Mem. Fac. Eng., Osaka City Univ., Vol. 46, pp. 77−82 (2005)

An Experimental Study on Reaeration by a Breakwater Generating Vertical Circulation Flow

徹 遠藤　孝昌 重松　祐哉 建部
Toru ENDO*, Takaaki SHIGEMATSU** and Yuya TATEBE***

(Received September 30, 2005)

Synopsis

In summer seasons severe hypoxia or anoxia has been generated near the sea bottom in enclosed seas. In order to restrain the hypoxia and anoxia, authors have developed a new breakwater which generates vertical circulation flow. Hydraulic effectiveness of the developed breakwater has already been verified. In this study, reaeration characteristic of the developed breakwater is examined by laboratory experiment. At first, the reaeration coefficient k_2 is estimated from the data of dissolved oxygen in a reaeration volume with different water depths. Furthermore, substance transfer coefficient K_L is calculated from the estimated k_2. Finally, K_L of the proposed breakwater is compared with K_L of other structures such as the slit-type caisson or rubble mound breakwater.

KEYWORDS: breakwater generating vertical circulation flow, reaeration capacity, reaeration coefficient, substance transfer coefficient

1. Introduction

In many seas surrounded by artificial structures such as vertical seawalls, the benthic ecosystems or coastal bottom environment are suffering from a chronic hypoxia or anoxia which is generated near sea bottom. It is necessary to restrain the hypoxia in such enclosed seas for restoration of coastal environment. One of the reasons why the hypoxia is generated is that oxygen supply near the sea bottom is obstructed by insufficient vertical mixing in front of the vertical wall especially under calm wave condition in summer season. Authors have developed a new breakwater which generates the

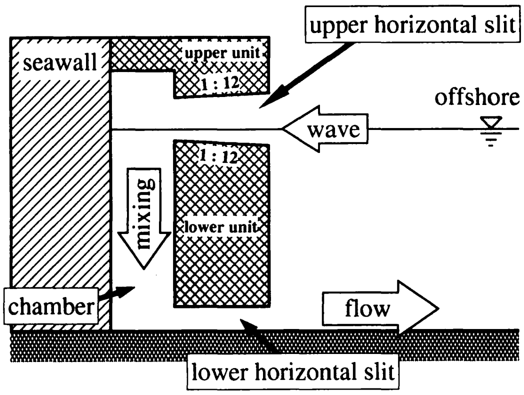


Figure 1: Illustration of the breakwater promoting vertical circulation flow

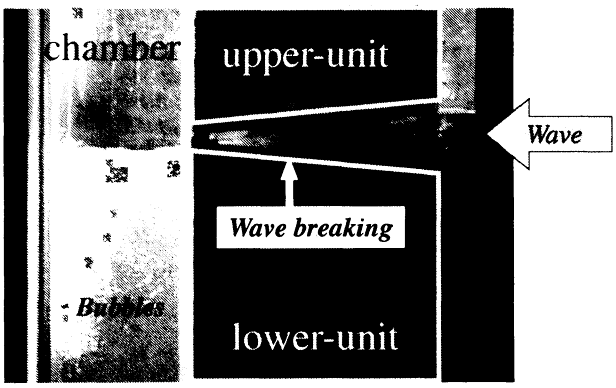


Figure 2: Wave breakings in the upper horizontal slit and bubbles in the chamber

---

* Student, Doctor Course of Dept. of Environmental Urban Engineering

** Associate Professor, Dept. of Environmental Urban Engineering

*** Student, Bachelor Course of Dept. of Environmental Urban Engineering vertical circulation flow from surface to bottom even under the clam wave condition. Schematic illustration of the breakwater is shown in Figure 1. Local flow toward offshore is generated from the lower horizontal slit by the pressure difference induced mass transfer when waves come into the chamber through the upper horizontal slit. Because the vertical circulation flow is transported the oxygen-rich surface water to the bottom, it is expected that the proposed breakwater is effective to restoration of environment near the sea bottom.

Hydraulic characteristics of the proposed breakwater have already verified by laboratory experiments 1),2),3). According to the experiments, wave breakings in the upper horizontal slit and many bubbles in the chamber were observed (see in Figure 2). It makes us expected that the developed breakwater has great reaeration capacity. However reaeration capacity of the proposed breakwater has never been evaluated.

In this study, therefore, reaeration coefficient k_2 of the breakwater generating vertical circulation flow, which is widely well-known as the index evaluating reaeration capacity, will be estimated by conducting laboratory experiment. Furthermore, substance transport coefficient K_L, which is characteristic coefficient of each structure, will be also estimated by using value of estimated k_2, aeration volume V and aeration area A.

2. Theory of the reaeration

Gas transfer from atmosphere into liquid was modeled by Streeter and Phelps 4) as follows,

$$\frac{dC}{dt} = -k_1 L + k_2(C_s - C) \tag{1}$$

where C is concentration of dissolved oxygen (DO), C_s is saturation dissolved oxygen, t is a given time, L is biological oxygen demand, k_1 and k_2 are coefficient. k_2 is called reaeration coefficient. For the case of hydraulic experiment without biological reaction, the first term in right side of equation (1) can be ignored. Hence equation (1) is rewritten

$$\frac{dC}{dt} = k_2(C_s - C). \tag{2}$$

Equation (2) is rewritten by dimensionless quantity for dissolved oxygen, D^*,

$$D^* = \frac{C_s - C}{C_s - C_0} \tag{3}$$

where C_0 is initial concentration of DO in experiment. When equation (2) is solved after substituting equation (3) into equation (2), we can obtain the following equation for k_2.

$$k_2 = \frac{-\ln D^*}{t} \tag{4}$$

It can be seen that we can obtain k_2 if time history of DO are measured.

On the other hand, Whitman and Lewis 5) modeled substance transfer from gas to liquid by using substance transfer coefficient K_L as follows.

$$N = \frac{1}{A} \cdot \frac{dm}{dt} = \frac{V}{A} \cdot \frac{dC}{dt} = K_L(C_s - C) \tag{5}$$

where m is mass of gas, A is aeration area, V is aeration volume. From equation (4) and (5), the relationship between k_2 and K_L is obtained.

$$k_2 = \frac{A}{V} K_L \tag{6}$$

From equation (4) and (6), K_L means the gas transfer velocity in the boundary layer of aeration area.

3. Experimental Setup

A schematic illustration of experiment is shown in Figure 3. Experiments were conducted in a wave flume with 20 m long, 0.6 m high and 0.5 m wide at Osaka City University. The model of the breakwater set 15.0 m away from a wave maker. Experimental conditions are shown in Table 1. An incident wave period T is 0.75 s and the wave steepness H/L is 0.02. The wave conditions were determined based on measured data in Osaka Bay during summer season because the hypoxia is easily generated under the calm wave condition. Water depths were $h = 30$ cm, 35 cm and 40 cm, and wave from offshore can not go into the chamber through the upper horizontal slit when water depth h is 30 cm. In order to secure aeration volume V, a plastic film was installed at 2.0 m away from impermeable wall for preventing substance from transporting through the plastic film without disturbing wave field.

Reflection coefficient K_r of the proposed breakwater was evaluated from the data of water surface elevations by using the estimation method of incident and reflection waves [6]. The water surface elevations were measured by using two capacitance wave gauges (KEYENCE). The wave gauges were installed at 1.0 and 1.1 m away from the breakwater inside the aeration volume. Sampling frequency of wage gauges is 50.0 Hz.

Time historical data of DO was measured by using two DO meters (YSI). On of them (No.1) was set at the bottom in the chamber and the other (No.2) was set in the middle of water depth at one wave length away from the breakwater. Before starting measurement, Cobalt chloride ($CoCl_2$) and sodium sulfite (Na_2SO_3) were added into the aeration volume in order to make the initial DO inside the aeration volume 0.0 mg/l. Sampling frequency of DO meters is 1.0 Hz and they were measured until the time enough to obtain k_2.

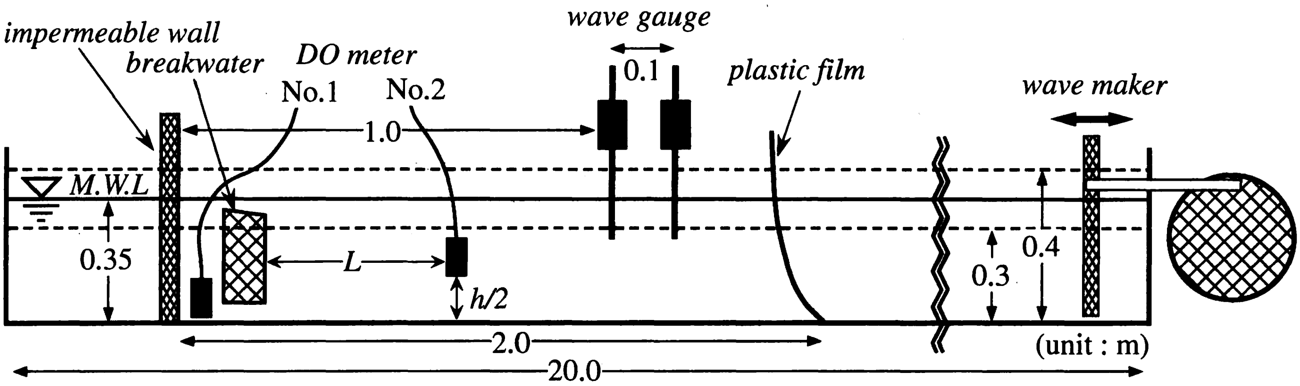


Figure 3: Experimental Setup

Table 1: Wave conditions and experimental results of reflection coefficient K_r

case	h (cm)	T (s)	L (cm)	H (cm)	H/L	K_r	wave breakings and bubbles
1	30.0	0.75	85.0	1.6	0.02	0.96	×
2	35.5	0.75	86.0	1.8	0.02	0.42	×
3	40.0	0.75	86.0	1.7	0.02	0.89	×

h: water depth, T: wave period, L: wave length, H: incident wave height, H/L: wave steepness, K_r: reflection coefficient, and the right column shows whether wave breakings in the upper horizontal slit and bubbles in the chamber were observed.

4. Results

Experimental results of reflection coefficient K_r is shown in Table 1. K_r for h =35 cm is 0.42 and K_r =30 cm and 40 cm are almost 0.9. It is found that wave absorbing function of the proposed breakwater strongly depends on the water depth. This tendency is shown in the experiments conducted in the past with larger scales [3]. Although wave breakings in the upper horizontal slit and many bubbles in the chamber were observed in the larger scale experiments, both of them were not observed in this experiment. Therefore following discussion on the oxygen transfer from atmosphere into water does not include the effect of the bubbles and turbulence induced by wave breakings.

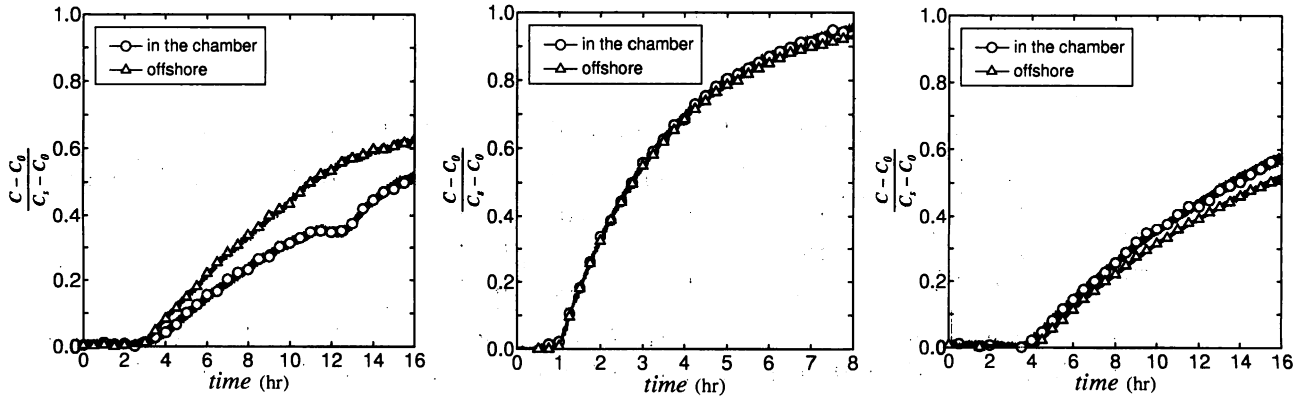
Figure 4 shows the time histories of dimensionless concentration of the dissolved oxygen after starting experiments. ○ represents the date of the concentration of DO in the chamber (No.1) and △ represents that at one wave length away from the breakwater (No.2). Figure 4 (a), (b), and (c) represent the results for the case of water depth h = 30, 35, 40 cm respectively. In the figure dimensionless concentration of DO is presented by using the initial concentration C_0 and saturate concentration C_s.

For the case of h = 30 cm, the concentration of DO at the offshore measurement point No.2 begin to recover faster than that in the chamber since water depth is too small to go into the chamber. For the case of h = 35 cm and 40 cm, which waves go into the chamber, the concentration of DO in the chamber recover slightly faster than the concentration of DO at the offshore measurment point. Considering to the results on the reflection rate, the recovery velocity of the dissolved oxygen has a close relationship with mechanism of wave absorbing.

On the basis of the experimental results on the concentration of DO measured in the chamber, the reaeration coefficient k_2 was calculated. Figure 5 showed time history of $-\ln D^*$. It is found that $-\ln D^*$ increases linearly as time progresses. k_2 is obtained by calculating the gradient of the data of $-\ln D^*$. Obtained k_2 for h = 30, 35 and 40 cm are 1.48×10^{-5}, 1.17×10^{-4}, 1.96×10^{-5} s^{-1} respectively. That is to say that k_2 for the case of h = 35 cm is one order higher than the other cases.

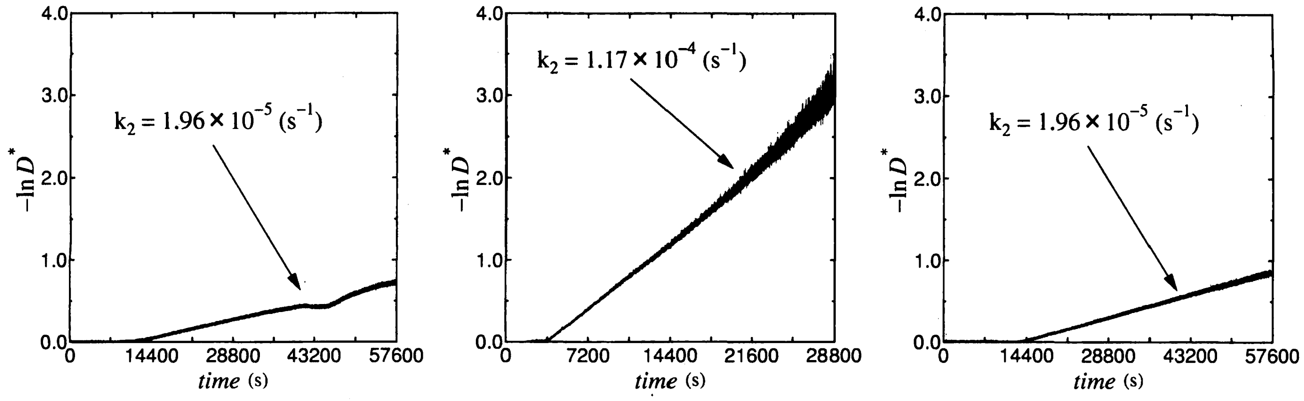
Kakuno et al.[7] have already conducted the experiment in order to obtain k_2 under the partial standing waves. According to their experiments, k_2 under the partial standing waves was $1.56 \times 10^{-5} s^{-1}$. Comparing with their result and k_2 for h = 30 and 40 cm presented in this study, it is found that both of them have almost same value and that experimental results presented in this study were reasonable.

Finally, K_L was calculated from k_2, A and V. A was assumed to be equivalent to the area of water surface at rest between impermeable wall and a plastic film because wave breakings in the upper slit and bubbles in the chamber were not observed. Table 2 shows value of K_L of the proposed breakwater



(a) h = 30 cm (b) h = 35 cm (c) h = 40 cm

Figure 4: Dimensionless concentration of DO in the aeration volume



(a) $h = 30$ cm (b) $h = 35$ cm (c) $h = 40$ cm

Figure 5: Time history of $-\ln D^*$ and k_2 at the bottom in the chamber

estimated in this study, slit-type caisson, rubble mound breakwater and slope with 1/20 estimated by Kakuno [7]. K_r of the proposed breakwater were larger than those of slit-type caisson and rubble mound breakwater. Although K_L for $h = 30$ and 40 cm have one order smaller than that for slit-type caisson and rubble mound breakwater, K_L for $h = 35$ cm has same order as them. That is to say that the proposed breakwater generating vertical circulation flow has oxygen transfer function from atmosphere into water as same as slit-type caisson and rubble mound breakwater under a certain water depth but that the function depends on the water depth. With considering to the function of generating vertical circulation flow, the proposed breakwater would be expected to be effective for restoration of sea bottom environment. K_r and K_L obtained by Kakuno with wave breakings over the inclined slope with 1/20 has one order higher value than that of the other structures. It implies that strong turbulence and bubbles induced by wave breakings affect k_2 and K_L.

Table 2: Comparison of k_2 and K_L with different structures

structure	h (cm)	T (s)	H/L	K_r	k_2 (s^{-1})	K_L (cm/s)
VCF	30.0	0.75	0.02	0.96	1.48×10^{-5}	4.44×10^{-4}
VCF	35.0	0.75	0.02	0.42	1.17×10^{-4}	4.10×10^{-3}
VCF	40.0	0.75	0.02	0.89	1.96×10^{-5}	7.84×10^{-4}
Slit	30.0	0.88	0.02	0.33	3.58×10^{-5}	1.07×10^{-3}
Rubble	30.0	0.88	0.02	0.29	5.82×10^{-5}	1.56×10^{-3}
Slope	30	0.88	0.06	-	1.87×10^{-3}	1.27×10^{-2}

VFC: breakwater generating vertical circulation flow, Slit: slit-type caisson, Rubble: rubble mound breakwater, Slope: slope with 1/20.

5. Conclusions

The conclusions of this study are summarized as follows, :

(1) It is confirmed that reaeration capacity of the proposed breakwater depends on the water depth strongly by estimating k_2 and K_L of the proposed breakwater.

(2) K_L of the breakwater generating vertical circulation flow for $h = 35$ cm was $4.10 \times 10^{-3} s^{-1}$ and K_L for $h = 40$ and 30 cm were one order smaller than K_L for $h = 35$ cm.

(3) K_L of the proposed breakwater was compared with that of slit-type caisson and rubble mound breakwater. It is found that the proposed breakwater has oxygen transfer function from atmosphere into water as same as those structures under a certain water depth.

It should be noted that wave breakings in the upper horizontal slit and bubbles in the chamber were not generated in this experiment. Therefore, this experimental results have the possibility that K_L was underestimated more than that of the actual scale. In the future, we thought that it is necessary to carry out the larger scale experiment in order to examine effect of wave breakings and bubbles on reaeration.

References

1) T. Shigematsu, K. Ikeda, K. Oda, and T. Fujita (2002): Development of a seawall generating vertical circulating flows for improving the bottom environment, Annual Journal of Coastal Engineering, JSCE, Vol.49, pp.796-800, (in Japanese).
2) T. Shigematsu, K. Ikeda, K. Oda, T. Koike, R. Nobuhiro, T. Endo, T. Fujita, and S. Togawa (2003): Effectiveness of a seawall generating vertical circulating flows in stratified wave field, Annual Journal of Coastal Engineering, JSCE, Vol.50, pp.1206-1210, (in Japanese).
3) T. Endo, T. Shigematsu and K. Oda (2005): Large-scale Experiments on Effectiveness of a Breakwater Promoting Vertical Circulation Flow, Asian and Pacific Coasts 2005, pp.239-242.
4) Streeter, H. W. and Phelps, E. B. (1925): A study of the pollution and natural purification of the Ohio River 3. Factors concerned in the phenomena of oxidation and reaeration, Public Health Bulletin, 146, 75.
5) Lewis, W. K. and Whitman, W. C. (1924): Principles of gas absorption, Industrial and Engrg. Chemistry, Vol.16.
6) Y. Goda, Y. Suzuki, Y. Kishira, and O. Kikuchi (1976): Estimation of incident and reflected waves in random wave experiments, Technical Note of, P.H.R.I., No.248, 24p.
7) S. Kakuno, Y. Nakata, M. Saito, N. Nakatani, T. Yoshida and K. Oda (1994): Experimental Study on Aeration Characteristics of Coastal Structures, Annual Journal of Coastal Engineering, JSCE, Vol.41, pp.1036-1040, (in Japanese).