Optimal location of artificial aeration in a tidal river for water quality improvement

S. Li*, G.H. Chen** and B.C. Yen**

*Institute of Environmental Science, Zhongshan University, Guangzhou, P. R. China
**Department of Civil and Structural Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, P. R. China

Abstract. Artificial aeration is one of the alternatives proposed for the improvement of DO level of the Shing Mun River in Hong Kong. This study employs Saint Venant equations and one-dimensional water quality models to simulate the hydrodynamics and DO distributions in the river, respectively. Processes affecting the river quality, such as biochemical degradation, oxygen production and consumption by algae and sediment oxygen demand are considered in the models. In-situ and laboratory tests were conducted to determine the values of reaction rates of these processes. By comparing the simulated results of DO concentration under different locations of the aeration equipment along the river with the present DO condition during spring and neap tides, the optimal position of artificial aeration is determined based on the effectiveness of water quality improvement. The effect of intermittent aeration and that of continuous aeration are compared and it is found that the increase of DO in the intermittent aeration case is about 50% of that in the continuous case on the cross-section of aeration. The influence of water temperature on the aeration is also discussed.

Keywords: Artificial aeration; dissolved oxygen; modeling; the Shing Mun River; simulation

Introduction

The Shing Mun River is a tidal river in Hong Kong. It receives the effluent of a domestic sewage treatment plant and some untreated sewage as well as non-point pollutants from storm water drainage. Due to the tidal influence, the river flow slows down and even stops during high and low tide, which results in the settling of particle pollutants. In the downstream reach, the water is obviously polluted by organic matter. This has caused low dissolved oxygen (DO) level in the water body and, as a result, odor emission occurs frequently. This situation has been repeatedly complained about by the residents. The river bed has been covered by organic mud which consumes a large amount of DO in the water body and sometime causes anaerobic condition in the overlying water of the river bed. Improvement of the oxygen level is urgently required.

Artificial aeration with circulation technology has proved to be one of the effective and yet low cost ways to increase DO level in polluted lakes and/or rivers (Iwasa, 1986; Huang, 1994). One of the authors (Chen, et al., 1996) proposed to introduce this technology to minimize the oxygen deficit in the Shing Mun River, with the aim of reducing and controlling the odor emission. A study on the DO budget in a water column of the river (Chen, in press) was conducted both in situ and indoors. The results revealed that processes dominating the oxygen demand are degradation of biochemical oxygen demand (BOD), algal respiration and sediment uptake, while the oxygen supply is mainly due to surface reaeration and production by algal photosynthesis. The study, however, did not take account of the hydrodynamic factor that usually dominates the DO budget by mixing and transport with the movement of river water. In order to determine the optimal location of artificial aeration so as to obtain the maximum effect of DO level improvement, a mathematical model is needed to develop and to simulate the distribution of DO level in the longitudinal direction of the river, taking account of all main factors affecting the demand and supply of DO.
Governing equations

Hydrodynamic model

The Shing Mun River is a gradually varied unsteady open-channel flow affected by tidal variation in Tolo Harbor. The hydrodynamics could be simulated by Saint Venant equations as follows:

\[
\frac{\partial z}{\partial t} + \frac{1}{B} \frac{\partial Q}{\partial x} - \frac{q}{B} = 0
\]  \hspace{1cm} (1)

\[
\frac{\partial Q}{\partial t} + (gA - \frac{BQ^2}{A^2}) \frac{\partial z}{\partial x} + \frac{2Q}{A} \frac{\partial Q}{\partial x} = \frac{Q_z}{A} \frac{\partial A}{\partial x} - \frac{gQQ}{AC_Z^2 R}
\]  \hspace{1cm} (2)

where \( x \) is the longitudinal distance; \( t \) is time; \( z \) is the elevation of the water surface above a datum; \( B \) is the top width of the river; \( Q \) is the flow rate; \( q \) is the lateral inflow per unit channel length per unit time; \( A \) is the flow area; \( g \) is acceleration of gravity; \( C_Z \) is Chezy coefficient; and \( R \) is the hydraulic radius.

Water quality model

Considering the tidal hydrodynamics and factors affecting the DO balance, the following one-dimensional unsteady advection-dispersion equation is used to simulate the coupling variation of BOD-DO in the river

\[
\frac{\partial (AL)}{\partial t} + \frac{\partial (QL)}{\partial x} = \frac{\partial}{\partial x} \left( K_x A \frac{\partial L}{\partial x} \right) - K_1AL + q_L
\]  \hspace{1cm} (3)

\[
\frac{\partial (AC)}{\partial t} + \frac{\partial (QC)}{\partial x} = \frac{\partial}{\partial x} \left( K_x A \frac{\partial C}{\partial x} \right) - K_1AL + K_2A(C_s - C) - K_3A + K_4A - K_5B + K_aA(C_s - C) + q_C
\]  \hspace{1cm} (4)

where \( L \) and \( C \) are BOD and DO concentration, respectively; \( K_x \) is the dispersion coefficient; \( K_1 \) is the BOD degradation rate; \( K_2 \) is the surface reaeration rate; \( K_3 \) is the oxygen uptake rate by algae; \( K_4 \) is the oxygen supply rate by algal photosynthesis; \( K_5 \) is the oxygen uptake rate by sediment; \( K_a \) is the artificial aeration rate; \( C_s \) is the saturation oxygen concentration; and \( q_L \) and \( q_C \) are the lateral inflow of BOD and DO load per unit channel length per unit time, respectively. Here in equation (4), the artificial aeration is described in the same form as that of the surface reaeration because they have a similar mechanism of DO increase.

Numerical methods

The hydrodynamic model and water quality model could be solved by finite difference methods. The weighted four-point implicit scheme (French, 1985), a well developed difference technique, is employed to discretize the hydrodynamic model. This numerical technique is favored by many users because it can be readily used with unequal distance steps and its stability-convergence properties can be controlled. The water quality model is discretized by explicit difference technique, with the time term in forward difference scheme, the advection term in up-wind difference scheme and the dispersion term in central difference scheme. These difference scheme are applied to the Shing Mun River to develop a numerical model to simulate the DO balance.

Determination of parameters and simulation conditions

Hydraulic features of the river

The Shing Mun River has a 7.5 km tidal reach from the river mouth. Its water level is dominated by the tidal variation of sea surface of the Tolo Harbor, an inland sea of Hong Kong. The average width of the tidal reach is 160 m, varying from 50 m in the upstream to 200 m in...
the downstream. The hydrodynamics of the river during spring and neap tide were simulated (Chen, et al., 1996) and some of the characteristics are listed in Table 1.

**Table 1. Hydraulic features of the Shing Mun River on the cross-section of 3 km from the river mouth**

<table>
<thead>
<tr>
<th>Tide</th>
<th>Flow velocity (m/s)</th>
<th>Flow rate (m³/s)</th>
<th>Water level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neap</td>
<td>-0.389~0.397 (0.16)</td>
<td>-131.1~122.2 (47.47)</td>
<td>1.2~2.5 (1.6)</td>
</tr>
<tr>
<td>Spring</td>
<td>-0.607~0.45 (0.26)</td>
<td>-218.2~130.6 (87.66)</td>
<td>1.04~3.0 (2.2)</td>
</tr>
</tbody>
</table>

Note: Figures in ( ) are mean values; Minus indicates the flow in upstream direction.

Determination of parameters
A field survey and laboratory analysis (Chen, in press) were conducted to study the DO budget in the Shing Mun River, with focus on the determination of parameters of DO demand and supply processes.

**BOD degradation rate.** Degradation of BOD in the water body results in the consumption of DO by suspended microorganisms. This DO demand process can be described by first-order reaction as

\[
\frac{dL}{dt} = -K_{1,20} \theta_w^{T-20} L
\]

where \( K_{1,20} \) is BOD degradation rate at 20°C; \( \theta_w \) is the temperature coefficient, usually 1.05; and \( T \) is the water temperature. The value of \( K_{1,20} \) usually varies from 0.1 to 0.2 day\(^{-1} \) and 0.1 day\(^{-1} \) is used in this study.

**Oxygen uptake rate by algae.** In situ test with “dark” bottle method was conducted in the river to determine the oxygen uptake rate by algae due to respiration. The oxygen consumption in a “dark” bottle is caused by both algae respiration and BOD degradation and can be described by

\[
\frac{dC}{dt} = -K_1 L - K_3 S_a
\]

where \( K_1 = K_{1,20} \times 1.05^{T-20} \); and \( K_3 = K_{3,20} \times 1.05^{T-20} \). The value of \( K_{3,20} \) was determined to be 0.39 day\(^{-1} \) by the survey data.

**Oxygen uptake rate by sediment.** Sediment of the river was collected by a core sampler for lab test, taking account of the water temperature and shear velocity over the samples. A formula was obtained from regression analysis of lab test data under conditions of water temperature varying from 11°C to 35°C and flow velocity varying from 0.035 m/s to 0.104 m/s

\[
K_s = 9.96U_s 1.079^T
\]

where \( U_s \) is the shear flow velocity above the sediment (m/s). Assuming that the flow velocity profile in the vertical direction follows a logarithmic distribution, \( U_s \) could be determined by

\[
U_s = 1.63 \left( \frac{H_s}{H_m} \right)^{0.5} U_m
\]
where \( H_s \) is the thickness of the shear layer above the sediment (m); \( H_m \) is the mean water depth of the river (m); and \( U_m \) is the mean flow velocity of the river cross-section (m/s).

**Surface reaeration rate.** The surface aeration rate, \( K_a \), can be determined by the following equation (O’Connor, et al., 1958):

\[
K_{a,20} = \frac{(D_{w_o} U)^{1/2}}{H^{1/2}}
\]

(9)

where \( K_{a,20} \) is the reaeration rate at 20 °C; \( D_{w_o} \) is the diffusivity of oxygen at 20 °C (1.6 cm²/day); \( U \) is the average stream velocity; and \( H \) is the average depth. The reaeration rate as a function of temperature is given by

\[
K_a = K_{a,20} \theta^{T-20}
\]

(10)

The value of \( \theta \) depends on the mixing condition of the water body. In practice a value of 1.024 is often used.

**Oxygen production rate of algal photosynthesis.** The oxygen production rate of algae was determined by in situ “light” bottle tests and lab tests (Chen, et al., in press). An overall equation to predict the algal oxygen production rate at different water temperature and depth was given by

\[
K_4 = (-2.54H + 3.88) 0.04T
\]

(11)

**Artificial aeration rate.** The artificial aeration rate, \( K_a \), is determined from the performance characteristic of the equipment to be used. At present, this parameter is not available. Since the purpose of this study is to choose an optimal location for the aeration, which needs only to compare the effectiveness of DO improvement between different aeration locations, an accurate value is not necessary. A value of 12 day⁻¹ is given in the simulation.

**Boundary conditions**

The simulation of tidal hydrodynamics and DO balance in the Shing Mun River is carried out for a 7.5 km reach starting from the river mouth. The downstream open boundary on the cross-section of the river mouth is imposed with water levels of typical spring and neap tides, while flow rate and pollutant flux are given for the upstream open boundary. Since the temporal variations of BOD and DO in Tolo Harbor is not significant, a fixed value of these concentrations are given for the downstream open boundary. There are small pollutant source inflows on cross-sections of 1.9 km, 2.0 km and 7.0 km, respectively. In the simulation, a space step of 80 m and a time step of 120 s are used.

**Results and discussion**

The optimal location of aeration

DO distributions along the river during spring and neap tides are calculated for three continuous aeration cases where the artificial aeration equipment is located at 3 km, 4 km and 5 km respectively, from the river mouth at water temperature of 20 °C. The results are shown in Figure 1. Compared to the situation without aeration, it is obvious that the 5 km location has significant effect of DO level improvement in a long reach of the river during low water and flood tide, followed by the 4 km location and then the 3 km location. There is little
difference in DO level between the three locations during high water. During ebb tide, however, the 4 km location appears the best. This could increase the DO concentration in the middle and lower reach where DO level is usually low. Judging from these results, the optimal location should be at 4~4.5 km from the river mouth.

Comparison of continuous and intermittent aeration
Since algae can produce oxygen by photosynthesis during daytime and consume DO due to respiration during night-time, an economic way to operate the aeration equipment is to run it for only 12 hours at night when DO level is relatively low. Figure 2 is the comparison of simulation results of DO distribution during neap tide under conditions of continuous aeration (24 hour operation) and those of intermittent aeration (12 hour operation at night). It reveals that on the 4 km cross-section where the aeration equipment is located, intermittent operation could reach to about 50 % of the DO improvement effect brought by continuous operation. On other cross-sections upstream or downstream, the effect of DO improvement by intermittent operation is less than 50 % of that by continuous operation.

Influence of water temperature on aeration
The simulation results of DO distribution during neap tide are shown in Figure 3 under water temperature of 10 ºC, 20 ºC and 30 ºC, respectively, when continuous artificial aeration is operated at the 4 km location. The DO improvement at 10 ºC appears similar to that at 20 ºC, with a maximum increase of 0.3~0.5 mg/l. At 30 ºC the DO level may increase by 0.7~0.9 mg/l. This implies that aeration may be more effective in summer when the river’s DO level is low. However, no significant difference in the range of DO improvement is found between the three temperature cases.

Conclusions
A mathematical model is developed to predict the DO distribution in the Shing Mun River based on the DO balance, taking account of main processes of DO demand and supply. The model is used to evaluate the effect of artificial aeration operation in the river and to
determine the optimal location of aeration operation. It is found by comparing the results of simulation for different locations that aeration on a cross-section 4~4.5 km upstream of the river mouth should have the best DO improvement effect. The effect of DO improvement by intermittent operation of artificial aeration is compared with that by continuous operation. It is found that the increase in DO level by intermittent operation is about 50% of that by continuous operation on the cross-section of aeration, and less than 50% on other cross-sections upstream or downstream. The influence of water temperature on the aeration is studied by comparing the simulation results at different temperature cases. It reveals that larger increase in DO level could be obtained when the water temperature is higher.

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References


