# CHAPTER 32

## Scale Effects in Oxygenation in the Breaker Zone of Coastal Structures

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### Abstract

The significance of oxygen transfer across the air-water interface with its associated impact on water quality and environmental pollution control in coastal zones has become a matter of concern for coastal engineers. In the present paper experimental data on oxygen transfer obtained in the large scale facility of Delft Hydraulics have been presented. The obtained oxygen transfer coefficients have been compared to existing models for gas transfer under breaking and non breaking waves. Scale effects are found to be an important factor which needs to be considered when laboratory results are translated to field conditions.

### Introduction

Oxygen transfer across the air-water interface with its associated impact on water quality and environmental pollution control in coastal zones has become increasingly important for coastal engineers. Systematic studies of the oxygenation of water systems commenced with the emergence of water pollution problems associated with river systems (Streeter and Phelps,1925). Years later these studies were augmented to incorporate lakes and oceans.

Understanding of the parameters influencing air-sea gas exchange has increased considerably in recent years, although little is known about the exact mechanisms that control the process. Recent research has also begun to investigate the penetration of other gases in water, including nitrogen oxide, $N_2O$, carbon dioxide, $CO_2$, helium, He, and sulfur hexafluoride, $SF_6$ (Keeling, 1993, Woolf, 1991, Wanninkhof, 1992, Wanninkhof et al.,1995). However, available data for the evaluation of the different gas exchange models is still limited.

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Experimental results indicate that wave action increases the penetration of gases into the water (Jähne, 1985, 1987, Hosoi, 1977, Hasse and Liss, 1980). It is therefore considered that waves have a positive effect on the oxygenation of water bodies. Breaking waves enhance the aeration process by entraining air bubbles and increasing turbulent mixing. Field, laboratory and theoretical studies have been performed to study this phenomenon in detail. The presence of air bubbles increases the air-water interface area available for gas exchange. The formation of bubbles and increased turbulence that result from the action of breaking waves contribute to the increase of dissolved oxygen (DO) in water. Hosoi and Murakami (1986) assumed that oxygenation due to non-breaking waves in their experiments was negligible and that the whole water body is oxygenated through the wave breaking zone. Wallace and Wirick (1992) observed that breaking waves can increase the rate of aeration by up to 200 times due to the entrainment of bubbles.

The role of coastal structures in water oxygenation has recently come under investigation (Moutzouris and Daniil, 1994b, Hosoi et al., 1977), as wave breaking results in high oxygenation rates and therefore in improvement of water quality in the vicinity of coastal structures. For oceans the transfer coefficient is usually correlated to the wind velocity (Wanninkhof, 1992, Wanninkhof et al., 1993). It should be noted though that laboratory and field data give significantly different correlations possibly (Liss, 1983) due to scale effects.

A research program has been initiated at the Laboratory of Harbour Works (LHW), National Technical University of Athens, to investigate and model air penetration in the wave breaker zone of inclined coastal structures. Initial experimental results from a small wave flume at LHW (Daniil and Moutzouris, 1993) indicated that scale effects should be investigated for application to field conditions. In order to quantify these effects and to compare to earlier results, further experiments were conducted in a larger facility. Measurements were carried out in the large wave flume of Delft Hydraulics (DH), the Netherlands, financed by the European Community, as part of the Large Installations Program (LIP): “Training and Mobility of Researchers- Access to Large Scale Facilities”.

This paper presents the preliminary results from this research program, which indicate that the scale of the phenomenon has a considerable influence on the transfer mechanisms. Oxygen transfer velocities determined from the large scale experimental result are compared in this paper to the models of Daniil and Gulliver (1991) for non-breaking waves and Daniil and Moutzouris (1994, 1995) for breaking waves, derived and verified from measurements in small scale facilities.

## Experimental Procedure

Large scale oxygenation experiments under breaking waves were performed at the Wind Wave Flume of Delft Hydraulics (DH) as a part of the European Program: "Training and Mobility of Researchers - Access to Large -Scale Facilities".

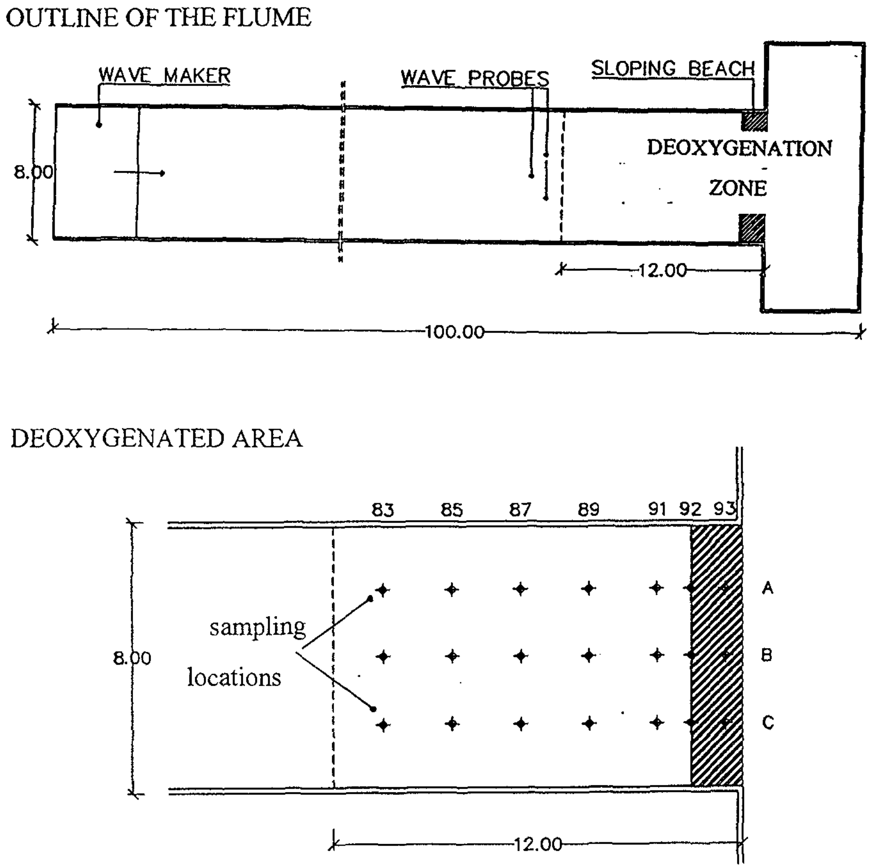
The wave flume of Delft Hydraulics is "T" shaped with a total length of 100m and 8m width while the last 9 m are 25m wide. The outline of the flume is shown in Figure 1. The flume is equipped with a hydraulic dual piston wave maker for the generation of mechanical waves. Waves are generated by a computer-controlled wave board with adjustable rotation and translation. Waves with frequencies between 0.65-0.90 Hz and heights between 8.5-20.5 cm were produced.

A concrete structure with a uniform slope of 1:2.3 was placed at one end of the flume in order to model a sloping beach and initiate wave breaking. The structure was watertight and no water exchange between the front and the back of the sloping beach was possible. The water depth was 0.72m for all experiments.

Three capacitance wave gauges were used for recording the wave characteristics (Figure 1). The experimental procedure consisted of two distinct phases. During the first set of experiments, the water was deoxygenated using sodium sulfite ($Na_2SO_3$) and cobalt chloride ($CoCl_2$). About 8 kg of $Na_2SO_3$ and 0.55 Kg of $CoCl_2$ $6H_2O$ were required for every experiment and these were sufficient to deoxygenate an area of 12m length and 8m width.

In the second set of experiments the water was deoxygenated using the nitrogen stripping method. Long elastic tubes with small pores were connected to nitrogen cylinders equipped with regulating pressure valves. The elastic tubes were placed in a 12m long area of the flume which was isolated during the deoxygenation process from the rest of the flume by a movable divider. Approximately 60-70 $m^3$ of nitrogen were needed for each experiment. For the deoxygenation process approximately 10 hours were required.

The concentration of DO in the water body was monitored over time by a portable oxygen meter type OXI-96, at 21 sampling locations along the flume (see Figure 1). In order to verify the accuracy of readings obtained with the oxygen meter, water samples were also taken and analyzed using the azide modification of the Iodometric Winkler titration method for D.O. determination The measurements of the dissolved oxygen concentration commenced immediately upon wave generation and continued until the DO value reached 80% of the estimated saturation level for the specific conditions of temperature and atmospheric pressure.


OUTLINE OF THE FLUME

DEOXYGENATED AREA

**Figure 1.** Schematic layout of the wave flume of the laboratory of Delft Hydraulics.

The transfer of oxygen between the air-water interface is a term of source or sink in the mass transfer equation. In the experiments performed the only source considered is oxygen transfer through the water surface. The oxygenation is characterized by the f oxygenation coefficient $K_2$ ($sec^{-1}$) or the oxygen transfer coefficient (or oxygen transfer velocity) $K_L$ (m/sec).

## Data analysis

For all sampling locations the change in DO concentration under wave action was monitored and DO-time histories were obtained. A comparison of DO -time histories for experiments in the large and small scale facilities with waves of about the same period and height, illustrating that the transfer velocity is lower for the large scale facility is shown in Figure 2.

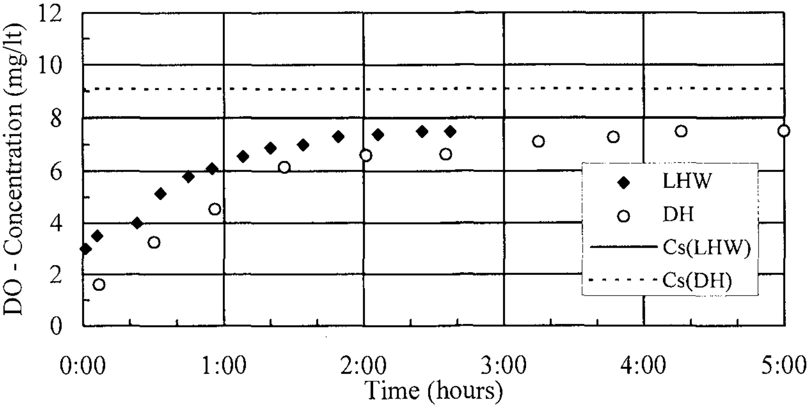


**Figure 2.** Comparison of DO-time histories at the wave breaking point for experiments in different scale facilities with approximately the same wave characteristics (T=1.55 sec H=18.3 cm).

The transfer coefficient $K_L$ is determined from the one dimensional transport equation, using linear regression and the measured DO concentration time history from a location where the horizontal transport can be assumed negligible:

$$\ln (C_s\text{-}C) = - K_L(A/V)t + \ln (C_s\text{-}C_0) \qquad (1)$$

where C is the concentration of DO (mg/l), $C_0$ is the initial concentration (mg/l), Cs is the saturation concentration (mg/l), $K_L$ is the oxygen transfer coefficient (m/sec), A is the projected free surface area ($m^2$), and V is the aerated volume ($m^3$). It is assumed that the saturation concentration is steady and for the initial time t=0 the concentration is $C=C_0$.

| **Exp No** | **T** (sec) | **H** (cm) | **L** (m) | **$\theta$** (°C) | **P** (mmHg) | **Sc** | **$K_L$ $*10^5$** | **$K_{L20}$ $*10^5$** |
|---|---|---|---|---|---|---|---|---|
| *Breaking Waves* | | | | | | | | |
| $D_1$ | 1.55 | 20.3 | 3.30 | 19.4 | 757.5 | 563 | 8.02 | 8.15 |
| $D_2$ | 1.55 | 18.26 | 3.30 | 19.3 | 760.0 | 566 | 6.91 | 7.04 |
| $D_4$ | 1.55 | 9.21 | 3.30 | 18.5 | 764.0 | 590 | 2.12 | 2.20 |
| $D_5$ | 1.30 | 12.52 | 2.50 | 18.6 | 757.5 | 587 | 6.02 | 6.24 |
| $D_6$ | 1.30 | 9.68 | 2.50 | 18.6 | 754.5 | 587 | 3.51 | 3.64 |
| $D_7$ | 1.30 | 10,30 | 2.50 | 18.6 | 751.0 | 587 | 4.82 | 5.00 |
| $D_8$ | 1.10 | 8,75 | 1.86 | 18.3 | 752.5 | 597 | 2.43 | 2.54 |
| $D_9$ | 1.10 | 10,92 | 1.86 | 18.0 | 759.0 | 606 | 3.49 | 3.68 |
| *Non Breaking Waves* | | | | | | | | |
| $D_{10}$ | 1.10 | 10.92 | 1.86 | 17.9 | 759.0 | 609 | 4.8 | 5.1 |
| $D_{11}$ | 1.55 | 20.32 | 3.30 | 17.9 | 759.0 | 609 | 6.2 | 6.5 |
| $D1_2$ | 1.55 | 12.52 | 2.50 | 17.9 | 751.1 | 609 | 3.0 | 3.1 |
| $A_4$ | 1.90 | 28.27 | 4.37 | 12.7 | 762.5 | 809 | 3.4 | 4.2 |
| $A_5$ | 1.90 | 21.14 | 4.37 | 13.2 | 761.0 | 785 | 3.5 | 4.2 |
| $A_7$ | 1.55 | 20.18 | 3.30 | 13.9 | 766.5 | 756 | 3.9 | 4.6 |

**Table 1.** Experimental data from Delft Hydraulies wind wave flume for breaking and non-breaking waves.

In order to compare experimental data, it is necessary to transform the coefficients obtained to their values at 20° C, using the equation given by Daniil and Gulliver (1988):

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

where $Sc = \nu/D$ is the Schmidt number, $\nu$ is the kinematic viscosity of water, D is the molecular diffusivity, $\theta$ is the water temperature in degrees Celsius, and $\rho$ is the water density. The water density and the kinematic viscosity were determined by the relations given by Heggen (1983).

The transfer coefficients $K_L$ at the wave breaking area and the transformed coefficients to 20 °C are presented in Table 1.

## Comparison of results with existing gas transfer models

Various models have been proposed for the prediction of the oxygen transfer coefficient. The most commonly used is the surface renewal model, first developed by Dankwerts (1951). In this model the transfer coefficient is expressed as a function of the surface renewal rate:

$$K_L \propto \sqrt{D\,r} \quad \text{or} \quad K_L Sc^{1/2} \propto \sqrt{\nu\, r} \tag{3}$$

where $K_L$ is the oxygen transfer coefficient ($LT^{-1}$), and r is the average surface renewal rate ($T^{-1}$).

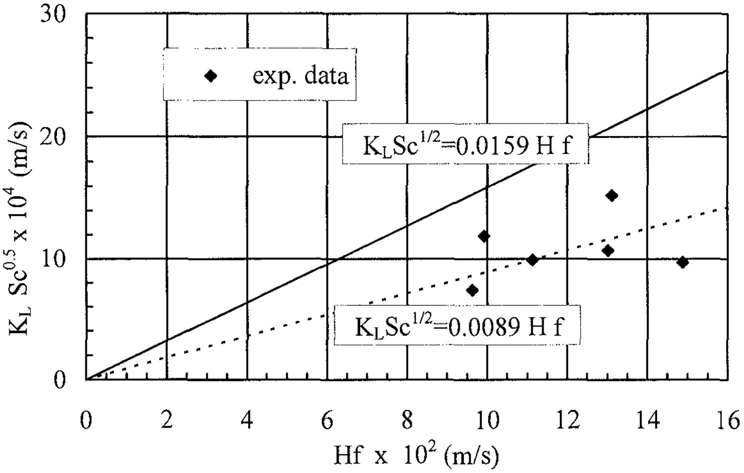


**Figure 3.** Comparison of large scale experiments to Daniil and Gulliver (1991) model for non-breaking waves.

### *Non Breaking waves*

Based on this surface renewal model Daniil and Gulliver (1991) expressed the renewal rate as a function of a wave Reynolds number, and proposed the following equation for the determination of the oxygen transfer coefficient, under non-breaking waves:

$$K_L = a\ H\ f\ Sc^{-1/2} \qquad (4)$$

The gas transfer coefficient is thus shown to be proportional to the vertical wave velocity at the water surface. Equation (4) provided the best comparison to the wave maker data and to data from other small scale flumes. Using data from the small scale facility of St. Antony Falls Hydraulic Laboratory the coefficient a was determined equal to 0.0159.

Experimental data from the large scale facility of Delft Hydraulic are compared to equation (4) in Figure 3. The experimental data are considerably lower than the predictive equation. Correlating experimental data from Delft Hydraulics, the constant of proportionality a for equation (4) is equal to 0.0089 which is approximately 0.60 of the predicted values of the model of Daniil and Gulliver (1991).

*Breaking waves*

For gas transfer under breaking waves, two models have been developed recently by Daniil and Moutzouris (1994, 1995). The constants were determined from experimental results in small scale facilities.

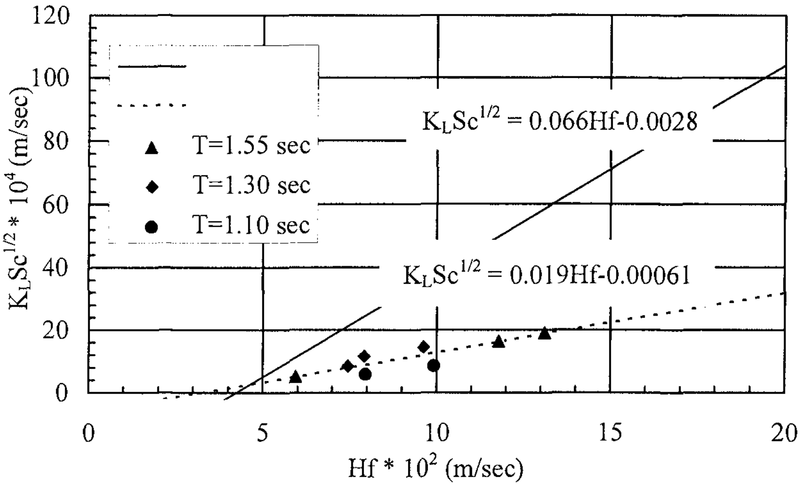


**Figure 4.** Comparison of large scale experiments to Daniil and Moutzouris, (1994) model for breaking waves.

Daniil and Moutzouris (1994), relate the transfer coefficient for breaking waves to the vertical wave velocity at the water surface with a qualitatively similar equation to Daniil and Gulliver (1991) equation as follows:

$$K_L Sc^{1/2} = a\,H\,f - b \qquad (5)$$

where H is the wave height, f is the wave frequency, a= 0.066 and b= 0.0028 m/sec. Data from experiments in Delft Hydraulics are compared to equation (5) in Fig. 4. Fitting equation (5) to data from Delft Hydraulics yields a=0.019 and b=0.0006 m/sec.

Daniil and Moutzouris (1995) proposed the vorticity based model for gas transfer under breaking waves, where the renewal rate was expressed as a function of the wave vorticity at the water surface and the term L/d that express the influence of relative depth:

$$K_L Sc^{1/2} = a\,(L/d)\,(\nu\omega)^{1/2} + b \qquad (6)$$

where L is the wave length, d is the water depth, $\nu$ is the water viscosity, $\omega$ is the wave vorticity at the water surface. Daniil and Moutzouris (1995) give a=2.86 and b=-0.00246 m/sec for breaking waves on a uniformly sloping beach based on a number of 9 experiments in the wave flume of LHW and mention that this model gives considerably better correlations, as compared to correlation with the vertical wave velocity and wave slope presented previously.

In Fig. 5 data from DH are compared to equation (6). Fitting equation (6) to data from DH give a=0.91 and b=-0.0004 m/sec.

Although data for breaking waves from the large scale facility of DH are lower, approximately 30% of the corresponding coefficients obtained from small scale facilities for the same wave characteristics, the correlation of the data to the wave parameters of the existing models is good. This indicates that the existing models include the important wave parameters, but an attenuation coefficient expressing the effect of length scale should also be included.

## Conclusions

Experimental data on oxygen transfer obtained in the large scale facility of Delft Hydraulics, as a part of the European program “Training and mobility of Researchers-Access to Large Scale Facilities”, have been presented. The obtained oxygen transfer coefficients have been compared to existing models for gas transfer under breaking and non breaking waves.

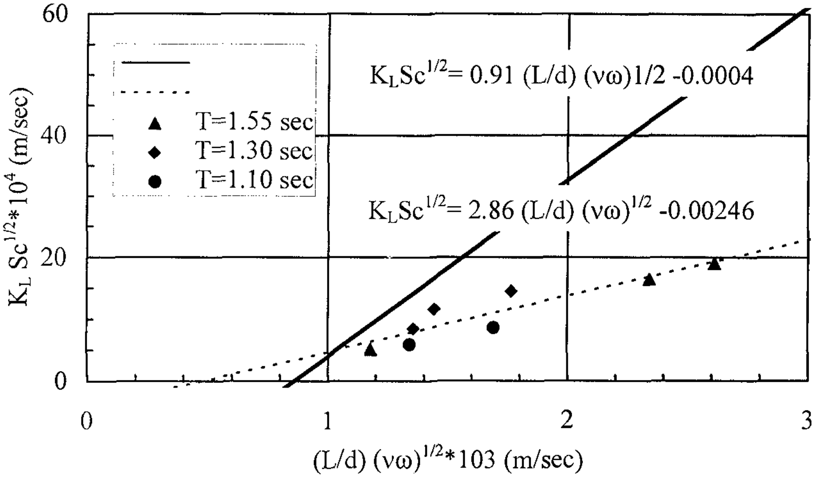


**Figure 5.** Comparison of large scale experiments to Daniil and Moutzouris model, (1995) for breaking waves.

In all cases the coefficients were considerably lower than the corresponding coefficients obtained from small scale facilities for the same wave characteristics. This could be possibly due to the minimized effect of solid boundaries in the large scale facility. Using the same wave parameters new constants were determined to the large scale experimental data with high correlation coefficients. For non breaking waves the coefficients obtained in the large scale facility were 60% of those obtained in the small wave facility for the same wave characteristics whereas for breaking waves the measured coefficients were 30% of those obtained in the small wave facility.

Finally it is concluded that the effect of scale is pronounced and should be taken into account when small scale laboratory results are translated to field conditions. The above comparisons and analysis indicate that the coefficients of the existing models should be expressed as a function of the length scale of the phenomenon.

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