CHAPTER 228

Water oxygenation in the vicinity of coastal structures due to wave breaking

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Abstract

Experiments on oxygenation due to breaking waves on a uniformly sloping beach and on an S - type breakwater were performed. The water was chemically deoxygenated and dissolved oxygen (D.O.) concentration was followed over time in characteristic locations. Experimental data showed that the transfer velocity increased with increasing wave height for waves of the same frequency. Experiments with waves of the same wave height but increasing wave frequency showed also an increase in transfer velocity. The breakwater data give lower transfer velocities as compared to the sloping beach data for the same wave characteristics.

The one - dimensional transport equation was used for the determination of the transfer coefficients. Analysis of the data indicated that the transfer coefficients varied almost linearly with the vertical wave velocity at the water surface. A rather good linear correlation was obtained for the breaking wave data on the sloping beach, with much higher slope as compared to the case of non-breaking waves.

Introduction

Air/water gas transfer for water bodies is one of the main sources of dissolved oxygen (D.O.), an often used water quality index. It also acts as a sink of carbon dioxide and other greenhouse gases and has a significant role in global biogeochemical cycles of atmospheric compounds. Finally, air/water gas transfer is an important parameter in the design of hydraulic structures, as in the case of stepped chute spillways (Chanson, 1994), and can be used beneficially, as in the case of the SEPA (sidestream elevated pool aeration) project of the Metropolitan Water Reclamation District of Greater Chicago, that was awarded the 1994 Outstanding Civil Engineering Achievement Award (Civil Engineering, 1994).

Research on oxygenation dates back to 1925 (Streeter and Phelps, 1925, Streeter, 1926), when river pollution problems started to appear. Gradually,

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interest spread to other water bodies (e.g. lakes and oceans) and other gases, such as carbon dioxide and methane (Brutsaert and Jirka, 1984, Wilhelms and Gulliver, 1991). Although air/water gas transfer is controlled by the interaction of the air/water boundary layer, the wave field is a parameter that has rarely been included in the predictive equations so far. However, its effect has often been noted qualitatively. Experiments on the effect of waves on gas transfer have been reported by Hosoi et al (1977), Hosoi and Murakami (1986), Jähne et al (1985,1987), Daniil and Gulliver (1991) and Wanninkhof and Bliven (1991). For lakes and oceans the transfer coefficient is usually correlated to the wind velocity. It should be noted though, that laboratory data and field data give different correlations and do not compare favorably (Liss, 1983, Daniil, 1988). It is generally recognized that the presence of waves increases the penetration of gases into the water. Gas concentrations in the water mass are found to be higher when waves are present, due to the action of a steering mechanism on the interface. Therefore, waves may be considered to have a positive effect on the oxygenation of water bodies. In the experiments of Hosoi et al (1977) D.O. was measured in one location of the flume only and neither the effect of horizontal diffusion nor the uniformity of D.O. concentration across the flume was investigated. Hosoi and Murakami (1986) measured the D.O. distribution across the flume. They concluded that oxygenation due to non-breaking waves was negligible and assumed that the whole flume is oxygenated through the breaking wave zone. This assumption yields much higher transfer coefficients than what would have been obtained if oxygenation through the remaining free surface had also been taken into account.

Wave breaking is a highly turbulent physical mechanism, that essentially creates a two phase flow, which facilitates the transfer of gases considerably. Therefore, it is believed that breaking waves have a further positive effect on the oxygenation of water masses. Until now the effect of wave breaking in water oxygenation has been described mostly qualitatively. Hosoi et al (1990) performed a number of experiments on reaeration due to wave breaking at coastal structures and proposed an equation indicating that the reaeration coefficient is correlated with the dissipated energy. They also note that in their experiments aeration increased with the height of incident waves and with the width of the breakwater. Moreover, impermeable sloping seawalls were more effective in promoting aeration than other structures.

A research program has started at the Laboratory of Harbour Works, Civil Engineering Department, National Technical University of Athens (NTUA) in order to investigate and quantify the effect of breaking waves on oxygenation. Oxygenation due to breaking waves is studied experimentally in a wave flume with a uniformly sloping beach (Daniil and Moutzouris, 1993, 1994a, b) and with an S-type breakwater. The influence of increasing wave frequency and wave height on the oxygen transfer coefficient is discussed.

Experimental Procedure

Experiments on the transfer of oxygen under breaking waves were conducted in a wave flume of the Laboratory of Harbour Works, NTUA. The dimensions of the flume are 27.40 (length) x 0.60 (width) x 1.53m (height). A smooth sloping beach with a uniform slope of 1 (vertical) : 2.3 (horizontal) was

placed at the one extremity of the flume (Fig. 1). The water was chemically deoxygenated. Details for the experimental setup have been presented previously (Daniil and Moutzouris, 1993, 1994 a, b).

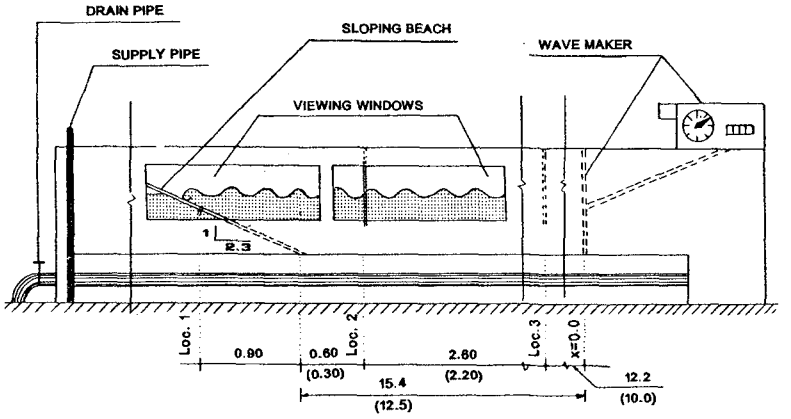

Fig. 1. Longitudinal view of the wave channel with the smooth sloping beach.

Additional experiments were performed with an S - type rubble mound breakwater with a slope of 1 (vertical) : 1.5 (horizontal) located 15.0 m from the wave maker (Fig. 2).

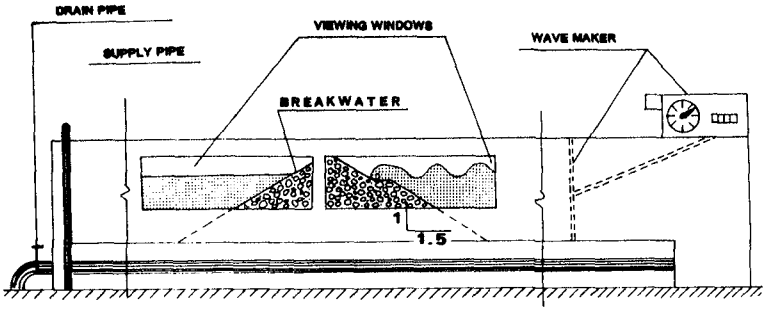

Fig. 2. Longitudinal view of the wave channel with the rubble mound breakwater.

Monochromatic waves were created by a wave generator of the piston type. The waves propagated along the flume and broke over the sloping beach or the breakwater. For the sloping beach experiments D.O. concentration in the water body was followed over time in three locations along the flume. Wave heights tested ranged from 5.6 to 15 cm and wave periods from 0.75 to 1.60 sec. For the breakwater experiments D.O. concentrations were measured in front and behind the structure. Wave heights tested ranged from 5.6 to 28.0 cm and wave periods from 0.75 to 1.60 sec. The water depth was 0.60 m for all experiments with the exception of experiment K6 that had a water depth of 0.83 m. Experimental conditions are shown in Table 1 for both sets of experiments.

Table 1 - Experimental conditions for experiments with the sloping beach and the breakwater

Exp. No.	Wave Period T (sec)	Wave Height H (cm)	Wave Length L (m)	Water Temp. θ (°C)	Atmosp. Pressure (mm Hg)
Sloping beach data					
A3	1.60	9.9	3.27	23.5	750
A2	1.45	7.6	2.85	24.0	750
B7	1.45	9.1	2.85	10.5	750
B6	1.45	12.0	2.85	9.6	749
B9	1.45	14.9	2.85	10.6	753
A4	0.75	5.6	0.88	21.5	750
A5	0.75	7.1	0.88	23.6	750
B8	0.75	7.3	0.88	7.5	759
Breakwater data					
K2a	1.60	9.9	3.27	14.9	747
K3	1.45	12.0	2.85	23.8	747
K6	1.45	28.0	3.07	12.7	757.5
K2b	0.75	5.6	0.88	14.7	747
K1	0.75	7.1	0.88	12.7	749

Data Acquired

Fig. 3 shows D.O. - time histories as obtained from experiments B9, B6 and B7 with waves of the same frequency (T=1.45sec), but different wave height

(H= 14.9, 12.0, 9.1 cm) in the presence of the sloping beach. It is concluded that the transfer velocity increases as the wave height increases. Moreover, D.O. concentration becomes more uniformly distributed seawards of the breaker zone as the wave height increases, due to increase of horizontal dispersion. Similar comparison of D.O. - time histories for experiments with waves of almost the same height, but differing frequency shows that the transfer velocity increases, as the wave frequency increases.

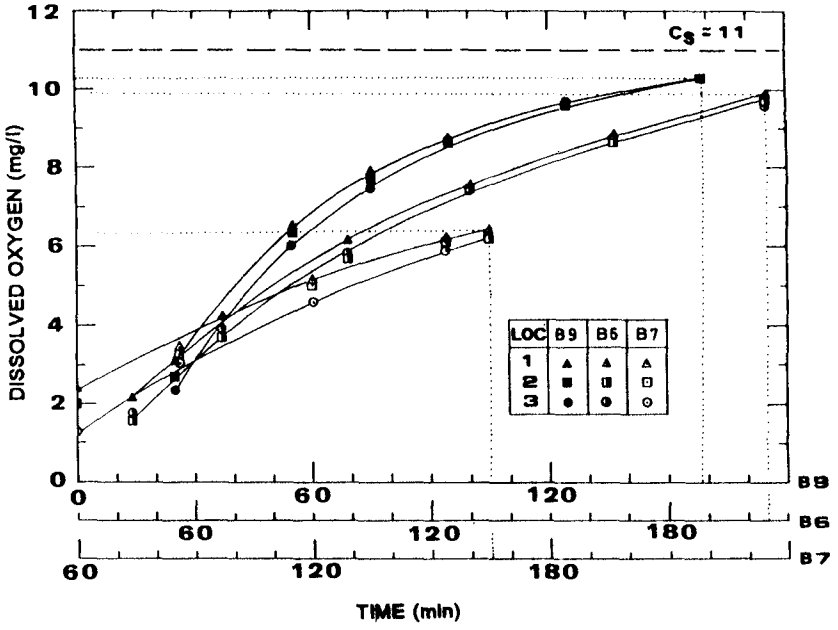

Fig. 3. Comparison of D.O. - time histories for waves of the same frequency but different wave height breaking on a sloping beach (after Daniil and Moutzouris, 1993)

D.O.- time histories in the presence of (i) a sloping beach and (ii) a breakwater are presented in Fig. 4. Concentrations are found to be lower in front of the breakwater than along the sloping beach, due to a more moderate wave breaking in the former case. D.O. concentrations are found to be very low behind the structure and to increase in time due to transport of oxygen through the body of the breakwater. The saturation concentration, Cs, is also noted for the two cases (Cs= 8.4 mg/l for the sloping beach and Cs = 9.86 mg/l for the breakwater).

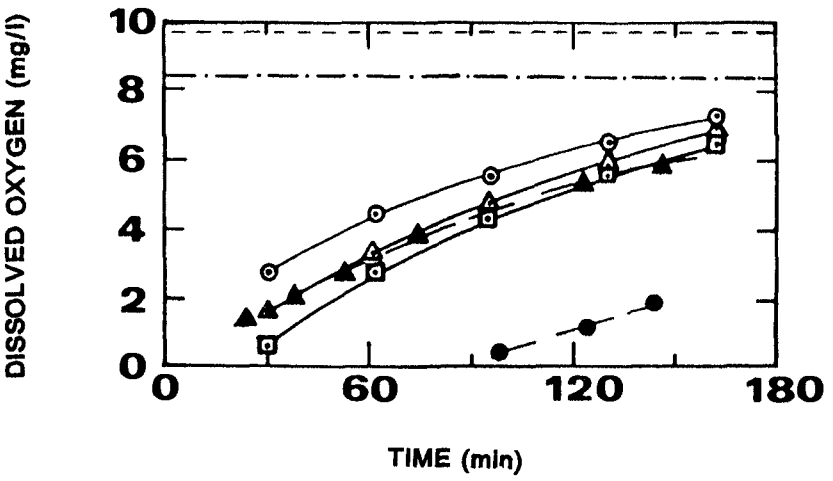

Fig. 4. D.O. - time histories for waves (incipient wave: H=7.1 cm, T=0.75 sec) breaking (i) on a sloping beach (open symbols) and (ii) on a breakwater (solid triangles refer to the concentration in front and solid circles to the concentration behind the breakwater).

Data Analysis

The one-dimensional transport equation was used for the analysis of the data. Data from locations where the composite effect of the horizontal transport was assumed to be negligible were used for determining the oxygen transfer coefficient. The transfer coefficient is determined from the following equation, using linear regression and the measured D.O. concentrations:

$$\ln (C_s - C) = - K_L (A/V)\, t + \ln (C_s - C_o) \qquad (1)$$

where C, C_o and C_s are the average, initial and saturation D.O. concentrations, respectively. K_L is the oxygen transfer coefficient, t is time, A is the projected free surface area on the horizontal plane and V is the aerated volume extending from the free surface to the bottom of the channel.

The coefficients K_L obtained from the above procedure, along with the wave parameters used in the correlations presented in the following sections, are listed in Table 2. The transfer coefficients were translated to 20° C according to the equation given by Daniil and Gulliver (1988):

$$(K_{L20}/K_L) = (Sc/Sc_{20})^{1/2} = (\nu/\nu_{20})\,[293/(\theta+273)]^{1/2}\,(\rho/\rho_{20})^{1/2} \qquad (2)$$

where $Sc = \nu/D$ is the Schmidt number ($Sc_{20} = 546$), ν is the kinematic viscosity of water, D is the molecular diffusivity of oxygen in the water, θ is the water temperature in degrees Celcius and ρ is the water density. The subscript 20 denotes the value of the corresponding parameter at 20° C. The water properties were determined by the relations given by Heggen (1983). H, L and f are the wave height, length and frequency, respectively.

Table 2. Oxygen Transfer Coefficients and wave parameters used in the correlations for breaking waves on a sloping beach and on a rubble mound breakwater

Exp. No.	Satur. Conc. Cs (mg/l)	Schmidt number Sc (-)	Hf x 100 (m/sec)	Transfer Coeff. $K_{L20} \times 10^5$ (m/sec)	Transfer Coeff. $K_L \times 10^5$ (m/sec)	Transfer Coeff. $K_L Sc^{1/2} \times 10^4$ (m/sec)
Sloping beach data						
A3	8.4	458	6.19	2.7	2.9	6.2
A2	8.3	446	5.24	5.0	5.5	11.6
B7	11.0	918	6.28	8.3	6.4	19.4
B6	11.2	967	8.28	15.0	11.3	35.1
B9	11.0	912	10.28	22.0	17.0	51.3
A4	8.7	506	7.47	5.1	5.3	11.9
A5	8.4	455	9.47	9.0	9.9	21.1
B8	12.0	1096	9.73	15.0	10.6	35.1
Breakwater data						
K2a	9.9	716	6.19	3.2	3.7	8.6
K3	8.3	450	8.28	6.9	6.3	14.6
K6	10.6	809	19.3	23.3	28.4	66.3
K2b	9.9	716	7.47	3.6	4.1	9.6
K1	9.9	701	9.47	6.3	7.1	16.7

The oxygen transfer coefficients K_L, as determined from the above analysis, are compared to the relation obtained for non-breaking waves by Daniil and Gulliver (1991). The two authors related the transfer coefficient to

the vertical wave velocity at the water surface and used a renewal model to express the average renewal rate as a function of a wave Reynolds number. They derived the following equation:

$$K_L Sc^{1/2} = 0.0159 \, H f \qquad (3)$$

For breaking waves on a sloping beach from the present experiments the following equation was fitted to the data:

$$K_L Sc^{1/2} = 0.066 \, H f - 2.80 \times 10^{-3} \quad (m/s) \qquad (4)$$

Equation (4) holds for $H f > 0.056$ m/s, which was approximately the low limit of the present experiments, and expresses the general trend of the oxygen transfer coefficient for breaking waves. It is felt that a further expansion is needed to include a parameter describing the non-linearity of the breaking.

A comparison of the results obtained (see Fig. 5) shows that oxygenation in front of a breakwater is less significant than in the presence of a sloping beach, due to a less intense penetration mechanism. Breakwaters are causing wave reflection, which reduces the degree of wave breaking.

Equations (3) and (4) are compared to the experimental data in Fig. 5.

Discussion

The experiments reported in the present paper demonstrate the importance of breaking waves in nearshore oxygenation. The oxygen transfer coefficient was described through a surface renewal model. The average surface renewal rate was correlated to the wave characteristics and the oxygen transfer coefficient was found to be proportional to the maximum vertical wave velocity at the water surface. The correlation for the breaking wave data on a sloping beach gave a much higher slope than that for non-breaking waves. Breakwater data give lower transfer coefficients compared to the sloping beach data, but higher than the non breaking waves for the same wave characteristics. The obtained relation for the sloping beach data needs to be extended in order to incorporate breaking wave parameters.

The experimental results presented here were obtained using tap water. They could be translated to seawater if the corresponding Schmidt number and the saturation concentration for seawater were introduced. Nevertheless, it is noted here that experiments by Downing and Truesdale (1955) on the effect of wind using seawater and distilled water had shown no significant difference.

Undoubtfully, the results are influenced by the scale of the experiments conducted. Scale effects are believed to be significant. For this reason, the research program of the Laboratory of Harbour Works, NTUA, was recently enlarged with further experiments executed in the large wind-wave facility of Delft Hydraulics, The Netherlands. The experiments were financed by the European Community Large Installations Program (LIP). A preliminary analysis of the experimental data collected clearly shows that oxygenation rates are considerably reduced, as a result of the larger dimensions (Tsoukala and Moutzouris, 1994, personal comm.).

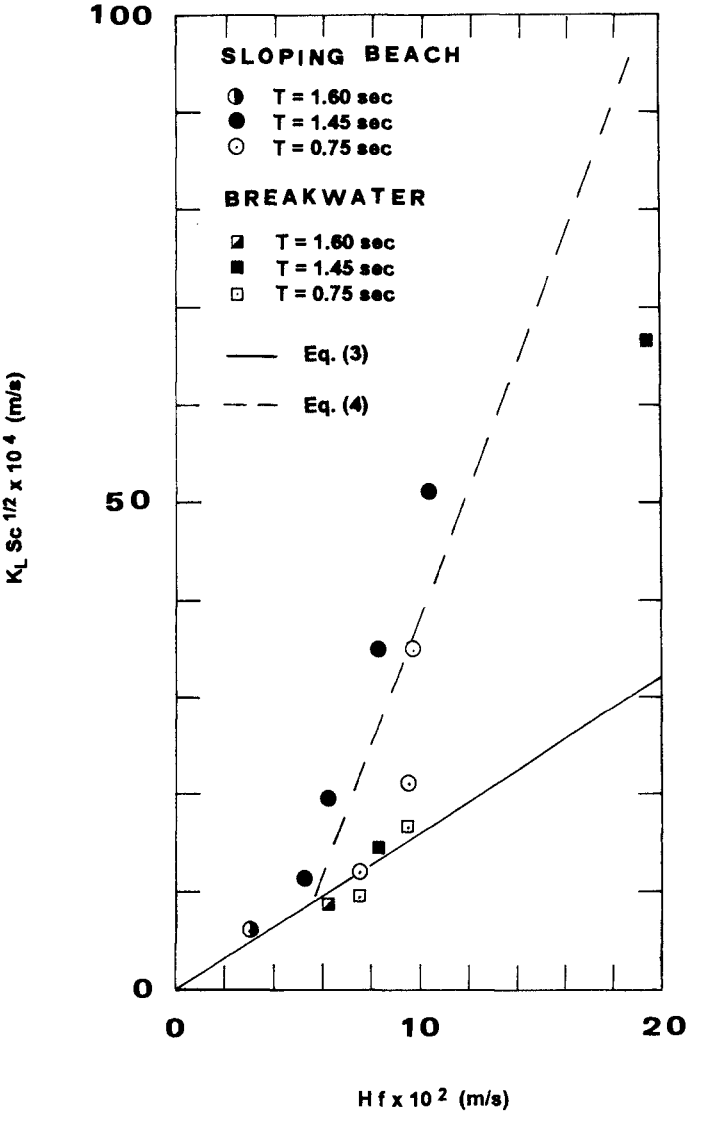

Fig. 5. Variation of the transfer coefficients with the wave parameter Hf.

A first conclusion from the present experiments is that incorporating wave characteristics in water quality models can improve the design of nearshore sewage outfalls, taking advantage of the "self-cleaning" capacity of the water body. Coasts in which wave breaking is a dominant mechanism present considerable advantages from the point of view of oxygenation of the effluent by physical mechanisms. Disposing the effluent near the breaking wave zone can possibly be combined with reduced treatment, thus leading to a more economic design.

A second conclusion is that coastal structures, such as breakwaters, reduce the oxygenation rate of seawater, due to increased wave reflection. This could have some negative influence on the fauna, although the beneficial effect of rubble-mound structures to the number of fish population and the types of species developed in the area is by now well documented.

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