CHAPTER 11

Characteristics of Diffusion and Aeration due to Wave Action near Permeable Breakwaters

Hitoshi MURAKAMI * and Yoshihiko HOSOI **

Abstract

This paper deals with the effect of wave action on the water purification near a permeable breakwater. When determining standards for water purification, three indexes are usually taken into account: the diffusion coefficient, the concentration reflection ratio and the reaeration coefficient.

In our study, the values of the diffusion coefficients Kx near the breakwater ranged from about $10^{-1} \text{ cm}^2/\text{sec}$ to $7 \times 10 \text{ cm}^2/\text{sec}$. The effect of aeration caused by setting up a permeable breakwater was limited to within a distance of only one wave length at either side of the breakwater. As a result, values of the reaeration coefficients were then estimated to be in the order of $10^{-5} - 10^{-4}/\text{sec}$.

1. Introduction

In recent years, many legitimate plans for harbor and coastal zone developments have been proposed in succession, e.g, the construction of an artificial island, respective steam and wave force power stations etc. Breakwaters which would protect these facilities must therefore be built in increasing numbers.

However, in response to the recent social demand for better environmental conditions, we are also aware that greater efforts should be made to prevent water pollution in these harbor areas.

* Professor, Technical College, The University of Tokusima, Minamijyosanjima, Tokusima, 770, Japan.

** Associate Professor, Technical college, The University of Tokusima.

As a result, the need to design a multipurpose breakwater is required. This means a breakwater effective not only for the reduction of incident wave energy but also for water purification through a permeable wall. The hydraulic characteristics of various kinds of permeable breakwater models have already been investigated both theoretically and experimentally. We also have discussed the effective cross section geometry of the vertical slit-type breakwater from viewpoints of both the hydraulic and water exchange discharge due to the wave action(Murakami et al., 1986).

In addition we may expect a diffusion and aeration function for a permeable breakwater, because of waves which break causing water turbulence along the permeable wall. Although we observed this function, a satisfactory discussion could not be presented in the preceding study.

The purpose of this study is to examine the effect of the vertical slit-type breakwater on water purification paying special attention to the functions of diffusion and aeration.

2. Diffusion Characteristics

2.1 Experimental apparatus and procedure

Models of the vertical slit-type breakwater in this study are shown in Fig.1. A wave tank equipped with a flap-type wave generator at one end and measuring $15m \times 18cm \times 30cm$ was used. The models were placed at a distance of 10m from the wave generator. The water depth h and the wave period T were kept at a constant of 15cm and 0.75sec, respectively. Consequently the wave length L was 75cm. Incident wave steepness H/L was maintained at a value of 0.02.

In the diffusion experiment, a drop of methylene-blue solution was directly introduced as a tracer at the point located one wave length L from the front wall of the breakwater as shown in Fig.2. Periodical changes in concentration of the tracer were measured at two points, one at L/3 and the other at 2L/3. Tests were performed on both the seaward and shoreward side of the breakwater.

Experimental conditions on the diffusion of the contaminant are represented in Table.1.



Fig.1 Horizontal cross sections of vertical slit-type breakwaters



Fig.2 Definition sketch and coordinate system

2.2 Analysis method on diffusion characteristics

The diffusion of a tracer near a permeable wall in a relatively narrow wave tank can be assumed to be a one dimensional diffusion phenomenon.

The diffusion equation on the concentration of tracer C with time factor t and in a given space x is given as follows,

$$\frac{\partial c}{\partial t} = K_{X} \frac{\partial^{2} c}{\partial X^{2}}$$
(1)

where Kx is the one dimensional diffusion coefficient. When the tracer material is introduced at the point x, the solution in Eq.(1) is easily obtained at an arbitrary point x under the following initial and boundary conditions,

$$C(0,0) = \infty$$

$$C(x,\infty) = 0$$

$$\int_{-\infty}^{\infty} C(x,t) dx = M$$

$$(2)$$

$$C(\mathbf{x},t) = \frac{M}{2\sqrt{\pi K_{\mathbf{x}}t}} \left(\exp\left\{-\frac{(\mathbf{x}-\mathbf{x}_{0})^{2}}{4K_{\mathbf{x}}t}\right\} + \exp\left\{-\frac{(\mathbf{x}+\mathbf{x}_{0})^{2}}{4K_{\mathbf{x}}t}\right\} \right) \quad \mathbf{x} > 0$$

$$C(\mathbf{x},t) = \frac{M}{2\sqrt{\pi K_{\mathbf{x}}t}} (1-r) \exp\left\{-\frac{(\mathbf{x}-\mathbf{x}_{0})^{2}}{4K_{\mathbf{x}}t}\right\} \quad \mathbf{x} < 0$$
(3)

where M is the mass of the introduced tracer material, r represents the concentration reflection ratio due to the existence of a breakwater, r=1 indicates the impermeability of the breakwater and r=0 signifies that no breakwater has been installed. Thus we can consider r as an index representing the water quality exchange through the permeable wall. We can clarify the diffusion mechanism from Eq.(2) only if the values of the diffusion coefficient Kx and r are to be correctly estimated. By using the simplex method, we derived values for Kx and r, in which the calculated values of the tracer concentration in Eq.(2) most resembled the observed values of the concentration.

As a result of estimating Kx and r by using the simplex method, we obtain the most approximate curve to the exprimental values as seen in Fig.3.

Values of Kx and r for each experiment are shown in Table.2. The lack of values for Kx and r in Table.2 means that unrealistic values for both had been obtained during the course of analysis.

2.3 Consideration of Kx and r

From Table 2, it became evident that values of the diffusion coefficient near a breakwater fall in the range of 10^{-1} cm²/sec to 7×10 cm²/sec. Generally speaking, the value of Kx is greater on the seaward side of a breakwater compared to that of the shoreward side; the value in GC and CE type breakwaters obtained particularly large values.

We would like to discuss the characteristics of Kx and r in more detail. We can only conjecture that the diffusion characteristics near a breakwater will be effected by the turbulence caused by an opening in a permeable wall. The rate of wave energy dissipation at the opening of this wall ε is expressed as follows;

$$\varepsilon = 1 - r_R^2 - r_T^2 \tag{4}$$

Table.1	Experimential	conditions
T=0.75sec	.,h=15cm,h/L=0.	20,H/L=0.02

No.	TYPE	µ ≈D/(D+B)	l=1 ₁ +1 ₂ (cm)	1 ₁ /(1 ₁ +1 ₂)	α (ο)	β(0)	$A(cm^2)$
1 2 3	S.P	0.0625 0.125 0.25	0				
4 5 6	G.C 1	0.0625 0.125 0.25	9.4		10		
7 8 9	G.C 2	0.0625 0.125 0.25	18.8				
10 11 12	G.E 1	0.0625 0.125 0.25	9.4		19		
13 14 15	G.E 2	0.0625 0.125 0.25	18.8				
16 17 18 19	C.E 1	0 125	.125 9.4	0.25	20 40 20 40	20 20 40 40	
20 21 22 23	C.E 2	0.12)		0.75	20 20 40 40	20 40 20 40	
24 25 26 27	E.C 1	0.125	9-4	0.25	20 40 46 68	7 16 20 40	30.08 40.42 45.12 77.08
28 29 30 31	E.C 2	(۵۱ س		0.75	7 16 20 40	20 40 46 68	30.08 40.42 45.12 77.08
32	R.S	0.125	9.4		0	0	
33	C.S	0.125	9.4				77.08

No.	TYPE	Kx (*10cm ² /S)		r	
		Seaward	Shoreward	Seaward	Shoreward
1 2 3	S.P	1.43 3.45	1.69 2.31	0.42 0.41	0.34 0.63
4 5 6	G.C 1	6.30	0.41 2.64	0.94	0.52 0.57
7 8 9	G.C 2	5.08 3.65	0.59 1.08 3.95	0.68 0.62	0.04 0.27 0.83
10 11 12	G.E 1	0.47 1.15 3.23	0.23 1.03	0.07 0.29 0.79	0.14 0.51
13 14 15	G.E 2	0.48	1.06 2.45 3.97	0.72	0.30 0.56 0.84
16 17 18 19	C.E 1	6.10 3.93 3.32 2.47	0.27 3.08 0.34 3.66	0.94 0.76 0.39 0.56	0.46 0.80 0.69 0.82
20 21 22 23	C.E 2	2.76 6.85	0.25 0.46	0.78 0.96	0.37 0.11
24 25 26 27	E.C 1	0.78 7.00	1.34 1.22 2.38	0.02 0.77	0.69 0.69 0.56
28 29 30 31	E.C 2	0.65 3.04 1.70 1.44	3.94 0.65 0.47 2.04	0.20 0.80 0.53	0.83 0.52 0.05 0.75
32	R.S	3.04	2.03	0.58	0.45

Table.2 Values of diffusion coefficient Kx and concentration reflection ratio r



Fig.4 Dependence of diffusion coefficient of the seaward side on energy dissipation rate

where $r_{\rm R}$ is the reflection coefficient which is defined by the ratio of the reflection wave height ${\rm H}_{\rm R}$ to the incident wave height ${\rm H}_{\rm I}$ and $r_{\rm T}$ is the transmission coefficient ${\rm H}_{\rm T}/{\rm H}_{\rm T}({\rm H}_{\rm T}$: transmission wave height).

Fig.4 shows the relationship between Kx on the seaward side of the breakwater and the rate of wave energy dissipation ε . Here, we notice a tendency emerge, where values of Kx increase concomitantly with an increase in the value of ε .

Likewise, on the shoreward side of the breakwater, the values of Kx increase with the increase in the value of the transmission coefficient $r_{\rm T}$ as shown in Fig.5. Under the condition where the constant value of the incident wave steepness at the wall opening is larger, values of Kx on both seaward and shoreward sides are greater as shown in Fig.6. In Fig.6 the opening ratio is defined by D/D+B as shown too in Fig.1.



Fig.5 Dependence of diffusion coefficient of the shoreward side on wave transmission coefficient

We may infer that the effect due to the existence of a breakwater on the diffusion coefficient will be limited to a small area close to the breakwater.

Next, let us consider the characteristics of the concentration reflection ratio r.



on opening ratio of permeable wall

Fig.7 shows the relationship between r on both sides of the breakwater and the opening ratio μ . As the opening ratio μ increases, values of r will similarly increase on both sides. This means that if a large opening in the permeable wall occurs, the contaminant near the breakwater will easily flow back with less dilution, regardless of its initial location. According to this inference, as the concentration reflection ratio r on the shoreward side is larger, the diffusion function on the seaward side must decrease, because the contaminant on one side can not easily flow out through the opening to the opposite side of the breakwater. The tendency in Fig.8 supports this suggestion.



diffusivity of the opposite side

3. Reaeration Characteristics

3.1 Experimental apparatus and procedure

The experiment on reaeration was carried out in the same wave tank and the same breakwater models were used as in the diffusion experiment. The range of the incident wave steepness H/L was extended from H/L=0.01 to 0.05. After the concentration of dissolved oxygen in the wave tank was compulsorily reduced by sodium sulfite, a wave was generated for one hour to observe the concentration change of the dissolved oxygen. The concentration of the oxygen was measured at time intervals of 15 minutes and values of concentration change for each location were estimated at 50cm apart from each other. The origin of these observation points was situated in the rear wall of the breakwater and is represented by zero on the abscissa.

Fig.9 shows some examples of spatial concentration distribution of the dissolved oxygen over certain periods of time for four breakwater types. The region containing the minus sign in these figures represents the seaward side of the breakwater. The abbreviation P.I on the right hand side of the lower figure stands for an impermeable plate, in this case the concentration change depends only on the aeration caused by the standing wave. Apart from this exception, the concentration of dissolved oxygen increases remarkably with time in the restricted area near to the breakwater.



3.2 Reaeration Coefficient

We shall explain the mechanism of reaeration briefly. Reaeration compensates for the defficiency in oxygen levels through the water surface exposed to the atmosphere. As shown in Fig.9, reaeration efficiency near the breakwater is greater than that in other areas. The mass conservation equation relating to the dissolved oxygen can be written as follows:

$$\frac{dC}{dt} = K_{L} \frac{A_{S}}{V} (C_{S} - C)$$
(5)

where C and C_S represent the dissolved oxygen concentration and its saturation value respectively. K_L indicates the mass transfer coefficient, A_S and V are surface area and water volume respectively.

The reaeration coefficient k_2 which represents "the aerateability", is defined as follows.

$$k_2 = K_L \frac{A_S}{V}$$
(6)

Then Eq.(5) is rewritten

$$\frac{\mathrm{dC}}{\mathrm{dt}} = \mathbf{k}_2 \left(\mathbf{C}_{\mathrm{S}} - \mathbf{C} \right) \tag{7}$$

Eq.(7) is solved as follows:

$$\ln \left(\frac{C - C_S}{C_0 - C}\right) = -k_2 t \tag{8}$$

From Eq.(8), we can easily arrive at the reaeration coefficient k_2 , if there has been a change of concentration in the dissolved oxygen over a certain period of time as seen in the experiment, where C_{α} represents the initial concentration of dissolved oxygen.

3.3 Consideration of k_2

The reaeration coefficient k_2 at each observation point was measured; concentration changes in the dissolved oxygen can be calculated from Eq.(8) as mentioned above. We examined first the effect on the reaeration by setting up the breakwater as follows: we isolated the effective region identifiable by its pronounced convex shape from the remaining spatial distribution of the dissolved oxygen as shown in Fig.9. We next calculated the value of k_2 for each section. Finally, we estimated the value of k_2 from the following procedure,

$$k_{2} = \frac{\sum_{i} K_{2i} V_{i}}{\sum_{i} V_{i}}$$
(9)

where \mathbf{k}_{21} is i-th the value of \mathbf{k}_2 and \mathbf{V}_1 is the volume of the i-th section.

Fig.10 shows the relationship between the reaeration coefficient k_2 and the wave steepness H/L. Generally, values of k_2 will only increase with the growth of the incident wave height because the wave length remains at a constant(L = 75cm) for all experiments. Furthermore, values of k_2 are seen to be larger as the breakwater width 1 becomes wider.

Consequently, the values of k_2 are in the range of $10^{-5} - 10^{-4}$ 1/sec. We have already decided on the equation to predict the reaeration coefficient by breaking waves on the uniform sloping bed(Hosoi et al.,1986). If we apply the equation to this experimental condition, we obtain values for k_2 approaching 10^{-3} 1/sec. This



logically implies that the effect of the slit-type breakwaters on aeration is about 1/10 less than that of the uniform slope bed.

Fig.10 Relationship between reaeration coefficient and incident wave steepness



Fig.11 represents the relationship between the value of k_2 and the amount of the dissipated energy at the permeable wall. In this figure the dissipated energy is standardized by the amount of the incident energy of a wave measuring H=1.5cm, which is similar to one of the wave conditions already experienced. We can then deduce that aeration through the water surface near the breakwater depends on the energy dissipation caused by turbulence regardless of other factors such as the shape of the opening in the breakwater.

4. Conclusion

The characteristics of the diffusion and aeration near a permeable breakwater due to the wave action were discussed.

Results are summarized as follows.

1) The diffusion coefficients near the breakwater on the seaward and shoreward sides were estimated in the range of $10^{-1} - 7 \times 10 \text{ cm}^2/\text{sec.}$ 2) The mechanism of the water quality exchange through a permeable wall can be explained by using the concentration reflection ratio r. 3) The reaeration coefficients near the breakwater were estimated at values in the order of $10^{-5} - 10^{-4}$ 1/sec. These values corresponded to a mean 1/10 the value of the breaking wave on the uniform slope bed. Furthermore, the value of the reaeration coefficient increased with the increase of the incident wave height and wave energy dissipation caused by turbulence near the breakwater.

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Reference

1) Hosoi.Y and H.Murakami: Effects of breaking waves on dissolved oxygen and organic matter, Proc. of 20th Conf. on Coastal Engng., pp.2498-2512,1986.

2) Murakami, H. and Y.Hosoi: Analysis of permeable breakwaters, Proc. of 20th Conf.on Coastal Engng., pp.2104-2118, 1986.