) and 2) were conducted under some different deep water wave heights.

4. Reaeration

4.1 Theoretical consideration

According to Danckwerts' surface renewal theory, which explains the gas transfer across the gas-liquid interface in the turbulent flow, the oxygen flux across the interface j and the oxygen transfer coefficient K_L are expressed as follows, respectively,

$$j = K_L (C_s - C) \quad (19), \quad K_L \sim (Dr)^{1/2} \quad (20)$$

where D is the molecular diffusion coefficient. r is the renewal rate which means that water elements near the surface are replaced by the bulk water, and has the dimension of the minus first power of time. It has a close relationship to the turbulent motion.

We assumed the dependence of r on the turbulence as follows (Hosoi et al.(1984)),

$$r \sim (\epsilon/\nu)^{1/2} \quad (21)$$

where ϵ and ν are the energy dissipation rate and the kinematic viscosity, respectively.

If we assume all of the energy which is transported by the wave from the offing toward the shore dissipates in the surf zone, we obtain

$$\epsilon = g^2 H_0^2 T / (32\pi V_s) \quad (22)$$

where V_s represents the water volume of the surf zone per unit width.

Placing Eqs.(20), (21) and (22) into Eq.(7), we obtain

$$\begin{aligned} k_2 &\sim (T/\nu V_s)^{1/4} (DgH_0)^{1/2} A_s / v_p \\ &= (T/\nu V_s)^{1/4} (DgH_0)^{1/2} (v_s/v_p) / \bar{h}_s \end{aligned} \quad (23)$$

where $\bar{h}_s$ is the mean depth of the surf zone and H_0 the deep water wave height.

If the surf zone has a plane slope, we can say $\bar{h}_s = h_b/2$, where h_b is the breaker depth.

4.2 Experimental results

Fig.3 shows the temporal changes of the dissolved oxygen profile in the experiment on reaeration. The increase rate in the dissolved oxygen is the greatest in the surf zone and becomes smaller as the distance from the shoreline increases.

As we previously indicated (Hosoi and Murakami(1981)), this figure makes us believe that the effect of oxygen absorption in the surf zone is so much greater than in other areas that the oxygen is absorbed only in the surf zone and transferred offshore.

On the basis of this consideration we evaluated the reaeration coefficient (Hosoi et al.(1984)). When we divided the examination area into the boxes as shown in Fig.4, we could obtain the following equation in the i box.

$$dC_i V_i / dt = V_i k_{2i} (C_s - C_i) + q_{i-1} (C_{i-1} - C_i) - q_i (C_i - C_{i+1}) \quad (24)$$

where suffix i represents the quantity in number i box and q_i the water exchange across the boundary between i and $i+1$ boxes. The box is divided so that the innermost box whose number $i=1$ becomes the surf zone, i.e., the area between the breaking point and the shoreline, and define the box $i=2,3,4,\dots$ in order towards the offing.

Summing up Eq.(24) from $i=1$ to n , and taking into consideration that the reaeration efficiency in the surf zone is so much greater than other parts that we can neglect their contribution, we obtained

$$d\sum C_i V_i / dt = V_1 k_{2,1} (C_s - C_1) + q_n (C_{n+1} - C_n) \quad (25)$$

As we saw in Fig.3, the influence of the reaeration in the surf zone did not extend far into the offing. Thus if n -box is taken far from the breaking point where C_n can be regarded as equal to C_{n+1} , Eq.(25) is rewritten as

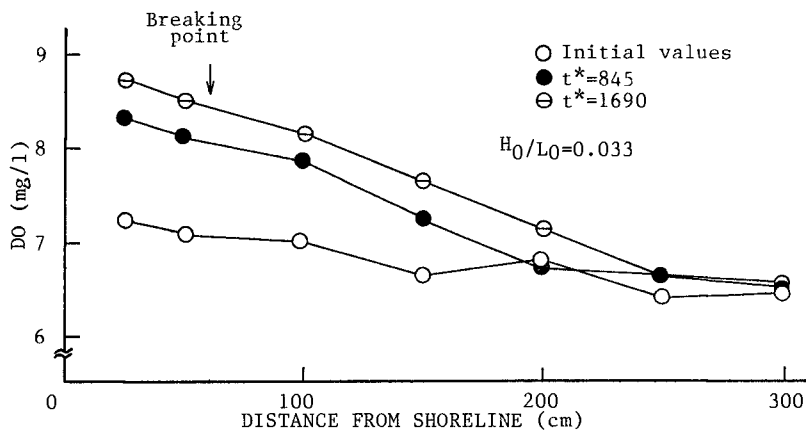


Fig.3 Variation of dissolved oxygen concentration

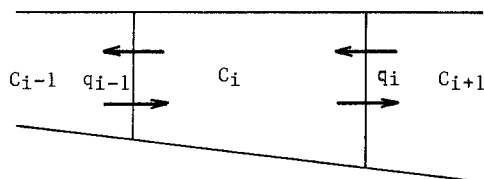
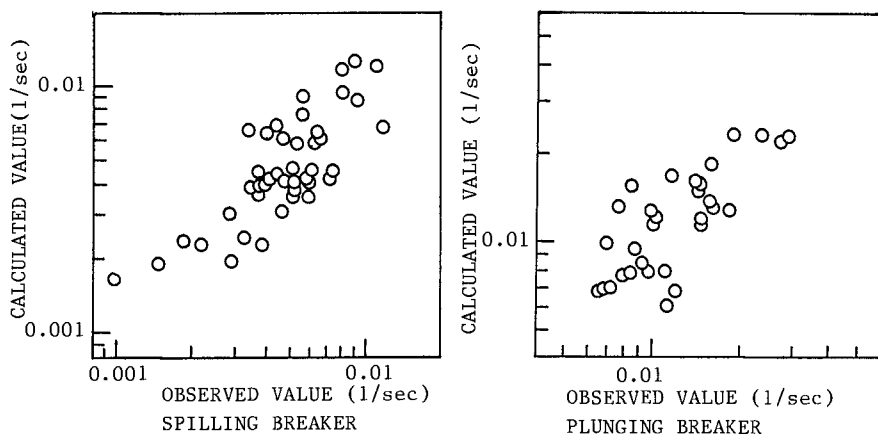


Fig.4 Box model

Fig.5 Relationship between observed k_2 and calculated k_2

$$d\Sigma C_i V_i / dt = V_1 k_{2,1} (C_s - C_1) \quad (26)$$

We calculated the reaeration coefficient in the surf zone by Eq.(24) and transformed it to the value at 20°C.

We decided the value of the proportional constant in Eq.(23) when $V = V_p$, from the experimental results. Fig.5 is the comparison between the calculated and the observed values. We obtained the following relation.

$$k_2 = \begin{cases} 0.144(T/v V_s)^{1/4} (DgH_0)^{1/2} (V_s/V_p)/\bar{h}_s & \text{(Spilling breaker)} \\ 0.184(T/v V_s)^{1/4} (DgH_0)^{1/2} (V_s/V_p)/\bar{h}_s & \text{(Plunging breaker)} \end{cases} \quad (27)$$

The difference in the value of the proportional constant between spilling and plunging breakers is due to the difference of bubble distribution in the surf zone. In spilling breakers, bubbles distribute only near the water surface, while, in plunging breakers, they reach down to the bottom (Hosoi and Murakami(1981)). Thus plunging breakers have a larger area of gas-liquid interface and a greater turbulent intensity than spilling breakers. It may affect the proportional constants in Eq.(27).

5. Decomposition of organic matter

5.1 Variation of COD and DO

The variation of COD and DO is shown in Fig.6. The plane slope extends 3 m from the shoreline, on which there is attached bacterial film.

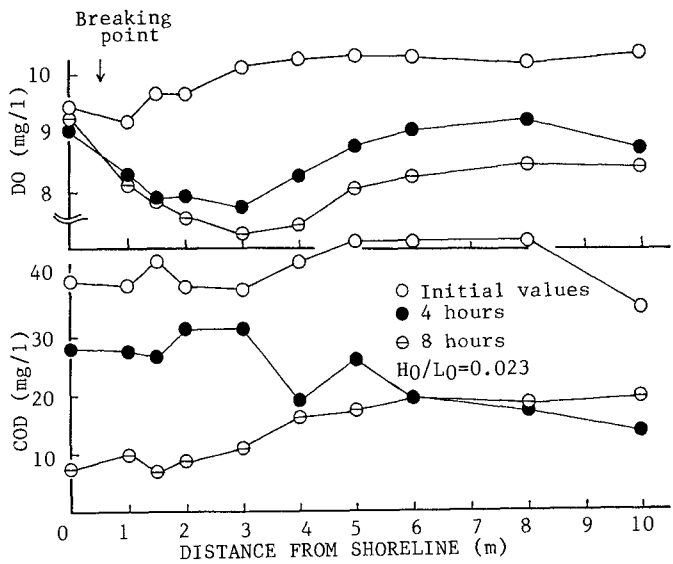
In the case of Fig.6(a), the initial COD is higher near the shoreline. After 2 hours, COD near the shoreline becomes low, but it scarcely changes at the sites far from the shoreline. As a result the COD profile becomes flat. This shows that the decrease in the organic matter is due to the oxidization in the slope area and not to the diffusion to the offing.

With the decomposition of organic matter the dissolved oxygen is consumed. The decline of DO is noticeable near the site 3 m away from the shoreline. As we have already described, oxygen absorption is far greater in the surf zone. Therefore at this point the main source of oxygen is from the transfer from the surf zone rather than the aeration occurring there. Thus the oxygen supply is not so large as compared with the surf zone. Nevertheless here exists the slope with a biofilm and here oxidization of organic matter takes place. As a result the oxygen deficit becomes noticeable in this area.

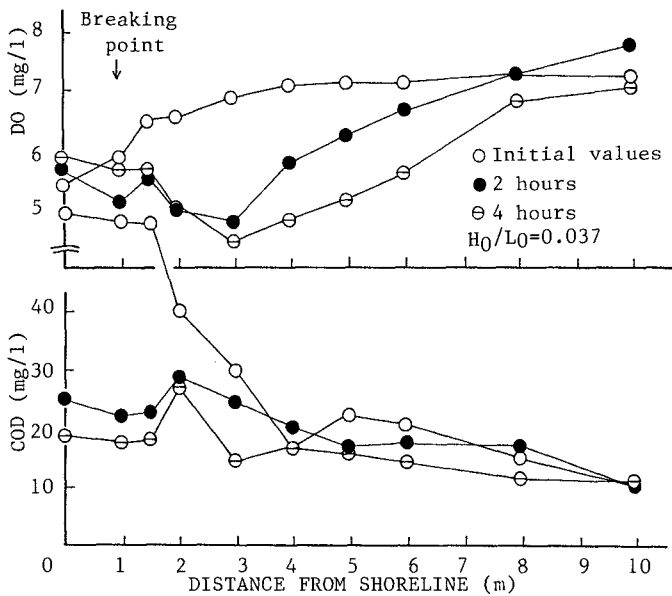
Fig.6(b) is another example which shows that the initial COD is rather uniform from the shoreline to the offing. COD decreases relatively uniformly. The decrease in DO shows the same trend as in the former case. Here again, we can assume that organic matter is decomposed in the slope area and purified water is transferred to the offing.

5.2 Attached bacteria

The attached biomass on the unit area of the slope bottom is shown



(b)



(a)

Fig.6 Variation of DO and COD

in Fig.7. Less biomass grew at the points where wave breaking happened during experiments (0.5-1.0 m away from the shoreline). This shows that the intense turbulence induced by wave breaking prohibits the development of bacterial attachment in the surf zone.

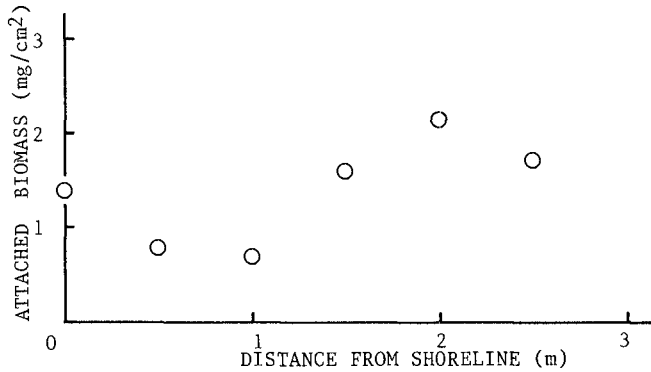


Fig.7 Biomass attached on slope bottom

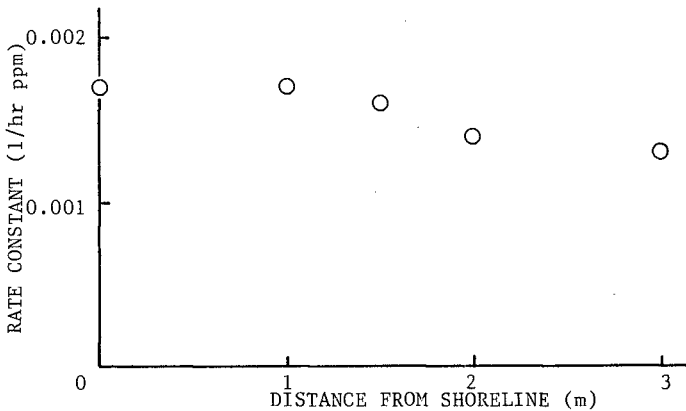


Fig.8 Bacterial activity

The activity of attached bacteria is shown in Fig.8. This shows the decomposition rate to be constant of bacteria suspended in the beaker. There was no significant difference found in the oxidization ability as to the distance from the shoreline.

5.3 Decomposition rate of organic matter on the beach

Generally, the reaction of organic matter oxidization is expressed

as the first power of its concentration. Therefore we write the changes of COD by the following equation.

$$\frac{d}{dt} f S_d V = -k A S_p \quad (28)$$

where S_p is the concentration of organic matter in the purification zone. From Eqs.(6) and (28) we obtain

$$k_1 V_p = -\frac{1}{S_p} \frac{d}{dt} f S_d V \quad (29)$$

This shows the overall oxidization ability in the purification zone.

Fig.9 shows the relation between the decomposition constant k_1 and the deep water wave steepness. We can see there is a positive relationship. It indicates that the water movement renews the water near the biofilm and promotes the supply of organic matter and DO to the biofilm. It is necessary to examine k_1 in relation to the quantities which represent the water movement structure in the surf zone. Here, however, we obtained the linear relationship shown in Fig.9 for the sake of the next consideration.

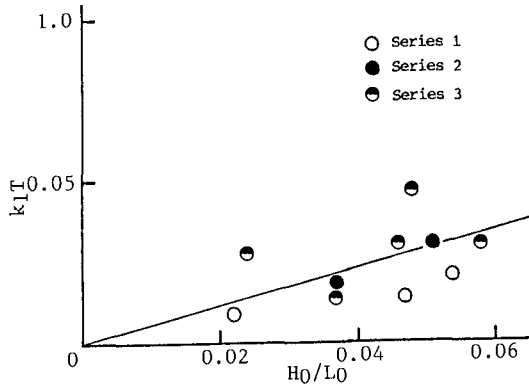


Fig.9 Decomposition rate constant

6. Numerical consideration

In order to consider the effect of incident waves on water quality we used a numerical model. When we take up the box model as shown in Fig.4, we obtain the following equations for DO and COD, respectively,

$$\begin{aligned} \frac{dC_i^*}{dt} = & -k_1 T S_i^* (S_0/C_s) + k_2 T (1 - C_i^*) \\ & + (q_{i-1} T/V_i) (C_{i-1}^* - C_i^*) - (q_i T/V_i) (C_i^* - C_{i+1}^*) \end{aligned} \quad (30)$$

$$\begin{aligned} \frac{dS_i^*}{dt} = & -k_1 T S_i^* + (q_{i-1} T/V_i) (S_{i-1}^* - S_i^*) \\ & - (q_i T/V_i) (S_i^* - S_{i+1}^*) \end{aligned} \quad (31)$$

where S is transformed into nondimensional form by the initial concentration S_0 . The first terms on the right hand side of Eqs.(30) and (31) express the utilization of DO or organic matter through bacterial metabolism. Thus they appear only in the purification zone. The second term on the right hand side of Eq.(30) describes reaeration, and therefore exists only in the surf zone.

The same beach condition as in this experiment was given, i.e., the water depth is 15.0 cm, and the beach slope is 1/20 and there is attached bacteria on the beach.

For the given condition of the deep water wave and the beach slope, the breaker depth was determined by the figure presented by Goda(1970). The wave transformation due to the shoaling effect was calculated by the small amplitude wave theory. The exchanging rate was given with reference to Nadaoka and Kondoh(1982) as follows.(Hosoi et al.(1984))

$$q_1 = 0.2\omega \left(\frac{H}{2}\right)^2 \frac{(1-(H/2h))\coth kh}{1-(H^2k/8h)\coth kh} \quad (32)$$

where H is the wave height, k the wave number and ω the angular frequency with reference to the fixed frames.

The reaeration coefficient was obtained by Eq.(27) and the decomposition rate constant was obtained from the regressive relationship shown in Fig.9.

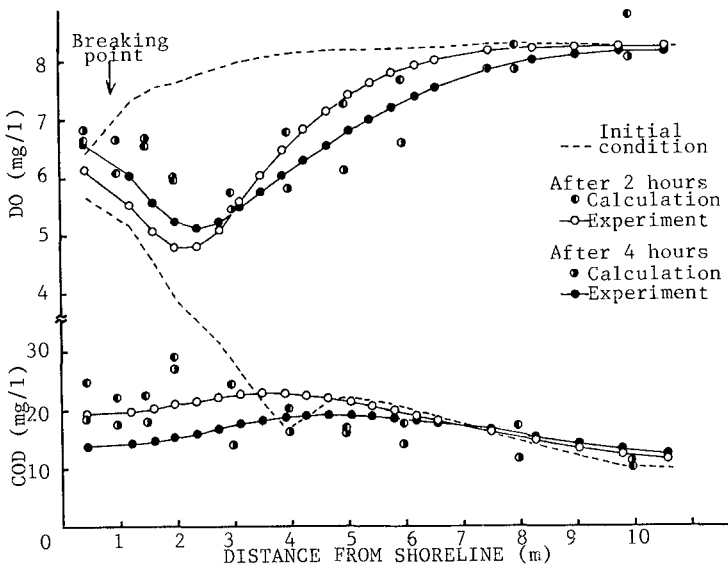


Fig.10 Water quality profiles

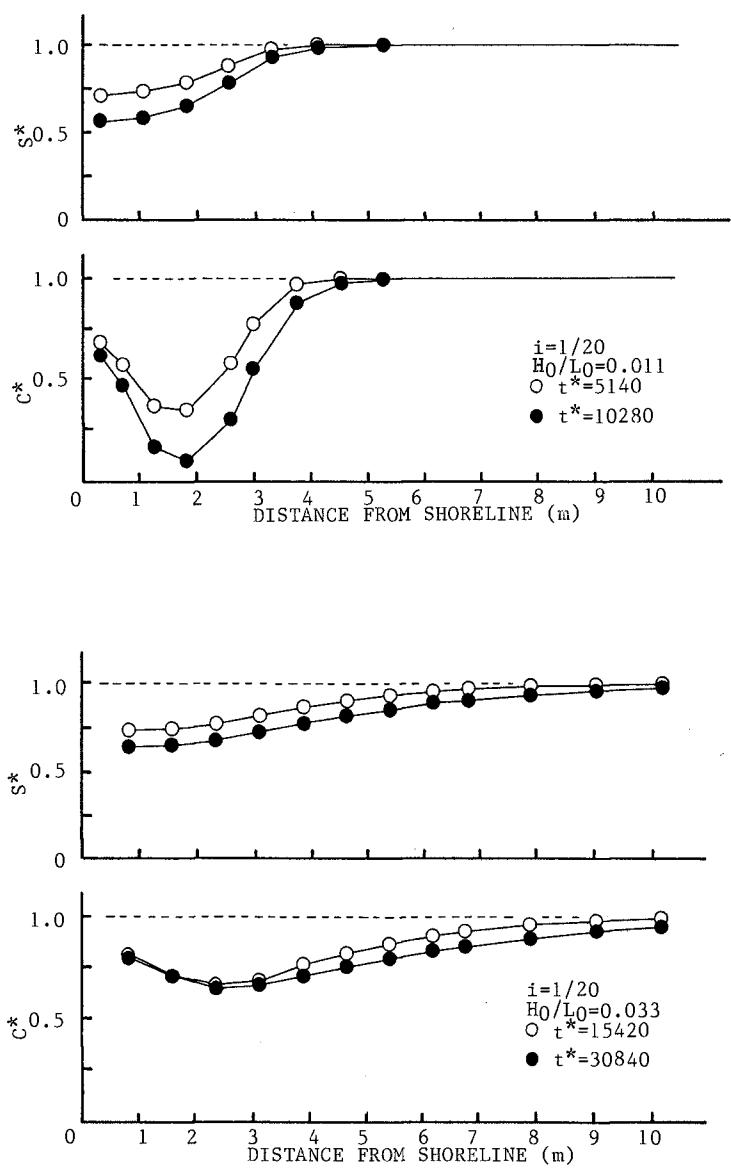


Fig.11 Results of water quality calculation

Fig.10 shows the comparison of water quality profiles between the experiment and the numerical simulation. The simulated results approximately agree with the experimental results. In particular, we could find the feature that DO has a minimum concentration a little outside of the surf zone.

Fig.11 shows the results of calculation under the initial condition that DO is saturated and organic matter distributes uniformly from the shoreline to the offing. In the case of smaller H_0/L_0 (the deep water wave steepness of the incident wave), the area where COD decreases is smaller. The decrease in DO is noticeable a little outside of the surf zone in both cases. When H_0/L_0 is small, the decrease in DO is remarkable and it shifts to the anaerobic condition.

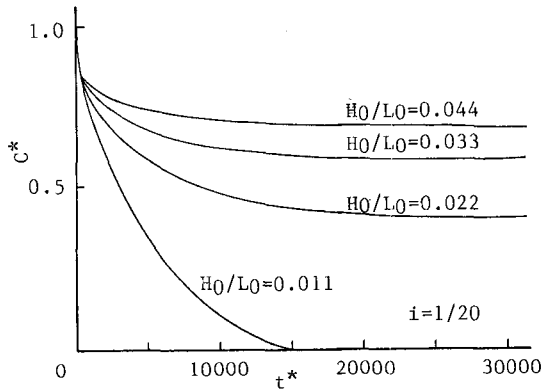


Fig.12 Change of the minimum concentration of the dissolved oxygen

Fig.12 shows the change of DO concentration at the point where it has the minimum value. Under the condition in our consideration, DO is used up completely when $H_0/L_0 = 0.011$ and the water environment is deteriorated to some extent even when $H_0/L_0 = 0.022$.

From the considerations so far we suppose that the water pollutant accommodation capacity in the nearshore area can be estimated from the beach shape, the incident wave and the bacterial activity.

7. Conclusions

We have considered the role of breaking waves in water quality near the surf zone. The general expression on DO and organic matter in nearshore area was derived. The variation of DO and organic matter was examined by experiments and a numerical model. Both the relationship between the reaeration coefficient and wave characteristics, and that between the decomposition constant and wave characteristics were shown. At this stage, our conclusion is limited in the experimental flume. The problem of how to apply these results in the field, hereafter still remains.

Acknowledgement

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