〈논문〉

# ON Salinity of Comduit Discharge from Selective Withdrawal Apparatus

## 選定된 排水管의 流出水 監分濃度에 관한 研究

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ABSTRACT □ A problem of outlet salinity from a stratified fluid with a well developed interface thickness consisting of an upper and lower layer differing slightly in density is considered. Three kinds of apparatus were used for the experimental test and salinity differences between inlet layer and outlet discharge were estimated by the functional relationship using the dimensionless values. For the critical incipient condition of withdrawal of upper layer, Densimetric Froude number is correlated by the inlet diameter and depth ratio in the tank.

要 旨:淡水化湖에서는 溫度 및 鹽度差에 의하여 成層流가 發生하며 水深이 깊은 淡水化湖의 경우 그 형상이 더욱 뚜렷하다. 본 研究는 깊은 淡水化湖를 對象으로 內部境界面이 잘 발달된 二層流에 있어서 底層排水管의 流出水 鹽分濃度를 實驗을 통하여 糾明하였다. 實驗에 利用된 底層排水管은 세가지 유형으로 流入層과 排水管의 流出水 鹽分濃度差를 無次元으로 數式化 하였고 流入層의 上層部 흐름이 순간적으로 排水되는 密度層의 限界條件을 密度 Froude數와 排水管의 直徑 및 水深의 函數로 方程式을 誘導하였다.

## I INTRODUCTION

The basic estuary problem of salinity intrusion, pollution by discharged wastes are assoiated density currents or gravity underflows also much concerned with discharge of the stratified flow. In these motions in the gravitational field which are originated or influenced by the variations in density or salinity distribution, the fluid are characterized by the term of stratified flow. Control of the density currents has long been considered technically desirable, as an example, various barriers have been proposed for the control of salt water intrusion in river, canals and especially in the freshening reservoir for the water resource development of the tidal land.

After sea dike was constucted at the river mouth or delta area in the bay, the salt water change to freshwater by operation of tidal gate or other hydraulic structures. Therefore the problem of salinity control has been suggested in the freshwater reservoir, so called freshening reservoir. Most of freshening reservoirs have two types of geomorphological aspect as one is deep and the other is shallow depth one. The shallow freshening reservoir has a large catchment area and much inflow but the deep one has comparatively a small catchment area with less

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** Seoul National Polytechnic Univ., Dept. of Civil Eng., Professor inflow. After created freshening reservoir, density or salinity problems will happen in the deep freshening reservoir.

In general usage, the term of stratified fluid implies a variation in density and salinity of the fluid on the vertical direction in the freshening reservoir. Usually, such flows are also assumed to be gravitational stable, that is, lighter liquids flow on the top of the heavier one's.

The purpose of this paper is to report on some experimental and analytical work dealing with oulet salinity control by means of withdrawal from the freshening reservoir through a model test in the field[15]. The independent variables of this study are the depth ratio of experimental data, salinity differences in the inlet layer and outlet, and vertical salinity distribution in the tank.

## Ⅱ PREVIOUS RESEARCHES

Most of published researches on the selective withdrawal from a stratified fluid have been related with two layer of stratified flow by temperature and density difference in a channel or reservoir. Craya[2] has treated the withdrawal of two-layer system with a horizontal inlet located on a vertical boundary. Gariel[7] has presented an experimental results for the conditions of horizontal line sinks and three dimensional flows to point sinks are considered for the case in which the vertical extent both the upper and lower layers is unlimited. Also, there are several papers on flow into a channel where the lighter fluid is retained by a skimmer wall(e.g., Harleman [4];Harleman and Morgan[5];Harleman and Elder[6];Jirka[8]).

Yih[16],[17], Ippen and Harleman[12] have obtained an analytical solution for the steady two dimensional flow of a stratified fluid toward a line sink located at the corner formed by the channel bottom and a vertical wall, for the case of an initially constant density gradient in the vertical direction. The discharge of a stratified fluid (with a stable linear density variation at infinity) through a horizontal slot at the end of channel has been experimentally investigated by W.R.Delber[14], D.G.Huber[3] and T.W.Kao[11]. Goldring[1] conducted on capped and uncapped circular intake holes in the bed of a flume, to determine the intake flow rate at which the upper layer of a stratified flow begins to be drawn into the intake concerned temperature differences and Chiba[10] also derived the experimental parameters for the withdrawal of stratified flow where cooling water for power generation or industrial processing must be drawn from a thermal stratified source. Especially, Kawachi[13] studied the experimental dimension analysis for the design of the efficiency on freshening reservoir pipe. But there was no solution on how to estimate the salinity of conduit discharge from selective the withdrawal apparatus

## Ⅲ GOVERNING EQUATIONS

### 1. Analytical consideration

For the analytical solution of one dimensional problem in formulating for the condition of corresponding to incipicient withdrawal of upper layer at the inlet point, Berneoulli quantity may be adapted. It is assumed that only the fluid is in motion and friction and streamline curvature effects are negligible. Using the notation of Fig. 1, the energy balance equation is

$$\rho_2 \frac{(d-y)}{\rho_1} + y = \rho_2 \frac{(d-y_a)}{\rho_1} + y_a + \frac{V_a^2}{2g} \qquad (1)$$

Expanding and simplifying by $\rho_2 = (\rho_1 - \Delta\rho)$, to yield

$$\frac{V_a^2}{2g(\Delta\rho/\rho_1)} = y - y_a \qquad (2)$$

where $\Delta\rho = \rho_1 - \rho_2$, and replace $(D_i - D_m)$ in stead of $(y - y_a)$ from the notation of Fig. 2 which is the real experimental profile of the model, it notes

$$\frac{V_a^2}{g\,\frac{\Delta\rho}{\rho_1}} = 2\,(D_i - D_m) \qquad (3)$$

Where $V_a = \bar{k}\, v_a$ of the real average velocity of the test, Eqn. (3) changes by dimensionless values.

$$\frac{V_a^2}{g\,\frac{\Delta\rho}{\rho_1}(D_i - D_m)} = \frac{2}{k^2} \qquad (4)$$

The term of the Eqn. (4) shows that the Densimetric Froude number may be considered as a function of dimensionless value of $(2/k^2)$ which influenced by the prototype and position of the inlet, also thickness of the interface layer etc..

## 2. Dimensional analysis for the selective drainage apparatus.

There are big needs for the developemnt of water resources from the estuary with the stratified density flow. To make plan and design of freshening reservoir, experimental equation for the estimation of salinity in the under drainage conduit is the most important problem which should be solved. Therefore the case of stratified flow in which there is a difference of density and salinity variation between inlet layer and outlet one's, the following values can be selected to define the problems of experimental model.

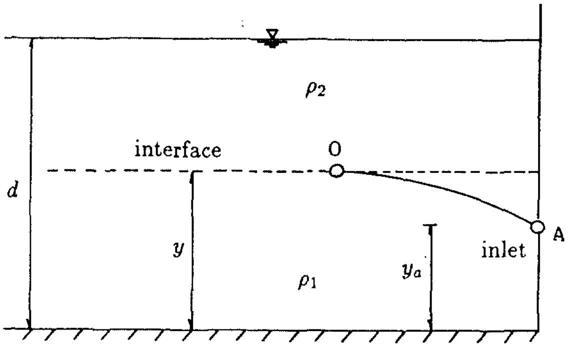

Fig. 1 Definition sketch for the withdrawal of lower layer

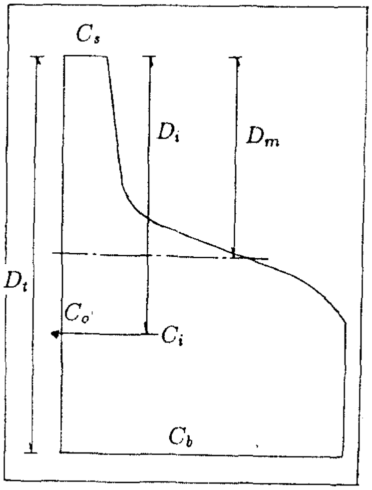

Fig. 2 Parameters profile in the tank

(1) Salinity of the outlet discharge :$C_0$ (kg/m$^3$)
(2) Salinity of the inlet layer :$C_i$ ( 〃 )
(3) Salinity of the surface water :$C_s$ ( 〃 )
(4) Salinity of the lower layer in the tank :$C_b$ ( 〃 )
(5) Depth of the inlet in the tank :$D_i$ (m)
(6) Total depth of the tank :$D_t$ (m)
(7) Depth of the interface in the tank:$D_m$ (m)

Let assumed the following values are related a functional relationship, and then

$$F(C_i,\ C_o,\ \Delta C,\ D_i,\ D_t,\ D_m) = 0 \qquad (5)$$

Where $\Delta C = C_b - C_s$, and the equation(5) can be combined the dimensionless parameters by the theorem of Buckingham Π

$$\Pi_1 = \frac{}{\Delta C},\ \Pi_2 = \frac{C_i - C_0}{D_i},\ \Pi_3 = \frac{D_m}{D_t} \qquad (6)$$

Therefore the form of dimensionless equation was developed

$$\frac{C_i - C_o}{\Delta C} = \Psi_2\left(\frac{D_i}{D_t},\ \frac{D_m}{D_i}\right) \qquad (7)$$

In which $\Psi_2$ is some function to be determined from observed data and especially the value of depth ratio($D_i/D_t$) converted to total depth ratio ($1- D_i/D_t$) for the convincing solution.

## Ⅳ EXPERIMENTAL APPARATUS

### 1. Experimental equipment

The experimental equipment is consist of three parts. The main part of a large tank in which the test was conducted is 0.5m deep, 2.5m wide and 3.0m in length. Second part is inflow facilities which connected in front of the mixing tank to supply freshwater through the three weirs for prevention of disturbance in the tank be caused inflow current. The other part is outflow structures which also consist of outlet pipes, control valve, and the weir of measuring discharges etc.. More detail diagram of the experimental equipment is shown in Fig. 3.

There are also two staff gages in the tank for measuring inlet depth and water level of the tank. In all tests, sea water was used for the lower layer liquid and freshwater for the upper layer. The inlet diameter used three kinds of

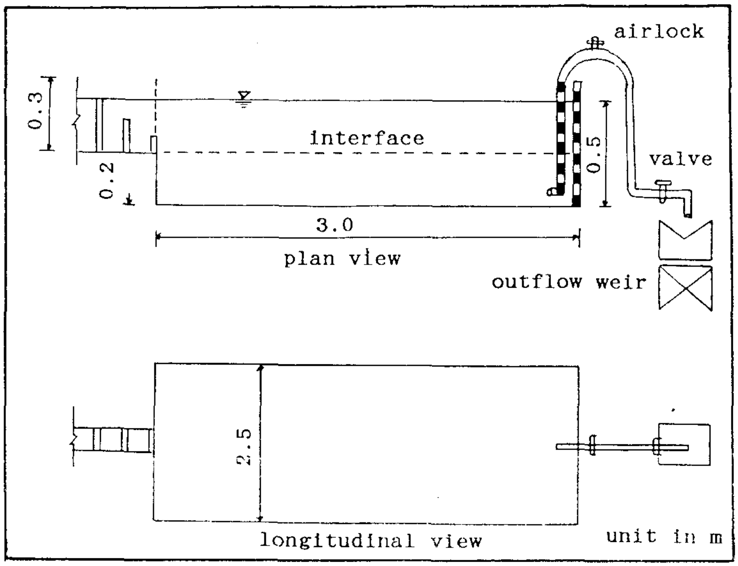

Fig. 3 Schematic diagram of the experimental equipment

type (D = 2.5, D=3.8 and D=6.0cm) and inflow channel scale is 30cm width by 40cm in depth.

### 2. Procedure

At the beginning of the test, sea water (nearly 27000ppm) pumped from the sea near the experimental place into the main tank of the model until the water level was desired at 20cm in most cases. The freshwater (nearly 800ppm) on the upstream side flows very slowly until the same as sea water depth through three prevention weir for turbulent movement. The interface of the tank was formed by slowly with a small quantity inflow of the fresh water and maintained until the water level of the total depth was nearly 40cm from the bottom. At the time of steady-state condition formed in the tank where there is no turbulent motion in the surface water, the test was performed by the following order.

(1) First of all, the vertical salinity distribution measured by 1cm depth in the tank.

(2) Controled the elevation of the inlet depth and checked water level of the tank.

(3) Open the outlet valve to control discharges and measured the overflow depth of the weir.

(4) After 0.2 or 0.5 minute, there is no distinguish variation of salinity in outer weir, checked the salinity of outlet discharges.

(5) Locked the outlet valve and go to the first step.

### 3. Range of test

The lower layers ranged from the bottom to the surface of the tank by depth interval 1cm at the time. In all test of the model, the test runs 16 cases, including the case of inlet prototype was changed. One case, it takes almost 15 times by changing the inlet depth 2cm interval of vertical direction in the tank. Each time salinity variation measured in steady-state of the tank as Fig. 4 and also the table 1 represent the summary of observed whole data list. Thickness of the interface layer was measured nearly 15cm in all cases and water temperature of the each layer was shown not so distinguished (±0.3 ℃). This test conducted to determine relative function between the inlet layer and outflow salinity below some boundary condition which influenced the density variation and discharges of the outlet. The total depth ($D_t$) was decided by average value between initial and ending water level of the test in each times.

## V EXPERIMENTAL RESULTS AND DISCUSSION

### 1. General tendency of the results

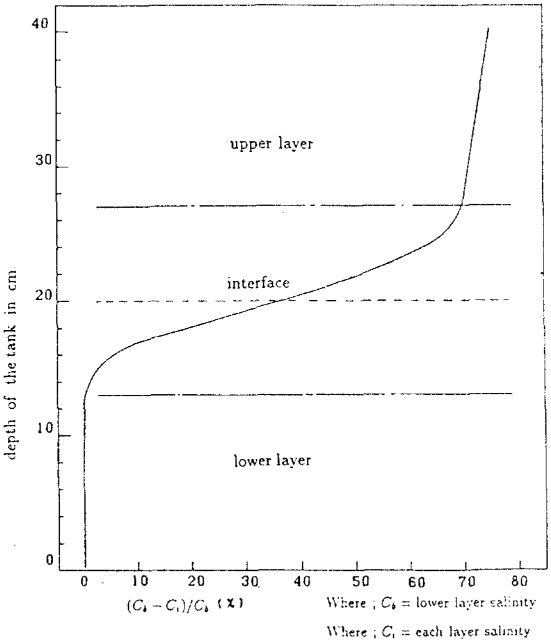

Fig. 4 Master salinity profile of the experimental tank

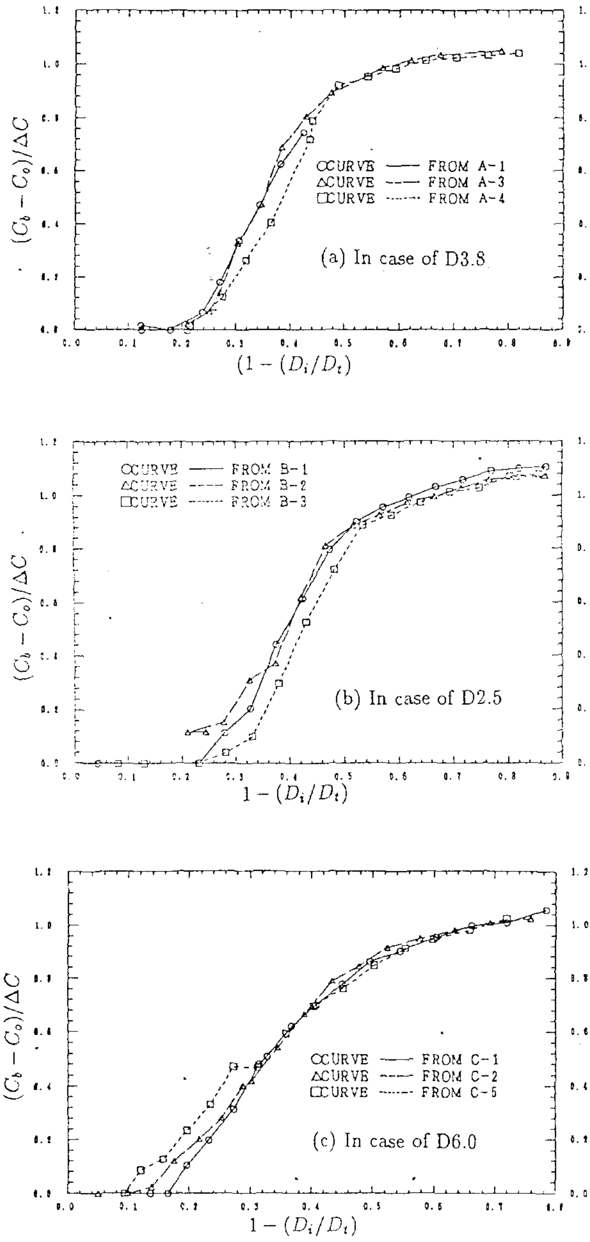

Fig. 5 Dimensionless curve between lower layer and outlet salinity variation by $\eta_1$

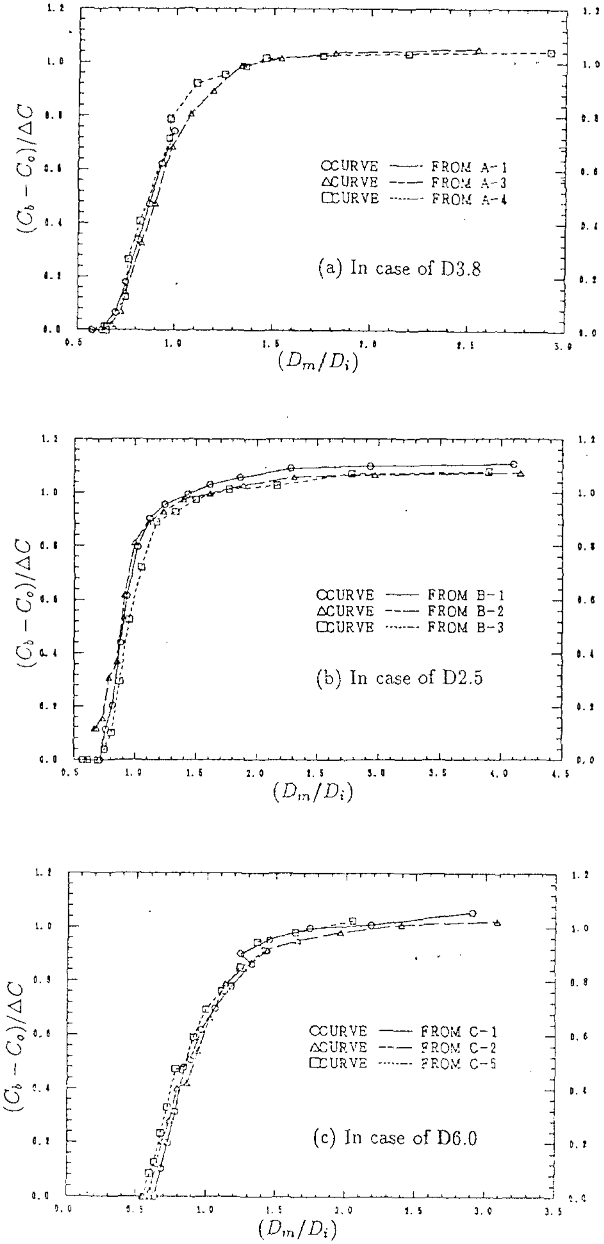

Fig. 6 Dimensionless curve between lower layer and outlet salinity variation by $\eta_2$

(1) The relationship between lower layer and outlet salinity variation by depth ratio : As illustrated and plotted in Fig. 5. and Fig. 6, the relationship between lower layer and outlet salinity was shown S-curve by some depth ratio. Horizontal line represent the depth ratio; $\eta_1 = 1 - (D_i/D_t)$, and $\eta_2 = (D_m/D_i)$, it means that the inlet depth increase from the bottom, if some critical depth ratio reached and then the outlet salinity suddenly changed. In this

curve, it was find out that the critical depth ratio is changed by the inlet prototype and thickness of the interface layer. By comparision of the depth ratio $\eta_1$ and $\eta_2$, the inclination of the $\eta_2$ is more steep because the interval of depth ratio is more shorter than $\eta_1$ value.
and outlet salinity variation by $\eta_2$

(2) The relationship between inlet and outlet salinity variation by depth ratio : As see in Fig. 7, the dimensionless variation value between inlet and outlet salinity represented as a function of depth ratio just like hydrograph. Depth ratio of the inlet increase from bottom of the tank which denoted comparing total depth ratio, salinity of the outlet was changed by some critical inlet depth reached. The relationship between inlet and outlet salinity variation influenced by the inlet depth ratio comparing with the total depth and also salinity variation of the vertical distribution in the tank. If the inlet depth exceeded some boundary transition layer, the variation of salinity also decreased. The average peak variation values of the $\eta_1$ can be expressed on $D_{2.5}$ = 0.38, $D_{3.8}$=0.35, $D_{6.0}$=0.30 of the each cases.

The case of dimensionless graph of the interface depth ratio with the inlet and outlet salinity variation (see Fig. 8) also represented the same as Fig. 7, the inlet layer and outlet salinity variation with the total depth ratio, but the shape was more steep and the range of distinct variation was more narrow. Also the average peak variation values of the $\eta_2$ shows $D_{2.5}$=0.9, $D_{3.8}$=0.85, $D_{6.0}$=0.8 of the each cases.

(3) Densimetric Froude number as a critical value : According to the analytical results,

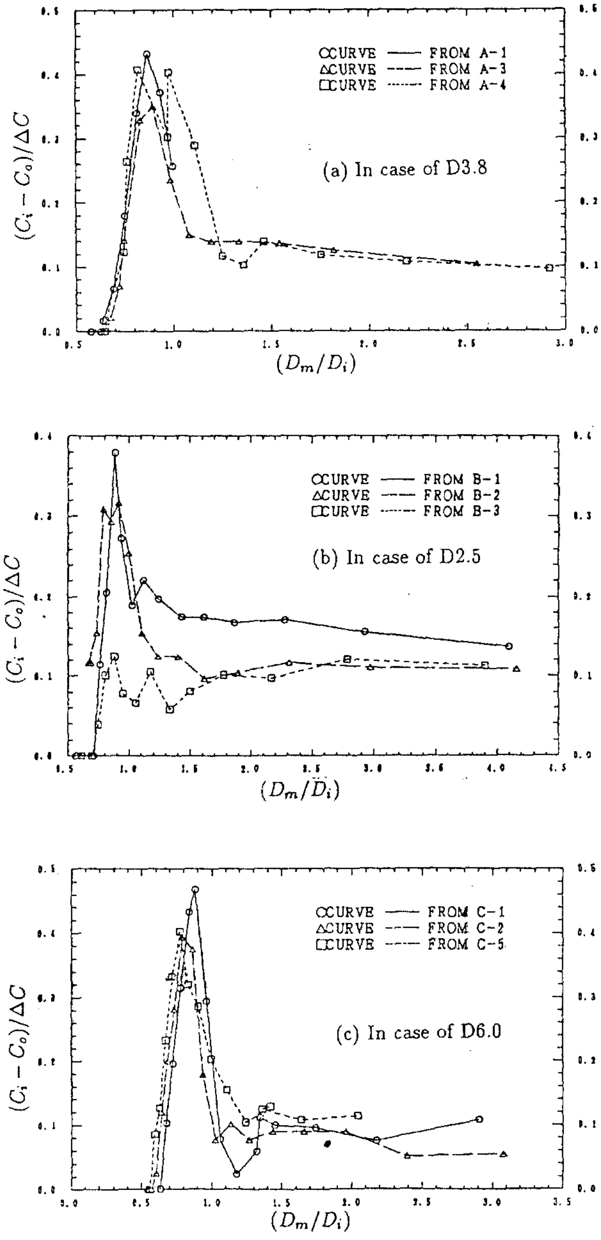

Fig. 7 Relationship between inlet layer and outlet salinity variation by $\eta_1$

Eqn. (4), the experimental data should be correlated by the two parameters $V_c / \sqrt{g'(D_i - D_m)}$ and some dimensionless depth ratio, $(D_i - D_m)/D$, as previous researches where $V_c$ = critical velocity at the inlet point. Craya[2] has treated the withdrawal of upper layer in which

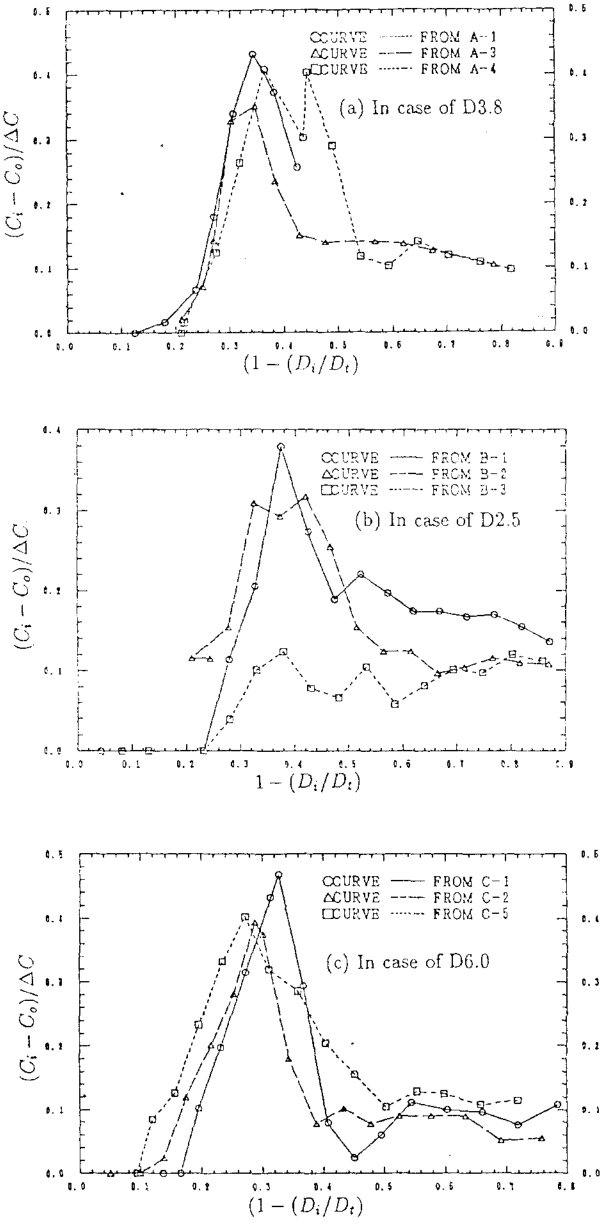

Fig. 8 Relationship between inlet layer and outlet salinity variation by $\eta_2$

intake is orifice and the length of flow was limited in $(D_i - D_m)$=1.5cm. For the withdrawal of lower layer. Huber[3] has treated the two dimensional flow through the slit in the bed of a flume, Chiba[10] has studied the horizontal intake conduit but the intake type was rectanguiar, also Harleman. Morgan. Purple[5] has considered for the vertical intake conduit but it was located in the bottom of the tank. All of the critical condition for the withdrawal of upper and lower layer were described very detailly by the Tamai[9] but most of derived formulas were conformed in condition of well defined interface.

This test was performed the conditions in which syphon conduit was installed and the interface thichness was a little well developed as shown in Fig. 4. Even though the experimental equipment was not so convenient and was conducted in the field, the data plotted in logarithmic coordinates should yield a straight line. The range of critical condition was limited in $1.6 \leq (D_i - D_m)/D \leq 3.0$

As shown in Fig. 9, the line defined by the following equation

$$\frac{V_c}{\sqrt{g'(D_i - D_m)}} = 0.263\left(\frac{D_i - D_m}{D}\right)^{2.919} \qquad (8)$$

Where $g' = g(\Delta\rho/\rho_1)$.

## 2. The Master dimensionless graph of salinity variation.

As see in Fig. 7 and Fig. 8, the observed plotting result of dimensionless parameters $((C_i - C_o)/\Delta C)$ appears a very sensitive tendency in entire range of the whole experimental tests, it may be concluded that the interface geometries on incipient stable state should be more complicated. Therefore, in order to make the representative equation for this experimental model, it must be establish the master dimensionless graph of the inlet layer and outlet salinity variation by depth ratio as so called Master curve. The Observed curves in master technics of Fig. 12 and Fig. 13 were overlapped

Table. 1 Summary of experimental data

| Case<br>No | Inlet type<br>D(cm) | Discharge $10^{-3}$<br>$m^3/sec$ | Number of times<br>No | Total dep. of tank<br>$D_t$(cm) | Range of inlet dep.<br>$D_i$(cm) | $D_i$–$D_m$ (Cri.)<br>(cm) | Graphing<br>simbols |
|---|---|---|---|---|---|---|---|
| 1 | 3.8 | 0.4680 | 9 | 40.0 | 35–28 | 8.5 | A–1 |
| 2 | // | // | 14 | 40.5 | 30–6 | 8.5 | A–2 |
| 3 | // | // | 12 | 40.5 | 32–7 | 8.5 | A–3 |
| 4 | // | 0.08723 | 15 | 40.5 | 32–6 | 5.5 | A–4 |
| 5 | // | 0.1498 | 15 | 40.5 | 32–5 | 6.5 | A–5 |
| 6 | // | 0.2330 | 15 | 39.9 | 30–6 | 7.5 | A–6 |
| 7 | 2.5 | 0.2330 | 15 | 40.8 | 39–5 | 7.5 | B–1 |
| 8 | // | 0.2330 | 15 | 41.0 | 31–5 | 6.5 | B–2 |
| 9 | // | 0.2330 | 15 | 38.1 | 35–5 | 7.0 | B–3 |
| 10 | // | 0.04344 | 14 | 41.1 | 32–6 | 4.5 | B–4 |
| 11 | // | 0.04344 | 15 | 40.1 | 30–2 | 4.0 | B–5 |
| 12 | 6.0 | 1.8165 | 16 | 40.5 | 35–6 | 14.0 | C–1 |
| 13 | // | 1.8165 | 17 | 40.0 | 38.7 | 13.5 | C–2 |
| 14 | // | // | 17 | 40.0 | 32–6 | 14.0 | C–3 |
| 15 | // | 1.01252 | 17 | 40.1 | 33–5 | 12.5 | C–4 |
| 16 | // | 1.01252 | 16 | 39.8 | 36–8 | 13.0 | C–5 |

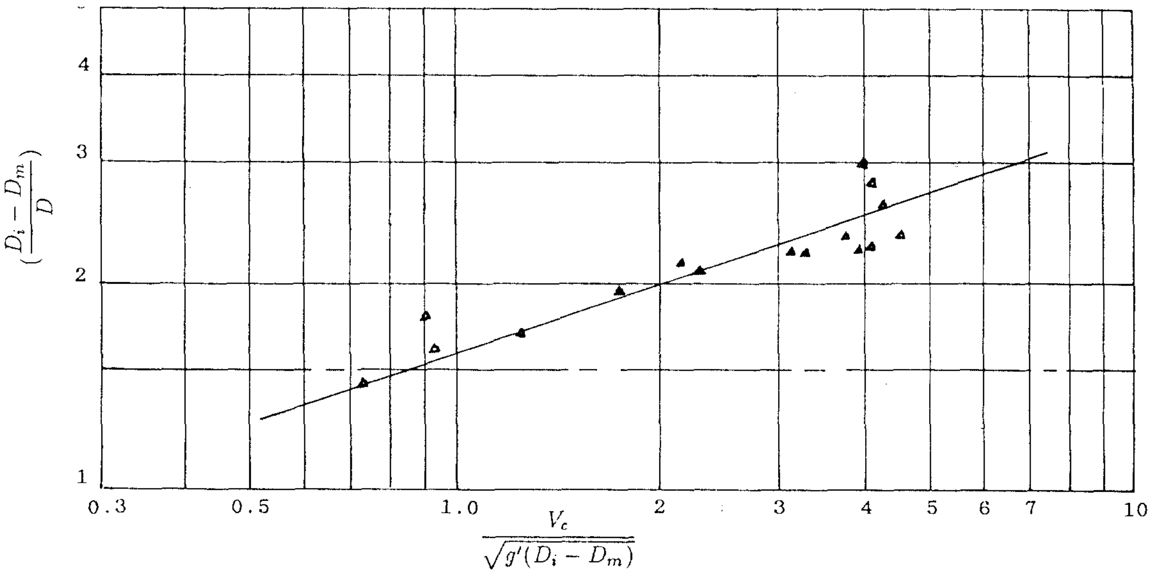

Fig. 9 Depth ratio of the critical condition as Densimetric Froude number

from (a), (b), and (c) of the Fig. 7 and Fig. 8.

The relationship between lower layer (so called reference salinity) and outlet salinity shows S-curve by some depth ratio with $(D_m/D_i)$ and $1-(D_i/D_t)$. Ultimately, the variation of inlet and outlet salinity influenced from vertical salinity distribution based on lower layer salinity, it is true that the variation of outlet salinity must be related the reference salinity which denoted the sublayer one. Therefore the Master S-curve (Fig. 10, 11) also were drawn by overlapped from (a), (b), and (c) of the Fig. 5 and Fig. 6.

Using the Master S-curve of the Fig. 10 and Fig. 11, the functional relationship between inlet layer and outlet salinity variation of the depth ratio can be yield as following equation.

$$\varepsilon(\eta-\Delta\eta) = \lim_{\eta - 0} \frac{S(\eta)-S(\eta-\Delta\eta)}{\eta} = \frac{dS(\eta)}{d\,\Delta\eta} \qquad (9)$$

$$\varepsilon_1(\eta_1) = \frac{\varepsilon_1(\eta_1) - \varepsilon_1(\eta_1 - \Delta\eta_1)}{\Delta\eta_1} \qquad (10)$$

$$\varepsilon_2(\eta_2) = \frac{\varepsilon_2(\eta_2) - \varepsilon_2(\eta_2 - \Delta\eta_2)}{\Delta\eta_2} \qquad (11)$$

where :

S = Representative value of $(C_b - C_o)/\Delta C$ from the S-curve.

$\varepsilon_1$ = The value of $(C_b - C_o)/\Delta C$ by shifted from S-curve (Fig. 10) of the depth ratio $\eta_1$.

$\varepsilon_2$ = The value of $(C_b - C_o)/\Delta C$ by shifted from S-curve (Fig. 11) of the depth ratio $\eta_2$.

$\Delta\eta$ = The interval of depth ratio,

$\Delta\eta_1 = 0.1$ and $\Delta\eta_2 = 0.2$.

### 3. Representative equation of the experimental results.

In the above mentioned procedure is adapted, the relationship between inlet layer and outlet salinity can be represented by three kinds of method. The real observed value is overlapped Master curve and, the others are the estimated values from derived equation and from the S-curve. Predicted equation which used in outlet

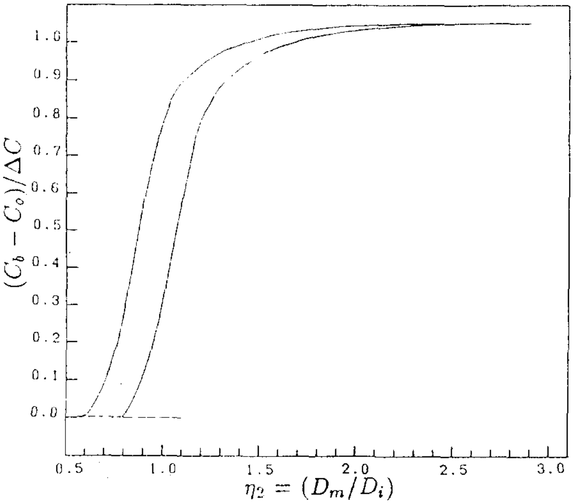

Fig. 10 Master dimensionless S-curve in depth ratio $\eta_1$

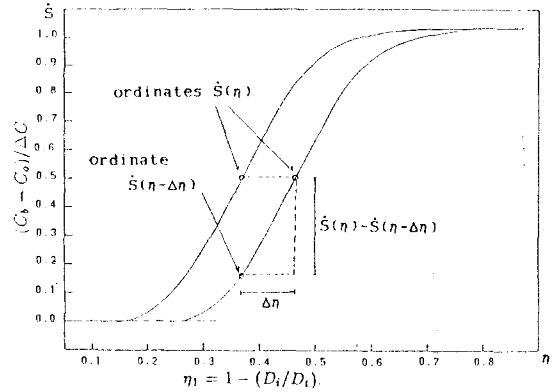

Fig. 11 Master dimensionless S-curve in depth ratio $\eta_2$

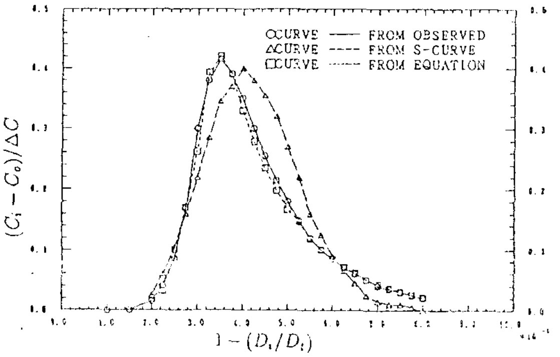

Fig. 12 Master and estimated dimensionless graph in depth ratio $\eta_1$

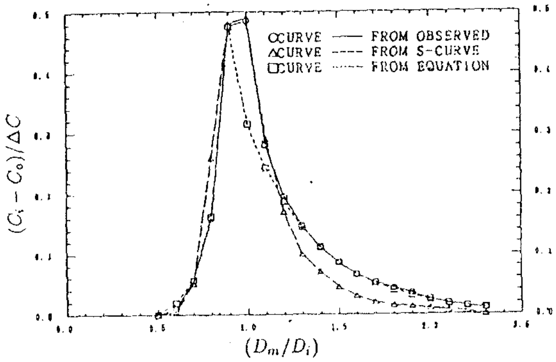

Fig. 13 Master and estimated dimensionless graph in depth ratio $\eta_2$

salinity computation are as follow by depth ratio $(1-(D_i/D_t)$ and $(D_m/D_i)$.

$$\frac{C_i - C_0}{\Delta C} = 0.018e^{\frac{(\eta_1 - 0.2)}{0.0476}} + \{1.24\eta_1 - 0.26\} \qquad (12)$$

$$\frac{C_i - C_0}{\Delta C} = 0.39e^{\frac{(0.375 - \eta_1)}{0.1478}} \qquad (13)$$

$$\frac{C_i - C_0}{\Delta C} = 0.01e^{\frac{(\eta_2 - 0.54)}{0.0932}} \qquad (14)$$

$$\frac{C_i - C_0}{\Delta C} = 0.315e^{\frac{(1 - \eta_2)}{0.3854}} \qquad (15)$$

In the above equation, the critical boundary condition can be calculated using the Eqn. (8).

### 4. Calibration of the estimated value.

There are two kinds of method which used for the calibration of experimental results in the outlet salinity.

$$\mathrm{RMS} = \left|\left| \frac{\sum_{i=1}^{n} (R_i - C_c)^2}{n} \right|\right|^{1/2} \qquad (16)$$

$$F = \frac{\sum_{i=1}^{n} (R_i - C_c)}{n} \qquad (17)$$

Where, $R_i$ = Observed value in Master graph,
$C_c$ = Computed value of the derived formula or the value from S-curve.

The calibration results compared with minimun value as in Table 2 and the value from derived formula was more adjusted.

## Ⅵ CONCLUSIONS

For the stratified fluid systems with a well developed interface between the liquids of similar densities and different salinity, the flow into a vertical inlet of various condition and prototypes are considered. The salinity differences between inlet layer and outlet discharge at some intake depth ratio studied by analytical and functional relationship for the drainage problems in which there is a freshening reservoir in the tidal land. This functional relationship will be contribute for the control of the outlet salinity variation in the freshening

Table 2. Calibration results for the derived formulars

| Calculation method | $(C_i-C_o)/\Delta C$ : $1-(D_i/D_t)$ | | $(C_i-C_o)/\Delta C$ : $(D_m/D_i)$ | |
|---|---|---|---|---|
| | From S-curve | From Eqn. | From S-curve | From Eqn. |
| R M S | 0.050648 | 0.016553 | 0.040045 | 0.034997 |
| F | 0.003485 | 0.000314 | 0.001750 | 0.001550 |

reservoir.

The results can be concluded as follows ;

(1) The most representative equation for the depth ratio of $\eta_1 = 1-(D_i/D_t)$ can be expressed
In condition of $(\eta_1)_{crit.} \le \eta_1 \le 0.325$ ;

$$C_o = C_i - \Delta C \left\{ 0.018e^{(\eta_1 - 0.2)/0.0476} + (1.24\eta_1 - 0.26) \right\} \tag{18}$$

In condition of $0.325 < \eta_1$ ;

$$C_0 = C_i - \Delta C \left\{ 0.39e^{(0.375 - \eta_1)/0.1478} \right\} \tag{19}$$

(2) The other representative equation for the depth ratio of $\eta_2 = D_m/D_i$ can be expressed
In condition of $(\eta_2)_{crit.} \le \eta_2 \le 0.9$ ;

$$C_0 = C_i - \Delta C \left\{ 0.01e^{(\eta_2 - 0.54)/0.0932} \right\} \tag{20}$$

In condition of $0.9 < \eta_2$ ;

$$C_0 = C_i - \Delta C \left\{ 0.315e^{(1-\eta_2)/0.03854} \right\} \tag{21}$$

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