Hydraulic Model Experiment on the Water Exchange between the Small Coastal Lake and the Open Sea through a Pipe

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Abstract

As the water pollution in the bay and in the coastal lake which is used as a fish farm advanced, a countermeasure plan is proceeding to conduct freah sea water into the lake through a pipe.

In this paper, the authers have given the fundamental equations in which the variations in concentration of pollutant and the displacement of the water level of the lake was expressed, and have numerically investigated after rearranging these equations with dimentionless parameters. subsequently, hydrauric model experiment have been made to confirm this equations.

Although the variation in concentration of the lake water is characterized by several dimentionless parameters, among these parameters, D^2/A, l/D, l/h, (D: pipe radius, A: surface area of the lake at a average depth, l: the length of pipe, h: average depth of the lake,) are the most important parameters that influence on the concentration variation of the lake.

As will be shown later, there exists a certain value for D^2/A where a drop in concentration has a maximum corresponding to given values for l/D, l/h, the most suitable design for the pipe can be determined according to these values.

1. Introduction

The promotion of industry and population increases has led to large-scale pollution of the water within the bay, the lake, situated near thickly populated area, damages of marine products by the outbreak of reddish brown tide — Akashio —, reduction of fishery, or loss of a fine landscape scenary, are becoming more and more serious problem of man's life. In the case of the bay of comparatively large (for example, Tokyo Bay, Ise Bay, The Inland Sea of Japan), a number of field observations and a large-scale hydraulic model experiments have been achieved in order to examine how the materials of pollutant diffuse in the water, how the bay water exchange with the open sea water. These studies began steadily to yield results.

In spite of such a large-scale investigation, at present, it is considerably difficult in these model experiment to explain clearly mechanism of diffusion and of tidal exchange, because these phenomenon are affected remarkably by the weather condition, topographical condition, biological, chemical factors.

In the closed bay and the coastal lake of comparatively small being in use as fishes-shellfishes farm, water pollution due to the inflow of household seweage, drainage from factories, the development anoxic conditions caused by the outbreak of Akashio tide

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is also a serious problem. For the improvement of the quality of water in such a coastal lake, a various trial such as conduction of fresh water into it through a pipe by harnessing tidal power is planned. For example, in a lake Myojin-ike, designated natural monument, a small volcanic coastal lake near Hagi-city, Yamaguchi Prefecture. It is becoming dirty recently. As a result of various investigations on the quality of water, a living thing, depositions of sediment. It has been concluded that the effective countermeasure was to exchange lake water for fresh sea water. At present, this lake is connected with the bay (Yunagi fishing harber) by underdrain. The bay in itself, however, is becoming dirty. Under these circumstances the most effective countermeasure is to conduct fresh sea water into the lake by lengthing the pipe in the offing.

As to the sea water exchange through a pipe by harnessing the tidal power, hydraulic calculations would be comparatively easy because we could no thought of topographical irregularities, meteorological factors.

We have calculated hydraulically from this point of view on the basis of assumptions, as discribed Part 2, and have examined the tidal exchange by a model experiment.

2. Hydraulic calculations of tidal exchange through a pipe

a) Transported volume of waters and tidal exchange ratio

In several studies on the tidal exchange of sea waters which have been investigated by various authors, Parker (1) defined the tidal exchange raito as follows.

$$E_i = \frac{Q_{O_i}}{Q_{E_i} + Q_{O_i}} \qquad \cdots\cdots\cdots(1)$$

Q_{O_i} is the flow of new water entering into the lake in time increment i (concentration C), Q_{E_i} is the flow of waters returning to the lake in time increment i.

As is defined above, the transport of volume of fresh waters into the coastal lake is changing every moment in one tidal period. Many observations and hydraulic model experiments have been achieved to estimate the tidal exchange ratio.

In this paper, the authors confined the discussions on tidal exchange to a comparatively small closed bay or the lake adjacent to sea shore. In these case, following assumptions can be admitted. It become relatively easy to estimate the flow conditions.

— Assumptions —

1. Linear scale of lake is small as compared with average lake depth h, therefore water surface of the lake is regarded as horizontal, that is, it is expected that flooding sea waters is uniformly mixed with lake waters during one tidal period

$$t = \frac{L}{V} \ll T \qquad \cdots\cdots\cdots(2,$$

$$\frac{dh_1}{dt} \times t \ll H \qquad \cdots\cdots\cdots(3)$$

in which: L = linear scale of lake; V = wave velocity of long wave; T = tidal period; h_1 = the fluctuations of sea water level; H = tidal amplitude.

2. Water flowing out of lake through pipe in the ebb tide does not, except water remaining in the pipe, enter into the lake in the following flood tide.

Under above assumptions, the authors define in this studies tidal exchange ratio in one tidal period as follows.

$$E=\frac{q_1}{Ah}=\frac{Q-q_0}{Ah} \qquad \cdots\cdots\cdots(4)$$

in which; q_0 = amount of water left behind in the pipe in the ebb tide; q_1 = amount of fresh sea water enter into the lake in the following flood tide; A = surface area of the lake at the average depth; h = average depth of lake; Q = the total volume of water enter into the lake in the flood tide (the volume between high and low water level of the lake).

As described later, in the case of the inner volume of the pipe being negligibly small as compared with the average volume of lake, q_0 can be neglected, in such a case, tidal exchange ratio is

$$E=\frac{Q}{Ah} \qquad \cdots\cdots\cdots(5)$$

b) Hydraulic calculations

(i) The fundamental equation which express the water level oscillation of the lake caused by tidal fluctuations of outer sea is as follows.

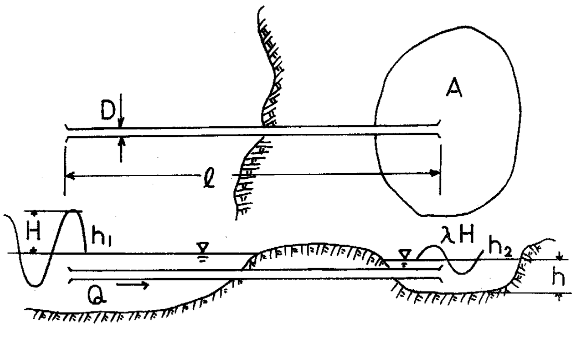

Fig. 1 Schematic view of water exchange through a pipe.

$$\left.\begin{aligned} &A\frac{dh_2}{dt}=B\sqrt{2g(h_1-h_2)} && \text{for } h_1\geqslant h_2 \\ &A\frac{dh_2}{dt}=-B\sqrt{2g(h_2-h_1)} && \text{for } h_2\geqslant h_1 \\ &B=\pi(D/2)^2/(1+f_u+2gn^2/R^{4/3})^{1/2} \\ &\quad=\pi(D/2)^2/(1+f_u+f_r l/D)^{1/2} \end{aligned}\right\} \qquad \cdots\cdots\cdots(6)$$

in which; h_1, h_2=fluctuations of sea water level and lake water level respectively; g=gravitational acceleration; B=loss coefficient of straighted pipe; D=inside pipe diameter; f_u=loss coefficient at the entrance of pipe; n=Manning coefficient; R=hydraulic radius; $f_r=8gn^2/R^{1/3}$=Resistant coefficient for friction at the inside pipe wall.

h_1, h_2 can be represented moderately realistically by a trigonometrical function such as

$$h_1=H\cos(2\pi/T\cdot t) \qquad \cdots\cdots\cdots(7)$$

$$h_2=\lambda H\cos(2\pi/T\cdot(t-\Delta T)) \qquad \cdots\cdots\cdots(8)$$

where λ is ratio of amplitude of lake water oscillation to tidal amplitude, we call this damping ratio, ΔT is the phase lag of lake water oscillation, substituting (7) (8) into (6), obtained the flux of volume of water entering into the lake at time t (q), and the exchange ratio E, as follows.

$$q=A\frac{dh_2}{dt}=-A\lambda H\cdot 2\pi/T\sin 2\pi/T\cdot(t-\Delta T) \qquad \cdots\cdots\cdots(9)$$

$$E=\{2\lambda H-\pi(D/2)^2 l/A\}/h \qquad \cdots\cdots\cdots(10)$$

in which;

$$\lambda=\lambda(H,\ T,\ g,\ l,\ D,\ A,\ f_u,\ f_r)=\{(1+4k)^{1/2}-1\}^{1/2}/(2k)^{1/2}$$

$$k=\pi^2/16\cdot(\alpha/\beta)^4,\quad \alpha=2\pi H^{1/2}/Tg^{1/2}\quad \beta=\sqrt{2}\frac{B}{A} \qquad \cdots\cdots\cdots(11)$$

$$\triangle T/T=\frac{1}{2\pi}\cos^{-1}\lambda$$

(ii) The variations in concentration of pollutant in the water. If the variations in chemical concentration, both the introduction of a pollutant and the consumption of that by the action of living thing, organic life in the lake, and the variation of turbidity caused by deposits, suspended materials, trapped in the water are all negligibly small during a few tidal period. In such a case, substituting a equation of motion into a continuity equation of concentration, obtained

$$\left.\begin{array}{ll} A\dfrac{d}{dt}\{C(h+h_2\}=C^*B\sqrt{2g(h_1-h_2)} & \text{for}\quad h_1\geqslant h_2 \\ C=\text{const} & \text{for}\quad h_2\geqslant h_1 \end{array}\right\} \cdots\cdots\cdots(12)$$

where C_* is concentration of sea water. On integrating above equation (12) by substituting (7) (8) into it, we get

$$C_n=(h-\lambda H)/(h+\lambda H)\cdot C_{n-1}+C^*\cdot 2\lambda H/(h+\lambda H) \qquad \cdots\cdots\cdots(13)$$

after some calculations, obtained the concentration of pollutant in the lake after n tidal period.

$$C_n = C_* + (C_0 - C_*)\{(h - \lambda H)/(h + \lambda H)\}^n \qquad \cdots\cdots\cdots(14)$$

therefore, it is shown that the concentration of the lake water approaches finally that of the sea water.

$$C_{n\to\infty} = C_* \qquad \cdots\cdots\cdots(15)$$

In the above argument, the influence of sea water remained in a pipe in the ebb tide on the concentration of the lake is thoroughly neglected. It is necessary to modify above equation. The amount of water level elevation of the lake $\varDelta h$ caused by the drawback of waters remained in a pipe is given as follows,

$$\varDelta h = \pi(D/2)^2 l/A \qquad \cdots\cdots\cdots(16)$$

as is evident from the definition of the exchange ratio E (10), the following condition is necessary in order that water exchange occur

$$2\lambda H > \varDelta h \qquad \cdots\cdots\cdots(17)$$

or

$$e \equiv \varDelta h/2\lambda H < 1 \qquad \cdots\cdots\cdots(18)$$

in case $2\lambda H \leqslant \varDelta h$, or $e \geqslant 1$, fresh water does not enter into the lake.

By integrating (12) with assumptions that concentration of pollutant in the lake does not vary until lake water level rise $\varDelta h$, obtained the equation expressing the concentration of the lake after n-tidal periods as follows

$$C_n = C_* + (C_0 - C_*)\{(h - \lambda H + \varDelta h)/(h + \lambda H)\}^n \qquad \cdots\cdots\cdots(19)$$

this value also approaches finally the concentration of the sea water, if the condition $e < 1$ satisfy,

$$C_{n\to\infty} = C_* \qquad \cdots\cdots\cdots(20)$$

c) Rearrangement of equation with dimensionless parameters

As mentioned before, the variations in concentration is expressed as a function of a number of characteristics which include physical parameters T, g, H, size and configurations of the lake A, h, size and length of pipe D, l, being artificially determined.

A dimensionless parameter is independant of the over all size of lake, pipe, and they permits limited experimental results to be applied to situations involving different physical, configurational dimensions, in this paper, we introduced several dimensionless parameters, have rearranged the equation (19) with these parameters in order to verify the equation (19) experimentally. In doing so, it is possible to describe the phenomenon in its entirety and not to restricted to discussing the speciallized experiment that was performed.

As a result of dimensional analysis, the following dimensionless parameters are chosen,

$$\sqrt{H}/T\sqrt{g},\ H/h,\ l/h,\ l/D,\ D^2/A,\ C_*/C_0,\ C_n/C_0 \qquad \cdots\cdots\cdots(21)$$

in terms of these dimensionless parameters, *eq* (19), λ may easily be rearranged to the form.

$$\lambda=\lambda(\sqrt{H}/T\sqrt{g},\ l/D,\ D^2/A,\ f_u,\ f_r) \qquad \cdots\cdots\cdots(22)$$

$$C_n/C_0=C_*/C_0+(1-C_*/C_0)\{(1-\lambda H/h+\pi/4\cdot l/h\cdot D^2/A)/(1+\lambda H/h)\}^n \cdots\cdots(23)$$

d) Numerical investigation on the variation in concentration of pollutant

eqs. (22) and (23) are graphically illustrated in Fig. 2, in Fig. 3, taking λ, C_n/C_0, as ordinate respectively, taking D^2/A, n, as abscessa respectively, assuming $\sqrt{H}/T\sqrt{g}=0.15\times10^{-4}$, $l/D=100$, 400, $f_u=1$, $f_r=0.03$, in *eq*. (22), $\lambda=0.55$, $H/h=0.5$, $l/h=45$, $D^2/A=0.35\times10^{-3}$, $C_*/C_0=0$, 0.1, 0.2, 0.3, in *eq*. (23).

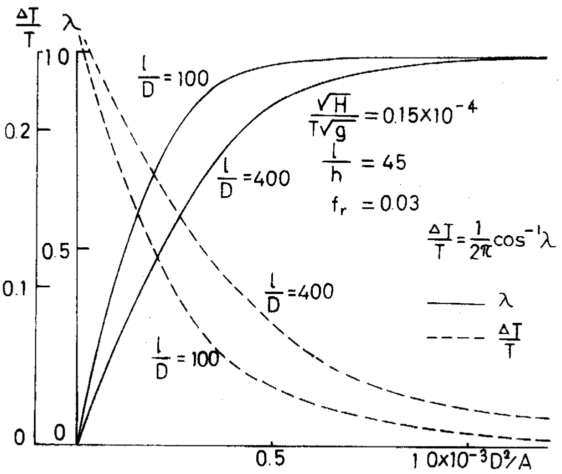

Fig. 2 A change in phase lag $\Delta T/T$ damping ratio λ, with increasing D^2/A, as a function of l/D.

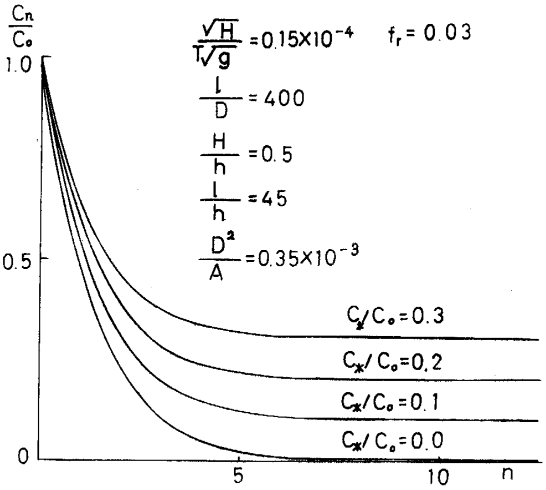

Fig. 3 Ratio of the concentration after complete n-tidal periods to the initial.

In Fig. 4, the relationship between the variation in concentration C_1/C_0 after one tidal period, and D^2/A, corresponding to $l/D=10$, 100, 500, 10^3, is shown, putting $C_*/C_0=0$, $\sqrt{H}/T\sqrt{g}=10^{-5}$, $H/h=0.4$, $l/h=500$, as a parameter. While in Fig. 5, the same relationship is shown, putting $C_*/C_0=0$, $\sqrt{H}/T\sqrt{g}=10^{-5}$, $H/h=0.4$, $l/D=500$, with $l/h=10$, 10^2, 5×10^2. 10^3, as a parameter. What is evident from these figure is that there exists the point where the variation in concentration is the largest at a certain value for D^2/A corresponding to values for, l/D or l/h. This fact, as already mentioned, may be attributed to the effect of lake water remained in the pipe in the ebb tide, but this effect is, in general, negligibly small. A drop in concentration approaches closely to a certain constant value regardless of value for D^2/A. This turning point is an important factor to the most suitable design of a pipe, after some consideration, it is

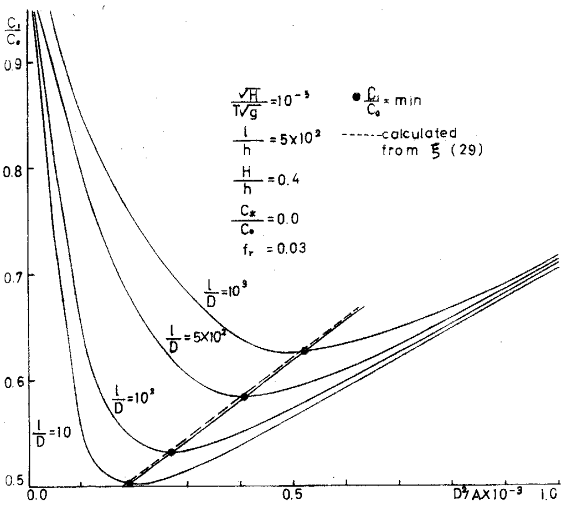

Fig. 4 Dependence of concentration drop C^1/C_0 on the ratio D^2/A at different value for l/D.

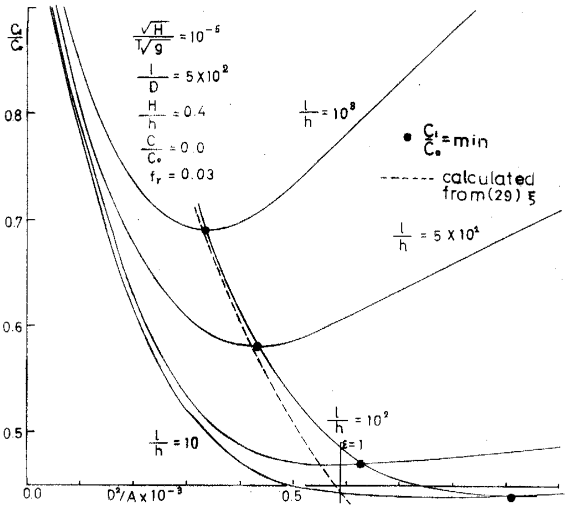

Fig. 5 Dependence of concentration drop C^1/C_0 on the ratio D^2/A at different value for l/h.

Table 1(a).

$\frac{l}{h}=10^2\ \frac{\sqrt{H}}{T\sqrt{g}}=10^{-5}\quad \frac{H}{h}=0.4\quad \frac{C^*}{C_0}=0.0$

$\frac{l}{D}$	$\frac{D^2}{A}\times10^{-3}$ $C_1/C_0=\max$	$\frac{C_1}{C_0}$	$\xi\times10^{-3}$	$\frac{C_1}{C_0}$
10	0.284	0.449	0.209	0.453
10^2	0.386	0.456	0.304	0.459
5×10^2	0.623	0.473	0.541	0.475
10^2	0.796	0.486	0.722	0.487
10^4	1.853	0.566	1.841	0.566

Table 1(b). Comparison of Culculated maximum diop in conentration C_1/C_0 and Corresponding value D^2/A with the ξ and corresponding value C_1/C_0.

$\frac{l}{h}=5\times10^2\ \frac{\sqrt{H}}{T\sqrt{g}}=10^{-5}\quad \frac{H}{h}=0.4\quad \frac{C^*}{C}=0.0$

$\frac{l}{D}$	$\frac{D^2}{A}\times10^{-3}$ $C_1/C=\max$	$\frac{C_1}{C_0}$	$\xi\times10^{-3}$	$\frac{C_1}{C_0}$
10	0.199	0.500	0.187	0.501
10^2	0.268	0.526	0.260	0.526
5×10^2	0.419	0.585	0.417	0.585
10^3	0.521	0.628	0.517	0.628
10^4	0.908	0.874	0.914	0.874

obvious from (29) that this point is expressed by the following number

$$\varepsilon \equiv \sqrt{\pi}\,\frac{\alpha}{\beta} = 8\sqrt{\pi}\cdot\sqrt{H}/T\sqrt{g}\cdot(2+f_r l/D)^{1/2}/D^2/A \qquad \text{for} \quad \Delta h/h<10^{-2} \qquad \cdots\cdots\cdots(24)$$

which contains only four dimensionless parameters, and according to $\varepsilon<1$, $\varepsilon>1$ (22), (23) are approximately written as *eqs.* (25) (26).

If $\varepsilon>1$, increasing values of this number indicate decreasingly water exchanged conditions, while, if $\varepsilon<1$, a drop in concentration C_1/C_0, become constant regardless of D^2/A.

In Fig. 6, the relationship between the above mentioned largest value of C_1/C_0, and the value for D^2/A where C_1/C_0 have a maximum is represented.

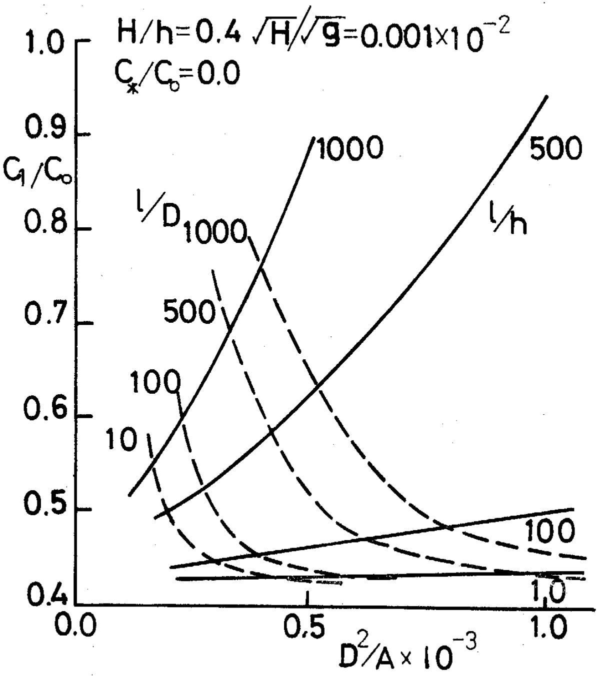

Fig. 6 Nomogram for determination of l/h and l/D from C_1/C_0 and D^2/A.

In case of the inner volume of a pipe is negligibly small as compared with the averaged lake volume, *eqs.* (22), (23) are approximately rewritten as follows.

$$\left.\begin{aligned}&\lambda\fallingdotseq 1/\sqrt[4]{k}\\&C_n/C_0=C_*/C_0+(1-C_*/C_0)\{(1-\eta D^2/A)/(1+\eta D^2/A)\}^n,\\&\qquad\qquad\qquad\qquad\qquad\text{for}\quad\varepsilon\gg 1\\&\eta=(H/h)/\{4\sqrt{\pi}\sqrt{H}/T\sqrt{g}(1+f_u+f_r l/D)^{1/2}\}\end{aligned}\right\}\cdots\cdots\cdots(25)$$

$$\left.\begin{aligned}&\lambda\fallingdotseq 1\\&C_n/C_0=C_*/C_0+(1-C_*/C_0)\{(1-H/h)/(1+H/h)\}^n=\text{const}\\&\qquad\qquad\qquad\qquad\qquad\text{for}\quad\varepsilon<1\end{aligned}\right\}\cdots\cdots\cdots(26)$$

While, in case that it is not to be neglected

$$\left.\begin{aligned}&\lambda \fallingdotseq \frac{1}{\sqrt[4]{k}}\\&C_n/C_0=C_*/C_0+(1-C_*/C_0)\{(1-(\eta-\gamma)D^2/A)/(1+\eta D^2/A)\}^n\\&\qquad\qquad\text{for}\quad D^2/A\ll\xi\end{aligned}\right\}\cdots\cdots(27)$$

$$\left.\begin{aligned}&\lambda \fallingdotseq 1\\&C_n/C_0=C_*/C_0+(1-C_*/C_0)\{(1-H/h+\gamma D^2/A)/(1+H/h)\}^n\\&\qquad\qquad\text{for}\quad D^2/A>\xi\end{aligned}\right\}\cdots\cdots\cdots(28)$$

where, $\gamma=\pi/4\cdot l/h$

from above approximate equation, the value for D^2/A where a drop in concentration after one tidal period has a maximum, is to be roughly estimated from following equation.

$$(D^2/A)_{C_1/C_0=\min}\fallingdotseq\xi=(2H/h)/(\eta+\gamma(1+H/h)) \qquad\cdots\cdots\cdots(29)$$

It is clear from Table 1, Fig. 4, Fig. 5, the deviation from exact value decrease with increasing the values for l/h, though this value deviate to a greater degree from exact value in the case of the value for l/h being under 10^2. As far as the final concentration is concerned, this fact is not to be important because as is shown graphically in Figs. 4, 5, or table 1, in such a case, a final concentration approaches a constant value regardless of the increasing value for D^2/A. For this reason, from economical, suitable planning point of view, this value ξ is more important rather than the true value for D^2/A where C_1/C_0 has a maximum.

3. Hydraulic model experiment on the exchange of waters

a) The purpose of this experiment is to confirm experiemntally the equation (22), (23) which consist of only dimensionless parameters.

b) The descriptions of experimental device

In Fig. 7, the outline of experimental device is sketched. As described in introduction, this studies originate in the actual problem in lake "Myojin-ike" as a countermeasure to a pollution of lake water, for this purpose, the apparatus was devised as follows.

They are generously composed of Sea Part (test flume being 0.4 m × 3 m × 1 m in size), Lake Part (made by acrylic plate being a rectangular box with a base 36 cm × 70 cm, and 13 cm in height), and Tide-generating equipment (it is possible to vary the tidal period from about 30 minutes to 3 hours), as a model of pipe, acrylic tube ($D=0.50$ cm, 0.90 cm, 1.07 cm in inside diameter), glass tube ($D=0.78$ cm), vinyl chloride tube ($D=1.30$ cm) was used. A tube was attached to near the bottom of lake model (about 1 cm from the bottom) so as to satisfy the assumption as previously shown, while, have been continuously recorded by conductive-meter (4.5 V fullscal). The experiment has been made in the following three cases.

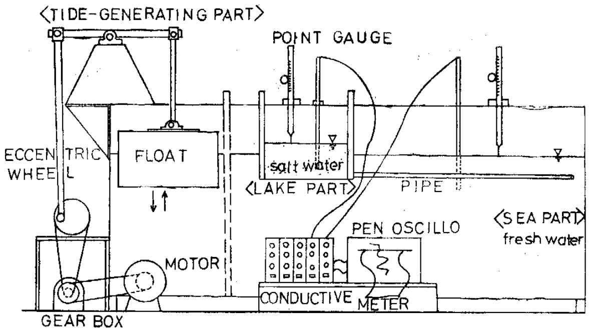

Fig. 7 A general view of experiment device.

(A) Inner volume of the pipe is negligibly small as compared with the average volume of the lake (it is considered to be in a general case where $\Delta h/h > 10^{-2}$).
(B) The influence of the waters remained in a pipe on the salinity in the lake is not to be neglected.
(C) Variation in salinity after n-tidal periods.

c) Experimental results

(i) Experiment A

Values for parameters put in this experiment are as follows; the surface area of the lake A is 36×10, 36×20, 36×30, 36×40, 36×70 square centi-meters, H is about 2.5 cm, T is 55 minutes.

Figs. 8, 9, 10, show the variations of water level of the sea part and of the lake mentioned (assumption 1).

In these apparatus, among the parameters prescribing the variation in concentration of the lake, A, H, h, l, D, T can be varied arbitrarily. Within the limits of our experiment, however, H, h, l, T being kept constant and varying only A, D, and have examined the relationship between such two parameters and concentration.

d) The methods of measurement

The elevation of water surface with time (lake part and sea part) was measured by point-gauge at intervals of 2.5 minutes. As a tracer to examine the variation in concentration of the lake, salt was used. Putting salt-fresh water into the lake model and fresh water into the test flume, have measured the salinity in the lake model with a part h_1, h_2, piezometric difference $\Delta h = h_1 - h_2$, variations in lake salinity C, plotted against time as a function of D^2/A, putting $l = 200$ cm, $D = 0.50$ cm, 0.78 cm, or ($l/D = 400, 256$, $l/h = 47$). As the value l/D increases, the transport volume of the sea water, the elevation of lake surface, phase lag, are all decrease. That is the natural result to be expected.

Fig. 11 shows the relation between C_1/C_0; the ratio of average salinity after one tidal period to the initial, and D^2/A as a function of l/D, putting $l/D = 400, 256, 222$, $l/h = 47$.

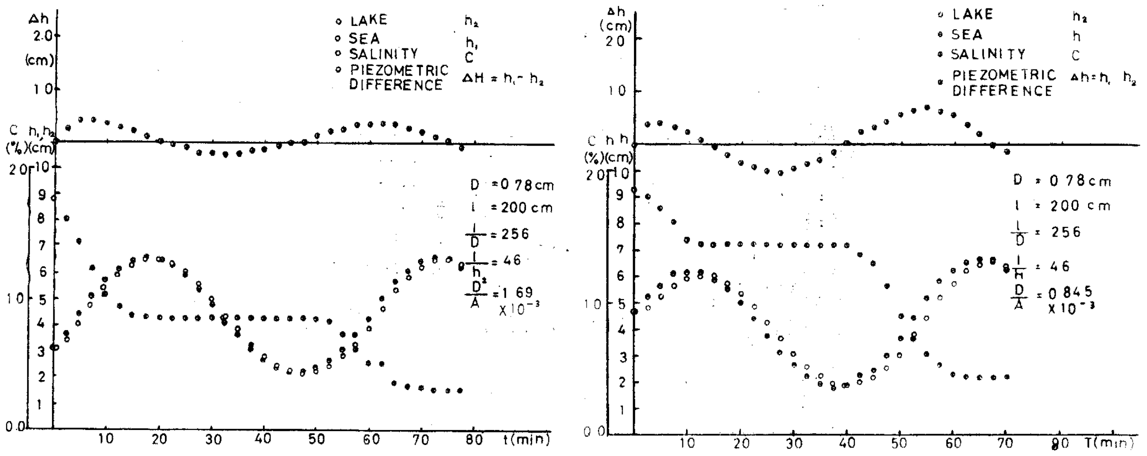

Fig. 8(a) Fig. 8(b)

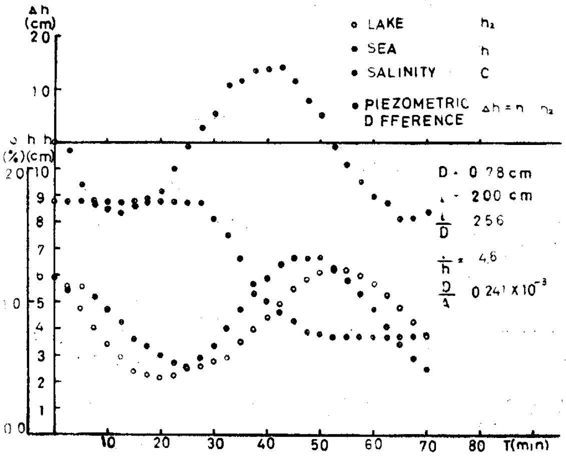

Fig. 8(c)

Fig. 8 The variations of water level of the sea part h_1 and of the lake part h_2 piezometric difference Δh, variations in lake salinity C.

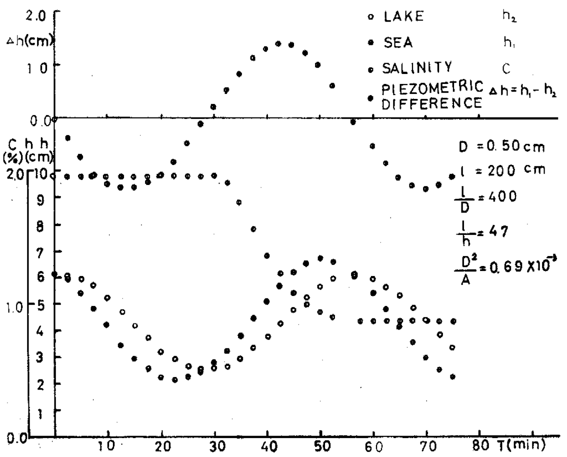

Fig. 9(a)

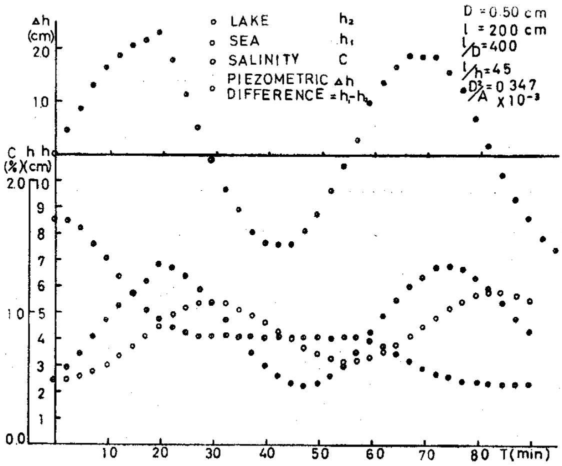

Fig. 9(b)

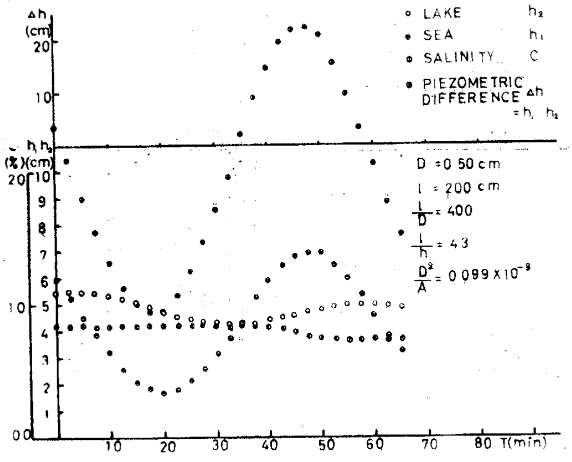

Fig. 9(c)

Fig. 9 The variations of water level of the sea part h_1 and of the lake part h_2 piezometric difference Δh, variation in lake salinity C.

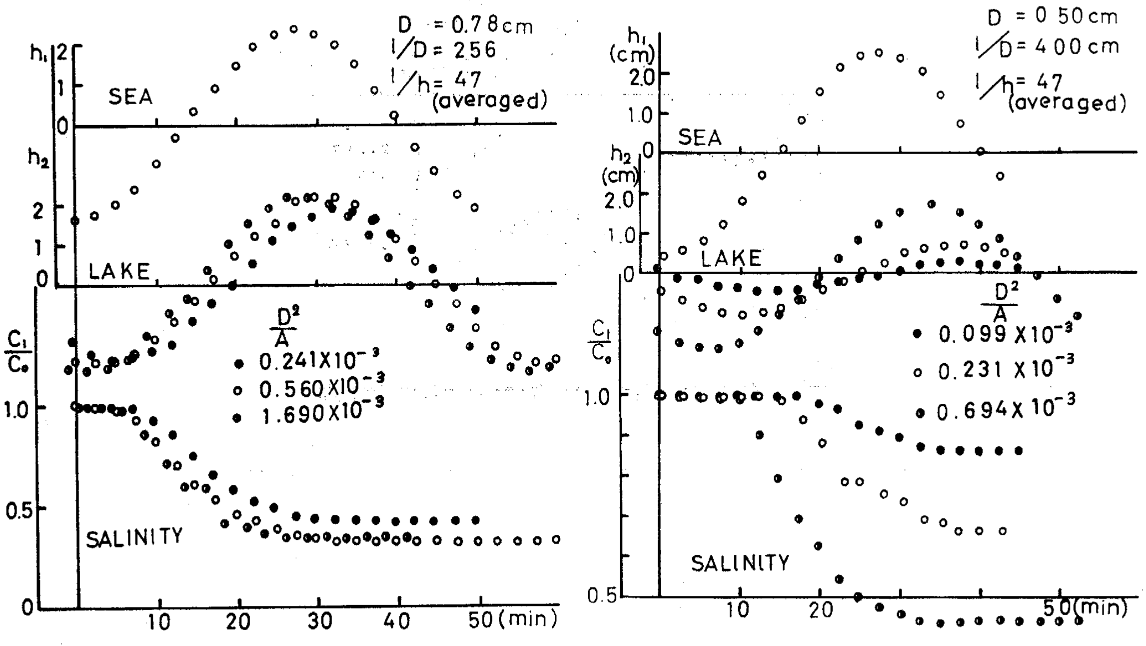

Fig. 10(a) Fig. 10(b)

Fig. 10 The variatins of water level of the sea part h_1 and of the lake part h, and the variations in lake salinity C_1/C_0.

It is shown in these figures that a drop in salinity approaches a constant value above a certain value for D^2/A which is roughly estimated by (24), putting $\varepsilon=1$, or

$$D^2/A > 8\sqrt{\pi}(\sqrt{H}/T\sqrt{g})(2+f_r l/D)^{1/2}$$

moreover, this ratio approaches almost the same values regardless of the values for l/D, this means, as was discussed (26), that the most imoptant parameters prescribing the final salinity are only two parameters H/h, f_r at $\varepsilon<1$, while λ, H/h, f_r or $\sqrt{H}/T\sqrt{g}$, l/D, H/h, D^2/A, f_r at $\varepsilon>1$. When $A=36\times10$ cm, the elevation of water level of the

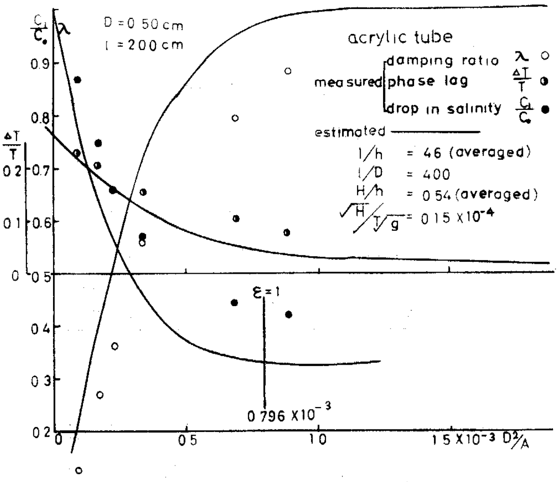

Fig. 11(a)

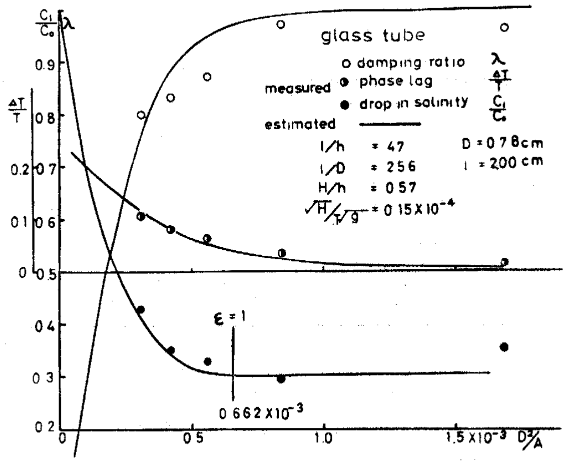

Fig. 11(b)

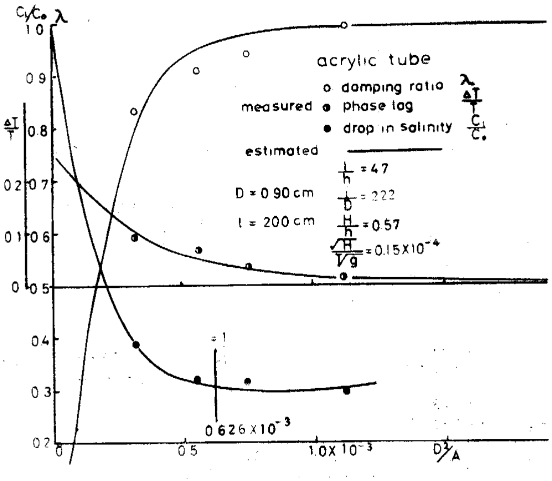

Fig. 11(c)

Fig. 11 Relation between D^2/A and the ratio of average salinity after one tidal period the initial C_1/C_0, phase lag $\Delta T/T$, damping ratio λ as a function of l/D.

lake due to the drawback of water remained in the pipe is 0.109 cm in case of 0.5 cm I-D acrylic tube, 0.265 cm in case of 0.78 cm I-D glass tube respectively, this value is negligibly small as compared with average lake depth $h=4.3$ cm.

Table 2(a). Relation between λ $\Delta T/T$, Q, E C_1/C_0 and D^2/A (observed value).
$l/D=256$ $H/h=0.56$ $l/h=47$ (averaged value)

$D^2/A\times10^{-3}$	0.241	0.423	0.563	0.845	1.127	1.69
λ	0.800	0.830	0.872	0.969	0.945	0.960
$\Delta T/T$	0.102	0.094	0.081	0.040	0.053	0.045
$Q=2\lambda HA$	9.395	5.688	4.482	3.420	2.327	1.548
$E=2\lambda H/h$	0.849	0.980	0.998	1.134	0.962	1.094
C_1/C_2	0.430	0.350	0.329	0.288	0.361	0.354
ε	2.75	1.56	1.18	0.78	0.57	0.39

Table 2(b).
$l/D=400$ $H/h=0.54$ $l/h=45.5$ (averaged value)

$D^2/A\times10^{-3}$	0.099	0.174	0.231	0.347	0.690	0.893
λ	0.135	0.270	0.360	0.568	0.796	0.881
$\Delta T/T$	0.228	0.206	0.191	0.154	0.103	0.078
$Q=2\lambda HA$	1.769	1.944	1.951	1.872	1.307	1.100
$E=2\lambda H/h$	0.150	0.317	0.415	0.583	0.848	0.895
C_1/C_0	0.869	0.750	0.660	0.572	0.441	0.442
ε	8.04	4.57	3.45	2.29	1.15	0.89

(ii) Experiment *B*

As already indicated, there exists a certain value for D^2/A which gives the greatest rate of tidal exchange. When the inner volume of pipe is not negligible, we have confirmed the existence of this peak attaching the longer glass tube $D=0.78$, $l=530$ cm, $h=3.5$ cm the other factors are maintained the same as above experiment. When $A=36\times10$ cm

$$\Delta h=0.704 \text{ cm}$$

Even if the fresh water began to enter into a pipe at the same time as tide changes from ebb to flood, the salinity in the lake does not vary for the first δ minutes (Fig. 12), this phenomenon is due to the influence of the inner volume of pipe, in Fig. 13 the above mentioned peak is clearly shown.

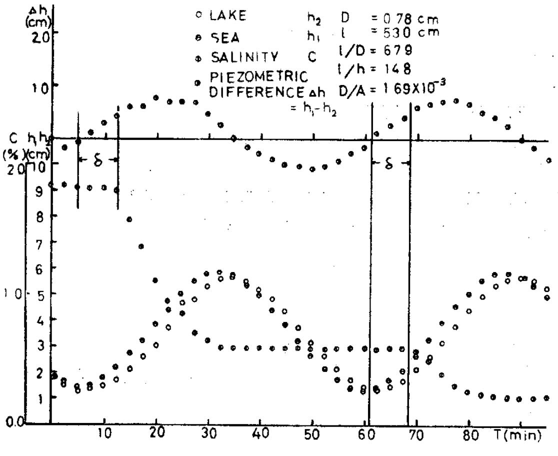

Fig. 12 The variation of water level of the sea part h_1 and of the lake part h_2, piezometric difference Δh and variation in salinity in case that pipe volume cannot be neglected.

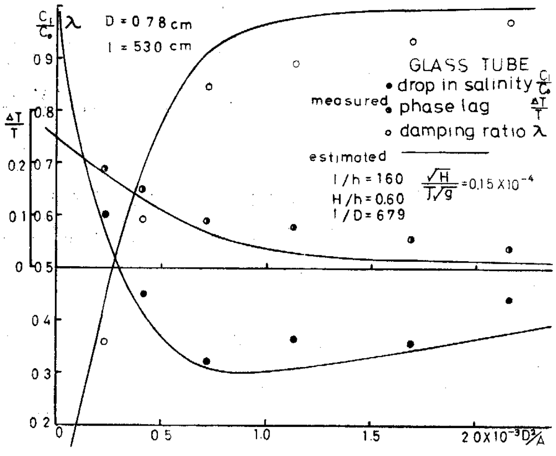

Fig. 13 Relation between D^2/A and the ratio of mean salinity C_1/C_0 in case that the inner volume of pipe cannot be neglected.

(iii) Experiment *C*

As was shown in (20), the salinity of the lake approaches closely to that of the sea, to verify this, the experiment has been made in one case ($D=0.5$ cm, $A=36$ cm $\times$ 20 cm). The other parameters are maintained the same as experiment *A*. The salinity of the lake has exponentially dropped except in the ebbing tide from the initial value of 1.7% to 0.1% after 4-tidal periods (in Fig. 14).

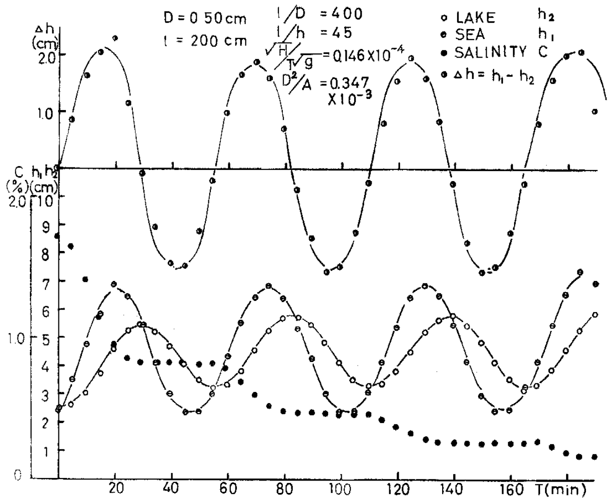

Fig. 14 The variation of water level of the sea part h_1 and of the lake part h_2 piezometric difference Δh, and variation in salinity during four tidal periods.

4. Summary and Conclusions

In these experiments, a drop in salinity after one tidal period has been mainly examined. As is evident from Fig. 11(a), the experimental values deviate from theoretical curve because we are obliged to put assumed values as a friction coefficient ($f_r = 0.03$, $f_u \fallingdotseq 1$). One of the most intractable, but important factors that influences the rate of the mixing of the salt and fresh water is friction factor of the pipe, in laminar flow, as a matter of fact, the friction coefficient is expressed as a function of Reynolds number, that is, $f = 64/Re$, therefore, in such a experiment as was reported in this paper, the friction coefficient is expected to change every moment. This fact is thought to be the cause of deviation. As the actual flow inside the pipe may be turburent, the friction coefficient is expected to be constant as was analyzed in these studies. It becomes clear, as far as the assumptions 1 and 2 permit, that the salinity of the lake has been dropped in accordance with the equation (23).

We summarize conclusions and points being left behind out of consideration from the experiment described above as follows.

1. Because of the density difference between the fresh and the fresh-salt water caused by the usage of salt as a tracer, the inflow water is not well mixed, and stratifies near the surface of the lake. For this reason, the average salinity was measured after stirring the lake water, in the actual lake or bay, this point is thought to be left out of consideration because the density of both waters are almost the same. Rather, topographic difference, and friction at the bottom are more important factors influencing the salinity variations on such lakes and bays having topographic irregularities, there is much

left to study.

2. There is a certain value for D^2/A where a drop in salinity after one tidal period is the largest. In the case of the volume of pipe being not neglected, as was proved by experiment C, the salinity of the lake approaches closely to that of sea after only a few tidal periods, therefore, for the most part, it doesn't necessary to consider this influence except the following case, that is,

(i) In the case that the production or the consumption rate of the pollutant materials in the lake waters (for example, the deficiency of dissolved oxygen in fishpond) exceeds the time scale of tidal exchange.

(ii) In the case that the lake of relatively small volume is connected with far-distant sea.

In above case, the most suitable radius of the pipe and the length of the pipe can be determined according to the equation (29).

5. Acknowledgement

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